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COORDINATED USER SCHEDULING IN THE MULTI-CELL MIMO DOWNLINK

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ABSTRACT

We propose a novel, coordinated user scheduling (CUS) algorithm for inter-cell interference (ICI) mitigation in the downlink of a multi-cell multi-user MIMO system. In the proposed algorithm, ICI mitigation is performed through the exchange of necessary channel state information (CSI) among the base stations, and the revision of the scheduling decisions and beamformer designs at each base station. Furthermore, ICI mitigation is performed only for the cell-edge users so that the amount of inter-base station signaling overhead is minimized. Our simulation results demonstrate that the proposed coordination scheduling algorithm significantly improves the cell-edge users' throughput compared to conventional systems with only a negligible amount of CSI sharing among the base stations and a relatively small throughput loss for the cell-interior users.

Index Terms— Multi-user MIMO, inter-cell interference, coordinated scheduling.

1. INTRODUCTION

Base station coordination has been proposed in the emerging wireless standards, such as 3GPP LTE-Advanced, as an efficient way to combat the performance-limiting ICI and to improve the spectral efficiency in multi-cell multi-user MIMO networks. Different base station coordination strategies have been proposed, which can be classified into two main categories based on the amount of information shared between base stations, namely coordinated multi-cell transmission (a.k.a *network MIMO*) and coordinated single-cell transmission [1].

In network MIMO, the data to each user is transmitted from multiple base stations. This requires a substantial amount of signaling to make the CSI and the data of all users available at all the coordinating base stations. This would be very difficult to implement due to the following main limitations: i) limited backhaul capacity for data sharing among the base stations, and ii) acquisition of CSI from all the users at all the coordinating base stations. In coordinated single-cell transmission, however, the data for each user is transmitted only from one base station (i.e. its *home* base station); as such, no inter-base station data exchange is required. The ICI mitigation is achieved via multi-cell scheduling and joint beamforming design. Furthermore, each user needs to feed back the CSI only to some of the neighboring base stations resulting in much lower signaling overhead with respect to network MIMO [1].

Although network MIMO has been widely studied in the literature (see e.g. [2] and references therein), the more practical coordinated single-cell transmission has been scantly treated. The authors in [3, 4] have studied the problem of multi-cell scheduling to mitigate the performance losses due to the uncertainty of ICI. In [5], it is proposed to design the beamformers such that the ICI to the cell-edge users in an adjacent cell is suppressed down to a threshold, assuming the cell-edge users' CSI is available at the neighboring base stations. Recently, ICI cancelation using zero-forcing beamforming was investigated in [6], where each base station during the user selection stage focuses on the direction of interference to the users in the adjacent cells. The proposed algorithm, however, requires each base station to know the CSI between itself and all users in its own cell as well as in the neighboring cells at each scheduling instance.

In this paper, we propose a novel, CUS algorithm, in which the base stations perform a first-step independent scheduling and a second step of scheduling revision to mitigate the ICI to the scheduled cell-edge users in the neighboring cells at the first step. In the proposed algorithm the CSI of the cell-edge users needs to be reported to the neighboring base stations only upon their selection, thereby limiting the amount of signaling overhead. The proposed strategy significantly improves the performance of the cell-edge users at the expense of a relatively small throughput loss for cell-interior users.

2. SYSTEM MODEL

We consider a simple linear two-cell downlink system, as shown in Fig. 1. This is similar to the two-cell downlink version of the Wyner's model [7], which, though simple, provides useful insights. Base stations are placed at positions $-D$ and D and are equipped with N_t antennas each. There

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are K single-antenna users in each cell, which are equally spaced at intervals $[-D, 0]$ and $[0, D]$ for cells 1 and 2, respectively. In each cell, the users are indexed such that user $k = 1$ is the closest to the base station and user K is the closest to the cell edge. Furthermore, each user is classified as a cell-interior or a cell-edge user depending on its pathloss difference between its home and adjacent base stations. If this pathloss difference is greater than a predetermined threshold, denoted as *coordination triggering threshold*, the user is considered as a cell-interior user, otherwise the user is classified as a cell-edge user. The cell-interior and cell-edge users are indexed as $\{1, \ldots, N\}$ and $\{N+1, \ldots, K\}$, respectively, in each cell as shown in Fig. 1. Let $\bar{i} = \text{mod}(i, 2) + 1, i = 1, 2$ denote the other base station/cell depending on the context. At any given time slot t and in each cell i, a proportional fairness (PF) scheduler is employed to select a subset of users[1] $\mathcal{S}_i(t)$ to be served according to [3]

$$\mathcal{S}_i(t) = \arg\max_{\tilde{\mathcal{S}}_i(t)} \sum_{k \in \tilde{\mathcal{S}}_i(t)} \frac{\tilde{R}_k(t)}{T_k(t-1)}, \quad (1)$$

where $\tilde{R}_k(t)$ and $T_k(t-1)$ denote the *estimated* rate and the windowed long-term average rate (a.k.a throughput) of user k, respectively. The estimated rate of each user is computed based on the available information at the beginning of each scheduling instance. The available information includes the perfect knowledge of the channel vectors[2] and pathlosses for all the users inside cell i, and the corresponding ICI power experienced by each user from cell $\bar{i}$. More details about the available ICI power will be given in the next section.

In this work, we focus on the signal-to-leakage-plus-noise ratio (SLNR) precoding [8] which takes both interference and noise into account and relaxes the constraints on the number of base stations and user antennas compared to zero-forcing. In this way, the number of served users can be larger than N_t in general. In practical applications, however, where $K \gg N_t$, serving all the users at the same time is not optimal, since serving any extra user causes leakage of interference to the others. In this case, a suboptimal greedy user selection algorithm (see e.g. [9] and references therein) can be used to select a subset of users to be served. The transmitted signal from each base station i at time slot t, $\mathbf{x}_i(t)$, consisting of the linearly precoded symbols of the users it serves, can be written as

$$\mathbf{x}_i(t) = \sum_{k \in \mathcal{S}_i(t)} \mathbf{w}_k(t) s_k(t), \quad (2)$$

where $\mathbf{w}_k(t) \in \mathbb{C}^{N_t \times 1}$ and $s_k(t)$ denote the beamforming vector and the data for user $k \in \mathcal{S}_i(t)$ at time slot t, respectively. Furthermore, the transmitted signal from cell i is assumed to fulfill the average power constraint $\mathbb{E}[\mathbf{x}_i^{\mathsf{H}}(t)\mathbf{x}_i(t)] \le P$. The received signal for user k in cell i, denoted as user k_i, and time slot t can be expressed as

$$y_{k_i}(t) = \sqrt{\rho_{k_i i}}\, \mathbf{h}_{k_i i}^{\mathsf{H}}(t) \sum_{k \in \mathcal{S}_i(t)} \mathbf{w}_k(t) s_k(t) + \sqrt{\rho_{k_i \bar{i}}}\, \mathbf{h}_{k_i \bar{i}}^{\mathsf{H}}(t) \sum_{j \in \mathcal{S}_{\bar{i}}(t)} \mathbf{w}_j(t) s_j(t) + n_{k_i}(t), \quad (3)$$

where $\rho_{k_i j}$ and $\mathbf{h}_{k_i j}(t) \in \mathbb{C}^{N_t \times 1}$ denote the pathloss and the fading channel vector from base station j to user k_i and time slot t, respectively, while $n_{k_i}(t) \sim \mathcal{CN}(0, \sigma^2)$ is the AWGN. The fading channel vector is assumed to be i.i.d block fading with elements $\sim \mathcal{CN}(0, 1)$. The first term on the right hand side of (3) is the signal received from the home base station, while the second term denotes the signal received from the interfering cell. The instantaneous ICI power experienced by user k_i at a given time slot t, $\eta_{k_i}^2(t)$, is given by

$$\begin{aligned} \eta_{k,i}^2(t) &= \mathbb{E}\left[\left| \sqrt{\rho_{k_i \bar{i}}}\, \mathbf{h}_{k_i \bar{i}}^{\mathsf{H}}(t) \mathbf{x}_{\bar{i}}(t) \right|^2 \middle| \mathbf{h}_{k_i \bar{i}}(t) \right] \\ &= \rho_{k_i \bar{i}}\, \mathbf{h}_{k_i \bar{i}}^{\mathsf{H}}(t) \mathbf{Q}_{\bar{i}}(t) \mathbf{h}_{k_i \bar{i}}(t) \end{aligned} \quad (4)$$

where $\mathbf{Q}_{\bar{i}}(t) = \mathbb{E}[\mathbf{x}_{\bar{i}}(t)\mathbf{x}_{\bar{i}}^{\mathsf{H}}(t)]$ is the transmit covariance matrix at cell $\bar{i}$. The instantaneous ICI power in (4) is unknown at the beginning of each scheduling instance. Therefore, the average ICI level is used to compute the estimated rate of each user [10]. The average ICI of user k_i is given by

$$\bar{\eta}_{k_i}^2 = \mathbb{E}\left[\eta_{k_i}^2(t)\right] = \rho_{k_i \bar{i}} P, \quad (5)$$

where the expectation is taken with respect to $\mathbf{h}_{k_i \bar{i}}(t)$.

3. PROPOSED ALGORITHM

In this section, we propose a new, coordinated scheduling algorithm to mitigate the effects of ICI from the cell-edge users in the adjacent cell. The transmission at any given time slot t consists of the following steps:

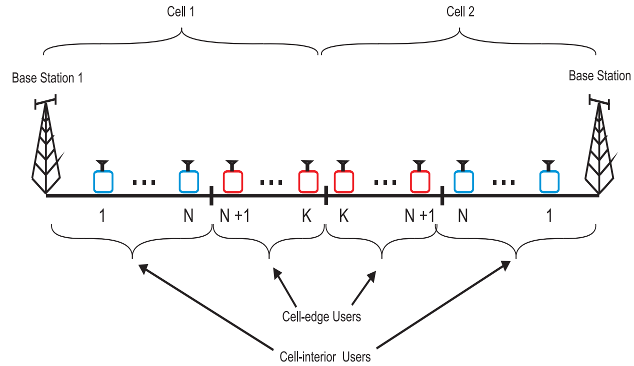

Fig. 1. Schematic illustration of a two-cell multi-user MIMO downlink system.

[1] As for notation we use lowercase boldface for vectors, uppercase boldface letters for matrices, and calligraphic for sets. $\log(\cdot)$, $\mathbb{E}[\cdot]$, $\mathbb{E}[\cdot|\mathbf{x}]$, $(\cdot)^{\mathsf{H}}$, and $|\mathcal{S}|$ denote 2-base logarithm, expectation, conditional expectation given $\mathbf{x}$, Hermitian transpose, and cardinality of a set $\mathcal{S}$, respectively.

[2] For simplicity, we assume the perfect CSI case in this paper which is not usually available in practice. We will, however, leave the study of the effect of imperfect CSI to our future work.

Step 1) **Coordinated Scheduling Initialization Step**: Each cell, given the perfect knowledge of its own users' channel $\{\mathbf{h}_{k_i i} : k = 1, \ldots, K\}$ and of only the average knowledge of ICI power for each user, performs an independent scheduling to select a subset of users for transmission. It is assumed that if a cell-edge user is selected, the ICI to that user will be suppressed down to some threshold ϵ during the revision step (to be explained later). Therefore, the average ICI for different users is obtained according to

$$\bar{\eta}_{k_i}^2 = \begin{cases} \epsilon & \text{for } k > N \\ \rho_{k_i \bar{i}} P & \text{for } k \leq N. \end{cases} \tag{6}$$

The estimated rate of user k is given by

$$\tilde{R}_{k_i}(t) = \log\left(1 + \frac{\rho_{k_i i} \,|\mathbf{h}_{k_i i}^{\mathsf{H}}(t)\mathbf{w}_k(t)|^2 \frac{P}{|\mathcal{S}_i|}}{\sigma^2 + \bar{\eta}_{k_i}^2 + \sum_{\substack{l \in \mathcal{S}_i(t) \\ l \neq k}} \rho_{k_i i} \,|\mathbf{h}_{k_i i}^{\mathsf{H}}(t)\mathbf{w}_l(t)|^2 \frac{P}{|\mathcal{S}_i|}}\right), \tag{7}$$

where equal power allocation is assumed among the users. If no cell-edge user is scheduled in either cell at this step, then no iteration is required and both cells move to the transmission step.

Step 2) **Coordinated Scheduling Revision Step**: In this step, based on the outcome of the initialization step, two cases can be distinguished as follows:

- Case I: only one of the cells has scheduled at least one cell-edge user.
- Case II: both cells have scheduled at least one cell-edge user.

For case I, assume cell i has at least one cell-edge user scheduled and let $\mathcal{U}_i(t)$ denote the set containing the index of the scheduled edge users. After $\sqrt{\rho_{l_i \bar{i}}}\,\mathbf{h}_{l_i \bar{i}}(t)$, $\forall l \in \mathcal{U}_i(t)$ are sent to base station $\bar{i}$, the latter starts to revise its scheduling according to (1). During revision base station $\bar{i}$ has to make sure that the ICI it causes to any user $l \in \mathcal{U}_i(t)$ is smaller than ϵ, i.e.

$$\eta_{l_i}^2 = \sum_{j \in \mathcal{S}_{\bar{i}}(t)} \rho_{l_i \bar{i}} \,|\mathbf{h}_{l_i \bar{i}}(t)\mathbf{w}_j(t)|^2 \leq \epsilon, \ \ \forall l \in \mathcal{U}_i(t). \tag{8}$$

If cell $\bar{i}$ can not schedule any user to satisfy the aforementioned condition, then it will remain silent in that slot (*coordinated silencing*). If during the revision, cell $\bar{i}$ selects any cell-edge user as well, then we end up with case II and one more revision step is required. Otherwise both cells move to transmission step.

For case II, since the main goal is to help the cell-edge users, the scheduled cell-edge users in both cells are kept scheduled during the revision too. Then, the ICI constraint is checked for both cells by considering only the cell-edge users. If the ICI threshold is attained in both cells, then each cell continues to select more users in a greedy manner. Selection of any new cell-edge users in addition to the already scheduled one will require more revisions. If the ICI threshold constraint is not attained, then the cell with a higher weighted sum rate in the first place moves on to the transmission step, while the other cell performs coordinated silencing.

Step 3) **Transmission and PFS Update Step**:

In this step, the base stations perform the transmission using the precoders designed in the scheduling phase. After each transmission phase, the long-term average rate $T_{k_i}(t)$ is updated according to

$$T_{k_i}(t) = \begin{cases} (1 - \frac{1}{\tau})T_{k_i}(t-1) + \frac{1}{\tau}R_{k_i}(t), & k \in \mathcal{S}_i(t) \\ (1 - \frac{1}{\tau})T_{k_i}(t-1), & k \notin \mathcal{S}_i(t). \end{cases} \tag{9}$$

Here, τ is a parameter related to the time interval over which fairness is achieved and $R_{k_i}(t)$ denotes the instantaneous achievable rate of user k_i at time slot t. The achievable rate of a user depends on the instantaneous ICI power and can be larger or smaller than the estimated rate [10].

4. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed CUS algorithm. For our simulation purposes, we set $D = 1$ km, $\tau = 200$, $N_t = 2$, and $K = 4$. The coordination triggering threshold used to classify the cell-interior and cell-edge users is 10 dB resulting in $N = 3$, i.e., only one cell-edge user. The pathloss model used is given by $\rho_{k_i j} = (\lambda/4\pi) \cdot d_{k_i j}^{-\upsilon}$, where $d_{k_i j}$ is the distance between the base stations j and user k_i, while $\lambda = 15$ cm and $\upsilon = 3.5$ are the carrier wavelength and the pathloss exponent, respectively. Without loss of generality, we let the noise power equal to the pathloss at the cell edge, i.e. $\sigma^2 = (\lambda/4\pi) \cdot D^{-\upsilon}$, such that the transmit power, P, of the base station represents the edge SNR. The ICI threshold ϵ in the proposed algorithm is set equal to the noise power. As a comparison, we consider the conventional [3], frequency reuse [3], and network MIMO [2] schemes. The conventional scheme is the same as the proposed CUS scheme when all the users in each cell are treated as cell-interior users (no ICI mitigation). In the frequency reuse scheme, the total system bandwidth is divided into two equal subbands and each subband is allocated to one of the cells. For the network MIMO scheme, assuming that the data and the CSI of all users are available at both base stations, the ICI can be completely eliminated [1].

In Fig. 2, the 5% outage rate of the cell-edge user versus edge SNR is plotted for different schemes. It is observed that the proposed CUS algorithm significantly enhances the outage rate of the cell-edge user. This enhancement at any scheduling instance, however, is achieved if the user is scheduled in that instance. On the other hand, the rate increase of the cell-edge user will increase its windowed long-term average rate, thereby decreasing its priority to be selected by the

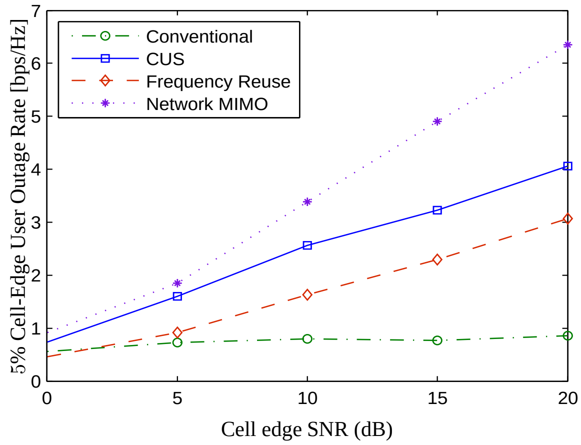

Fig. 2. 5% cell-edge user outage rate vs. cell-edge SNR for $N_t = 2$, $K = 4$ and $N = 3$.

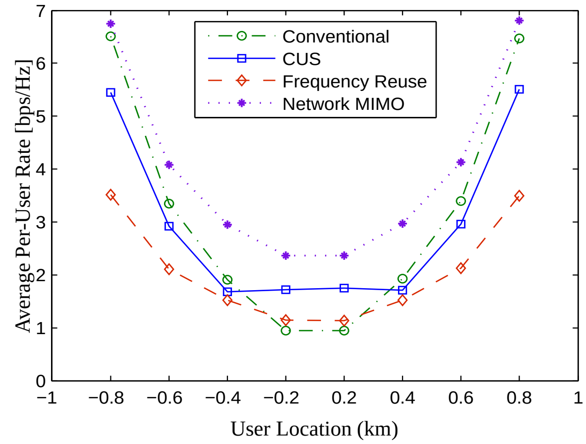

Fig. 3. Average user rates vs. user locations for $N_t = 2$, $K = 4$ and $N = 3$ with edge SNR of 10 dB.

scheduler in the future. This causes a decrease in the user activity w.r.t conventional setup.

Figure 3 compares the average user rates in each of the two cells as a function of the user location for different schemes. It is easily seen that the cell-edge user average rate is significantly improved in the proposed CUS algorithm w.r.t conventional and frequency reuse schemes. Furthermore, the cell-edge user in the proposed CUS algorithm achieves a large fraction of the cell-edge user average rate offered by the highly complex network MIMO. This implies that the proposed scheme can serve as a less complex alternative to the computationally prohibitive network MIMO. In addition, we highlight the fact that in the proposed CUS scheme the ICI mitigation is being performed only for the cell-edge users which are typically not scheduled that often. We notice that only these users have to estimate the channel vectors from both base stations upon their selection. According to our simulations, the channel estimation overhead is about about 3.4% compared to the conventional system for an edge SNR of 10 dB.

It should be noted that although the proposed algorithm was explained for a two-cell configuration, it can be easily extended to the multi-cell case. The only limitation is that the number of revisions might become too large, making the total latency caused by inter-cell information exchange over the backhaul, too long for the CSI to be valid anymore. This can be tackled by e.g., putting a limit on the number of cell-edge users which can be served in each cell. A more detailed investigation of this issue is, however, left to our future work.

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