Joint Relay and User Selection for Two-hop Multi-relay Multi-user MIMO Systems

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***Abstract*—In this work, we investigate the joint relay and user selection problem in two different multi-relay multi-user MIMO transmission modes, namely, an existing competition mode and a proposed cooperation mode. Each user is served by a single relay in competition mode while multiple users are served by active relays cooperatively in cooperation mode. Due to the high computational complexity of the optimal exhaustive enumeration algorithm, we propose a suboptimal capacity-based best-fit algorithm, which achieves above 86% and 89% of the system capacity of the optimal algorithm in competition and cooperation mode, respectively, while the computational complexity is linear with the number of relays and users in the system. Our simulation results also show that the proposed cooperation transmission mode has a better system performance than competition mode when signal-to-noise ratio is high.**

***Index Terms*—MU-MIMO, multi-relay, block diagonalization**

I. INTRODUCTION

Multi-user multiple-input multiple-output (MU-MIMO) relay systems have been studied extensively, e.g., [1], [2]. In these studies, base station (BS) serves a group of user equipments (UEs) via a single relay station (RS). The coexistence of broadcast channels at both BS–RS and RS–UE links is investigated in [3], where BS serves a group of RSs via MU-MIMO while each RS serves a group of cell edge UEs. In this paper, we call them as *competition mode*. Only the interference alignment problem is considered in [3]. In order to overcome the interference among UEs served by different RSs, we propose another transmission mode, *cooperation mode* which coordinates the interference by allowing RSs to serve UEs cooperatively.

Dirty paper coding (DPC) is the optimal precoding algorithm for MU-MIMO systems to maximize the system capacity. However, it is an impractical algorithm due to the high computational time it takes. Block diagonalization (BD) algorithm proposed in [4] is a practical linear precoding method to eliminate inter-user interference (IUI) in MU-MIMO systems. By projecting the precoding matrix of each UE into the null space of channel state information (CSI) of all other co-channel UEs, each UE can obtain an interference-free channel. However, the total number of receive antennas is required to be less than or equal to the total number of transmit antennas. Consequently, a problem arises, how to select a subset of active UEs among all the UEs to transmit in MU-MIMO system such that the capacity is maximized? This user selection problem in MU-MIMO systems has been studied but without the assistance of relays. The convex grouping algorithm proposed in [5] solves the user selection problem by formulating a quadratic optimization problem. In [6], the authors present a survey of user selection algorithms for MU-MIMO systems. The joint relay and user selection problem in point-to-point single antenna system is investigated in [7]. The objective is to minimize the total power consumption and the problem is decomposed into convex optimization problems. For multi-relay MU-MIMO systems, this problem is of high computational complexity. It cannot be transformed into mathematically tractable problems. Therefore, suboptimal heuristic algorithm is necessary. To the best of our knowledge, joint relay and user selection in a multi-relay MU-MIMO system with broadcast channels at both BS–RS and RS–UE links has not been investigated.

In this paper, we investigate the problem of, *How to select users and relays so as to maximize the system capacity in multi-relay MU-MIMO systems by using BD precoding?* The main contributions of this paper are summarized as follows:

- We propose a cooperation transmission mode by allowing relays to serve the same set of users cooperatively;
- We formulate a joint relay and user selection problem for each transmission mode (competition and cooperation). The objective is to maximize the system capacity;
- We develop one suboptimal algorithm, namely, capacity-based best-fit (CAP-BF) algorithm to select relays and users jointly in each transmission mode;
- We analyze the computational complexity and study the performance of the proposed algorithm. We compare the proposed algorithm with the optimal exhaustive enumeration and the random relay and user selection algorithms.

Our results show that our proposed cooperation mode has a better system capacity performance than the competition mode when SNR is high.

The rest of the paper is organized as follows. The system model is described in Section II. Our proposed cooperation mode is presented in Section III. Section IV studies the problem formulation for each transmission mode. The proposed algorithm and its computational complexity are specified in Section V. The simulation results are discussed in Section VI followed by conclusion and future work in Section VII.

Notations: The boldface uppercase and lowercase letters are used to represent matrices and vectors, respectively. $\mathbb{C}$ denotes the complex space. $\mathbf{A}^H$ represents the conjugate transpose of matrix $\mathbf{A}$. $\mathbf{I}_N$ stands for the $N \times N$ identity matrix. $|\mathcal{S}|$ is the

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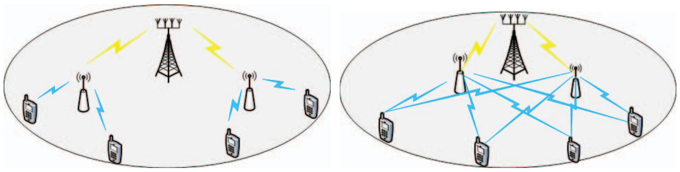
cardinality of the set $\mathcal{S}$. $\mathcal{S}(i)$ denotes the ith element of the set $\mathcal{S}$. $\cup$ is the union of sets while $\mathcal{S}\backslash s$ represents the set after deleting element s from set $\mathcal{S}$.

II. SYSTEM MODEL

In this section, we will explain the system model we consider for the relay and user selection as well as the existing transmission mode (competition mode) briefly. We consider a multiple relay assisted MU-MIMO single-carrier downlink (DL) data transmission network with one BS, a set of fixed RSs $\mathcal{R} = \{1, 2, \cdots, R\}$, and a set of UEs $\mathcal{U} = \{1, 2, \cdots, U\}$. BS and each UE are assumed to be equipped with A_B and A_U antennas, respectively. Each RS is equipped with A_{RT} transmit antennas and A_{RR} receive antennas. We focus on cell edge users that need the help of amplify-and-forward (AF) half-duplex (HD) RSs. We assume that there is no direct link between BS and any of U UEs. A time division channel allocation is used to facilitate the transmission. In the first time slot, BS broadcasts data packets to RSs. Then each RS amplifies the signals received and forwards them to the serving UEs. In this work, we study an existing competition transmission mode investigated in [3] and propose another transmission mode, called cooperation mode. An example of system architectures of both modes is shown in Fig. 1.



(a) Existing mode: Competition (b) Proposed mode: Cooperation

Fig. 1: Transmission modes

In the existing competition mode, each UE is served by a single RS. BS firstly broadcasts the data streams of all active UEs to the selected active RSs. Each RS then forwards the data streams to its serving UEs. In such cases, UEs suffer from IUI due to the simultaneous and separate transmissions from different RSs to independent UE groups. Let $\mathcal{R}_B \subset \mathcal{R}$ and $\mathcal{U}_R \subset \mathcal{U}$ denote the sets of selected active RSs and UEs, respectively. Since each UE is served by a single RS in competition mode, we define $\mathcal{U}_r$ as the set of active UEs served by RS r and $\mathcal{U}_R = \cup_{r\in\mathcal{R}_B}\mathcal{U}_r$ as the total selected UEs for transmission. During the first time slot, the data symbol vector $\mathbf{s}_u \in \mathbb{C}^{N\times 1}$ of UE u served by RS r is precoded at the BS by the precoding matrix $\mathbf{B}_{r,u}$. N is the number of data streams for each UE. The overall data vector received at RS r from the BS is

$$\hat{\mathbf{s}}_r = \mathbf{F}_r\mathbf{H}_r \sum_{r'\in\mathcal{R}_B} \mathbf{B}_{r'}\mathbf{s}_{r'} + \mathbf{F}_r\mathbf{n}_r, \tag{1}$$

where $\mathbf{s}_r = [\mathbf{s}^H_{\mathcal{U}_r(1)}, \cdots, \mathbf{s}^H_{\mathcal{U}_r(|\mathcal{U}_r|)}]^H$ is the data vector for RS r. It contains data streams for each UE served by RS r. $\mathbf{B}_r = [\mathbf{B}_{r,\mathcal{U}_r(1)}, \cdots, \mathbf{B}_{r,\mathcal{U}_r(|\mathcal{U}_r|)}]$ is the precoding at BS for RS r. $\mathbf{F}_r = [\mathbf{F}^H_{r,\mathcal{U}_r(1)}, \cdots, \mathbf{F}^H_{r,\mathcal{U}_r(|\mathcal{U}_r|)}]^H$ is the post-processing matrix at RS r, which is composed of post-processing sub-matrix for each UE u. $\hat{\mathbf{s}}_r = [\hat{\mathbf{s}}^H_{r,\mathcal{U}_r(1)}, \cdots, \hat{\mathbf{s}}^H_{r,\mathcal{U}_r(|\mathcal{U}_r|)}]^H$ is the receiving signal. $\mathbf{n}_r \sim \mathcal{CN}(0, \Xi_r)$ is the AWGN received by RS r.

In the second time slot, RS r multiplies the received signal $\hat{\mathbf{s}}_r$ by the precoding matrix $\mathbf{V}_r$ and broadcasts the processing signal to its serving UEs. The data vector transmitted from RS r is, $\hat{\mathbf{x}}_r = \mathbf{V}_r\hat{\mathbf{s}}_r$, where $\mathbf{V}_r = [\mathbf{V}_{r,\mathcal{U}_r(1)}, \cdots, \mathbf{V}_{r,\mathcal{U}_r(|\mathcal{U}_r|)}]$. Assume a linear receiver $\mathbf{T}_u \in \mathbb{C}^{N\times A_U}$ is employed at UE u, it can be shown that the estimated data vector is

$$\begin{aligned}\tilde{\mathbf{s}}_u =& \boldsymbol{\Gamma}_{r,u} + \sum_{u'\in\mathcal{U}_r\backslash u} \boldsymbol{\Upsilon}_{r,u',u} + \sum_{r'\in\mathcal{R}_B\backslash r}\sum_{u'\in\mathcal{U}_{r'}} \boldsymbol{\Upsilon}_{r',u',u} \\ &+ \sum_{r'\in\mathcal{R}_B} \boldsymbol{\Omega}_{r',u} + \mathbf{T}_u\mathbf{n}_u,\end{aligned} \tag{2}$$

where $\boldsymbol{\Gamma}_{r,u} = \mathbf{T}_u\mathbf{H}_{r,u}\mathbf{V}_{r,u}\mathbf{F}_{r,u}\mathbf{H}_r\mathbf{B}_{r,u}\mathbf{s}_u$ is the desired receiving signal. $\boldsymbol{\Upsilon}_{r,u',u} = \mathbf{T}_u\mathbf{H}_{r,u}\mathbf{V}_{r,u'}\mathbf{F}_{r,u'}\mathbf{H}_r\mathbf{B}_{r,u'}\mathbf{s}_{u'}$ and $\boldsymbol{\Upsilon}_{r',u',u} = \mathbf{T}_u\mathbf{H}_{r',u}\mathbf{V}_{r',u'}\mathbf{F}_{r',u'}\mathbf{H}_{r'}\mathbf{B}_{r',u'}\mathbf{s}_{u'}$ are the interference from other UEs served by the same RS r and other RSs, respectively. $\boldsymbol{\Omega}_{r',u} = \mathbf{T}_u\mathbf{H}_{r',u}\mathbf{V}_{r'}\mathbf{F}_{r'}\mathbf{n}_{r'}$ is the amplified and forwarded noise received at UE u from RS r'. $\mathbf{H}_{r,u} \in \mathbb{C}^{A_U\times A_{RT}}$ is the MIMO channel matrix between RS r and UE u. $\mathbf{n}_u \sim \mathcal{CN}(0, \Xi_u)$ is the AWGN received by UE u.

Single-cell BD precoding algorithm is applied to eliminate IUI at each broadcast channel. However, applying BD in competition mode can only eliminate IUI from UEs served by the same RS. IUI from UEs served by other active RSs simultaneously is still severe. The system capacity $C_1(\mathcal{R}_B, \mathcal{U}_R)$ of existing competition mode is given by

$$C_1(\mathcal{R}_B, \mathcal{U}_R) = \frac{1}{2}\sum_{r\in\mathcal{R}_B}\sum_{u\in\mathcal{U}_r} \log\det\left(\mathbf{I}_{A_U} + \frac{\boldsymbol{\Gamma}_{r,u}\boldsymbol{\Gamma}^H_{r,u}}{\boldsymbol{\Phi}_u}\right), \tag{3}$$

where $\boldsymbol{\Phi}_u = \sum_{u'\in\mathcal{U}_r\backslash u} \boldsymbol{\Upsilon}_{r,u',u}\boldsymbol{\Upsilon}^H_{r,u',u} + \sum_{r'\in\mathcal{R}_B} \boldsymbol{\Omega}_{r',u}\boldsymbol{\Omega}^H_{r',u} + \sum_{r'\in\mathcal{R}_B\backslash r}\sum_{u'\in\mathcal{U}_{r'}} \boldsymbol{\Upsilon}_{r',u',u}\boldsymbol{\Upsilon}^H_{r',u',u} + \mathbf{T}_u\mathbf{T}^H_u$. A normalized noise variance for Ξ is assumed, i.e., $\Xi_r = \mathbf{I}_{A_{RR}}$, $\Xi_u = \mathbf{I}_{A_U}$. The factor $\frac{1}{2}$ results from the fact that data is transmitted over two time slots.

In order to get rid of IUI in competition mode, we propose cooperation mode. Both competition and cooperation modes facilitate broadcast channels at both BS–RS and RS–UE links. However, instead of serving different groups of UEs, RSs are allowed to transmit cooperatively to the same group of UEs in cooperation mode. Different from multicast model proposed in [8], RSs cooperatively serve a group of UEs rather than a single UE. The precoding and postcoding at RSs and UEs should be designed jointly so as to coordinate IUI.

III. PROPOSED MODE: COOPERATION MODE

In this section, we will explain our proposed transmission mode which we call cooperation mode. The existing transmission mode exploits the multi-user diversity in the RS–UE link but the multi-relay diversity in the BS–RS link is restricted since each UE is served by a single RS. The main theme of our cooperation is to allow multiple RSs to cooperatively serve a group of UEs. The multi-relay diversity is further explored. The AF-HD relaying channel model where BS transmits symbols to UE $u \in \mathcal{U}_R$ via active RS set $\mathcal{R}_B$ in cooperation mode is formulated as follows. Parameters not specified in the proposed cooperation mode have the same definition as in competition mode. Different from existing competition mode, data symbol vectors of active UEs are broadcast to all active RSs without preprocessing during the first time slot. Therefore, the data symbol vector of a single UE $\mathbf{s}_u \in \mathbb{C}^{N\times 1}$ is transmitted through the selected channels $\mathbf{H}_{r,u}^{BR} \in \mathbb{C}^{A_{RR}\times N}$ from $\mathbf{H}_r \in \mathbb{C}^{A_{RR}\times A_B}$, where $\mathbf{H}_r = [\mathbf{H}_{r,\mathcal{U}_R(1)}^{BR}, \cdots, \mathbf{H}_{r,\mathcal{U}_R(|\mathcal{U}_R|)}^{BR}]$.

The overall data vector received at RS r from the BS is

$$\hat{\mathbf{s}}_r = \mathbf{F}_r\mathbf{H}_r\mathbf{s} + \mathbf{F}_r\mathbf{n}_r, \tag{4}$$

where $\mathbf{s} = [\mathbf{s}_{\mathcal{U}_R(1)}^H, \cdots, \mathbf{s}_{\mathcal{U}_R(|\mathcal{U}_R|)}^H]^H$ is the data vector for all active UEs. $\mathbf{F}_r = [\mathbf{F}_{r,\mathcal{U}_R(1)}^H, \cdots, \mathbf{F}_{r,\mathcal{U}_R(|\mathcal{U}_R|)}^H]^H$ and $\hat{\mathbf{s}}_r = [\hat{\mathbf{s}}_{r,\mathcal{U}_R(1)}^H, \cdots, \hat{\mathbf{s}}_{r,\mathcal{U}_R(|\mathcal{U}_R|)}^H]^H$ are the post-processing matrix and the data vector received at RS r, respectively.

The data vector transmitted from RS r in the second time slot is $\hat{\mathbf{x}}_r = \mathbf{V}_r\hat{\mathbf{s}}_r$, where $\mathbf{V}_r = [\mathbf{V}_{r,\mathcal{U}_R(1)}, \cdots, \mathbf{V}_{r,\mathcal{U}_R(|\mathcal{U}_R|)}]$ is the precoding matrix. It can be shown that signal received at UE u in cooperation mode is

$$\tilde{\mathbf{s}}_u = \boldsymbol{\Gamma}_{\mathcal{R}_B,u} + \boldsymbol{\Upsilon}_{\mathcal{R}_B,u} + \boldsymbol{\Omega}_{\mathcal{R}_B,u} + \mathbf{T}_u\mathbf{n}_u, \tag{5}$$

where $\boldsymbol{\Gamma}_{\mathcal{R}_B,u} = \sum_{r\in\mathcal{R}_B} \mathbf{T}_u\mathbf{H}_{r,u}\mathbf{V}_{r,u}\mathbf{F}_{r,u}\mathbf{H}_{r,u}^{BR}\mathbf{s}_u$ is the effective desired receiving signal from all active RSs at UE u. $\boldsymbol{\Upsilon}_{\mathcal{R}_B,u} = \sum_{r'\in\mathcal{R}_B}\sum_{u'\in\mathcal{U}_R\setminus u} \mathbf{T}_u\mathbf{H}_{r',u}\mathbf{V}_{r',u'}\mathbf{F}_{r',u'}\mathbf{H}_{r',u'}^{BR}\mathbf{s}_{u'}$ is the composite IUI from all other active UEs. $\boldsymbol{\Omega}_{\mathcal{R}_B,u} = \sum_{r'\in\mathcal{R}_B} \mathbf{T}_u\mathbf{H}_{r',u}\mathbf{V}_{r'}\mathbf{F}_{r'}\mathbf{n}_{r'}$ is the composite AF noise received at UE u from active RSs.

The data streams transmitted to all RSs are the same. There is no IUI. Postcoding matrix $\mathbf{F}_r \in \mathbb{C}^{N|\mathcal{U}_R|\times A_{RR}}$ at RS r is designed by using of zero-forcing postcoding, $\mathbf{F}_r = (\mathbf{H}_r^H\mathbf{H}_r)^{-1}\mathbf{H}_r$. The precoding matrices $\mathbf{V}_r$ at RSs and postcoding matrices $\mathbf{T}_u$ at UEs are designed jointly at BS.

The joint CSI matrix from active RSs to UE u is

$$\mathbf{H}_u = \left[\mathbf{H}_{\mathcal{R}_B(1),u}, \cdots, \mathbf{H}_{\mathcal{R}_B(|\mathcal{R}_B|),u}\right]. \tag{6}$$

The joint precoding matrix of all active RSs to UE u is

$$\mathbf{V}_u = \left[\mathbf{V}_{\mathcal{R}_B(1),u}^H, \cdots, \mathbf{V}_{\mathcal{R}_B(|\mathcal{R}_B|),u}^H\right]^H. \tag{7}$$

Multi-cell BD algorithm is applied to design $\mathbf{V}_u$ for each UE such that $\mathbf{H}_{u'}\mathbf{V}_u = \mathbf{0}, \forall u' \neq u$ as discussed in [9]. The postcoding matrix $\mathbf{T}_u$ is designed such that the channel from all RSs to UE u is diagonalized. Note that the joint design of precoding and postcoding matrices results in the change of effective receiving signal at each UE. The effective receiving signal is the superposition of signals from all active RSs. Given above transmission and interference model, the system capacity of cooperation mode $C_2(\mathcal{R}_B,\mathcal{U}_R)$ is given by

$$C_2(\mathcal{R}_B,\mathcal{U}_R) = \frac{1}{2}\sum_{u\in\mathcal{U}_R} \log\det\left(\mathbf{I}_{A_U} + \frac{\boldsymbol{\Gamma}_{\mathcal{R}_B,u}\boldsymbol{\Gamma}_{\mathcal{R}_B,u}^H}{\boldsymbol{\Phi}_u}\right), \tag{8}$$

where $\boldsymbol{\Phi}_u = \boldsymbol{\Upsilon}_{\mathcal{R}_B,u}(\boldsymbol{\Upsilon}_{\mathcal{R}_B,u})^H + \boldsymbol{\Omega}_{\mathcal{R}_B,u}(\boldsymbol{\Omega}_{\mathcal{R}_B,u})^H + \mathbf{T}_u\mathbf{T}_u^H$. Equation (8) is different from equation (3). Cooperative design of precoding of RSs results in the change of the effective desired signal and interference. The superposition of the signal received from all RSs will enhance the desired signal as well as coordinate interference.

IV. PROBLEM FORMULATION

In this section, we will formulate the problem of relay and user selection in existing competition and proposed cooperation modes. As the antenna constraints are different for both transmission modes, the problem of joint relay and user selection is formulated separately. The objectives of both problem are to maximize the system capacity.

The optimal UE and RS selection policies $\mathcal{R}_B^*, \mathcal{U}_R^*$ in competition mode are given by

$$\begin{aligned}
&(\mathcal{R}_B^*, \mathcal{U}_R^*) = \arg\max_{\mathcal{R}_B\subset\mathcal{R},\mathcal{U}_R\subset\mathcal{U}} \quad C_1(\mathcal{R}_B,\mathcal{U}_R) && \text{(9a)}\\
\text{s.t.}\quad & A_{RR}|\mathcal{R}_B| \leq A_B && \text{(9b)}\\
& A_U|\mathcal{U}_r| \leq A_{RT}, \forall r \in \mathcal{R}_B && \text{(9c)}\\
& \mathcal{U}_r \cup \mathcal{U}_{r'} = \emptyset,\ \forall r \neq r' \in \mathcal{R}_B && \text{(9d)}
\end{aligned}$$

The objective (9a) is to maximize the system capacity of competition mode. Constraint (9b) and (9c) are antenna constraints for MU-MIMO with BD. The number of antennas of BS A_B is required to be larger than or equal to the number of receive antennas of all active RSs $A_{RR}|\mathcal{R}_B|$. The number of receive antennas of all active UEs served by the same RS $A_U|\mathcal{U}_r|$ should be less than or equal to the number of transmit antennas of that RS A_{RT}. (9d) guarantees each UE is served by at most one RS and RSs serve separate groups of UEs.

The optimal UE and RS selection policies $\mathcal{R}_B^*, \mathcal{U}_R^*$ in cooperation mode are given by

$$\begin{aligned}
&(\mathcal{R}_B^*, \mathcal{U}_R^*) = \arg\max_{\mathcal{R}_B\subset\mathcal{R},\mathcal{U}_R\subset\mathcal{U}} \quad C_2(\mathcal{R}_B,\mathcal{U}_R) && \text{(10a)}\\
\text{s.t.}\quad & A_U|\mathcal{U}_R| \leq A_{RT}|\mathcal{R}_B| && \text{(10b)}\\
& A_U|\mathcal{U}_R| \leq A_B \leq A_{RR} && \text{(10c)}\\
& A_{RT}|\mathcal{R}_B| \leq A_{RR} && \text{(10d)}
\end{aligned}$$

The objective (10a) is to maximize the system capacity of cooperation mode. Constraint (10b) is the antenna constraint of applying multi-cell BD precoding algorithm. The number of transmit antennas of all active RSs $A_{RT}|\mathcal{R}_B|$ is required to be larger than or equal to the number of receive antennas of all active UEs $A_U|\mathcal{U}_R|$. (10c) guarantees that the data streams of all active UEs can be transmitted from BS and successfully received by each active RS. Constraint (10d) ensures that the data streams of all active UEs is transmitted with all interference coordinated by multi-cell BD from RSs. The maximum number of active RSs that can be served in cooperation mode is infinite if without constraint (10d).

Both of the optimization problems are computationally complex when N_R and N_U in the system is large. An exhaustive enumeration over all possible UE and RS sets guarantees the system capacity is maximized, but with combinatorial complexity since the possible sets of UEs and RSs are all combinations of choosing a subset of UEs and RSs from all UEs and RSs in the system. Therefore, we propose a suboptimal algorithm with low complexity for each mode.

V. LOW-COMPLEXITY SELECTION ALGORITHM

As discussed in the previous section, the formulated problems (9a)–(9d) and (10a)–(10d) are with high computational complexity. In this section, we study a suboptimal algorithm to solve the formulated problem for both modes. In order to simplify the selection and computational complexity analysis, the following assumptions will be made:

Assumption 1: The spatial layers of each channel are fully utilized, i.e., $A_{RR}|\mathcal{R}_B| = A_B$ and $A_U|\mathcal{U}_r| = A_{RT}, \forall r \in \mathcal{R}_B$ for competition mode. $A_U|\mathcal{U}_R| = A_{RT}|\mathcal{R}_B|$ and $A_U|\mathcal{U}_R| = A_B$ for cooperation mode.

Assumption 2: The number of receive antennas at each RS in cooperation mode is just enough to receive data streams of all active UEs, i.e., $A_U|\mathcal{U}_R| = A_{RR}$. In this way, the number of RS is restricted by the number of RS receive antennas as, $A_{RT}|\mathcal{R}_B| = A_B$ based on assumption 1 and 2.

In this paper, we propose a capacity-based best-fit (CAP-BF) algorithm to select RSs and UEs jointly as specified in Algorithm 1. Both active RS set $\mathcal{R}_B^*$ and active UE set $\mathcal{U}_R^*$ are initialized to be empty. In the first step, the best BS–RS–UE link will be selected in each iteration according to joint RS and UE selection metric

$$\{r^*, u^*\} = \arg \max_{r\in\mathcal{R}\setminus\mathcal{R}_B^*, u\in\mathcal{U}\setminus\mathcal{U}_R^*} C_i\left(\mathcal{R}_B^* \cup \{r\}, \mathcal{U}_R^* \cup \{u\}\right). \tag{11}$$

$i = 1$ denotes the capacity of competition mode while $i = 2$ represents cooperation mode. The RS and UE providing the best capacity along with the sets of already selected RSs $\mathcal{R}_B^*$ and UEs $\mathcal{U}_R^*$ are selected. It is repeated until the maximum number of active RSs that can be included in the system is reached (Line 1–5). After this step, the active RSs set $\mathcal{R}_B^*$ is determined. Step 1 of CAP-BF is the same for both modes. Other UEs served by each RS in competition mode or served by all active RSs in cooperation mode are determined based on the UE selection metric in the second step (Line 6–11 for competition mode, line 12–15 for cooperation mode). The UE selection metric adopted to select UEs in the second step is

$$u^* = \arg \max_{u\in\mathcal{U}\setminus\mathcal{U}_R^*} C_i\left(\mathcal{R}_B^*, \mathcal{U}_R^* \cup \{u\}\right). \tag{12}$$

The UE providing the highest system capacity together with the already selected RSs $\mathcal{R}_B^*$ and UEs $\mathcal{U}_R^*$ will be selected in each iteration until the maximum number of active UEs served by each RS and all RSs are reached for competition and cooperation mode, respectively. We assume $A_{RR} = A_{RT}$ in competition mode. Hence, line 2 in Algorithm 1 ensures constraint (9b) for competition mode and (10c), (10d) for cooperation mode. Line 7 and line 12 guarantee constraints (9c) and (10b), respectively. User selection condition in line 8 ensures constraint (9d).

The objective of proposing suboptimal algorithm is to reduce the computational complexity. Therefore, the complexity of the algorithm shall be investigated. According to assumption 1 and assumption 2, the maximum number of active UEs that can be served in each mode is $N_U = \lfloor A_B/A_U \rfloor$ for both competition mode and cooperation mode. The maximum number of active UEs served by each RS is $N_{U_r} = \lfloor A_{RT}/A_U \rfloor$ in competition mode. The maximum number of active RSs that can be served is $N_R^1 = \lfloor A_B/A_{RR} \rfloor$ for competition mode and $N_R^2 = \lfloor A_B/A_{RT} \rfloor$ for cooperation mode. BD algorithm applied to the system with a transmit antennas at the transmitter, b receive antennas at each receiver and c receiver has the complexity of $\varpi(a, b, c) = \mathcal{O}(a^2bc + ab^2c^2 + b^3c^3)$ for each receiver.

Algorithm 1: CAP–BF Algorithm

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input: $\mathcal{U}, \mathcal{R}, A_B, A_{RR}, A_{RT}, A_U, \mathbf{H}$
output: $\mathcal{R}_B^*, \mathcal{U}_R^*, \mathcal{U}_r^*, \forall r \in \mathcal{R}_B$

Step 1: Joint RS and UE selection:
1  $\mathcal{R}_B^* = \emptyset$; $\mathcal{U}_R^* = \emptyset$;
2  while $A_{RT}|\mathcal{R}_B^*| \le A_B$ do
3      RS and UE selection metrics in (11) ;
4      $\mathcal{R}_B^* \leftarrow \mathcal{R}_B^* \cup \{r^*\}$; $\mathcal{U}_r^* = \{u^*\}$; $\mathcal{U}_R^* \leftarrow \mathcal{U}_R^* \cup \{u^*\}$ ;
5  end

Step 2: UEs served by RSs selection:
Competition Mode:
6  for $r \in \mathcal{R}_B^*$ do
7      while $A_U|\mathcal{U}_r^*| \le A_{RT}$ do
8          UE selection metrics for competition mode in (12);
9          $\mathcal{U}_r^* \leftarrow \mathcal{U}_r^* \cup \{u^*\}$; $\mathcal{U}_R^* \leftarrow \mathcal{U}_R^* \cup \{u^*\}$;
10     end
11 end

Cooperation Mode:
12 while $A_U|\mathcal{U}_R^*| \le A_{RT}|\mathcal{R}_B^*|$ do
13     UE selection metrics for cooperation mode in (12);
14     $\mathcal{U}_r^* \leftarrow \mathcal{U}_r^* \cup \{u^*\}$; $\mathcal{U}_R^* \leftarrow \mathcal{U}_R^* \cup \{u^*\}$;
15 end
```

In the first step, the UE and RS provide the highest total capacity together with the already selected UE and RS are selected from the remaining unselected UEs and RSs. In each iteration i, BD algorithm applied to BS–RS link requires $\varpi(A_B, A_{RR}, i)$ complexity for each active UE. For each RS, the UE selected is the first UE served by it. The SVD precoding and capacity calculation require low computational complexity compared with BS–RS link. UEs are selected for each RS in the second step. BD algorithm is applied to RS–UE link. The computational complexity of each active UE in iteration i is $\varpi(A_{RT}, A_U, i)$. The overall computational complexity of CAP-BF for competition mode is given by

$$\begin{aligned}\psi_{Cap}^1 = &\sum_{i=2}^{N_R^1}(R-i+1)(U-i+1)\varpi(A_B, A_{RR}, i)\cdot i \\ &+ \sum_{r=1}^{N_R^1}\sum_{i=2}^{U_r}(U-i+1)\varpi(A_{RT}, A_U, i)\cdot i \\ &\approx \mathcal{O}\left((N_R^1)^5 A_{RR}^3 RU\right)\end{aligned}. \tag{13}$$

The computational complexity of CAP-BF for cooperation mode is given by

$$\begin{aligned}\psi_{Cap}^2 &= \sum_{i=2}^{N_R^2}(R-i+1)(U-i+1)\varpi(A_{RT}\cdot i, A_U, i)\cdot i \\ &+ \sum_{i=U_R-N_R^2}^{U_R}(U-i+1)\varpi(A_{RT}\cdot i, A_U, i)\cdot i \\ &\approx \mathcal{O}\left((N_R^2)^5 A_{RT}^2 A_U R U\right)\end{aligned} . \quad (14)$$

In order to test the performance of our proposed algorithm CAP-BF, we compare it with the optimal selection algorithm: exhaustive enumeration. The latter conducts a brute-force searching over all possible active RS and UE sets. The system capacity of each combination of active RS and UE sets is calculated and compared. The candidates providing the best system capacity will be selected. It ensures the capacity of the system is maximized. However, the computational time is extremely high especially when the searching space is large. The complexity of the optimal algorithm is calculated as follows.

BD algorithm applied at BS–RS and RS–UE links require computational complexity of $\varpi(A_B, A_{RR}, N_R^1)$ for each RS in $\mathcal{R}_B$ and $\varpi(A_{RT}, A_U, N_{U_r})$ for each UE served by RS r. The calculation of system capacity has computational complexity $\sigma_1 = \mathcal{O}(N_U^3 A_B A_{RR})$ for competition mode. The overall complexity of optimal algorithm for competition mode is

$$\begin{aligned}\psi_{Opt}^1 &= \begin{pmatrix} R \\ N_R^1 \end{pmatrix}\begin{pmatrix} U \\ N_U \end{pmatrix}\cdot\Big(\varpi(A_B, A_{RR}, N_R^1)N_R^1 \\ &+ \varpi(A_{RT}, A_U, N_{U_r})N_U + \sigma_1\Big) \\ &\approx \mathcal{O}\left(\begin{pmatrix} R \\ N_R^1 \end{pmatrix}\begin{pmatrix} U \\ N_U \end{pmatrix}((N_R^1)^3 A_{RR}^3 + A_U^3 N_{U_r}^3 N_U)\right)\end{aligned} . \quad (15)$$

Similarly, the overall complexity of optimal algorithm for cooperation mode is given by

$$\begin{aligned}\psi_{Opt}^2 &= \begin{pmatrix} R \\ N_R^2 \end{pmatrix}\begin{pmatrix} U \\ N_U \end{pmatrix}\cdot\left(\varpi(A_{RT}N_R^2, A_U, N_U)N_U + \sigma_2\right) \\ &\approx \mathcal{O}\left(\begin{pmatrix} R \\ N_R^2 \end{pmatrix}\begin{pmatrix} U \\ N_U \end{pmatrix} A_{RT}^2 (N_R^2)^2 N_U^2 A_U\right)\end{aligned} . \quad (16)$$

Note that the ZF postcoding at RSs has low computational complexity compared with BD algorithm applied at RS–UE link, which is omitted here. Consequently, the optimal user selection algorithm has combinatorial computational complexities while our proposed CAP–BF algorithm has linear complexities with U and R for both competition and cooperation modes.

For both modes, the information exchange procedures are assumed to be the same. Each RS in $\mathcal{R}$ firstly sends pilot to all UEs in the system. Each UE feedbacks the estimated CSI. Then BS sends pilots to all RSs. Each RS feedbacks its CSI as well as CSI received from all UEs. We assume CSI between BS to each RS and CSI between each RS to each UE are perfectly known at BS after this step. The joint RS and UE selection algorithm will be performed at BS. The problem of control overhead can be solved by reusing UL pilots which is in general beyond the scope of this work.

VI. SIMULATION AND NUMERICAL RESULTS

In this section, we compare the performance of our proposed algorithm with the optimal exhaustive enumeration and random user selection algorithms in each transmission mode.

Fig. 2 shows the relationship between ergodic capacity of the system (averaged over 10^4 channel realizations) and signal-to-noise ratio (SNR) in competition mode and cooperation mode. In the simulation, the BS is equipped with $A_T = 8$ transmit antennas. $U = 10$ candidate UEs are equipped with $A_U = 2$ receive antennas each. $R = 4$ candidate RSs are equipped with $A_{RR} = 8$ receive antennas and $A_{RT} = 4$ transmit antennas each. In competition mode, each RS is required to serve at most $\frac{A_{RT}}{A_U} = 2$ UEs. Hence, there are extra receive antennas and only a subset of 4 receive antennas at RS is required. In this paper, we select receive antennas sequentially without applying antenna selection algorithms. The result shows that the competition mode has worse capacity than cooperation mode when SNR is higher than around 10 dB (intersection point of system capacity of two modes). It proves that IUI in competition mode can inflict significant performance losses, especially at high SNR. When SNR is low (below 10 dB), cooperation mode has worse performance. Because noise is more significant than interference when SNR is low. UEs in cooperation mode are served by two more RSs, resulting in two more folds of noise received at each UE. As SNR increases, the advantage of cooperative transmission comes into surface. The capacity is increasing significantly.

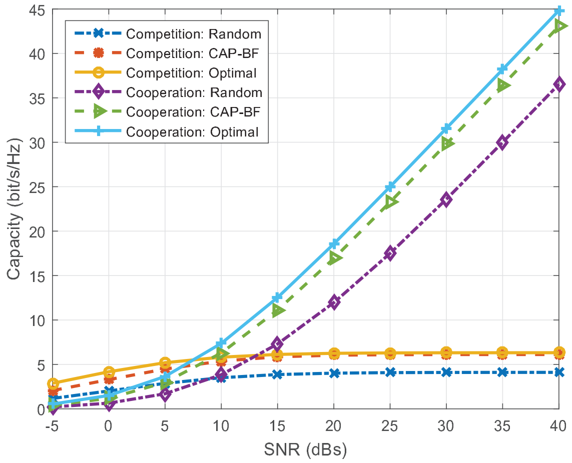

Fig. 2: Ergodic capacity vs. SNR of different user selection algorithms in two modes

Fig. 3 shows the ergodic capacity of the system (averaged over 10^4 channel realizations) versus the number of candidate UEs in competition mode and cooperation mode. The SNR is 20 dB in the simulation. Other parameters remain the same.

The result shows that when the number of UEs increases, the capacity gap between the proposed algorithm and the optimal exhaustive enumeration algorithm also increases. The reason is that it is more difficult for the proposed algorithm to find the optimal user set due to the enlarged searching space of UEs when the number of UEs are increased. The CAP–BF user and relay selection algorithm achieves above 86% and 89% of the system capacity of the optimal algorithm in competition mode and cooperation mode, respectively.

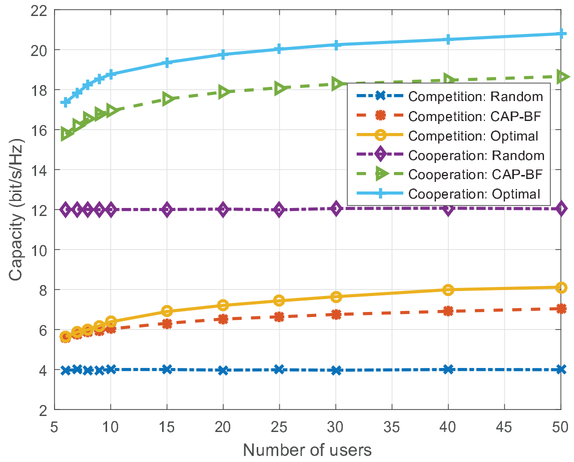

Fig. 3: Ergodic capacity vs. number of users of different user selection algorithms in two modes

Fig. 4 shows the average runtime (averaged over 10^4 channel realizations) versus the total number of candidate UEs in the system of the proposed CAP–BF algorithm and the optimal exhaustive enumeration algorithm. It shows the optimal algorithm has an exponential computational time with respect to the number of UEs in the system. Whereas, our proposed CAP–BF algorithm has linear computational time with the number of UEs in the system. The runtime of cooperation mode is slightly higher than that of competition mode, although the order of complexity is the same. The increase in the runtime of cooperation mode is because of the joint formation of precoding matrices. BD algorithm is applied to matrices with higher dimension than that in competition mode for each UE.

VII. Conclusion and Future Work

To conclude, we analyze the user selection problem in competition and cooperation transmission modes in MU-MIMO systems with multiple relays and multiple users. The objective is to strategically select a subset of active relays and users to maximize the system capacity while keeping the computational complexity as low as possible. The optimal user selection algorithm, exhaustive enumeration algorithm achieves the highest system capacity. However, the computational complexity is too high to be implemented. Therefore, we propose a low complexity suboptimal user selection algorithm, namely CAP–BF algorithm for each transmission mode. Computational complexity analysis and simulation results show that our proposed CAP–BF algorithm has a suboptimal performance, which achieves above 86% and 89% of the system capacity of the optimal algorithm in competition mode and cooperation mode, respectively. And computational cost of CAP–BF algorithm linearly increases with the total number of relays and users. Simulation results also show that the proposed cooperation transmission mode has a better system performance than the competition mode when SNR is high at the sacrifice of more receive antennas at relays. For future work, we plan to investigate the relay and user selection problem in non-ideal conditions, such as when the CSI is imperfect.

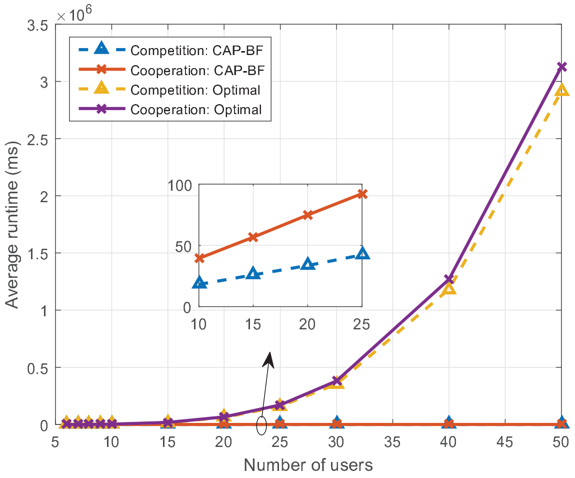

Fig. 4: Average runtime vs. number of users of different user selection algorithms in two modes

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