Distributed Coordinated Multi-Point Downlink Transmission with Over-the-Air Communication

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Abstract—**Base station cooperation transmission, which is also known as coordinated multi-point (CoMP) transmission, is a promising technique to improve system spectrum efficiency in cellular networks, especially for multiple antenna systems. However, the performance gain is significant only when cooperative base stations can gather channel state information (CSI) from all their serving users and can share CSI without delay. In this paper, we propose a distributed downlink CoMP transmission scheme through over-the-air communication among all base stations, which can reduce not only the infrastructural overhead but also the delay of acquiring CSI. We first analyze the CSI acquisition methods in centralized and decentralized CoMP framework. Then we propose a distributed multi-user scheduling and precoding method. Simulation results show that the proposed framework and scheduling algorithm outperforms the centralized and decentralized CoMP when the outdated CSI led by backhaul latency is considered.**

I. Introduction

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

In centralized CoMP systems, cooperative base stations (BSs) should be connected with a central processing unit (CU) by low latency backhaul links [2,3]. Under such a framework, each user feeds back its channel state information (CSI) to its local BS, and then the CU collects CSI from all BSs through backhaul links. With CSI of all users at CU, the centralized CoMP systems enable globally optimal cooperation among BSs, which however pays the penalty of increasing infrastructural costs, unaffordable feedback overhead and difficulty of network upgrading. In currently deployed cellular systems and emerging mobile standards, the backhaul latency is in an order of 10 to 20 milliseconds [4]. This leads to severe performance deterioration of multi-user multiple-antenna CoMP systems.

In order to cope with the drawbacks of the centralized CoMP systems, various distributed or decentralized transmission strategies are proposed [5–9]. Distributed resource allocation and precoding methods were given in [5, 6], and iterative message passing procedure was showed in [7] to exchange information between neighboring BSs. To avoid the infrastructural costs of centralized CoMP, a decentralized CoMP strategy is proposed in [8,9], which requires neither CU nor low latency backhaul links. In this framework, each user feeds back its CSI not only to its local BS but also to other cooperative BSs. Then every BS can obtain all CSI from all users within the cooperative cluster, and hence can schedule users and compute multi-user precoder individually. However, due to the lack of communications among the cooperating BSs, round-robin (RR) scheduling is employed to ensure multiple BSs make the same scheduling decisions. RR scheduling is a simple fair scheduling method, which does not exploit CSI to provide multiuser diversity gain.

In this paper, a distributed CoMP framework is proposed, which aims at reducing both the infrastructural cost and the CSI delay of the centralized CoMP systems. Simply by introducing a time slot in downlink frame structure, required CSI information and scheduling results can be shared among cooperative BSs through over-the-air communication (OTAC). We then propose a distributed scheduling algorithm, which selects users iteratively among BSs to maximize the sum rate. Simulation results show that our scheme provides better cell average and cell edge throughput than centralized and decentralized CoMP schemes when typical backhaul latency is taken into account.

The rest of the paper is organized as follows. In Section II, we present the system model and analyze the CSI acquisition scheme in centralized and decentralized CoMP frameworks [8]. In Section III, we propose a distributed CoMP framework and a distributed scheduling and precoding method. Simulation results are provided to evaluate the performance of our method in Section IV, followed by conclusions in Section V.

II. System Model and CSI Acquisition

A. System Model

Consider a CoMP system consisting of M base stations (BSs), each with N_t antennas and jointly serving K users with single antenna. Let $\mathcal{U}_i = \{u_{i1}, u_{i2}, \ldots, u_{iK}\}$ denote the set of users in the ith cell, $i = 1, \ldots, M$, then $\mathcal{U} = \mathcal{U}_1 \cup \cdots \cup \mathcal{U}_M$ denotes the set of total users in all cells, where $\cup$ is a union operation. Let $\mathbf{h}_{u_{ik}} = [\mathbf{h}_{u_{ik}1}, \mathbf{h}_{u_{ik}2}, \ldots, \mathbf{h}_{u_{ik}M}] \in \mathbb{C}^{1\times MN_t}$ denote the downlink channel vector of user u_{ik}, where $\mathbf{h}_{u_{ik}n} \in \mathbb{C}^{1\times N_t}$ is the composite channel vector from BS n to user u_{ik} including both large scale and small scale fading, $n = 1, \ldots, M, k = 1, \ldots, K$.

Define $\mathcal{S} = \{s_1, \ldots, s_L\}$ as the set of users served by M BSs simultaneously with multi-user precoding, $\mathcal{S} \subset \mathcal{U}$. Then the signal received by user s_l can be expressed as

$$y_{s_l} = \mathbf{h}_{s_l}\mathbf{w}_{s_l}^H x_{s_l} + \sum_{j=1,j\neq l}^{L} \mathbf{h}_{s_l}\mathbf{w}_{s_j}^H x_{s_j} + z_{s_l} \tag{1}$$

where x_{s_l} is the transmitted signal for user s_l, $\mathbf{h}_{s_l} \in \mathbb{C}^{1\times MN_t}$ is its downlink composite channel vector from M BSs, $\mathbf{w}_{s_j} \in \mathbb{C}^{1\times MN_t}$ is its precoding vector, $(\cdot)^H$ is the conjugate transpose operation, z_{s_l} is the additional white Gaussian noise with zero mean and variance σ^2, and the term $\mathbf{h}_{s_l}\mathbf{w}_{s_j}^H x_{s_j}$ denotes the inter-user interference (IUI) from user s_j to user s_l.

The signal to interference plus noise ratio (SINR) at user s_l is

$$\mathrm{SINR}_{s_l} = \frac{|\mathbf{h}_{s_l}\mathbf{w}_{s_l}^H|^2}{\sum_{j=1,j\neq l}^{L} |\mathbf{h}_{s_l}\mathbf{w}_{s_j}^H|^2 + \sigma^2}. \tag{2}$$

Zero-forcing beamforming (ZFBF) is a low complexity yet effective precoder to eliminate IUI [10, 11], which is commonly applied in CoMP systems. For ZFBF with perfect CSI, $\mathbf{h}_{s_l}\mathbf{w}_{s_j} = 0$ for $j \neq l$, $j, l = 1, \dots, L$, where $L \leq MN_t$ is the number of users served concurrently. The ZFBF precoding matrix for these users can be obtained as

$$\mathbf{W} \triangleq \left[\mathbf{w}_{s_1}^H, \dots, \mathbf{w}_{s_L}^H\right] = \mathbf{GP}, \tag{3}$$

where $\mathbf{G} = \mathbf{H}_{\mathcal{S}}^H \left(\mathbf{H}_{\mathcal{S}}\mathbf{H}_{\mathcal{S}}^H\right)^{-1}$ is the pseudo-inverse of $\mathbf{H}_{\mathcal{S}}$, $\mathbf{H}_{\mathcal{S}} = \left[\mathbf{h}_{s_1}^H, \dots, \mathbf{h}_{s_L}^H\right]^H \in \mathbb{C}^{L\times MN_t}$ is the channel matrix composed of composite channel vectors of L simultaneously served users, and $\mathbf{P} = \mathrm{diag}\{p_{s_1}, \dots, p_{s_L}\} \in \mathbb{C}^{L\times L}$ is a power allocation matrix.

By using ZFBF, the SINR of user s_l reduces to

$$\mathrm{SINR}_{s_l} = \frac{p_{s_l}^2}{\sigma^2}, \tag{4}$$

and its achievable data rate is given by

$$R_{s_l} = \log_2\left(1 + \frac{p_{s_l}^2}{\sigma^2}\right). \tag{5}$$

Before downlink CoMP transmission, we should schedule L users from total MK users. By exploiting CSI of all users, user scheduling can provide the multi-user diversity gain [11, 12]. The user scheduling problem aimed at maximizing sum rate can be formulated as

$$\begin{aligned} \max_{\mathcal{S},\mathbf{P}} \quad & \sum_{s_l\in\mathcal{S}} \log_2\left(1 + \frac{p_{s_l}^2}{\sigma^2}\right) \\ s.t. \quad & \mathcal{S} \subset \mathcal{U}, \\ & \sum_{j=1}^{L} |\mathbf{G}_{ij}|^2 p_{s_j}^2 \ \leq P_{max},\ i = 1, \dots, MN_t, \end{aligned} \tag{6}$$

which is a joint optimization of user selection and power allocation. To highlight the distributed scheduling to be addressed, we select the best user set given equal power allocation, which is widely applied in practical systems [1].

Before we propose the distributed user scheduling, we first discuss the problems of CSI acquisition for frequency division duplexing (FDD) centralized [2] and decentralized [8] CoMP systems.

B. CSI Acquisition in CoMP Systems

By sending training signals from cooperative BSs, each user can estimate the channel coefficients from M BSs. Then each user feeds back the estimated downlink composite channel vector from M BSs, $\mathbf{h}_{s_l}$, to its local BS as in Fig. 1(a). In this way, every BS has downlink channel vectors of its local users. In centralized CoMP systems, a central unit (CU) connects with cooperative BSs by low latency backhaul, which assists to gather CSI from the BSs. When the CSI from all users is available, CU can select users and compute precoding vectors and then announce the results to all BSs.

It is known that the performance of multi-user scheduling and precoding degrades severely with outdated CSI [13]. In centralized CoMP systems, CSI delay is composed of following two parts:

- *Feedback delay* : the delay led by uplink feedback;
- *Cooperative delay* : the delay led by sending CSI from BSs to CU.

The cooperative delay is the interface latency between CU and BSs, which is often very large [2, 7]. As to be shown in later simulation results, the performance of centralized CoMP is limited by a large delay of CSI.

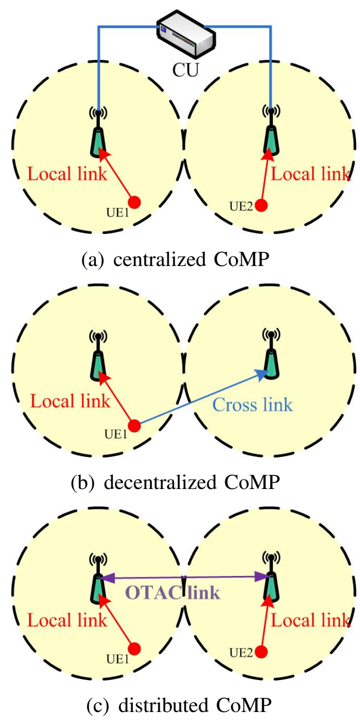

Fig. 1. CSI acquisition for different CoMP schemes

To avoid the infrastructure cost of centralized CoMP, a decentralized framework for cooperative transmission is proposed in [8, 9], which way to obtain CSI is shown in Fig. 1(b). Assuming that each user can feed back its downlink channel vector from all BSs not only to its local BS but also to the cooperative BSs, CSI of all users is available at every BS. Hence, each BS can pre-process multiple users scheduling and precoding individually.

To understand the impact of such a CSI acquisition scheme on user scheduling, here we briefly analyze the capacity of uplink channel that is used for feeding back channel vectors.

The uplink composite channel between user u_{ik} and BS j can be modeled as follows,

$$\mathbf{g}_{u_{ik}j} = \sqrt{P_u d_{u_{ik}}^{-\alpha} \gamma} \mathbf{\Gamma}_{u_{ik}}, \tag{7}$$

where P_u is the transmit power of all users, $d_{u_{ik}}$ is the distance between user u_{ik} and BS j, α is the path loss factor, γ is the shadowing factor, and $\mathbf{\Gamma}_{u_{ik}} \in \mathbb{C}^{N_t \times 1}$ is the uplink small scale channel vector, each of its elements subjecting to complex Gaussian distribution. Then the capacity of the uplink channel between user u_{ik} and BS j normalized by the uplink bandwidth is

$$\begin{aligned} C_{u_{ik}j} &= \log_2 \left(1 + \frac{|\mathbf{g}_{u_{ik}j}|^2}{\sigma^2} \right) \\ &= \log_2 \left(1 + \frac{G d_{u_{ik}}^{-\alpha} \gamma |\mathbf{\Gamma}_{u_{ik}}|^2}{\sigma^2} \right). \end{aligned} \tag{8}$$

We call $C_{u_{ik}i}$ and $C_{u_{ik}j},\ j \neq i$, the capacity of local link and cross link, respectively.

The uplink feedback rate of user u_{ik}, which determines the feedback delay of CSI, is limited by the link with minimum capacity,

$$R_{u_{ik}}^{fb} = \min_{j=1,\ldots,M} C_{u_{ik}j}. \tag{9}$$

Apparently, the cross link has a lower capacity than the local link due to larger signal attenuation, which becomes a bottleneck for the uplink feedback rate. We'll show the cumulative distribution function (cdf) of the local link capacity and cross link capacity in a typical network configuration via simulations in Section IV.

Moreover, the received channel vector $\hat{\mathbf{h}}_{u_{ik}}$ at different BSs may be not the same, since independent feedback errors occur in different feedback links. Therefore, the scheduling results obtained at one BS may conflict with those at another BS [8]. Since there is no communication among the cooperative BSs in the framework proposed in [8, 9], such a confliction can not be solved by coordination. As a result, only round-robin scheduling is used, which reduces system performance without exploiting the multiuser diversity.

III. Distributed Downlink BS Cooperative Transmission

To reduce the CSI delay while providing the multiuser diversity, we propose a distributed downlink CoMP transmission scheme. The basic ideas of the distributed scheme are as follows,

- each user feeds back the estimated CSIs from M BSs via local link to its local BS, which will reduce the feedback delay with a higher feedback rate,
- BSs share CSI among each other through OTAC, which will significantly reduce the cooperative delay,
- each BS schedules among its local users and then sends the CSI of the selected user to other BSs, thus only the CSI of scheduled users is shared through OTAC,
- every BS transmits to the selected users using distributed precoder.

A. Distributed Scheduling and Precoding

Fig. 1(c) illustrates the principle of the proposed distributed CoMP system. Without CU and backhaul links to collect CSI of all users, each BS shares information with other BSs through OTAC.

In order to implement the communication among cooperative BSs over wireless links, a frame structure is introduced as in Fig. 2. An OTAC time slot is inserted before the original downlink frame, during which BSs can exchange necessary information.

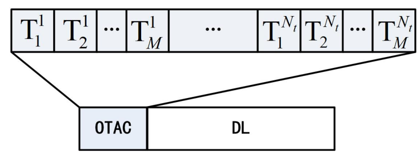

Fig. 2. A frame structure for OTAC

The OTAC time slot is divided into MN_t time slices (TS), $T_j^i, i = 1, \cdots, M, j = 1, \cdots, N_t$. During the period of the first TS, T_1^1, the 1^{st} BS selects one user from its local users set $\mathcal{U}_1$ based on their CSI, and then broadcasts the index and CSI of the selected user to other BSs. During the period of the next TS, the 2^{nd} BS selects one user from $\mathcal{U}_2$ based on their CSI and the selected user by 1^{st} BS, and then broadcasts its index and CSI to other BSs. During the period of T_i^p, the ith BS selects one user from $\mathcal{U}_i$ based on those already selected users and then broadcasts the index and CSI. Finally, at most MN_t users will be scheduled during the OTAC time slot.

The problem of user scheduling at the ith BS aimed at maximizing the sum rate can be formulated as

$$\begin{aligned} &\max_{u_s} R\left(\mathcal{S} \cup \{u_s\}\right) \\ &s.t.\ u_s \in \mathcal{U}_i,\ u_s \notin \mathcal{S}, \end{aligned} \tag{10}$$

where $\mathcal{S}$ is the set of currently selected users by all BSs, and $R\left(\mathcal{G}\right) = \sum_{g \in \mathcal{G}} R_g$ denotes the sum rate of users in set $\mathcal{G}$.

The proposed scheduling method is named the distributed scheduling, where every BS selects users only from its local users in each iteration. Without using CU to gather CSI, OTAC provides an efficient way to share required information among all BSs. The cooperative delay of distributed CoMP is just the length of OTAC time slot.

After several iterations of the distributed scheduling, all BSs get the results of the selected users to be served cooperatively, and every BS has obtained the CSI of all scheduled users. Denoting the set of the selected users as $\mathcal{S} = \{s_1, \ldots, s_L\}$, the distributed ZFBF is used at each BS as follows,

$$\mathbf{D}_i = \mathbf{H}_i^H \left(\mathbf{H}_{\mathcal{S}} \mathbf{H}_{\mathcal{S}}^H \right)^{-1} \mathbf{P}, \tag{11}$$

where $\mathbf{D}_i$ is the precoding matrix computed by BS i, $\mathbf{H}_i = \left[\mathbf{h}_{s_1 i}^H, \ldots, \mathbf{h}_{s_L i}^H\right]^H \in \mathbb{C}^{L \times N_t}$ is the downlink composite channel between BS i and L selected users, and $\mathbf{H}_{\mathcal{S}}$ and $\mathbf{P}$ is defined as in (3).

The procedure of the distributed CoMP downlink transmission is summarized as follows.

1) Initialization: $t = 1$, $\mathcal{S} = \phi$, where t denotes the index of TS, and ϕ is empty set.
2) When $t \leq MN_t$, schedule one user by the ith BS, where $i = (t - 1 \mod N_t) + 1$.
   a) Find a user u_s from $\mathcal{U}_i$ according to (10).
   b) If $R(\mathcal{S} \cup \{u_s\}) > R(\mathcal{S})$, BS i broadcasts u_s's user index and channel $\mathbf{h}_{u_s}$ to other BSs in the tth TS, and then add u_s in $\mathcal{S}$,
   $$\mathcal{S} = \mathcal{S} \cup \{u_s\}.$$
   Otherwise, keep $\mathcal{S}$ unchanged.
   c) update $t \rightarrow t+1$, and then repeat step 2) iteratively.
3) When $t > MN_t$, the iteration of step 2) will stop and the selected user set $\mathcal{S}$ is obtained. Each BS computes its own precoding matrix according to (11).

B. Downlink Data Rate

Since the OTAC time slot occupies the resources of the downlink, we need to compute the net downlink data rate by excluding the introduced overhead. Assume that the length of OTAC slot is T_O, and the length of downlink frame is T_D, then the net downlink data rate of user u is obtained by

$$R_u^* = R_u \times \frac{T_D}{T_O + T_D}, \tag{12}$$

where R_u is the achievable data rate of the user obtained from (5). T_O can be computed by

$$T_O = MN_t \frac{B}{R_O}, \tag{13}$$

where B is the total bits required to transmit the index and CSI of each user, and R_O is the transmission rate of OTAC link.

Suppose that the user index is quantized by B_i bits, and the channel coefficient between each user and each BS antenna is quantized by a bits. To facilitate OTAC link among multiple BSs, training signals for synchronization and channel-estimation should be transmitted together with the data conveying the index and CSI of the selected user. Supposing that the training signals are inserted periodically in frequency domain with the interval of correlation bandwidth, and each period contains B_p bits of training signals, then the total bits B can be expressed as

$$B = \frac{B_{DL}}{B_{co}} \left(MN_t a + B_p\right) + B_i, \tag{14}$$

where B_{DL} is the downlink transmission bandwidth, $B_{co} = 1/10\tau$ is the correlation bandwidth of frequency-selective channels, and τ stands for the rms (root mean square) delay spread of downlink channels.

The OTAC rate R_O can be obtained as

$$R_O = B_{DL} \log_2 (1 + \eta), \tag{15}$$

where η is the SINR of the OTAC link.

IV. Simulation Results

In this section, we evaluate the performance of the proposed distributed CoMP via simulations by comparing it with the centralized [2] and decentralized [8] CoMP systems.

A three-cell CoMP system is considered, with a 1 km BS-to-BS distance and a 10 MHz bandwidth. Each BS has two antennas with an antenna gain of 14 dBi. The maximal transmission power is 46 dBm. The path loss factor is 3.76, the shadowing standard deviation is 8 dB, the average power loss at the reference distance of 1 m is 36.3 dB, and the minimum distance from every user to BS is 35 m. There are 10 users in each cell which are dropped uniformly, and each user has a receiver noise figure of 9 dB. For each drop of users, the independent identically distributed Rayleigh fading channels are assumed among transmit and receive antennas. All the following results are averaged over 1000 drops.

We first compare the uplink capacity of local link and cross link obtained by (8) via simulations. The cdf of the capacity normalized by the uplink bandwidth is shown in Fig. 3. As expected, it is shown that the capacity of the cross link is much lower than that of the local link, which leads to a longer delay of CSI feedback.

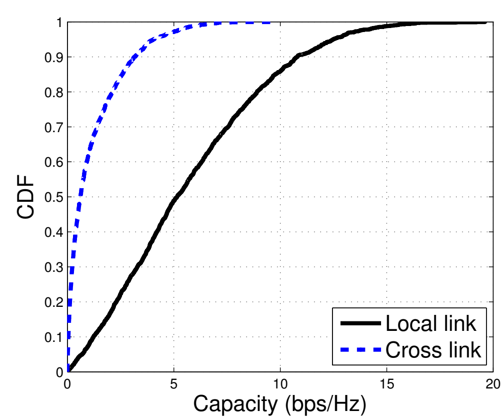

Fig. 3. Uplink capacity of local and cross link

To evaluate the system throughput for mobile users, we suppose that the feedback delay of local link is 1 ms (which is the length of a subframe in 3GPP-LTE system [14]). It can be seen from Fig. 3 that the average capacity of local link is approximately 3 times as that of cross links. Thus, a feedback delay of 3 ms is considered for decentralized CoMP systems in simulations.

In order to get a realistic length of OTAC time slot, we use typical system parameters of 3GPP-LTE system, where $\tau = 1$ us, $a = 6$ bits, $B_p = 4$ bits, $B_i = 6$ bits, and $\eta = 15$ dB in (14) and (15), then the length of $T_O = 0.48$ ms. The length of downlink frame is assumed to be 5 ms.

We use both cell-average and cell-edge rate as the metrics to compare system performance, where the cell-average rate is defined as the average data rate of all users, and the cell-edge rate is defined as the 5% point of the cdf of all users' data rate. The data rate we considered is the net data rate we discussed in Section IV.B.

Fig. 4 and Fig. 5 show the cell average and cell edge rate of four cellular systems for 3km/h and 30km/h mobile users respectively. Non-CoMP systems denote the ordinary cellular networks which have non cooperation among BSs. Centralized and Decentralized CoMP systems denote the networks described in [2] and [8] respectively, while Distributed CoMP systems stand for the networks proposed in this paper.

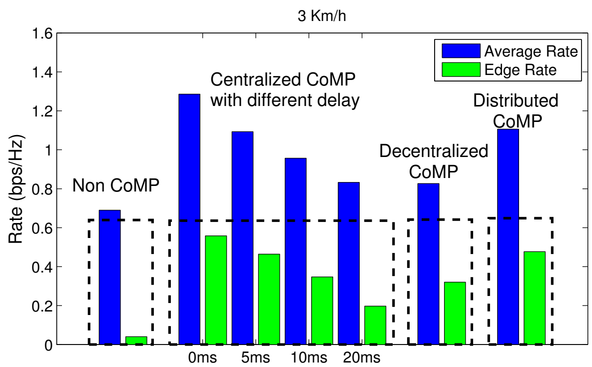

Fig. 4. Performance comparison for 3km/h mobile users

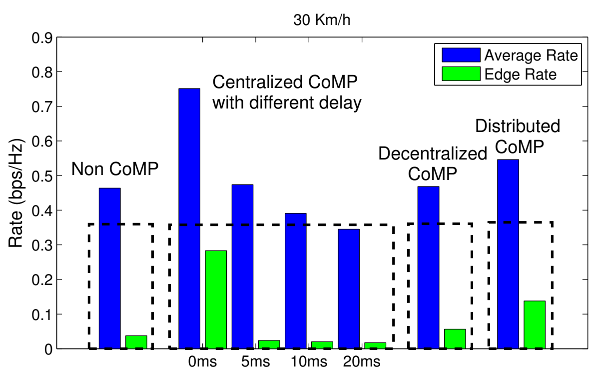

Fig. 5. Performance comparison for 30km/h mobile users

It is shown that centralized-CoMP systems improve both cell-edge and cell-average rate compared with Non-CoMP systems when the cooperative delay is small. However, if the delay or the moving speed is large, centralized-CoMP systems will lose the benefit and even be inferior to Non-CoMP systems.

The typical cooperative delay of interface between BSs and CU is in between 10ms and 20ms [2, 4]. With large CSI delay, the decentralized CoMP systems [8] outperform the centralized CoMP systems for 30km/h users. When the moving speed is low, the decentralized CoMP systems have a large performance gap from the no-delay centralized CoMP systems due to the lack of multiuser diversity.

The performance of distributed-CoMP systems always exceed that of centralized and decentralized CoMP systems, and is close to the performance of the no-delay centralized CoMP systems.

V. Conclusion

The backhaul latency leads to significant performance degradation of cooperative BS systems. In this paper, we introduce a distributed CoMP framework by exchanging channel information among BSs through OTAC. We then propose a distributed scheduling method, which selecting users to maximize sum rate in an iterative manner among BSs. Simulation results demonstrate that our distributed CoMP scheme achieves higher cell average and cell edge throughput than centralized and decentralized CoMP schemes when practical backhaul latency is considered.

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] V. Jungnickel, T. Wirth, M. Schellmann, T. Haustein, and W. Zirwas, "Synchronization of cooperative base stations," in *Proc. IEEE ISWCS*, 2008.

[3] A. Alexiou and F. Boccardi, "Coordination and cooperation for next generation wireless systems- overhead signalling requirements and cross layer considerations," in *Proc. IEEE ICASSP*, 2009.

[4] 3GPP, "Evolved universal terrestrial radio access network (e-utran): X2 general aspects and principles," in *TSG RAN TS 36.420 V9.0.0*, 2009.

[5] D. Gesbert, S. Kiani, A. Gjendemsj, and G. E. Oien, "Adaptation, coordination, and distributed resource allocation in interference-limited wireless networks," *Proceedings of IEEE*, vol. 95, pp. 2393–2409, Dec. 2007.

[6] B. L. Ng, J. S. Evans, S. V. Hanly, and D. Aktas, "Distributed downlink beamforming with cooperative base stations," *IEEE Trans. Information Theory*, vol. 54, pp. 5491–5499, Dec. 2008.

[7] E. Bjornson, R. Zakhour, D. Gesbert, and B. Ottersten, "Distributed multicell and multiantenna precoding: characterizaion and performance evaluation," in *Proc. IEEE GLOBECOM*, 2009.

[8] A. Papadogiannis, E. Hardouin, and D. Gesbert, "A framework for decentralising multi-cell cooperative processing on the downlink," in *Proc. IEEE GLOBECOM Workshops*, 2008.

[9] ——, "Decentralising multicell cooperative processing: a novel robust framework," in *EURASIP J. Wireless Commun. and Networking*, 2009.

[10] Q. H. Spencer, A. L. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multiuser mimo channels," *IEEE Trans. Signal Processing*, vol. 52, pp. 461–471, Feb. 2004.

[11] 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.

[12] G. Dimic and N. D. Sidiropoulos, "On downlink beamforming with greedy user selection: performance analysis and a simple new algorithm," *IEEE Trans. Signal Processing*, vol. 53, pp. 3857–3868, Oct. 2005.

[13] T. R. Ramya and S. Bhashyam, "Eigen-beamforming with delayed feedback and channel prediction," in *Proc. IEEE ISIT*, 2009.

[14] 3GPP, "Evolved universal terrestrial radio access network (e-utran): Lte physical layer general description," in *TSG RAN TS 36.201 V9.0.0*, 2009.