Transmission Mode Selection in Cooperative Multi-cell Systems Considering Training Overhead

Qian Zhang and Chenyang Yang
School of Electronics and Information Engineering, Beihang University, Beijing, 100191, China
Email: qianzhang@ee.buaa.edu.cn, cyyang@buaa.edu.cn

***Abstract*—Cooperative base station transmission, also known as coordinated multi-point (CoMP) transmission, is a promising technique to improve spectrum efficiency of cellular networks. However, coherent CoMP joint transmission needs huge training overhead which will reduce the effective data transmission rate. In this paper, a downlink transmission mode selection method is proposed, aiming at improving cell-edge throughput without reducing cell-center user rate. To reduce the adverse impact of the overhead, we select the following users for CoMP transmission: those can obtain significant performance gain from CoMP and those can increase the multiplexing gain. A threshold for large scale SINR is defined to find cell-edge users. An adaptive orthogonal threshold is designed for selecting partner users for the cell-edge users. Impact of the two thresholds are analyzed and performance of the proposed method are evaluated through simulations, which shows evident performance gain over both Non-CoMP and Full-CoMP systems.**

I. INTRODUCTION

Other-cell interference (OCI) is a major bottleneck to improve spectrum efficiency in universal frequency reuse cellular networks. Among various interference avoidance and mitigation schemes, cooperative base station (BS) transmission, also known as coordinated multi-point (CoMP) joint transmission in 3GPP, has been recognized as a promising technique that is able to convert OCI into useful signals [1, 2].

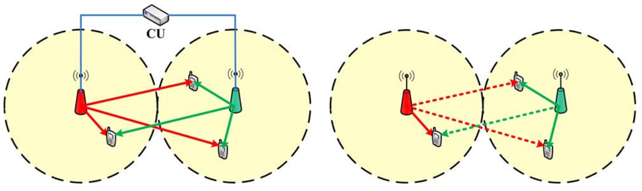
Training symbols are usually applied for channel estimation at the user end, which occupy resources for downlink data transmission. For multi-user (MU) multi-input multi-output (MIMO) systems, the overhead introduced by the training signals is in proportion to either the number of transmit antennas or the number of users [3–5]. For coherent CoMP transmission, the cooperative BSs compose a large MIMO system and more users can be served concurrently, thereby huge training overhead will be required. When considering the overhead, the net data rate of some users under CoMP transmission may be even less than those under Non-CoMP transmission [5]. Therefore, it is necessary to select proper users to be served with CoMP transmission mode.

Transmission mode selection has been extensively studied for single cell MIMO systems, see [6–8] and the reference therein. By switching the transmission mode between using single user (SU) and MU-MIMO precoding, or between transmitting single and multiple data streams based on the channel condition, higher spectrum efficiency can be achieved.

In this paper, a mode selection method for downlink CoMP transmission is proposed. To combat the negative effect of the overhead on system throughput, we allow the following users for CoMP transmission: those who can gain more benefit from CoMP and those who can increase the multiplexing gain. These users include cell-edge users that demand for help from BS cooperation to avoid OCI, as well as the users who can be served together with the cell-edge users without degrading the performance of each other. To this end, we first introduce a threshold to find cell-edge users only depending on the large scale fading gain. To select partner users of cell-edge users for CoMP MU-MIMO transmission, we then derive an adaptive orthogonal threshold for user scheduling. Simulation results show that the proposed method can improve the cell-edge throughput without reducing the cell-center users' rate.

II. SYSTEM MODEL

Consider a cellular system consisting of M BSs each with N_t antennas and K single-antenna users. Let $\mathcal{U}_n = \{u_{n1}, u_{n2}, \ldots, u_{nK}\}$ denote the set of users in the nth cell, $n = 1, \ldots, M$, then $\mathcal{U} = \mathcal{U}_1 \cup \cdots \cup \mathcal{U}_M$ denotes the set of all users in all coordinated cells, where $\cup$ is a union operation. Let $\mathbf{h}_{u_{nk}} = [\alpha_{u_{nk}1}\mathbf{h}_{u_{nk}1}, \ldots, \alpha_{u_{nk}M}\mathbf{h}_{u_{nk}M}] \in \mathbb{C}^{1\times MN_t}$ denote the downlink channel vector of user u_{nk}, where $\alpha_{u_{nk}m}$ and $\mathbf{h}_{u_{nk}m} \in \mathbb{C}^{1\times N_t}$ are respectively the large scale fading gain and the small scale channel vector from BS m to user u_{nk}, $m = 1, \ldots, M, k = 1, \ldots, K$.



(a) CoMP system (b) Non-CoMP system

Fig. 1. CoMP and Non-CoMP downlink transmission

A. CoMP Transmission

Under this transmission mode, M BSs are connected with a central unit (CU) by low latency backhaul links and act as a large MIMO system, as shown in Fig. 1(a). Denote $\mathcal{Q} = \{q_1, \ldots, q_L\}$ as the set of L users which are served

---

This work is supported by the International S&T Cooperation Program of China (ISCP) (No. 2008DFA12100).

978-1-4244-8331-0/11/$26.00 ©2011 IEEE

by the M BSs at the same time, $\mathcal{Q} \subset \mathcal{U}$. The data of these users are shared via advanced gateway among the M BSs, and the channel state information (CSI) of each user is collected from its serving BS and then forwarded to the CU. The CU computes the global precoding and then announces the results to all BSs. The received signal of user q_l can be expressed as

$$y_{q_l} = \mathbf{h}_{q_l}\mathbf{m}_{q_l}^H x_{q_l} + \sum_{j=1, j\neq l}^{L} \mathbf{h}_{q_l}\mathbf{m}_{q_j}^H x_{q_j} + z_{q_l}, \tag{1}$$

where x_{q_l} is the transmit signal to the user q_l, $\mathbf{m}_{q_j}^H \in \mathbb{C}^{MN_t \times 1}$ is the precoding vector of the M BSs for user q_j, and z_{q_l} is the white Gaussian noise with zero mean and variance σ^2. The second term on the right side of the equal mark in (1) is the inter-user interference (IUI).

We consider zero-forcing beamforming (ZFBF) as the MU-MIMO precoding, which is a low complexity yet effective precoder to eliminate IUI [9]. With ZFBF, $\mathbf{h}_{q_l}\mathbf{m}_{q_j}^H = 0$ for $j \neq l$, $j, l = 1, \ldots, L$, and $L \leq MN_t$. The ZFBF precoding matrix for these users can be obtained as

$$\left[\mathbf{m}_{q_1}^H, \ldots, \mathbf{m}_{q_L}^H\right] = \mathbf{DP}, \tag{2}$$

where $\mathbf{D} = \mathbf{H}_{\mathcal{Q}}^H \left(\mathbf{H}_{\mathcal{Q}}\mathbf{H}_{\mathcal{Q}}^H\right)^{-1}$, $\mathbf{H}_{\mathcal{Q}} = \left[\mathbf{h}_{q_1}^H, \ldots, \mathbf{h}_{q_L}^H\right]^H \in \mathbb{C}^{L \times MN_t}$ is the channel matrix composed of channel vectors of L simultaneously served users in set $\mathcal{Q}$, and $\mathbf{P} = \mathrm{diag}\{p_{q_1}, \ldots, p_{q_L}\}$ is the power allocation matrix for them.

When using ZFBF, the received signal of user q_l becomes

$$y_{q_l} = \mathbf{h}_{q_l}\mathbf{m}_{q_l}^H x_{q_l} + z_{q_l} = p_{q_l} x_{q_l} + z_{q_l}. \tag{3}$$

B. Non-CoMP Transmission

In Non-CoMP transmission mode, every BS only schedules its local users and computes precoder independently, as shown in Fig. 1(b). Denote a set $\mathcal{R}_n = \{r_1, \ldots, r_{L_n}\}$ which contains L_n users that are served by BS n simultaneously, $\mathcal{R}_n \subset \mathcal{U}_n$, then the received signal of user r_l is expressed as

$$\begin{aligned} y_{r_l} = {} & \alpha_{r_l n}\mathbf{h}_{r_l n}\mathbf{w}_{r_l n}^H x_{r_l} + \sum_{j=1, j\neq l}^{L_n} \alpha_{r_l n}\mathbf{h}_{r_l n}\mathbf{w}_{r_j n}^H x_{r_j} \\ & + \sum_{m=1, m\neq n}^{M} \alpha_{r_l m}\mathbf{h}_{r_l m}\mathbf{W}_m \mathbf{x}_m + z_{r_l}, \end{aligned} \tag{4}$$

where x_{r_l} is the transmit signal to user r_l, $\mathbf{w}_{r_j n}^H \in \mathbb{C}^{N_t \times 1}$ is the precoding vector for user r_j at BS n, $\mathbf{W}_m \in \mathbb{C}^{N_t \times L_m}$ is the precoding matrix at BS m for the L_m users it served, $\mathbf{x}_m \in \mathbb{C}^{L_m \times 1}$ is the transmit signal for the L_m users from BS m, and z_{r_l} is the white Gaussian noise with zero mean and variance σ^2. The second term on the right hand side of (4) denotes the IUI within a cell, and the third term is the OCI.

When using ZFBF, the precoding matrix at the BS n can be obtained as

$$\left[\mathbf{w}_{r_1 n}^H, \ldots, \mathbf{w}_{r_{L_n} n}^H\right] = \mathbf{G}_n \mathbf{P}_n, \tag{5}$$

where $\mathbf{G}_n = \mathbf{H}_{\mathcal{R}_n}^H \left(\mathbf{H}_{\mathcal{R}_n}\mathbf{H}_{\mathcal{R}_n}^H\right)^{-1}$, $\mathbf{H}_{\mathcal{R}_n} = \left[\alpha_{r_1 n}\mathbf{h}_{r_1 n}^H, \ldots, \alpha_{r_{L_n} n}\mathbf{h}_{r_{L_n} n}^H\right]^H \in \mathbb{C}^{L_n \times N_t}$ is the channel matrix composed of channel vectors between the BS n and the L_n simultaneously served users in set $\mathcal{R}_n$, $\mathbf{P}_n = \mathrm{diag}\{p_{r_1}, \ldots, p_{r_{L_n}}\}$ is the power allocation matrix.

Then, (4) becomes

$$y_{r_l} = p_{r_l} x_{r_l} + \sum_{m=1, m\neq n}^{M} \alpha_{r_l m}\mathbf{h}_{r_l m}\mathbf{W}_m \mathbf{x}_m + z_{r_l}. \tag{6}$$

III. PERFORMANCE OF COMP AND NON-COMP TRANSMISSION

Considering sum power constraint for all BSs in CoMP system [1] (with total power M) and equal power allocation for each served user, the power for user q_l in (3) is

$$p_{q_l} = \sqrt{\frac{M}{L\left[\mathbf{D}^H\mathbf{D}\right]_{l,l}}}\ , \tag{7}$$

where $[\cdot]_{l,l}$ denotes the element on lth row and lth column of a matrix. Note that

$$1/\left[\mathbf{D}^H\mathbf{D}\right]_{l,l} = \mathbf{h}_{q_l}\left(\mathbf{I} - \overline{\mathbf{H}}_{q_l}^H(\overline{\mathbf{H}}_{q_l}\overline{\mathbf{H}}_{q_l}^H)^{-1}\overline{\mathbf{H}}_{q_l}\right)\mathbf{h}_{q_l}^H\ , \tag{8}$$

where $\overline{\mathbf{H}}_{q_l} \in \mathbb{C}^{(L-1)\times MN_t}$ is the channel matrix containing the channel vectors of all users in $\mathcal{Q}$ except q_l. Then the received signal to noise ratio (SNR) of user q_l under CoMP transmission is

$$\gamma_{q_l}^{\mathbf{C}} = \frac{p_{q_l}^2}{\sigma^2} = \frac{M\beta_{q_l}^{\mathcal{Q}}\|\mathbf{h}_{q_l}\|^2}{L\sigma^2}, \tag{9}$$

where the value of

$$\beta_{q_l}^{\mathcal{Q}} = \mathbf{h}_{q_l}\left(\mathbf{I} - \overline{\mathbf{H}}_{q_l}^H(\overline{\mathbf{H}}_{q_l}\overline{\mathbf{H}}_{q_l}^H)^{-1}\overline{\mathbf{H}}_{q_l}\right)\mathbf{h}_{q_l}^H/\|\mathbf{h}_{q_l}\|^2 \tag{10}$$

is within 0 and 1, which represents the orthogonality between the channel of user q_l and the channels of its partner users in $\mathcal{Q}$. A larger $\beta_{q_l}^{\mathcal{Q}}$ means better orthogonality and leads to larger SNR for user q_l under CoMP transmission.

Similarly, in Non-CoMP system with sum power constraint for each BS and equal power allocation, the power for user r_l in (6) is

$$p_{r_l} = \sqrt{\frac{1}{L_n\left[\mathbf{G}_n^H\mathbf{G}_n\right]_{l,l}}}\ . \tag{11}$$

The received SINR of user r_l under Non-CoMP transmission can be expressed as

$$\gamma_{r_l}^{\mathbf{NC}} = \frac{\lambda_{r_l}^{\mathcal{R}_n}\alpha_{r_l n}^2\|\mathbf{h}_{r_l n}\|^2/L_n}{\sum_{m=1, m\neq n}^{M}\alpha_{r_l m}^2\|\mathbf{h}_{r_l m}\mathbf{W}_m\|^2 + \sigma^2}, \tag{12}$$

where

$$\lambda_{r_l}^{\mathcal{R}_n} = \frac{\mathbf{h}_{r_l n}\left(\mathbf{I} - \overline{\mathbf{H}}_{r_l n}^H(\overline{\mathbf{H}}_{r_l n}\overline{\mathbf{H}}_{r_l n}^H)^{-1}\overline{\mathbf{H}}_{r_l n}\right)\mathbf{h}_{r_l n}^H}{\|\mathbf{h}_{r_l n}\|^2} \tag{13}$$

denotes the orthogonality between the channel of user r_l and the channels of its partner users in $\mathcal{R}_n$.

Since the precoders $\mathbf{W}_m$ in (6) are independently generated in other cells, we consider the average interference caused by $\mathbf{W}_m$ which can be derived as (see Appendix),

$$\mathrm{E}_{\mathbf{W}_m}\{\|\mathbf{h}_{r_l m}\mathbf{W}_m\|^2\} = \frac{1}{N_t}\|\mathbf{h}_{r_l m}\|^2, \tag{14}$$

---

[1] Although per-BS power constraint is more practical, for the prevalent multi-carrier systems, the results obtained under these two power constrains are almost the same according to our simulation.

where $\mathrm{E}_x\{\cdot\}$ denotes averaging over x. Then the Non-CoMP SINR of user r_l is

$$\gamma_{r_l}^{\mathbf{NC}} = \frac{\lambda_{r_l}^{\mathcal{R}_n} \alpha_{r_l n}^2 \|\mathbf{h}_{r_l n}\|^2 / L_n}{\sum_{m=1, m \neq n}^{M} \alpha_{r_l m}^2 \|\mathbf{h}_{r_l m}\|^2 / N_t + \sigma^2}. \qquad (15)$$

IV. TRANSMISSION MODE SELECTION

Now we start from analyzing the spectrum efficiency of CoMP transmission when training overhead is considered. We then develop a simple way to find the cell-edge users that prefer CoMP transmission. Next, we design an orthogonal threshold to select partner users for the cell-edge users for MU-MIMO transmission aiming at increasing sum rate. Finally, we present the transmission mode selection method.

A. Net Downlink Spectrum Efficiency

In downlink transmission, training signals should be transmitted to facilitate channel estimation at the user side [3], which consume available downlink resources for data transmission. The induced overhead either grows in proportion to the number of transmit antennas or the number of users, depending on the purpose of training [3–5]. In this paper, we consider the antenna-specific training signals, whose overhead only depends on the total number of antennas [5].

When the training overhead is considered, the net spectrum efficiency for a user u of downlink transmission is [5]

$$R_u = (1 - N_a v_a) \log_2 (1 + \gamma_u) \quad \text{bit/s/Hz} \qquad (16)$$

where γ_u is the SNR or SINR, v_a is the percentage of training overhead occupied by each antenna in the downlink resources, and N_a is the number of antennas in the system. N_a equals N_t and MN_t respectively under Non-CoMP and CoMP transmission.

Since γ_u is inside log function but $1 - N_a v_a$ is a multiplicative factor, the training overhead led by CoMP transmission may counteract the SINR gain if it is not high enough. This motivates to select transmission mode for each user.

B. Cell-center and Cell-edge Users

It is well-known that the performance of cell-edge users will be improved significantly with CoMP since they experience severe OCI without BS cooperation. It is natural to define those users as cell-edge users who have low SINR under Non-CoMP transmission. Considering that large scale fading gain dominates the SINR, we use the average SINR over small scale channels. Specifically, we need to resort to CoMP transmission for a user if its average SINR with SU-MIMO Non-CoMP transmission is low, which is

$$\mathrm{E}\{\gamma_{r_l}^{\mathbf{NC}}|_{L_n=1}\} \approx \frac{\alpha_{r_l n}^2 \mathrm{E}\{\|\mathbf{h}_{r_l n}\|^2\}}{\sum_{m=1, m \neq n}^{M} \alpha_{r_l m}^2 \mathrm{E}\{\|\mathbf{h}_{r_l m}\|^2\} / N_t + \sigma^2} \qquad (17)$$

$$= \frac{\alpha_{u_{nk} n}^2}{\sum_{m=1, m \neq n}^{M} \alpha_{r_l m}^2 / N_t + \sigma^2} \triangleq I_{u_{nk}},$$

where the approximation is often applied in the literature [10].

$I_{u_{nk}}$ is referred to large scale SINR (LSINR) of user u_{nk}. Given a threshold η_I, the users satisfying $I_{u_{nk}} \leq \eta_I$ are regarded as cell-edge users that prefer CoMP transmission, while the users whose $I_{u_{nk}} > \eta_I$ are cell-center users that are prone to Non-CoMP transmission. We will analyze the selection of threshold η_I later via simulation.

C. Orthogonal Threshold for CoMP Users Scheduling

When a user resort to CoMP transmission, we need further to decide if it should be served under CoMP SU-MIMO or MU-MIMO mode. If a user can be served with CoMP MU MIMO mode, we need to schedule proper users to be served together with it. Now we analyze the requirement on the partner users to ensure that CoMP transmission has significant performance gain. If we select user u_{nk} as a CoMP user, its CoMP SNR should exceed its maximum Non-CoMP SINR, i.e.,

$$\gamma_{u_{nk}}^{\mathbf{C}} \; > \; \gamma_{u_{nk}}^{\mathbf{NC}} \, |_{\lambda_{u_{nk}}^{\mathcal{R}_n} = 1}. \qquad (18)$$

Define a CoMP gain for user u_{nk} as follows,

$$G_{u_{nk}} \triangleq \frac{\gamma_{u_{nk}}^{\mathbf{C}}}{\gamma_{u_{nk}}^{\mathbf{NC}}}$$

$$\frac{\|\mathbf{h}_{u_{nk}}\|^2}{\alpha_{u_{nk} n}^2 \|\mathbf{h}_{u_{nk} n}\|^2} \cdot \frac{\sum_{m=1, m \neq n}^{M} \alpha_{u_{nk} m}^2 \|\mathbf{h}_{u_{nk} m}\|^2 / N_t + \sigma^2}{\sigma^2}, \qquad (19)$$

and assume that $ML_n = L$ and $L_n = L_0$ for $n = 1, \cdots, M$ in (9) and (15), which means CoMP systems can serve M times users as Non-CoMP systems. Then to satisfy the condition shown in (18), the orthogonality among users should satisfy

$$\beta_{u_{nk}}^{\mathcal{Q}} > \frac{1}{G_{u_{nk}}}. \qquad (20)$$

Apparently, $1/G_{u_{nk}}$ is the lower bound of $\beta_{u_{nk}}^{\mathcal{Q}}$, where $G_{u_{nk}} > 1$. Generally, cell-edge users have large CoMP gain (or small $1/G_{u_{nk}}$) due to removing strong OCI, which means that they have looser requirement on the orthogonality of its partner users compared with center users. This makes it easy for them to find partner users under CoMP transmission, but this will lead to low $\gamma_{u_{nk}}^{\mathbf{C}}$ as shown in (9). When we consider the training overhead, we need to select partner users more strictly for CoMP transmission. Otherwise, the small SINR gain may be counteracted by the training overhead. Therefore we need a more strict requirement on $\beta_{u_{nk}}^{\mathcal{Q}}$. Due to the non-linear relationship between the net spectrum efficiency shown in (16) and $\beta_{u_{nk}}^{\mathcal{Q}}$, it is difficult to derive an explicit expression of the required $\beta_{u_{nk}}^{\mathcal{Q}}$ that ensures the spectrum efficiency of CoMP exceeding that of Non-CoMP. Alternatively, we introduce an adjusting factor $0 \leq \theta \leq 1$ to reflect the impact of the overhead, i.e.,

$$\beta_{u_{nk}}^{\mathcal{Q}} \; > \; \eta_{G u_{nk}} \triangleq \max\{1/G_{u_{nk}}, \theta\}, \qquad (21)$$

where $\eta_{G u_{nk}}$ serves as the orthogonal threshold when selecting partner users for user u_{nk}. When $1/G_{u_{nk}}$ is too small, θ will prevent too loose requirement on $\beta_{u_{nk}}^{\mathcal{Q}}$. The selection of θ is shown in Section IV through simulation.

D. Downlink Transmission Mode Selection

Now we propose the transmission mode selection method.

Firstly, all the users is divided into cell-center user set $\mathcal{C}$ and cell-edge user set $\mathcal{E}$ according to their LSINR defined in (17) and the given LSINR threshold η_I.

Then, each user u in set $\mathcal{E}$ selects its partner users from set $\mathcal{E}$ one by one. The scheduling metric is to maximize the sum rate whereas satisfy the orthogonal threshold in (21) for all partner users. To increase the multiplexing gain, after selecting partner users from set $\mathcal{E}$, we proceed to select partner users for user u from set $\mathcal{C}$ by the same metric. Although the users in set $\mathcal{C}$ prefer Non-CoMP transmission, pairing them with edge users allows to serve as many users as possible during each time slot. Further considering that the orthogonal threshold in (21) ensures no performance loss of the partner center users, the system spectrum efficiency will improve.

After selecting partner users for all users in set $\mathcal{E}$, the left users in set $\mathcal{C}$ are served with Non-CoMP transmission. When selecting partner users for Non-CoMP transmission, existing user scheduling methods such as semi-orthogonal user selection (SUS) [9] can be applied. To guarantee fairness among users which is essential in CoMP systems, each user is served only once before all users are served as in [11].

The procedure of downlink transmission mode selection method is summarized as follows.

1) Divide cell-center and cell-edge user sets: The users satisfying $I_{u_{nk}} > \eta_I$ form cell-center user set $\mathcal{C}$, while other users form cell-edge user set $\mathcal{E} = \{e_1, \ldots, e_{|\mathcal{E}|}\}$.
2) Initialization: The selected user set $\mathcal{S} = \{e_l\}$, for $l = 1 \to |\mathcal{E}|$.
3) Select users from $\mathcal{E}$ into orthogonal user set $\mathcal{T}$: Clear the orthogonal user set $\mathcal{T}$ as empty set, $\mathcal{T} = \Phi$. Then for any user a in $\mathcal{E}$, if it satisfies (22), add it to $\mathcal{T}$,
$$\beta_u^{\mathbf{Q}} > T_u, \ \forall u \in \mathcal{S} \cup \{a\}, \tag{22}$$
where $\beta_u^{\mathbf{Q}}$ and T_u are obtained from (10) and (21).
4) Schedule users from $\mathcal{T}$ to maximize the sum rate: For any user t in $\mathcal{T}$, compute the sum rate based on (9) as follows,
$$R^{\mathbf{C}}\left(\{t\} \cup \mathcal{S}\right) = \sum_{u \in \{t\} \cup \mathcal{S}} \log_2\left(1 + \gamma_u^{\mathbf{C}}\right). \tag{23}$$
Then select a certain user t_s from $\mathcal{T}$ that maximizes the sum rate,
$$t_s = \arg\max_{t \in \mathcal{T}} R^{\mathbf{C}}\left(\{t\} \cup \mathcal{S}\right). \tag{24}$$
Add t_s into $\mathcal{SS} \to \mathcal{S} \cup \{t_s\}$.
5) Go back to step 3) and 4), until the number of users in $\mathcal{S}$ reaches MN_t, or $\mathcal{T} = \Phi$ in 3).
6) Proceed to select users from set $\mathcal{C}$ with the same metric as in 3), 4) and 5). Then serve the users in $\mathcal{S}$ together for CoMP transmission.
7) $l \to l + 1$, and go back to 2), 3), 4) and 5) to select partner users for another user e_l until $l = |\mathcal{E}|$.
8) Serve the left users in set $\mathcal{C}$ with Non-CoMP transmission using SUS.

V. SIMULATION RESULTS

In this section, we show the impact of the critical parameters and evaluate the proposed method through simulations.

We use (M,N_t,K) to describe a multi-cell system, i.e., (3,4,10) stands for a 3-cell system each with a 4-antennas BS and 10 users. The inter site distance is 500 m. The path loss factor is 3.76, the shadowing standard deviation is 8 dB, and the average power loss at the reference distance of 1 m is 36.3 dB. The users in each cell are dropped uniformly, and the SIR at cell edge is fixed as 0 dB. For each drop of users, the independently identical distributed flat fading Rayleigh channels are assumed among transmit and receive antennas. All the following results are averaged over 1000 drops.

Figure 2 shows the impact of LSINR threshold η_I on the cell-average and 5% cell-edge rate for the proposed mode selection method, where v_a in (16) is 4%. We can see that there is optimal value of η_I for both cell-edge and cell-average rate. This is because if η_I is too small, there will be few users to be served by CoMP transmission, thus the cell-edge throughput cannot be improved significantly. With the increase of η_I, more cell-edge users are chosen for CoMP transmission, then the cell-edge rate improves, but since more cell-center users are selected for CoMP transmission whose rate may degrades due to the overhead, the cell-average rate reduces. We can see that $\eta_I = 15$ dB is good for both cell edge and average rate under all conditions in simulation. We find by exhaustive searching from more simulations that the proper LSINR threshold depends on the training overhead. They are respectively 30 dB when $v_a = 0\%$-3%, 15 dB when $v_a = 4\%$-5%, and 7 dB when $v_a = 6\%$. Such a large LSINR is somewhat surprising since it is often recognized that cell-edge users should have similar average gain for local and cross channels

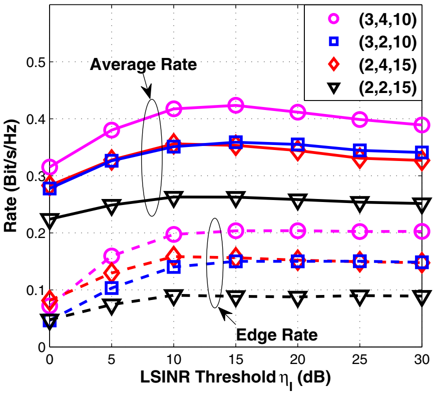


Fig. 2. Impact of LSINR threshold η_I on the user rate

Figure 3 shows the impact of the orthogonal threshold adjusting factor θ on the cell average and edge rate, where the system configuration is (3,4,10). Large θ causes strict orthogonal threshold and makes it hard to find partner users, thus reduces the multiplexing gain and leads to low average and cell-edge rate. On the other hand, for small θ, $\eta_{G_{u_{nk}}}$ is mainly determined by $1/G_{u_{nk}}$. For cell-edge users, loose orthogonal threshold cannot help them to find partner users for good performance. The results for other configurations are similar and the proper value of θ is almost identical, thus is not shown due to lack of the space.

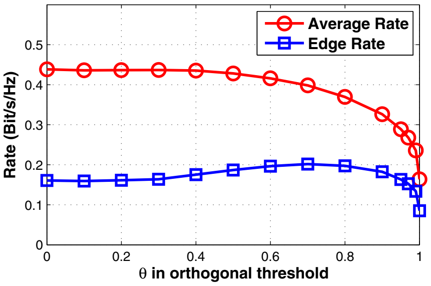


Fig. 3. Impact of θ on the user rate

In Fig. 4, we compare the cumulative distribution function (CDF) of user rate of three different systems, Non-CoMP system and Full-CoMP systme using SUS scheduling (with threshold 0.3), and the system with the proposed transmission mode selection method. Referring to the 3GPP-LTE standard [12], we set $v_a = 4\%$, and also provide the results with $v_a = 0\%$, i.e., no training overhead. We can see that Full-CoMP system can improve cell-edge rate relative to Non-CoMP system, however, it causes severe performance loss for center users when considering the training overhead. Using the proposed method, the performance of cell-edge users improves without performance loss of cell-center users. Note that even without overhead, our method still outperforms Full-CoMP. This is led by the adaptive threshold shown in (21), which is more proper in CoMP system than the fixed threshold in SUS.

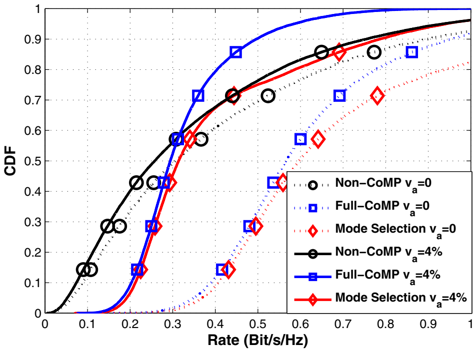


Fig. 4. CDF of the user rate, $\eta_I = 15$ dB and $\theta = 0.6$.

VI. CONCLUSION

In this paper, a transmission mode selection method for downlink CoMP systems is proposed. To find cell-edge users who have large CoMP gain, we introduced a LSINR threshold whose value depends on the training overhead. To find other CoMP users for concurrent transmission so as to provide large multiplexing gain, we derived an adaptive orthogonal threshold. The proposed method can improve the rate of cell-edge users without reducing the rate of cell-center users. It is interesting to observe that some cell-center users may also prefer CoMP transmission, despite that they have minor SINR CoMP gain and the training overhead is taken into account.

APPENDIX

In (12), the precoder $\mathbf{W}_m$ at BS m contains L_m beams that cause OCI to user u_{nk}. To derive the average OCI, we use a random direction vector $\mathbf{a}(\Omega) = \left[1, e^{j2\pi\frac{d\sin\Omega}{\lambda}}, \ldots, e^{j2\pi(Nt-1)\frac{d\sin\Omega}{\lambda}}\right]$ to represent the direction of each beam in $\mathbf{W}_m$. Under equal power allocation, the lth column of $\mathbf{W}_m$ can be expressed as $\mathbf{a}^H(\Omega_l)/\sqrt{N_t L_m}$, and Ω_l uniformly distributes between 0 and 2π and is independent from $\mathbf{h}_{u_{nk}m}$. Then we have

$$\begin{aligned}
&\mathrm{E}_{\mathbf{W}_m}\{\|\mathbf{h}_{u_{nk}m}\mathbf{W}_m\|^2\} \\
&\quad = \mathbf{h}_{u_{nk}m}\left(\frac{1}{N_t L_m}\sum_{l=1}^{L_m}\mathrm{E}_{\Omega_l}\{\mathbf{a}^H(\Omega_l)\mathbf{a}(\Omega_l)\}\right)\mathbf{h}_{u_{nk}m}^H \\
&\quad = \mathbf{h}_{u_{nk}m}\left(\frac{1}{N_t L_m}\sum_{l=1}^{L_m}\int_0^{2\pi}\frac{1}{2\pi}\mathbf{a}^H(\Omega_l)\mathbf{a}(\Omega_l)d\Omega_l\right)\mathbf{h}_{u_{nk}m}^H \\
&\quad = \mathbf{h}_{u_{nk}m}\left(\sum_{i=1}^{L_m}\frac{1}{L_m N_t}\mathbf{I}\right)\mathbf{h}_{u_{nk}m}^H = \|\mathbf{h}_{u_{nk}m}\|^2/N_t \ .
\end{aligned}$$

REFERENCES

[1] M. K. Karakayali, G. J. Foschini, and R. A. Valenzuela, “Network coordination for spectrally efficient communications in cellular systems,” *IEEE Wireless Commun. Mag.*, vol. 13, pp. 56–61, Aug. 2006.

[2] D. Gesbert, S. Hanly, H. Huang, S. Shamai, O. Simeone, and W. Yu, “Multi-cell MIMO cooperative networks: A new look at interference,” *IEEE J. Select. Areas Commun.*, vol. 28, no. 9, pp. 1380–1408, Dec 2010.

[3] G. Auer and I. Cosovic, “Pilot design of MIMO-OFDM with beamforming,” in *Proc. IEEE ICC*, 2009.

[4] E. Y. Kim and J. Chun, “Coordinated beamforming with reduced overhead for the downlink of multiuser MIMO systems,” *IEEE Commun. Lett.*, vol. 12, pp. 810–812, Nov. 2008.

[5] G. Caire, A. Ramprashad, and C. Papadopoulos, “Rethinking network mimo: Cost of csit, performance analysis and architecture comparison,” in *Proc. information theory and applications workshop*, May 2010.

[6] C. Wang and R. D. Murch, “Adaptive downlink multi-user MIMO wireless systems for correlated channels with imperfect CSI,” *IEEE Trans. Commun.*, vol. 5, pp. 2435–2446, Sept. 2006.

[7] R. Chen, Z. Shen, J. G. Andrews, and R. W. Heath, “Multimode transmission for multiuser MIMO systems with block diagonalization,” *IEEE Trans. Signal Processing*, vol. 56, pp. 3294–3302, July 2008.

[8] M. Schellmann, L. Thiele, T. Haustein, and V. Jungnickel, “Spatial transmission mode switching in multiuser MIMO-OFDM systems with user fairness,” *IEEE Trans. Veh. Technol.*, vol. 1, pp. 235–247, Jan. 2010.

[9] T. Yoo and A. Goldsmith, “On the optimality of multiantenna broadcast scheduling using zero-forcing beamforming,” *IEEE J. Select. Areas Commun.*, vol. 24, pp. 528–541, Mar. 2006.

[10] M. Kobayashi and G. Caire, “Joint beamforming and scheduling for a multi-antenna downlink with imperfect transmitter channel knowledge,” *IEEE J. Select. Areas Commun.*, vol. 25, no. 7, pp. 1468–1477, Sept. 2007.

[11] S. S. Kulkarni and C. Rosenberg, “Opportunistic scheduling policies for wireless systems with short term fairness constraint,” in *Proc.IEEE GlobeCom*, 2003.

[12] 3GPP, “Evolved universal terrestrial radio access (E-UTRA):physical channels and modulation (release 9),” *3GPP TS 36.211 v9.0.0*, Dec. 2009. [Online]. Available: www.3gpp.org