

estimated from the phase information transmitted in CSP_2 . The phase information estimated from CSP_2 becomes less distinguishable as the number of nodes increases. However, the performance degradation of node ID estimation will be insignificant when the number of nodes is small, since the node ID is estimated by averaging the estimated value over N subcarriers in the frequency domain. From this figure, one can see that the performance degradation is minimal when the number of nodes is less than 18. Although it is not shown in this paper, the probability of hop number detection in the proposed approach, as given by (8), will be almost the same when the number of hops varies. That is because the information on the hop number is transmitted in an orthogonal manner in the frequency domain. Performances of other synchronization algorithms (initial STO, fractional CFO, frame detection, and integer CFO) will be almost the same for both the conventional and proposed approaches due to similar structures of the CP and the repetitive pattern of the preamble.

V. CONCLUSION

Since the proposed handover technique with the hierarchical preamble is performed in the physical layer without interpreting the *MSH-NCFG* message, it has the following advantages. First, it can overcome the hidden-node problem by using the property of quasi-orthogonality in CSP_2 . Second, the node can distinguish an intercluster handover with the SCLRs measured by CSP_1 from an intracluster handover with the SNDRs measured by CSP_2 . Third, the node can select a new sponsor node with the smallest number of hops from the CH. Fourth, the performance of the time synchronization for edge routers connecting adjacent clusters can be improved due to the same pattern in CSP_1 regardless of the cluster ID. Finally, the proposed technique can reduce the time-consuming scanning activity and the handover overhead.

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Transmission Mode Selection for Downlink Coordinated Multipoint Systems

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Abstract—Coordinated multipoint (CoMP) transmission has been widely recognized as a spectrally efficient technique in future cellular systems. To exploit the abundant spatial resources provided by the co-operating base stations (BSs), however, considerable training overhead is required to acquire the channel information. To avoid the extra overhead outweighing the cooperative gain, we propose a method that allows each user to select transmission mode between coherent CoMP and non-CoMP. We first analyze the average throughput of each user under CoMP and non-CoMP transmission after taking into account the downlink training overhead. A closed-form mode selection rule is then developed, which depends on the user location and system settings, i.e., the number of cooperating BSs and transmit antennas, training overhead, and cell-edge signal-to-noise ratio (SNR). Simulation results show that the proposed downlink transmission mode selection method achieves higher throughput than CoMP for cell-center users and than non-CoMP for cell-edge users after accounting for the overhead. As a by-product, the backhaul load is also significantly reduced.

Index Terms—Coordinated multipoint (CoMP) transmission, training overhead, transmission mode selection.

I. INTRODUCTION

Recently, base-station (BS) cooperative transmission, which is known as coordinated multipoint (CoMP) in Third Generation Partnership Project Long-Term Evolution-Advanced (3GPP LTE-Advanced), has been widely recognized as a promising technique to enhance throughput by avoiding intercell interference (ICI), particularly for cell-edge users [1]–[3].

The BS cooperative strategies can be roughly divided into CoMP joint processing (CoMP-JP) and coordinated beamforming (CoMP-CB), depending on the information exchanged among the BSs. CoMP-JP can exploit the abundant spatial resources provided by the cooperating BSs with joint multiuser multiple-input–multiple-output (MU-MIMO) precoding, where both data and channel state information (CSI) need to be shared [1]. By contrast, CoMP-CB avoids ICI by using individual precoding at each BS, where only CSI is shared [4]. Since sharing CSI requires much lower capacity than sharing data [4], CoMP-CB needs much lower backhaul capacity than CoMP-JP. In [5]–[7], the performance of CoMP-JP, CoMP-CB, and non-CoMP systems was compared. The results show that when the cell-edge signal-to-noise ratio (SNR) is high, CoMP-CB is superior to non-CoMP [5] and even outperforms CoMP-JP if the backhaul capacity is low [6]. When the number of cooperative BSs or the number of

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antennas at each BS is large, CoMP-JP has no throughput gain over non-CoMP after accounting for the training overhead to assist channel estimation [7].

A key factor differentiating the two categories of CoMP is the backhaul. If the backhaul has infinite capacity and zero latency, CoMP-JP is more spectrally efficient than CoMP-CB. This is true even when the training overhead is taken into account because the two CoMP strategies need comparable overhead. Note that, although the backhaul links in existing cellular systems have much lower capacity than what CoMP-JP requires [4], there are no technical challenges to upgrade the backhaul with a high-speed optical fiber. When the backhaul links are perfect, however, CoMP-JP may not always be superior to non-CoMP, as expected [7]. This is because the performance of CoMP transmission largely depends on the users' location, i.e., cell-edge users will benefit more from cooperative transmission than cell-center users, and the throughput gain for the cell-center users may be counteracted by the extra training overhead in practice.

In this paper, we strive to mitigate the adverse effect of training overhead on the downlink throughput of the CoMP system by switching between CoMP-JP and non-CoMP transmission modes. Transmission mode selection has been extensively studied in single-cell MIMO systems, e.g., in [8] and [9]. By switching the mode based on channel conditions between transmitting single and multiple data streams [8] or between applying statistical beamforming and spatial multiplexing [9], either spectral efficiency can be increased or transmission reliability can be improved. However, there are few studies in the literature addressing the transmission mode selection in multicell systems. In [5], Zhang and Andrews suggested to switch the transmission strategy between CoMP-CB and non-CoMP at the BSs' side to maximize the sum rate, depending on whether the user is noise or interference limited.

In contrast to the transmission mode selection in single-cell systems that primarily depends on the channel conditions, mode selection in CoMP also depends on the backhaul and overhead. In this paper, we consider the backhaul with unlimited capacity. To achieve a tradeoff between the cooperative gain and the training overhead, we develop a method for each user to select either CoMP-JP or non-CoMP transmission mode. To avoid introducing additional control overhead, we select the transmission mode based on the statistical channel information at the user side.

II. SYSTEM MODEL

Consider a cooperative cluster consisting of B BSs, each equipped with N_t antennas. K users, each with a single antenna, are located in each cell, and each user treats the closest BS as its local BS. The assumption of single-antenna users is for simplicity and does not preclude applying the proposed method to multiple-antenna users. Denote $\mathbf{g}_{iu} \in \mathbb{C}^{N_t \times 1}$ as the small-scale fading channel vector between BS i and user u , each entry of which is complex Gaussian random variable with unit variance, and all the channel vectors are assumed as independent and identically distributed (i.i.d.). $\mathbf{h}_u = [\alpha_{1u}\mathbf{g}_{1u}^H, \dots, \alpha_{Bu}\mathbf{g}_{Bu}^H]^H \in \mathbb{C}^{BN_t \times 1}$ represents the global channel vector of user u , where α_{iu} is the large-scale fading channel gain from BS i to the user, which includes path loss and shadowing. For simplicity, we refer to CoMP-JP as CoMP in the rest of this paper.

Under CoMP transmission mode, we consider that the B BSs are connected with a central unit (CU) via backhaul links of unlimited capacity and zero latency. After collecting CSI from each BS, the CU selects multiple users from the user pool in the B cells and then computes the global precoding vectors for the coscheduled users. Then, it sends the precoded data to the B BSs, who jointly transmit to the active users. Consider that the number of total active users

jointly served by the B BSs is BM , where $M \leq K$ and $M \leq N_t$. $BM - 1$ partner users are coscheduled with user u to share the same time-frequency resource with it.

The received signal of user u under CoMP transmission mode is given by

$$y_u^C = \mathbf{h}_u^H \mathbf{v}_u x_u + \sum_{j=1}^{BM-1} \mathbf{h}_u^H \mathbf{v}_{q_j} x_{q_j} + z_u \quad (1)$$

where $(\cdot)^H$ is the conjugate transpose of a vector or a matrix; x_u, x_{q_j} are the data intended to user u and user q_j that have unit average energy, i.e., $\mathbf{E}\{\|x_u\|^2\} = \mathbf{E}\{\|x_{q_j}\|^2\} = 1$; z_u denotes the noise at user u , which is a white Gaussian random variable with zero mean and variance σ^2 ; $\mathbf{v}_u, \mathbf{v}_{q_j} \in \mathbb{C}^{BN_t \times 1}$ are the global precoding vectors for user u and user q_j ; $\text{IUI}_{q_j}^C \triangleq \mathbf{h}_u^H \mathbf{v}_{q_j} x_{q_j}$ represents the interuser interference (IUI) from user q_j to user u ; and \triangleq means definition.

We consider a zero-forcing (ZF) precoder for downlink MU-MIMO transmission, which is a low-complexity yet asymptotically optimal precoder [10]. The precoding matrix can be expressed as $\mathbf{V} = \mathbf{H}(\mathbf{H}^H \mathbf{H})^{-1} \mathbf{P}$, where $\mathbf{V} = [\mathbf{v}_u, \mathbf{v}_{q_1}, \dots, \mathbf{v}_{q_{BM-1}}]$, $\mathbf{H} = [\mathbf{h}_u, \mathbf{h}_{q_1}, \dots, \mathbf{h}_{q_{BM-1}}]$ is the channel matrix of the BM active users, and $\mathbf{P} = \text{diag}\{\sqrt{p_u^C}, \sqrt{p_{q_1}^C}, \dots, \sqrt{p_{q_{BM-1}}^C}\}$ represents the power-allocation matrix. Then, the received signal-to-noise-plus-interference ratio (SINR) of user u is

$$\gamma_u^C = \frac{p_u^C}{\sigma^2}. \quad (2)$$

Under non-CoMP transmission mode, each BS selects multiple users from the K users located in its serving cell. Subsequently, each BS serves these active users with ZF precoding, and each user receives the desired signal from its local BS suffering ICI from other BSs. In order to serve the same number of users in the whole cluster, as in the CoMP transmission mode, we consider that each BS serves M active users in non-CoMP transmission mode.

The received signal of user u in cell b under this mode is given by

$$y_u^{\text{NC}} = \sum_{i=1}^B \alpha_{iu} \mathbf{g}_{iu}^H \mathbf{W}_i \mathbf{x}_i + z_u = \alpha_{bu} \mathbf{g}_{bu}^H \mathbf{w}_{bu} x_u + \sum_{j=1}^{M-1} \alpha_{bu} \mathbf{g}_{bu}^H \mathbf{w}_{bs_j} x_{s_j} + \sum_{i=1, i \neq b}^B \alpha_{iu} \mathbf{g}_{iu}^H \mathbf{W}_i \mathbf{x}_i + z_u \quad (3)$$

where $\mathbf{x}_i \in \mathbb{C}^{M \times 1}$ is the data vector at BS i for its M active users; $\mathbf{W}_i = [\mathbf{w}_{iu}, \mathbf{w}_{is_1}, \dots, \mathbf{w}_{is_{M-1}}] \in \mathbb{C}^{N_t \times M}$ is the precoding matrix at BS i , whose columns represent the precoding vectors for the M active users; \mathbf{g}_{bu} is the channel vector of user u in cell b ; $\text{IUI}_{bs_j}^{\text{NC}} \triangleq \alpha_{bu} \mathbf{g}_{bu}^H \mathbf{w}_{bs_j} x_{s_j}$ represents the IUI from user s_j to user u ; and $\text{ICI}_{iu}^{\text{NC}} \triangleq \alpha_{iu} \mathbf{g}_{iu}^H \mathbf{W}_i \mathbf{x}_i$, where $i \neq b$, represents the ICI from BS i to user u .

The ZF precoding matrix at BS b is $\mathbf{W}_b = \mathbf{G}_b (\mathbf{G}_b^H \mathbf{G}_b)^{-1} \mathbf{P}_b$, where $\mathbf{G}_b = [\mathbf{g}_{bu}, \mathbf{g}_{bs_1}, \dots, \mathbf{g}_{bs_{M-1}}]$ is the channel matrix of the M active users in cell b , and $\mathbf{P}_b = \text{diag}\{\sqrt{p_u^{\text{NC}}}, \sqrt{p_{s_1}^{\text{NC}}}, \dots, \sqrt{p_{s_{M-1}}^{\text{NC}}}\}$ is the power-allocation matrix. By assuming that all the ICIs are uncorrelated Gaussian noise and further considering the average interference derived in [11], i.e., $\mathbf{E}\{|\text{ICI}_{iu}^{\text{NC}}|^2\} = P \alpha_{iu}^2$, the received SINR of user u under non-CoMP transmission mode is obtained as

$$\gamma_u^{\text{NC}} = \frac{\alpha_{bu}^2 p_u^{\text{NC}}}{\sum_{i \neq b}^B \mathbf{E}\{|\text{ICI}_{iu}^{\text{NC}}|^2\} + \sigma^2} = \frac{\alpha_{bu}^2 p_u^{\text{NC}}}{P \sum_{i \neq b}^B \alpha_{iu}^2 + \sigma^2} \quad (4)$$

which can serve as a lower bound of the SINR.

III. TRANSMISSION MODE SELECTION CONSIDERING TRAINING OVERHEAD

Here, we design a method for downlink transmission mode selection accounting for the impact of downlink training overhead. By choosing a transmission mode between CoMP and non-CoMP, each user can achieve its maximal net throughput. As a result, the system can attain a higher overall throughput.

A. Net User Throughput Considering Training Overhead

To facilitate downlink MU-MIMO precoding, the CSI of scheduled users should be available at the CU. In frequency-division duplexing systems, the CSI is first estimated at the user side via downlink training and then is obtained via uplink feedback with various techniques, such as limited feedback. In time-division duplexing systems, the CSI is estimated via uplink training by exploiting channel reciprocity or is obtained with limited feedback when the reciprocity does not hold due to antenna calibration errors [12]. Since it is not proper to simply count the uplink overhead into the downlink throughput [12], we only consider downlink training overhead, as in [7]. Although channel estimation errors or quantization errors have a large impact on the throughput of MU-MIMO, the impacts on CoMP and non-CoMP are similar. Limited feedback strategies for CoMP are an ongoing research topic [13], which will not be explored here. To highlight the impact of the overhead, we suppose that perfect CSI can be obtained and leave the imperfect CSI issues for future work.

Except for the downlink training for CSI feedback (i.e., the common pilots in the context of LTE-Advanced), dedicated pilots are also required during downlink transmission to assist each user to estimate an equivalent channel after precoding for data detection. The overhead of the common pilots and that of the dedicated pilots are, respectively, in proportion to the number of BS antennas and that of data streams, and both occupy downlink time or frequency resources.

Specifically, consider a block-fading channel with $C = T_c W_c$ channel uses in a coherence block, where T_c and W_c are, respectively, the channel coherence time and coherence bandwidth [12]. In non-CoMP systems, suppose that C_c channel uses are employed for common pilots of each antenna, and C_d channel uses are employed for dedicated pilots of each data stream. Then, the downlink training overhead is $v^{\text{NC}} = (N_t C_c + N_r C_d)/C$, where N_r is the number of data streams and is equal to one in this paper since we assume single-antenna users. In CoMP systems, the overhead can be expressed as $v^{\text{C}} = (\beta B N_t C_c + \epsilon N_r C_d)/C$, where $\beta \leq 1$ indicates that CoMP systems should use sparser common pilots¹ than non-CoMP systems; otherwise, the overhead will be too large. In addition, $\epsilon \geq 1$ indicates that more dedicated pilots are required to enhance the orthogonality among different users, as suggested in [14] and the references therein. The scaling factor of B in v^{C} is due to the fact that the intercell common pilots are orthogonal, as suggested in [15].²

After taking into account the downlink training overhead, the net downlink throughputs of user u under CoMP and non-CoMP transmission can be, respectively, expressed as [7]

$$R_u^{\text{C}} = (1 - v^{\text{C}}) \log_2 (1 + \gamma_u^{\text{C}}) \quad (5)$$

$$R_u^{\text{NC}} = (1 - v^{\text{NC}}) \log_2 (1 + \gamma_u^{\text{NC}}). \quad (6)$$

It shows that the net throughputs decrease with the overhead linearly but increase with SINR in log scale. Therefore, the throughput gain of

¹Sparser pilots will lead to less accurate channel estimation, which is not modeled here.

²An example of the structure of intercell common pilots can be found in a 3GPP proposal [16], which is mentioned in [15].

CoMP may be counteracted by its training overhead, although $\gamma_u^{\text{C}} > \gamma_u^{\text{NC}}$. This motivates the transmission mode selection from the view of each user.

B. Transmission Mode Selection

To maximize the overall net throughput of the system, we should allow each user, e.g., user u , to select CoMP transmission when $R_u^{\text{C}} > R_u^{\text{NC}}$ but non-CoMP when $R_u^{\text{C}} < R_u^{\text{NC}}$. However, such transmission mode selection is dynamic because R_u^{C} and R_u^{NC} depend on small-scale fading channels, which can achieve better performance but will induce large signaling overhead and high protocol complexity. In practice, semidynamic mode selection based on average channel gains is more preferable. Therefore, we consider a rule for selecting CoMP transmission mode as follows:

$$\mathbf{E} \{ R_u^{\text{C}} \} > \mathbf{E} \{ R_u^{\text{NC}} \} \quad (7)$$

where $\mathbf{E}\{\cdot\}$ is the expectation over small-scale fading channels.

From (5) and (6), we obtain upper bounds of $\mathbf{E}\{R_u^{\text{C}}\}$ and $\mathbf{E}\{R_u^{\text{NC}}\}$ by using Jensen's inequality as follows:

$$\mathbf{E}\{R_u^{\text{C}}\} \leq (1 - v^{\text{C}}) \log_2 (1 + \mathbf{E} \{ \gamma_u^{\text{C}} \}) \triangleq \mathbf{E}\{R_u^{\text{C}}\}^{ub} \quad (8)$$

$$\mathbf{E}\{R_u^{\text{NC}}\} \leq (1 - v^{\text{NC}}) \log_2 (1 + \mathbf{E} \{ \gamma_u^{\text{NC}} \}) \triangleq \mathbf{E}\{R_u^{\text{NC}}\}^{ub}. \quad (9)$$

In later simulations, we will show that the mode selection using these two upper bounds instead of the true values of the average throughput has negligible impact on the system performance.

The expressions of the upper bounds can also be written in the following forms:

$$\mathbf{E}\{R_u^{\text{C}}\}^{ub} = \log_2 (1 + \eta^{\text{C}} \mathbf{E} \{ \gamma_u^{\text{C}} \}) \quad (10)$$

$$\mathbf{E}\{R_u^{\text{NC}}\}^{ub} = \log_2 (1 + \eta^{\text{NC}} \mathbf{E} \{ \gamma_u^{\text{NC}} \}) \quad (11)$$

where

$$\eta^{\text{C}} \triangleq \frac{(\mathbf{E} \{ \gamma_u^{\text{C}} \} + 1)^{1 - v^{\text{C}}} - 1}{\mathbf{E} \{ \gamma_u^{\text{C}} \}}$$

$$\eta^{\text{NC}} \triangleq \frac{(\mathbf{E} \{ \gamma_u^{\text{NC}} \} + 1)^{1 - v^{\text{NC}}} - 1}{\mathbf{E} \{ \gamma_u^{\text{NC}} \}} \quad (12)$$

reflect the impact of the overhead on the SINR under CoMP and non-CoMP transmission mode, respectively, and $0 < \eta^{\text{C}} < \eta^{\text{NC}} < 1$. Then, the decision rule in (7) can be derived as

$$\eta^{\text{C}} \cdot \mathbf{E} \{ \gamma_u^{\text{C}} \} > \eta^{\text{NC}} \cdot \mathbf{E} \{ \gamma_u^{\text{NC}} \}. \quad (13)$$

To obtain a closed-form decision rule for selecting transmission mode, we will derive the expressions of $\mathbf{E}\{\gamma_u^{\text{C}}\}$ and $\mathbf{E}\{\gamma_u^{\text{NC}}\}$ in the following.

1) *Average SINR Under CoMP Transmission:* Denote the transmit power at each BS as P . For analytical tractability, we assume that, under CoMP transmission mode, the sum power of all BSs, i.e., BP , is equally allocated to the BM active users. This corresponds to the per-user power constraint, as in [3], whose performance approaches that of the per-BS power constraint, when each cell has a large number of users [17]. Then, we have

$$p_u^{\text{C}} = \frac{BP}{BM [(\mathbf{H}^H \mathbf{H})^{-1}]_{1,1}} = \frac{P}{M [(\mathbf{H}^H \mathbf{H})^{-1}]_{1,1}} \quad (14)$$

where $[\cdot]_{k,k}$ denotes the element on the k th row and the k th column of a matrix.

Define $\theta_u^C \triangleq \angle(\mathbf{h}_u, \overline{\mathbf{H}})$ as the angle between the channel of user u and a subspace spanned by the channels of its $BM-1$ coscheduled users under CoMP transmission, where $\overline{\mathbf{H}} = [\mathbf{h}_{q_1}, \dots, \mathbf{h}_{q_{BM-1}}]$. Then, we can derive that

$$\begin{aligned} \frac{1}{[(\mathbf{H}^H \mathbf{H})^{-1}]_{1,1}} &= \left| \mathbf{h}_u^H \left(\mathbf{I} - \overline{\mathbf{H}}(\overline{\mathbf{H}}^H \overline{\mathbf{H}})^{-1} \overline{\mathbf{H}}^H \right) \right|^2 \\ &= |\mathbf{h}_u|^2 \sin^2(\theta_u^C). \end{aligned} \quad (15)$$

Substituting (14) and (15) into (2), the received SINR of user u can be obtained as

$$\gamma_u^C = \frac{P}{M\sigma^2} \frac{1}{[(\mathbf{H}^H \mathbf{H})^{-1}]_{1,1}} = \frac{P|\mathbf{h}_u|^2 \delta_{BM-1}}{M\sigma^2} \quad (16)$$

where $\delta_{BM-1} \triangleq \sin^2(\theta_u^C)$, whose value is between 0 and 1, and a larger value of it indicates a better orthogonality between user u and its coscheduled users, which leads to a larger value of γ_u^C .

From (16), the average SINR of user u is $\mathbf{E}\{\gamma_u^C\} = (P/M\sigma^2)\mathbf{E}\{|\mathbf{h}_u|^2 \delta_{BM-1}\}$. The random variables $|\mathbf{h}_u|^2$ and δ_{BM-1} are, in general, mutually dependent. Nonetheless, if all coscheduled users have equal large-scale channel gains from all the B BSs,³ their global channels become $\mathbf{h}_j = \alpha[\mathbf{g}_{1j}^H, \dots, \mathbf{g}_{Bj}^H]^H$, $j = 1, \dots, BM$ and are i.i.d., because \mathbf{g}_{ij} was assumed i.i.d. This corresponds to the worst case in CoMP systems since each ‘‘cell-edge user’’ always prefers to be coscheduled with cell-center users to achieve higher average SINR [11]. Further, consider that \mathbf{h}_u and \mathbf{h}_j are Gaussian random vectors. In this special case, due to the independence between the norm and the direction of a Gaussian vector with i.i.d. entries, $|\mathbf{h}_u|^2$ is independent from δ_{BM-1} because δ_{BM-1} only depends on the global channel direction vectors of the coscheduled users. In the general case where the users are not the ‘‘cell-edge users,’’ the average SINR can be approximated as

$$\begin{aligned} \mathbf{E}\{\gamma_u^C\} &\approx \frac{P\mathbf{E}\{|\mathbf{h}_u|^2\}\mathbf{E}\{\delta_{BM-1}\}}{M\sigma^2} \\ &= \frac{PN_t \left(\sum_{i=1}^B \alpha_{iu}^2 \right) \mathbf{E}\{\delta_{BM-1}\}}{M\sigma^2} \end{aligned} \quad (17)$$

which can serve as a lower bound of the average SINR under CoMP transmission. The second equality in (17) comes from the fact that $\mathbf{E}\{|\mathbf{h}_u|^2\} = \sum_{i=1}^B \alpha_{iu}^2 \mathbf{E}\{|\mathbf{g}_{iu}|^2\} = N_t \sum_{i=1}^B \alpha_{iu}^2$.

2) *Average SINR Under Non-CoMP Transmission:* For a fair comparison with CoMP transmission, we consider that each BS equally allocates its transmit power to its M active users, i.e.,

$$p_u^{\text{NC}} = \frac{P}{M[(\mathbf{G}_b^H \mathbf{G}_b)^{-1}]_{1,1}}. \quad (18)$$

Define $\theta_u^{\text{NC}} \triangleq \angle(\mathbf{g}_{bu}, \overline{\mathbf{G}}_b)$ as the angle between the channel of user u and a subspace spanned by the channels of its $M-1$ coscheduled users under non-CoMP transmission, where $\overline{\mathbf{G}}_b = [\mathbf{g}_{bs_1}, \dots, \mathbf{g}_{bs_{M-1}}]$. Then, the received SINR of user u can be obtained from (4) and (18) as

$$\begin{aligned} \gamma_u^{\text{NC}} &= \frac{P\alpha_{bu}^2}{M[(\mathbf{G}_b^H \mathbf{G}_b)^{-1}]_{1,1} \left(P \sum_{i \neq b}^B \alpha_{iu}^2 + \sigma^2 \right)} \\ &= \frac{P\alpha_{bu}^2 |\mathbf{g}_{bu}|^2 \lambda_{M-1}}{M \left(P \sum_{i \neq b}^B \alpha_{iu}^2 + \sigma^2 \right)} \end{aligned} \quad (19)$$

³Note that the global channels of cell-edge users do not necessarily exhibit such a statistic. We refer to the users with these kinds of channels as ‘‘cell-edge users’’ because they behave similar to cell-edge users.

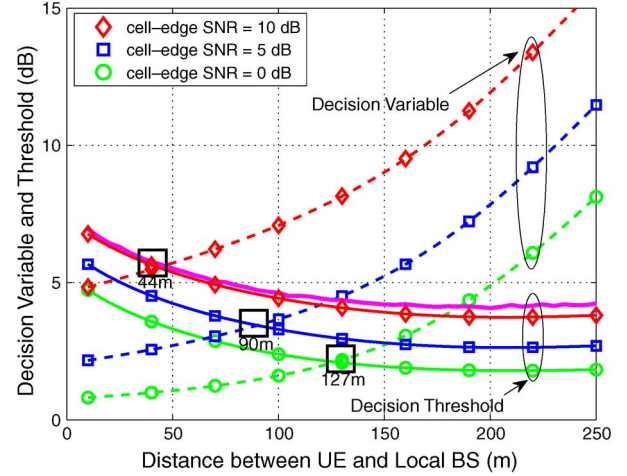


Fig. 1. Values of the decision variable and decision threshold obtained by numerical and simulation results. The solid curve without a marker is the simulated decision threshold, where the SUS scheduler [10] is used, $K = 10$, and the cell-edge SNR = 10 dB.

where $\lambda_{M-1} \triangleq \sin^2(\theta_u^{\text{NC}})$. Similar to δ_{BM-1} defined for CoMP transmission, λ_{M-1} reflects the orthogonality between user u and its $M-1$ coscheduled users.

Since, under non-CoMP, the channel vector of each user is a Gaussian random vector with i.i.d. entries, $|\mathbf{g}_{bu}|^2$ and λ_{M-1} are mutually independent, i.e., $\mathbf{E}\{|\mathbf{g}_{bu}|^2 \lambda_{M-1}\} = \mathbf{E}\{|\mathbf{g}_{bu}|^2\} \mathbf{E}\{\lambda_{M-1}\} = N_t \mathbf{E}\{\lambda_{M-1}\}$. Then, the average SINR of user u is

$$\mathbf{E}\{\gamma_u^{\text{NC}}\} = \frac{PN_t \alpha_{bu}^2 \mathbf{E}\{\lambda_{M-1}\}}{M \left(P \sum_{i \neq b}^B \alpha_{iu}^2 + \sigma^2 \right)}. \quad (20)$$

3) *Decision Rule of the Transmission Mode Selection:* After substituting $\mathbf{E}\{\gamma_u^C\}$ and $\mathbf{E}\{\gamma_u^{\text{NC}}\}$ in (17) and (20), the rule in (13) to select transmission mode for user u turns into

$$\frac{\sum_{i=1}^B \alpha_{iu}^2}{\alpha_{bu}^2} \cdot \frac{P \sum_{i \neq b}^B \alpha_{iu}^2 + \sigma^2}{\sigma^2} > \frac{\eta^{\text{NC}}}{\eta^C} \cdot \frac{\mathbf{E}\{\lambda_{M-1}\}}{\mathbf{E}\{\delta_{BM-1}\}} \quad (21)$$

which can be rewritten as

$$\underbrace{\left(1 + \frac{\sum_{i \neq b}^B \alpha_{iu}^2}{\alpha_{bu}^2} \right)}_{\text{Decision Variable}} \underbrace{\left(1 + \frac{P \sum_{i \neq b}^B \alpha_{iu}^2}{\sigma^2} \right)}_{\text{Decision Threshold}} > \frac{\eta^{\text{NC}}}{\eta^C} \cdot \frac{\mathbf{E}\{\lambda_{M-1}\}}{\mathbf{E}\{\delta_{BM-1}\}} \triangleq T_\eta \cdot T_o. \quad (22)$$

The value of $T_o = \mathbf{E}\{\lambda_{M-1}\} / \mathbf{E}\{\delta_{BM-1}\}$ in the decision threshold depends on the scheduling method. With random user scheduling, it was obtained in [11] that $\mathbf{E}\{\lambda_{M-1}\} = (N_t - M + 1) / N_t$ and $\mathbf{E}\{\delta_{BM-1}\} = (BN_t - BM + 1) / BN_t$, and then, $T_o = (B(N_t - M) + B) / (B(N_t - M) + 1)$. When other scheduling methods, such as semiorthogonal user scheduling (SUS) [10], are applied and the number of candidate users is large, both the values of $\mathbf{E}\{\lambda_{M-1}\}$ and $\mathbf{E}\{\delta_{BM-1}\}$ approach 1, and then $T_o \approx 1$. The value of $T_\eta = \eta^{\text{NC}} / \eta^C$ also relates to the scheduling. This can be seen from the expressions of η^C and η^{NC} in (12), and the expressions of $\mathbf{E}\{\gamma_u^C\}$ and $\mathbf{E}\{\gamma_u^{\text{NC}}\}$ in (17) and (20). When there are large numbers of candidate users,

TABLE I
DOMINATING FACTORS IN THE DECISION VARIABLE OBTAINED FROM (22)

Cell-edge SNR	Switching Distance	Percentage of CoMP-users	Term (a)	Term (b)	Decision Variable
10 dB	44 m	71%	0.02 dB	5.53 dB	5.55 dB
5 dB	90 m	63%	0.13 dB	3.31 dB	3.44 dB
0 dB	127 m	54%	0.42 dB	1.69 dB	2.11 dB

the selected users are orthogonal in high probability. In this case, $\lambda_{M-1} \approx 1$, and $\delta_{BM-1} \approx 1$; then, we have

$$\eta^C \approx \frac{(\bar{\gamma}_u^C + 1)^{1-v^C} - 1}{\bar{\gamma}_u^C}$$

$$\eta^{NC} \approx \frac{(\bar{\gamma}_u^{NC} + 1)^{1-v^{NC}} - 1}{\bar{\gamma}_u^{NC}} \quad (23)$$

where $\bar{\gamma}_u^C \triangleq \mathbf{E}\{\gamma_u^C | \delta_{BM-1} \approx 1\} \approx PN_t (\sum_{i=1}^B \alpha_{iu}^2) / M\sigma^2$ and $\bar{\gamma}_u^{NC} \triangleq \mathbf{E}\{\gamma_u^{NC} | \lambda_{M-1} \approx 1\} \approx PN_t \alpha_{bu}^2 / M(P \sum_{i \neq b}^B \alpha_{iu}^2 + \sigma^2)$ are obtained from (17) and (20), respectively, by setting $\lambda_{M-1} \approx 1$ and $\delta_{BM-1} \approx 1$. This implies that the threshold is approximately independent from the specific scheduling method when the number of candidate users is large. Note that the value of T_η also depends on the number of coscheduled users. We will show by numerical results later that the impact of the user number is minor.

The term (a) in the decision variable is in fact a ratio of the interference-to-noise ratio (INR) to SNR (i.e., the reciprocal of the signal-to-interference ratio) and the term (b) is the INR of user u under non-CoMP mode. Therefore, the proposed transmission mode selection can divide users into two groups of CoMP and non-CoMP users with a predetermined decision threshold, and the result depends on the system configuration and user location. This seems similar to the distance threshold proposed in [17] and to the soft handover (SHO) region mentioned in [2]. Nonetheless, we explicitly reveal the dependence of the threshold on the user location and the systems parameters. Contrarily, in [17], a coordinate distance is found via simulation to maximize an effective sum rate, and in [2], the metric to determine SHO is essentially the term (a) in (22), which reflects the imbalance of the average channel gains of user u . As will be shown later, the term (b) dominates the decision variable. This suggests that each user can simply employ INR to determine its transmission mode, particularly for high cell-edge SNR where CoMP is more desirable.

When the proposed decision rule is applied, each user decides its transmission mode based on its average channel gains from multiple BSs and then conveys one bit to indicate its preferred mode to its serving BS. After collecting the preference from all users, the CU selects coscheduled users separately from the two user groups with a fast scheduler to achieve high throughput and ensure fairness among the users. Such a distributed and semidynamic mode selection at the user side has low signaling overhead between the users and the BSs compared with that at the BS side.

IV. SIMULATION AND NUMERICAL RESULTS

Here, we verify our analysis and evaluate the performance of the proposed mode selection scheme by comparing with CoMP and non-CoMP systems from simulation and numerical results.

A cooperative cluster of three hexagonal cells is considered with cell radius $R = 250$ m. The path loss $\alpha_{iu}^2 = \alpha_0^2 (R/d_{iu})^\tau$, where α_0^2 is the path loss at the distance R , d_{iu} is the distance between user u and BS i , and $\tau = 3.76$ is the path-loss factor. The cell-edge SNR is defined as the received SNR of the user located at the distance R from the BS, where the intercluster interference is included and regarded as white noise. Ten users are randomly placed in each cell. Suppose

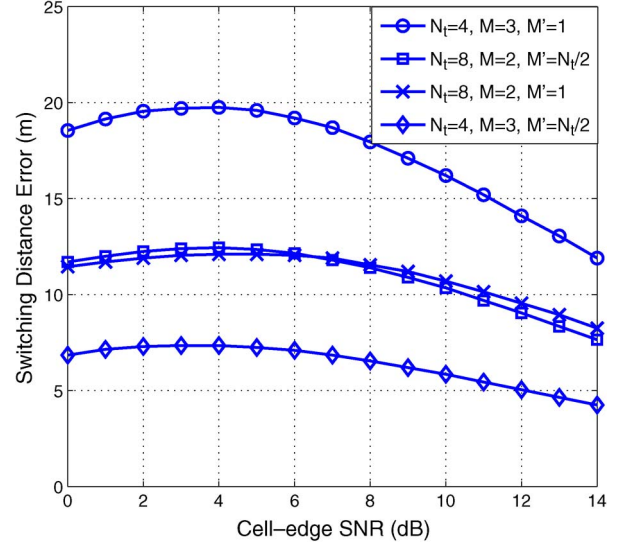


Fig. 2. Decision threshold error with estimated number of the scheduled users.

that a coherence block contains 500 channel uses ($C = 500$, e.g., $T_c \approx 1.83$ ms and $W_c \approx 274$ kHz, corresponding to a user speed of 50 km/h in an urban macrocell scenario of 3GPP [18]). Then, the optimal numbers of the channel uses for common and dedicated pilots can be computed as $C_c = 9.69$ and $C_d = 24.2$, respectively, from the results in [12] and [19]. Because there are no available results for the overhead of CoMP in literature, we set $\beta = 1$ and $\epsilon = 1$, and then, $v^{NC} = 12.59\%$ and $v^C = 28.09\%$. Unless otherwise specified, we employ this overhead in the sequel, and we consider $M = 2$ and $N_t = 4$. Fig. 1 shows the values of the decision variable and the threshold provided in (22). The border between cell-center and cell-edge regions, where the decision variable equals the decision threshold, is also marked. We can find that the mode selection results largely depend on the cell-edge SNR. As the SNR grows, the CoMP region increases, i.e., CoMP transmission is more desirable for a system with a higher cell-edge SNR. To show that the threshold is independent from the scheduling methods, even with a finite number of candidate users, we also provide a simulated result where the value of T_o in the threshold is obtained by simulation with SUS.

In Table I, the mode switching distance under 10-, 5-, 0-dB cell-edge SNRs are listed, which are computed from (22). We also list the corresponding terms (a) and (b) in (22). We can see that term (b), i.e., the INR, dominates the decision variable, particularly for the high cell-edge SNR.

Remember that T_η in the threshold depends on the coscheduled user number M , but each user does not know how many users will be scheduled. In practice, we can roughly estimate the coscheduled user number as $M' = N_t/2$ or even simply as $M' = 1$. In Fig. 2, we present the switching distance error caused by the estimated M , which is numerically obtained from (22). It shows that the error is up to 20 m in various settings.

To demonstrate the impact of the overhead on the mode switching, Fig. 3 shows the percentage of CoMP users versus coherence block size obtained by simulation. A large coherence block size corresponds

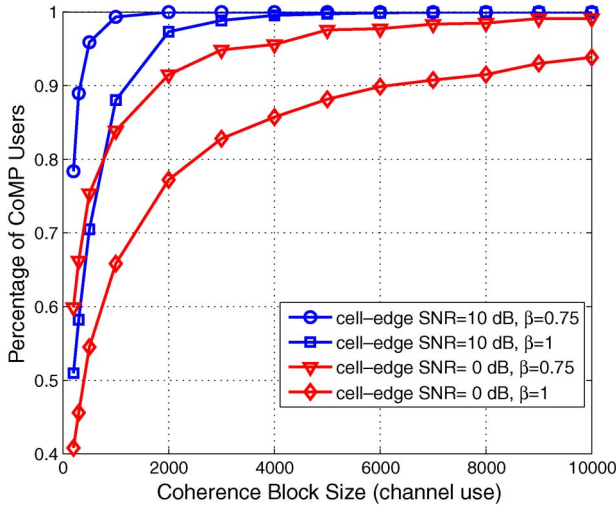


Fig. 3. Percentage of CoMP users.

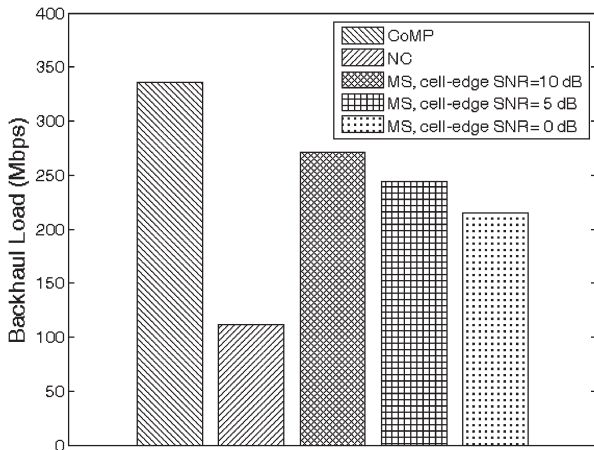


Fig. 4. Backhaul load comparison. The legend “CoMP” denotes a system where all users are served by CoMP; the legend “NC” denotes a system where all users are served by non-CoMP, and “MS” denotes the system with the proposed transmission mode selection.

to lower speed users for a given channel delay spread, which implies less training overhead. The parameter $\beta = 0.75$ reflects the fact that the CoMP system is expected to employ sparser common pilots than the non-CoMP system. When $\beta = 1$, the CoMP system employs common pilots with the same density as the non-CoMP system, and the overall downlink overhead is 2.2 times over non-CoMP, i.e., $v^C/v^{NC} = 2.2$. According to the spatial channel model in 3GPP [15], the coherence time T_c ranges from 0.76 to 30.5 ms, and the coherence bandwidth W_c is from 308 to 1177 kHz, which corresponds to the coherence block size ranging from 234 to 35 899 channel uses. We can see that the number of CoMP users decreases sharply with the increase of the overhead, particularly when the cell-edge SNR is high.

In addition to mitigating the adverse impact of the overhead, the mode switching also leads to a backhaul load reduction by reducing the number of CoMP users. In Fig. 4, we compare the backhaul loads of three systems, which are the average data rate from the CU to each BS, where the load for sharing CSI is ignored [4]. We consider an orthogonal frequency-division multiplexing system with a bandwidth of $W = 20$ MHz that is divided into 1024 subcarriers, and the symbol duration is $71 \mu s$. 16-ary quadrature-amplitude-modulation is employed; thereby, the data rate of each user is $C_s = 4 \text{ bit}/71 \mu s/20 \text{ KHz} = 2.8 \text{ bps/Hz}$. Under non-CoMP, each BS only

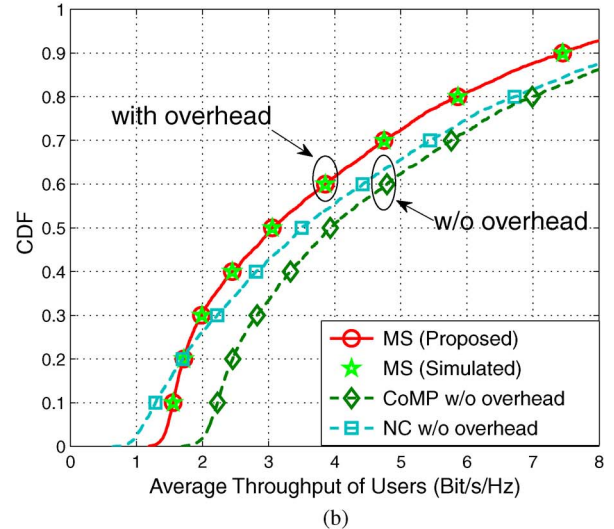
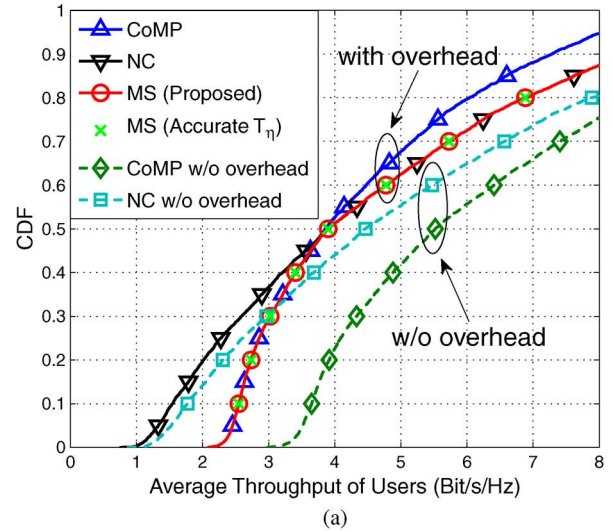


Fig. 5. Average throughput of users: “CoMP w/o overhead” and “NC w/o overhead,” respectively, denote the throughputs of the systems where all users are served by CoMP and by non-CoMP, and the overhead is not considered. (a) Cell-edge SNR = 5 dB: The legend “MS (Accurate T_η)” denotes mode selection based on accurate T_η without the approximations in (23), and the legend “MS (Proposed)” is the proposed mode selection method. (b) Cell-edge SNR = 0 dB: The legend “MS (Simulated)” denotes mode selection based on the simulated average throughputs rather than the throughput upper bounds in (8) and (9).

needs the data for the M local users; hence, the backhaul load is MC_sW bps. Under CoMP, the data for all the BM scheduled users should be available at each BS; thus, the load is BMC_sW bps. By selecting transmission mode between the two modes, the backhaul load is $(p_c B + 1 - p_c)MC_sW$ bps, where p_c denotes the percentage of CoMP users. We can see from the simulation results that the backhaul load after mode selection is about half of that under CoMP system in a cell-edge SNR of 0 dB.

In Fig. 5, we simulate the average throughput of the proposed mode selection method and compare it with those of pure CoMP and non-CoMP transmission. The results are obtained through 1000 random trials, where, in each trial, the throughput of the selected users are averaged over 100 i.i.d. Rayleigh flat-fading channels. The SUS algorithm is applied for scheduling. As expected, CoMP outperforms non-CoMP when the overhead is not considered. However, after taking into account the overhead, only cell-edge users have performance gain under CoMP transmission, whereas cell-center users suffer from

performance loss compared with non-CoMP transmission. The proposed transmission mode selection can adapt to the user location and cell-edge SNR and thus achieves good performance for both cell-edge and cell-center users. We can see in Fig. 5(a) that the approximation on η^{NC} and η^{C} in (23) almost has no impact on the performance. In Fig. 5(b), we provide the performance of the mode selection schemes under a different cell-edge SNR when the mode is selected based on the simulated average throughput and on the throughput upper bounds in (8) and (9). The results of these two schemes are overlapped, which indicates that the upper bounds are very tight. To make the figure more clear, we do not show the performance for CoMP and non-CoMP, which is similar to those in Fig. 5(a).

V. CONCLUSION

We proposed a semidynamic transmission mode selection method between CoMP-JP and non-CoMP, aiming at maximizing the downlink throughput after accounting for the training overhead. The decision rule is in closed form, which has an explicit relationship with the average channel gains of each user and various system parameters. Simulation results showed that each user should employ an INR rather than simply use channel gain imbalance to decide its transmission mode, particularly at a high cell-edge SNR, where most of the users moving with moderate speed prefer CoMP transmission.

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