DOWNLINK MULTICELL COOPERATIVE TRANSMISSION WITH IMPERFECT CSI SHARING

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ABSTRACT

This paper studies downlink multicell cooperative transmission with imperfect CSI sharing led by backhaul latency, assuming full data sharing amongst coordinated base stations (BSs). Different from the traditional centralized cooperative transmission systems where multicell precoder is designed at a central unit, a so-called BS-processing system is considered, which enables a decentralized design of multicell precoder at each BS. We show that the resulting precoder design problem falls within the framework of team decision theory, based on which a decentralized multicell precoder is proposed, aimed at maximizing the weighted sum rate. We evaluate the performance of our precoder through simulations.

Index Terms— Coordinated multi-point (CoMP) transmission, multicell precoder, imperfect CSI sharing.

1. INTRODUCTION

Inter-cell interference (ICI) is a major bottleneck for achieving high spectral efficiency in universal frequency reuse cellular networks. Among various interference mitigation techniques, multicell cooperative transmission, also known as coordinated multi-point (CoMP) transmission, is promising and has attracted much attention recently [1].

In centralized CoMP systems, multiple cooperative base stations (BSs) share data and channel state information (CSI) through backhaul links. With global channel information known at a central unit (CU), such a system can be viewed as a giant multi-input and multi-output (MIMO) system with non-collocated antennas. By using multiuser precoding, coherent cooperative transmission can fully exploit the benefit of CoMP, with which both the cell-average and the cell-edge throughput can be significantly improved.

In practice, the performance gain of coherent CoMP transmission comes at a cost of various overhead and expensive backhaul networks. To address the imperfect backhaul link issue, an extreme case of no CSI sharing but with full data sharing among the BSs is considered in [2, 3], where a distributed virtual signal-to-interference plus noise ratio (SINR) precoder is proposed. In [4], imperfect CSI sharing with channel estimation errors is considered, and its impact on capacity region of CoMP systems is investigated.

In this paper, we design multicell cooperative precoder assuming fully shared data but imperfectly shared CSI led by the backhaul latency among the BSs, which is in an order of 10 to 20 milliseconds in currently deployed cellular systems. Differing from the centralized CoMP systems where the multicell precoder is obtained at the CU with severely outdated CSI, we consider a so-called *BS-processing* CoMP system described in Section II, in which the precoder is designed at each BS in a decentralized manner based on outdated cross CSI (the CSI shared from other BSs) and much accurate local CSI (the CSI from a BS to all users). In the considered CoMP system, each cooperative BS has a different estimate of the same global channel vector. Thereby the problem of designing decentralized multicell precoder falls within the framework of team decision theory. This theory is first applied for multicell distributed precoder design in [5], where quantized channels are fed back from users and received by different BSs with different qualities. A decentralized precoder is suggested but without details on how to obtain it.

Aimed at maximizing the weighted sum rate of multiple users served by cooperative BSs, we propose a decentralized multicell precoder by using person-by-person optimization strategy to solve the team decision making problem. Simulation results show that the proposed multicell precoder in BS-processing system can effectively alleviate the performance loss led by the backhaul latency, therefore provides an evident performance gain over centralized CoMP systems.

2. SYSTEM MODEL

2.1. BS-processing Systems

Consider a time division duplex (TDD) downlink CoMP system, which consists of N_u single-antenna users, N_c BSs each equipped with N_t antennas, and a CU connected to all cooperative BSs via backhaul links. We call the channels between all users and a BS as local channels of the BS, and the channels between all users and other supporting BSs as cross

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channels of it.

To implement centralized CoMP transmission, all coordinated BSs first estimate their local CSI by exploiting uplink-downlink reciprocity, then forward the estimates to the CU through backhaul links. With the global CSI of all users, the CU performs user scheduling, computes transmit precoding for scheduled users, and sends the scheduling results and precoding weighting vectors to all BSs for downlink transmission. It is not hard to see that a delay of double backhaul latency exists between the estimated CSI for computing precoder and the actual CSI during downlink transmission in such a centralized CoMP system.

Different from the traditional centralized CoMP system where the BSs merely act as remote antennas, we consider a BS-processing system where the precoder is designed at each BS in a decentralized manner. To this end, each BS needs to estimate its local CSI and to receive cross CSI, which is first collected from all BSs by the CU and then broadcasted to each BS. Since training symbols facilitating local CSI estimation are periodically transmitted, much accurate local CSI can be obtained in the BS-processing system, while the cross CSI is delayed for double backhaul latency due to the BS-CU-BS CSI transfer. More importantly, in BS-processing systems each BS obtains a different estimate of the same global CSI.

2.2. Channel Model

Define $\mathbf{h}_i = [\mathbf{h}_{i1}, \ldots, \mathbf{h}_{iN_c}] \in \mathbb{C}^{1\times N_c N_t}$ as the global downlink channel vector of the ith user (denoted by MS_i), where $\mathbf{h}_{ik} \in \mathbb{C}^{1\times N_t}$ is the independent and identically distributed (i.i.d.) flat fading channel vector from BS_k (the kth BS) to MS_i. Then the whole channel matrix from all BSs to all users can be expressed as $\mathbf{H} = [\mathbf{h}_1^H, \ldots, \mathbf{h}_{N_u}^H]^H$, of which the submatrix $\mathbf{H}_{L,k} = [\mathbf{h}_{1k}^H, \ldots, \mathbf{h}_{N_u k}^H]^H$ is the local CSI of BS_k and the left part is its cross CSI, denoted by $\mathbf{H}_{C,k}$.

Denote the backhaul latency and uplink training period as τ_b and τ_c, respectively. Then to perform downlink CoMP transmission at time t in BS-processing systems, BS_k needs to : i) at time $t - 2\tau_b - \tau_c$, predict local CSI of time t based on the received uplink training symbols and forward it to the CU, ii) at time $t - \tau_c$, predict local CSI of time t based on training symbols and receive shared cross CSI via backhaul links. Assume that the CSI sharing via backhaul is error-free. We can see that the CSI available at BS_k includes three parts, i.e., the predicted local CSI at time $t - \tau_c$ denoted by $\hat{\mathbf{H}}_{L,k}$, the predicted local CSI at time $t - 2\tau_b - \tau_c$ denoted by $\bar{\mathbf{H}}_{L,k}$, and the received cross CSI denoted by $\hat{\mathbf{H}}_{C,k}$.

Apparently, for the two predicted local CSI, $\hat{\mathbf{H}}_{L,k}$ is more accurate than $\bar{\mathbf{H}}_{L,k}$ since the uplink training period is generally much smaller than the double backhaul latency. In this paper, we simply discard the coarse local CSI $\bar{\mathbf{H}}_{L,k}$ and employ the fine local CSI $\hat{\mathbf{H}}_{L,k}$ and the cross CSI $\hat{\mathbf{H}}_{C,k}$ to design precoders at each BS. In future work, we will study how to exploit $\bar{\mathbf{H}}_{L,k}$ to improve system performance.

The channel $\mathbf{h}_{ik}$ can be modeled as

$$\mathbf{h}_{ik} = \hat{\mathbf{h}}_{ik} + \mathbf{e}_{ik},\ i \in \{1, \ldots, N_u\}, k \in \{1, \ldots, N_c\}, \quad (1)$$

where $\hat{\mathbf{h}}_{ik}$ is the predicted channel that can be viewed as the channel mean, and $\mathbf{e}_{ik}$ corresponds to the prediction errors with i.i.d. Gaussian entries with zero mean and variance σ_{ik}^2. This model is particularly suitable when a minimum mean square error (MMSE) predictor is applied.

2.3. Signal Model

When linear precoding is used and multiple BSs are synchronized, the signal received by MS_i can be expressed as

$$y_i = \mathbf{h}_i \sum_{j=1}^{N_u} \mathbf{w}_j^H x_j + z_i, \quad (2)$$

where $[x_1, \ldots, x_{N_u}] \in \mathbb{C}^{1\times N_u}$ is the data symbols for all users shared among the BSs, which entries are assumed as i.i.d. Gaussian random variables with zero mean and unit variance, z_i is the additive white Gaussian noise with zero mean and variance σ^2, $\mathbf{w}_j = [\mathbf{w}_{j1}, \ldots, \mathbf{w}_{jN_c}] \in \mathbb{C}^{1\times N_c N_t}$ is the whole precoding vector for MS_j with $\mathbf{w}_{jk} \in \mathbb{C}^{1\times N_t}$ representing the precoding vector at BS_k, and the precoder for all users at BS_k can be expressed as $\mathbf{W}_k = [\mathbf{w}_{1k}^H, \ldots, \mathbf{w}_{N_u k}^H] \in \mathbb{C}^{N_t \times N_u}$, $k = 1, \ldots, N_c$.

The SINR of MS_i, $i \in \{1, \ldots, N_u\}$ can be obtained as

$$\text{SINR}_i = \frac{\mathbf{w}_i \mathbf{h}_i^H \mathbf{h}_i \mathbf{w}_i^H}{\sigma^2 + \sum_{j=1, j\neq i}^{N_u} \mathbf{w}_j \mathbf{h}_i^H \mathbf{h}_i \mathbf{w}_j^H}. \quad (3)$$

The maximal achievable instantaneous data rate is accordingly $R_i = \log(1 + \text{SINR}_i)$.

3. DECENTRALIZED MULTICELL PRECODER

In this section, we propose a decentralized multicell precoder in BS-processing CoMP systems, where data is shared among the BSs. As discussed earlier, the BSs have different views of the same global downlink channel. Such a problem falls within the framework of team decision theory. In the following, we first briefly introduce the team decision theory, based on which the performance utility and optimization problem are presented and solved.

3.1. Brief Introduction to Team Decision Theory

Team decision theory was introduced to model economic problems of decentralized statistical decision making. The general principle is described as follows [5, 6]: i) each decision maker (here the BS) has different but correlated observations (i.e., the predicted CSI $\hat{\mathbf{h}}_{ik}$) of underlying uncertain variables (i.e., the true CSI $\mathbf{h}_{ik}$), ii) a performance utility is defined as a function of uncertain variables and decision variables to be designed (i.e., the precoders $\mathbf{w}_{ik}$), and iii) by taking the expectation of the performance utility over the uncertain variables as the objective function, each decision maker optimizes decision variables based on its observations.

The team decision making problem is conceptually simple but very difficult to solve [6]. Instead of seeking the optimal solution, we can find a suboptimal solution by a person-by-person optimization method, with which one decision maker optimizes its decision variables given that other team member's decision variables are fixed. In the following, we propose a decentralized multicell precoder based on this idea.

3.2. Performance Utility and Problem Formulation

Different design criteria can be used as the performance utility of precoder design. Considering the goal of CoMP transmission to improve both cell-average and cell-edge throughput, we maximize the weighted sum rate of multiple users, $R_s = \sum_i^{N_u} \alpha_i R_i$, where the weights are used to reflect the priorities of different users, $\alpha_i > 0$.

According to team decision theory, the objective of the considered team of N_c BSs is to maximize the expectation of the performance utility over channel $\mathbf{h}_{ik}$, i.e., $\bar{R}_s = \mathrm{E}\{R_s\}$. In order to obtain an explicit expression for the objective function, the expectation is approximated as

$$\bar{R}_s \approx \sum_i^{N_u} \alpha_i \log\left(1 + \frac{\mathbf{w}_i \mathbf{R}_i \mathbf{w}_i^H}{\sigma^2 + \sum_{\substack{j=1 \\ j\neq i}}^{N_u} \mathbf{w}_j \mathbf{R}_i \mathbf{w}_j^H}\right) \triangleq \sum_i^{N_u} \alpha_i \bar{R}_i, \tag{4}$$

where $\mathbf{R}_i = \mathrm{E}\{\mathbf{h}_i^H \mathbf{h}_i\}$, $\bar{R}_i = \log(1 + \overline{\mathrm{SINR}}_i)$, and $\overline{\mathrm{SINR}}_i = \frac{\mathbf{w}_i \mathbf{R}_i \mathbf{w}_i^H}{\sigma^2 + \sum_{j\neq i} \mathbf{w}_j \mathbf{R}_i \mathbf{w}_j^H}$. This approximation is often used for precoder design when only statistics information is available in multiuser MIMO and CoMP systems, e.g. in [5]. It becomes asymptotically optimal when channel prediction is with high accuracy. Then the multicell precoder design problem aimed at maximizing the average weighted sum rate can be formulated as

$$\max_{\mathbf{w}_{ik}} \; \bar{R}_s, \; i = 1, \ldots, N_u, \; k = 1, \ldots, N_c \tag{5a}$$

$$s.t. \; \mathrm{Tr}\left(\mathbf{W}_k \mathbf{W}_k^H\right) \le P_0, \; k = 1, \ldots, N_c, \tag{5b}$$

where (5b) reflects the per-BS power constraints (PBPC) and P_0 is the maximal transmit power of each BS.

3.3. Person-By-Person Optimization

Bearing the spirit of person-by-person optimization of team decision making problems, we next propose a decentralized multicell precoder which is designed individually at each BS given other BSs' precoders. Different from the original team decision problem considered in [6] where decision makers are allowed to share their decision results, in our scenario the CSI shared among BSs suffers from a severe delay and becomes useless when the backhaul latency is large. Therefore, in order to perform person-by-person optimization, each BS needs to first estimate other BSs' precoders, then designs its own precoder. This means that each BS needs to jointly design all BSs' precoders, from which its own precoder is then obtained. To this end, problem (5) should be solved at each BS based on the available CSI.

Problem (5) is non-convex since its objective function is not convex. Instead of directly maximizing the weighted sum rate, we can alternatively characterize the weighted achievable rate region, denoted by $(\alpha_1 \bar{R}_1, \ldots, \alpha_{N_u} \bar{R}_{N_u})$, with which the maximum weighted sum rate can be obtained by searching over the boundary of the rate region. In [7], a concept of *rate profile*, denoted by $\boldsymbol{\beta} = [\beta_1, \ldots, \beta_{N_u}]$, was introduced to efficiently characterize boundary rate-tuples of a capacity region, where $\beta_i = \alpha_i \bar{R}_i / \bar{R}_s$ for $i \in \{1, \ldots, N_u\}$, $\beta_i \ge 0$ and $\sum_{i=1}^{N_u} \beta_i = 1$. For a given $\boldsymbol{\beta}$, a corresponding boundary point of rate region can be obtained by maximizing $\bar{R}_s$ subject to the rate-profile constraints specified by $\boldsymbol{\beta}$. The resulting optimization problem can be formulated as

$$\max_{\mathbf{w}_{ik}} \; \bar{R}_s, \; i = 1, \ldots, N_u, \; k = 1, \ldots, N_c$$

$$s.t. \; \bar{R}_i \ge \frac{\beta_i}{\alpha_i} \bar{R}_s, \; i = 1, \ldots, N_u, \tag{6a}$$

$$\mathrm{Tr}\left(\mathbf{W}_k \mathbf{W}_k^H\right) \le P_0, \; k = 1, \ldots, N_c. \tag{6b}$$

Noting that the constraints (6a) can be rewritten as $\overline{\mathrm{SINR}}_i \ge 2^{\beta_i \bar{R}_s / \alpha_i} - 1 \triangleq c_i$ and $\mathbf{w}_i \mathbf{R}_i \mathbf{w}_i^H = \mathrm{Tr}\left(\mathbf{R}_i \mathbf{X}_i\right)$ with $\mathbf{X}_i \triangleq \mathbf{w}_i^H \mathbf{w}_i$, problem (6) can be equivalently rewritten as

$$\begin{aligned} \max_{\mathbf{X}_i} \; & \bar{R}_s, \; i = 1, \ldots, N_u \\ s.t. \; & \mathrm{Tr}\left(\mathbf{R}_i \mathbf{X}_i\right) - c_i \sum_{j\neq i} \mathrm{Tr}\left(\mathbf{R}_i \mathbf{X}_j\right) \ge c_i \sigma^2, \\ & \sum_{i=1}^{N_u} \mathrm{Tr}\left(\mathbf{B}_k \mathbf{X}_i\right) \le P_0, \; k = 1, \ldots, N_c, \\ & \mathbf{X}_i \succeq 0, \; \mathrm{rank}(\mathbf{X}_i) = 1, \; i = 1, \ldots, N_u, \end{aligned} \tag{7}$$

where $\mathbf{B}_k$ is a properly defined row-selection matrix to ensure the PBPC.

The only non-convex constraint in (7) is the rank-one restriction. We omit this constraint by using semi-definite relaxation (SDR) to obtain a standard semi-definite programming (SDP) feasibility problem as suggested in [8], by which the maximal $\bar{R}_s$ can be obtained with any accuracy via the bisection method. If the obtained optimal $\mathbf{X}_i$ is of rank-one, then we can easily recover the optimal solution to (7) from $\mathbf{X}_i$. In practice, our experience shows that the CVX software [9] usually provides a rank-one solution automatically. Otherwise, the widely used randomization method [8] can be employed to obtain a suboptimal rank-one solution.

So far, we have found one boundary point of rate region for a given $\boldsymbol{\beta}$. In this manner, we can obtain the whole weighted achievable rate region by considering all possible $\boldsymbol{\beta}$, with which the optimal $\boldsymbol{\beta}$ maximizing the weighted sum rate can be searched and precoders $\mathbf{w}_i$ for $i \in \{1, \ldots, N_u\}$ can accordingly be computed. It should be pointed out that the precoder $\mathbf{w}_i$ decomposed from $\mathbf{X}_i$ may experience a phase ambiguity, which does not affect the performance of single-cell multiuser MIMO systems, but has a large impact on the performance of CoMP systems. It leads to a destructive combination of useful signals from different BSs. Therefore, we adjust the phase of $\mathbf{w}_i$ to ensure $\Im(\hat{\mathbf{h}}_i \mathbf{w}_i^H) = 0$, where $\Im(\cdot)$ is the imaginary part of a complex variable. After obtaining precoders for all BSs, each BS selects its own precoder for downlink CoMP transmission.

4. SIMULATION RESULTS

Consider a cell consisting of three sectors each with a two-antenna BS. The BS-to-BS distance is 500 m. A "sector-edge area" with a minimum distance of 150 m from all BSs is defined for CoMP transmission, where two single-antenna users are uniformly distributed both moving with the speed 3 km/h. The interference from non-cooperative sectors is modeled as white noise. The noise level and maximal transmit power are set such that the average signal to noise ratio for a user at the exact sector-edge is 10 dB. The small-scale fading channels are i.i.d Rayleigh fading, whose dynamics follow Jakes' model. The path loss exponent is 3.76, and the lognormal shadowing standard deviation is 8 dB. A typical operation frequency of 2 GHz is considered, and the uplink training period is set to be 5 ms. Equal rate weighting factors α_i across users are used. All the results are averaged over 50 drops.

Figure 1 shows the weighted sum rate of the propose precoder in both centralized CoMP and BS-processing systems as a function of backhaul latency. When perfect CSI sharing is assumed, the two CoMP systems in fact are the same and an identical precoder can be obtained. However, when CSI sharing delay led by backhaul latency is considered, the obtained CSI for precoding in centralized CoMP systems is severely outdated, which leads to a significant performance degradation. Yet by using the proposed precoder in BS-processing systems, an evident performance gain can be observed.

5. CONCLUSIONS

In this paper, we presented a new framework of downlink CoMP transmission with full data sharing but imperfect CSI sharing among BSs, which allows a decentralized design of multicell precoder at each BS. We showed that under this framework each BS obtains a different estimate of the same global CSI, therefore team decision theory can be applied for precoder design and a decentralized precoder is then proposed. Simulation results showed that our precoder for BS-processing systems effectively alleviates the performance loss led by backhaul latency.

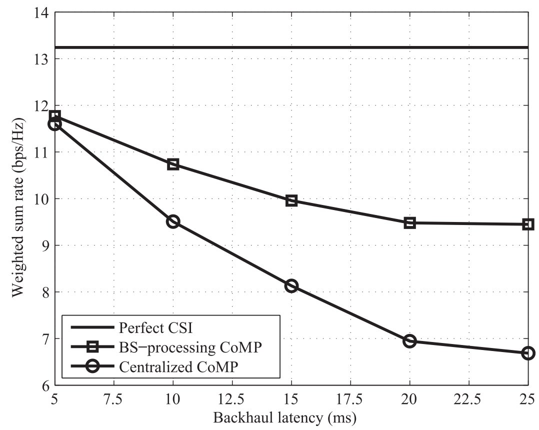

Fig. 1. Weighted sum rate of the proposed multicell precoder.

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