SLNR-based User Scheduling for MISO Downlink Cellular Systems

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***Abstract*—In this paper, we consider a user scheduling problem which maximizes the weighted sum-rate (WSR) in multicell multiple input single output (MISO) downlink systems. Since an exhaustive search algorithm requires high computational complexity, we propose a low complexity algorithm which finds a user set in terms of WSR maximization. We first consider a greedy user selection algorithm which almost achieves the system performance of the exhaustive search algorithm in high SNR regime. Next, a distributed user scheduling algorithm is proposed by employing the maximized signal-to-leakage-and-noise ratio (SLNR) in the selection criteria. This leads to a reduction of the system overhead of exchanging channel state information and computational complexity. From simulation results, we show that the performance of our proposed scheme is very close to the conventional greedy user scheme with lower overhead.**

I. Introduction

As demands for high rate data services increase in wireless cellular networks, universal frequency reuse is employed for an efficient use of spectrum resources. However, this gives rise to the problem of inter-cell interference (ICI), which becomes major bottlenecks to improve system performance. Recently, base station (BS) coordination strategies, called network multiple-input multiple-output (MIMO), have been proposed to increase both the cell average and cell edge throughput by cooperation among BSs [1].

Depending on the BS cooperation level, the network MIMO can be classified into two categories [2]: coordinated scheduling/beamforming (CS/CB) and joint processing (JP). The CS/CB is accomplished under the condition of channel state information (CSI) exchange without data sharing. In this case, joint resource management such as user scheduling and/or power allocation can be adopted for improving the performance. On the other hand, the JP exchanges all transmit data and CSI of users among BSs. In practical systems with finite capacity backhaul links, sharing all users' data at the BSs may not be feasible. Therefore, this paper focuses on the network MIMO CS/CB systems.

In this multicell context, various beamforming strategies have been studied for interference channels with multiple antennas to improve system performance [2]–[4]. Moreover, the optimal power control is studied for two cell single antenna systems in [5], and is extended to multicell systems in [6]. In spite of its necessity in practical systems, however, relatively few efforts have been devoted to developing a user selection scheme. Recently, user scheduling which selects users in different cells to be served by cooperative BSs was examined in [7], and this method provided new opportunities to enhance the performance. In addition, intercell scheduling has been considered in [6] and [8], but these studies did not take beamforming designs into account. In this paper, we develop the user scheduling policies using linear beamforming designs.

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First, we consider a low complexity user selection algorithm for multiple-input single-output (MISO) downlink CS/CB systems with multiple users in each cell. We investigate an efficient greedy user selection (GUS) algorithm which extends the single cell strategy in [9] to multicell wireless networks and show that a large fraction of the system performance of the exhaustive search case can be recovered. However, the GUS algorithm requires the global CSI to select the users. Thus, we propose a signal-to-leakage-and-noise ratio (SLNR) based user selection algorithm (SUS) which exploits only local CSI and reduces computational complexity compared to GUS. Numerical results show that the proposed SUS scheme exhibits the performance very close to the GUS scheme in all SNR range with much reduced CSI overhead.

The organization of the paper is as follows: Section II presents the system model and the problem formulation for user scheduling in coordinated multicell system. Section III briefly reviews conventional user selection algorithms. In Section IV, we explain our proposed user selection algorithm on the basis of SLNR. Subsequently, we compare with conventional algorithm in Section V. Through the simulation results in Section VI, we confirm the effectiveness of our proposed algorithms. Finally, this paper is terminated with conclusions in Section VII.

Throughout this paper, we use the following notations. Normal letters represent scalar quantities, bold face letters indicate vectors, and boldface uppercase letters designate matrices. The superscript $(\cdot)^H$ stands for Hermitian transpose and the two-norm of a vector is denoted by $\|\cdot\|$. The expectation operation is given as $\mathbb{E}[\cdot]$.

II. System Model and Problem Formulation

We consider an L-cell downlink cellular network where each BS has N_t transmit antennas and communicates to K users with a single antenna within a cell. The BSs share a certain level of users' CSI through limited bandwidth backhaul links, but not users' data. In each time slot, we assume that users are independent and randomly distributed within a cell and one active user is served by each BS. The set of all users is denoted by $U = \{U_1, U_2, ..., U_L\}$ where $U_l = \{k_l | k =$

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$1, \cdots, K\}$ stands for the set of users with k_l indicating the k-th user in cell l.

First, we define the beamforming vector $\mathbf{v}_{k_i} \in \mathbb{C}^{N_t \times 1}$ for user k_i with $\|\mathbf{v}_{k_i}\|^2 \leq 1$ and the complex-valued data symbol s_{k_i} of user k_i with $\mathbb{E}[|s_{k_i}|^2] = 1$. Suppose that N is the number of selected users from user scheduling, we denote the set of N selected users served by BSs as S_N with $|S_N| = N$. Then, the received signal of user k_i can be written as

$$y_{k_i} = \sqrt{\alpha_{k_i,i}} \bar{\mathbf{h}}_{k_i,i}^H \mathbf{v}_{k_i} s_{k_i} + \sum_{j \in S_N \setminus k_i} \sqrt{\alpha_{k_i,j}} \bar{\mathbf{h}}_{k_i,j}^H \mathbf{v}_{k_j} s_{k_j} + z_{k_i} \quad (1)$$

where $\bar{\mathbf{h}}_{k_i,j}$ is the channel vector from BS j to user k_i whose entries are independent and identically distributed (i.i.d.) complex Gaussian with zero mean and unit variance, z_{k_i} represents the additive white Gaussian noise with variance N_o, and $\alpha_{k_i,j}$ indicates the received power determined by the distance-dependent pathloss model $\alpha_{k_i,j} = \alpha_j (d_0/d_j^{k_i})^\beta$. Here, $d_j^{k_i}$ stands for the distance from BS j to user k_i, α_j is the received power at the reference distance d_0 from BS j and β equals the pathloss exponent. For notational simplicity, we denote $\mathbf{h}_{k_i,j}$ as $\mathbf{h}_{k_i,j} = \sqrt{\alpha_{k_i,j}} \bar{\mathbf{h}}_{k_i,j}$.

The individual rate of user k_i for single user detection is given by

$$R_{k_i} = \log_2(1 + \mathsf{SINR}_{k_i}) \quad (2)$$

where SINR_{k_i} represents the signal-to-interference-plus-noise ratio (SINR) of user k_i as

$$\mathsf{SINR}_{k_i} = \frac{|\mathbf{h}_{k_i,i}^H \mathbf{v}_{k_i}|^2}{N_o + \sum_{k_j \in S_N \setminus k_i} |\mathbf{h}_{k_i,j}^H \mathbf{v}_{k_j}|^2}. \quad (3)$$

Under fairness considerations for users, the weighted sum rate (WSR) can be defined as

$$\mathrm{WSR}(S_N) = \sum_{i \in S_N} w_{k_i} R_{k_i} \quad (4)$$

where the weight term w_{k_i} denotes the weight of user k_i which is determined by the required quality of service (QoS) for applications.

By employing linear beamforming strategies such as maximum ratio transmission (MRT) and zero-forcing beamforming (ZFBF), the author in [10] proposed a user scheduling algorithm for maximizing the WSR. However, to support all users in large networks, the ZFBF strategy may require a large number of BS antennas. As we are interested in general cases in this paper which include the $N_t < L$ case, we adopt minimum mean square error (MMSE) beamforming instead of the MRT or the ZFBF.

The MMSE beamforming vector for user k_i can be obtained as

$$\mathbf{v}_{k_i} = \frac{1}{\gamma_{k_i}} \left(\sum_{k_j \in S_N} \mathbf{h}_{k_j,i} \mathbf{h}_{k_j,i}^H + N_o \mathbf{I} \right)^{-1} \mathbf{h}_{k_i,i} \quad (5)$$

where γ_{k_i} is the normalizing factor. In [5], it is shown that a performance loss due to binary power allocation is negligible in multicell single antenna systems. Thus, we employ the binary power allocation where only selected BSs transmit with full power while the others are shut down. By assuming full power transmissions for the selected users, the normalizing factor γ_{k_i} is given by $\|(\sum_{k_j \in S_N} \mathbf{h}_{k_j,i} \mathbf{h}_{k_j,i}^H + N_o \mathbf{I})^{-1} \mathbf{h}_{k_i,i}\|$.

As a result, our goal becomes finding the set of active users that maximizes the WSR for the MMSE beamforming strategy with full power transmission where one active user is served by each BS. Then, we can mathematically formulate this problem as

$$\begin{aligned} \hat{S}_N &= \arg\max_{S_N} \mathrm{WSR}(S_N) \\ &= \arg\max_{S_N} \sum_{k_i \in S_N} w_{k_i} R_{k_i}(S_N). \end{aligned} \quad (6)$$

In the following section, we first review conventional user scheduling algorithms and then develop an efficient user scheduling algorithm.

III. Overview of user scheduling schemes

A. Exhaustive Search

The optimal solution $\hat{S}_N$ of (6) can be obtained by comparing the WSR over all possible candidates of users. Thus, it requires exhaustive search (ES) with search complexity given by $\mathcal{O}(2^L K^L)$, which accounts for combinations of all possible user sets and binary power allocation. It is clear that the search complexity is prohibitive if L or K is large. Also, in order to compute $\mathrm{WSR}(S_N)$ for all combinations of S_N, global CSI should be exchanged over backhaul links among BSs and the central unit (CU) which carries out user scheduling and beamforming designs. To reduce the search complexity and the CSI exchange among the BSs, we investigate several scheduling algorithms in what follows.

B. Individual Search

For the individual search (IS) method [10], a user with the largest rate is selected for each cell, which can be formulated as

$$\hat{k}_i = \max_{k_i \in U_i} w_{k_i} \log\left(1 + \frac{\|\mathbf{h}_{k_i,i}\|^2}{N_o}\right), \quad \text{for } i = 1, ..., L. \quad (7)$$

Compared to the ES strategy, we observe that its search complexity is significantly reduced to $\mathcal{O}(KL)$ and each BS only needs local CSI for user scheduling. However, there is a substantial throughput loss in interference limited environments when $N_t < L$, as will be shown in Section VI. This is due to the fact that the IS algorithm does not consider ICI.

C. Greedy User Search

In [9], the authors have proposed the GUS algorithm using simple zero-forcing (ZF) beamforming for single cell downlink systems. In this subsection, the GUS algorithm is expanded to multicell systems. Here, we utilize MMSE beamforming instead of ZFBF and the algorithm is described as followings. At the initialization step ($N = 1$), a user which has the largest rate among all users is selected while ignoring ICI. Then the index of the selected user is included in S_1. In the iteration steps ($N \geq 2$), the CU determines the MMSE beamforming vectors for users in $S_{N-1} \cup \{k_m\}$ with $k_m \in U \backslash G_{N-1}$ and computes $\mathrm{WSR}(S_{N-1} \cup \{k_m\})$. A new user will be selected by comparing all $\mathrm{WSR}(S_{N-1} \cup \{k_m\})$. Note that $\mathrm{WSR}(S_N)$ indicates the maximum weighted sum rate in the

N-th iteration. If $\mathrm{WSR}(S_N)$ is less than $\mathrm{WSR}(S_{N-1})$, users in S_{N-1} are selected and the algorithm is finished. Otherwise, repeat the iteration process until $N = L$.

By successively selecting a user in each iteration, its search complexity is reduced from $\mathrm{O}(2^L K^L)$ to $\mathrm{O}(L^2 K)$. Simulation results show that the GUS scheme approaches the average sum rate of the ES method at high SNR. Here, we can see that the algorithm needs global CSI to compute the WSRs. Thus, the GUS algorithm requires a large amount of resources for BS cooperations, which would incur too much burden to be allowed over limited capacity backhaul links. In the next section, we propose a distributed user scheduling algorithm whose performance is very close to the GUS scheme with a significant reduction in the CSI exchange overhead.

IV. Proposed SLNR based user selection algorithm

In this section, we propose a distributed user scheduling algorithm by modifying the GUS algorithm. The GUS algorithm selects users by comparing the WSRs of all remaining users. Instead of the WSR criteria for user selection, we present new criteria to maximize the SLNR, which is defined for user k_i as

$$\mathsf{SLNR}_{k_i} = \frac{|\mathbf{h}_{k_i,i}^H \mathbf{v}_{k_i}|^2}{N_o + \sum_{k_j \in S_N \setminus k_i} |\mathbf{h}_{k_j,i}^H \mathbf{v}_{k_i}|^2}. \quad (8)$$

Motivated by the leakage based approach in [11], we can formulate the selection criteria to account for the sum of leakage power which affects all other selected users.

It is known that MMSE precoding maximizes the SLNR for systems with single antenna receivers [12]. By using the MMSE beamforming in (5), the maximized SLNR can be written as

$$\mathsf{SLNR}_{k_i} = \frac{1}{1 - \mathbf{h}_{k_i,i}^H \left(\sum_{k_j \in S_N} \mathbf{h}_{k_j,i} \mathbf{h}_{k_j,i}^H + N_o \mathbf{I}\right)^{-1} \mathbf{h}_{k_i,i}} - 1. \quad (9)$$

Now, we denote a new parameter Π_{k_i} as $\Pi_{k_i}^{-1} = 1 + \mathsf{SLNR}_{k_i}$ where Π_{k_i} is given by

$$\Pi_{k_i} = 1 - \mathbf{h}_{k_i,i}^H \left(\sum_{k_j \in S_N} \mathbf{h}_{k_j,i} \mathbf{h}_{k_j,i}^H + N_o \mathbf{I} \right)^{-1} \mathbf{h}_{k_i,i}. \quad (10)$$

Instead of using the rate $\mathrm{WSR}(S_N) = \sum_{k_i \in S_N} w_{k_i} R_{k_i}$ for user selection, we define the weighted sum virtual rate (WSVR) as

$$\mathrm{WSVR}(S_N) = \sum_{k_i \in S_N} w_{k_i} \log_2 \frac{1}{\Pi_{k_i}} \quad (11)$$

where $\log_2 \Pi_{k_i}^{-1}$ represents the virtual rate (VR) of user k_i. To calculate the WSVR for selecting user, each BS only requires the information of its local CSI and operates in distributed manner which reduces the computing load of the CU. Then, this SLNR-based user selection algorithm (SUS) algorithm is described in Algorithm 1. The difference between both algorithms is the selection criteria such that the proposed SUS algorithm selects a user by comparing the WSVR instead of the WSR.

Algorithm 1 SLNR based User Selection Algorithm

- Initialization:

1) Set $N = 1$.
2) Find a user $\hat{k}_l$ such that
$\hat{k}_l = \arg\max_{k_i \in U} \; w_{k_i} \log\left(1 + \frac{\|\mathbf{h}_{k_i,i}\|^2}{N_o}\right)$.
3) Set $S_1 = \{\hat{k}_l\}, G_1 = U_l$ and
denote the achieved weighted virtual rate as $\mathrm{WSVR}(S_1)$.

- Iteration:

4) Increase N by 1.
5) Find a user $\hat{k}_m$ such that
$\hat{k}_m = \arg\max_{k_m \in U \setminus G_{N-1}} \; \mathrm{WSVR}(S_{N-1} \cup \{k_m\})$.
6) Set $S_N = S_{N-1} \cup \{\hat{k}_m\}, G_N = G_{N-1} \cup U_m$ and denote the achieved rate as $\mathrm{WSVR}(S_N)$.
7) If $\mathrm{WSVR}(S_N) \le \mathrm{WSVR}(S_{N-1})$, decrease N by 1 and stop. Otherwise, go to 4) and repeat the iteration until $N = L$.

Compared to the conventional GUS scheme, the following observations can be made for the proposed scheme. First, the CSI exchange overhead is significantly reduced when computing (11) instead of (4). Here, we can see in (10) that only local CSI is needed for obtaining the VR, and each BS transmits the VR value to the CU after computing the weighted VR. Then, the CU determines the best user by comparing scalar feedbacks from the BSs without requiring global CSI.

Second, the proposed algorithm does not need the information of the beamforming vector for user scheduling, and thus the computational complexity of the proposed algorithm is much lower than the conventional one. Also, applying the Sherman-Morrison formula [13] to (10) yields

$$\begin{aligned}\Pi_i^{-1} &= 1 - \mathbf{h}_{k_i,i}^H \left(\sum_{k_j \in S_{N-1}} \mathbf{h}_{k_j,i} \mathbf{h}_{k_j,i}^H + N_o \mathbf{I} + \mathbf{h}_{k_m,i} \mathbf{h}_{k_m,i}^H \right)^{-1} \mathbf{h}_{k_i,i} \\ &= 1 - \mathbf{h}_{k_i,i}^H \left(\mathbf{A}_i^{-1} - \frac{\mathbf{A}_i^{-1} \mathbf{h}_{k_m,i} \mathbf{h}_{k_m,i}^H \mathbf{A}_i^{-1}}{1 + \mathbf{h}_{k_m,i}^H \mathbf{A}_i^{-1} \mathbf{h}_{k_m,i}} \right) \mathbf{h}_{k_i,i} \end{aligned} \quad (12)$$

where $\mathbf{A}_i^{-1} = (\sum_{k_j \in S_{N-1}} \mathbf{h}_{k_j,i} \mathbf{h}_{k_j,i}^H + N_o \mathbf{I})^{-1}$. Because the computation of $\mathbf{A}^{-1}$ at each BS is carried out only once for all candidate users $k_m \in S_N \setminus G_{N-1}$, the computational complexity is further reduced compared to the GUS.

V. Comparison of GUS and SUS

In this section, we compare our proposed scheme with the conventional scheme in terms of the CSI exchange overhead and the computational complexity. We first clarify the overhead amount of information exchanged over backhaul links among BSs and the CU. In the proposed SUS process, the WVR values of candidate users are exchanged for selecting a new user. For the first layer ($N = 1$), all user rates are computed and these L rates are transmitted to the CU. In the second layer ($N = 2$), the process needs $(L-1)K + (L-1)K$ real values where the first term accounts for the calculated values in the selected BS and the second term corresponds to the remaining BSs. Generalizing this result to the N-th layer, $N(L - N + 1)K$ computed rates are transmitted to the CU.

TABLE I
NUMBER OF THE CSI EXCHANGE OVERHEAD AND COMPLEX MULTIPLICATIONS

Configurations		CSI exchange overhead	Complex multiplications
$L=3, N_t=2, K=3$	Proposed	24 real values	68 (per each BS)
	Conventional	81 complex values	294 (CU)
$L=7, N_t=4, K=10$	Proposed	777 real values	2740 (per each BS)
	Conventional	1960 complex values	44660 (CU)

Thus, the total number of the exchanged information is given by $L+\sum_{N=2}^{L} N(L-N+1)K = L\left(\frac{K(L+1)(L+2)-6K+6}{6}\right)$.

In contrast, the conventional GUS algorithm should transmit all users' CSI to the CU which requires L^2KN_t complex values. Table I presents the required overhead of both the proposed and conventional schemes. From this table, we verify that our proposed scheme exhibits a reduction of 85.2% and 80.2% in terms of the CSI exchange overhead in comparison to the conventional scheme with $L=3, N_t=2, K=3$ and $L=7, N_t=4, K=10$, respectively.

Also, the computational complexity for user scheduling is listed in Table I in terms of the number of complex multiplications. In the first layer $(N=1)$, the multiplications of both algorithms are equal to N_tKL which results from computing the channel norm of all users. In the N-th layer, the GUS algorithm requires $\{(N-1)((N_t^2+2N_t)K(L-N+1)+N_t^2+N_t)+(N_t^2+2N_t)K(L-N+1)\}+\{N_tKL(N-1)^2\}$ complex multiplications where the first term is identical to the SUS algorithm but the second term is an additional burden. This increase is due to the fact that the GUS algorithm needs the beamforming vectors to compute the WSR. As a result, the computational savings of the proposed SUS algorithm are $N_tKL\sum_{N=1}^{L}(N-1)^2 = N_tKL^2\frac{(L-1)(2L-1)}{6}$, which exhibits a reduction of 30.6% and 57.1% in terms of the computational complexity with $L=3, N_t=2, K=3$ and $L=7, N_t=4, K=10$, respectively. It should also be mentioned that the SUS algorithm can be distributively implemented at each BS, whereas the GUS algorithm must be carried out in the CU.

VI. SIMULATION RESULTS

In this section, we present the performance of our user scheduling algorithm in multicell MISO downlink systems. In our simulation, users are randomly generated and placed uniformly with the cell radius $R=0.5$ km. The pathloss exponent is set to $\beta=3.75$. For small scale fadings, we employ spatially uncorrelated MIMO Rayleigh fading channels which are independently generated for each transmission. Unless otherwise stated, the received power at each BS is set to the same power as $\alpha_i=\alpha$ for $\forall i$. For users' weight computation, we utilize proportional fair scheduling, which provides a good trade-off between the system throughput and fairness among users. Then, the weight w_{k_i} for user k_i is the reciprocal of its past average throughput T_{k_i}. In each time slot t, the average throughput can be updated by

$$T_{k_i}(t+1)=\begin{cases}(1-\frac{1}{t_c})T_{k_i}(t)+\frac{1}{t_c}R_{k_i}(t) & \text{, if } k_i=\hat{k}_i \text{ at time } t\\ (1-\frac{1}{t_c})T_{k_i}(t) & \text{, if } k_i\neq\hat{k}_i \text{ at time } t\end{cases}$$

where t_c is a parameter which adjusts the fairness. As a typical value, t_c is set to $t_c=100$.

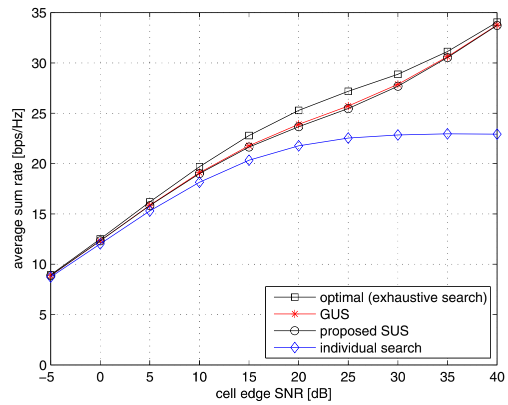

Fig. 1. Average sum rate performance of a three cell network with $N_t=2$ and $K=3$

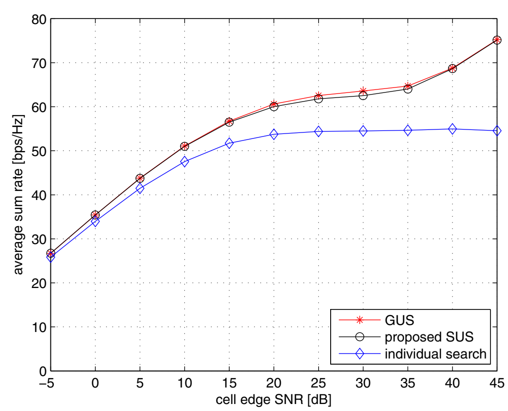

Fig. 2. Average sum rate performance of a seven cell network with $N_t=4$ and $K=10$

Fig. 1 depicts the average sum rate throughput of various schemes for three cell systems with $N_t=2$ and $K=3$ users as a function of the cell edge received SNR. The plot shows that the GUS algorithm achieves 94.5% of the sum rate of the ES and also approach the throughput of the ES algorithm at high SNR. Compared to the conventional algorithm, the proposed scheme exhibits a negligible performance loss for all simulated SNRs, while only local CSI is required. As expected, the IS algorithm produces poor performance because of strong ICI.

Fig. 2 shows the performance for seven cell networks with $N_t=4$ and $K=10$ users in each cell. The result of the ES is omitted in this figure due to its prohibitive computational complexity. Similar to the previous results, the proposed user scheduling algorithm exhibits almost the same performance

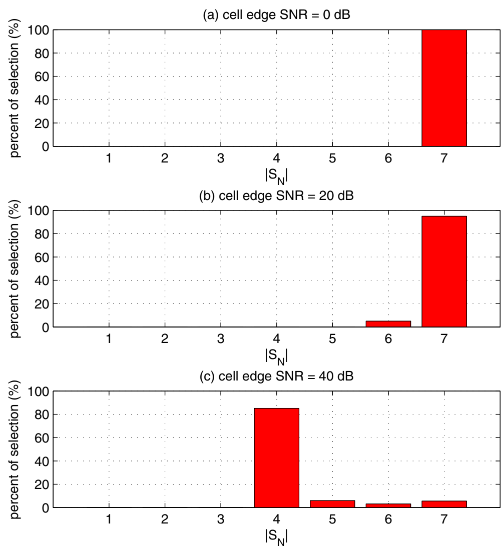

Fig. 3. Histogram of the size of active users $|S_N|$ for SUS.

as the GUS algorithm.

In Fig. 3, we plot the histogram of the size of active users $|S_N|$ of the SUS algorithm in various SNR ranges for seven cell systems with $N_t = 4$. It can be seen that the number of active users of the SUS algorithm decreases up to the number of BS antennas N_t as the edge SNR increases. These simulation results show that the SUS algorithm chooses the number of active users depending on the cell edge SNR. As a result, we see that the SUS algorithm can improve the throughput by adaptively supporting users. Note that the IS algorithm always serves the active users $|S_N| = L$ in all SNR ranges.

Fig. 4 exhibits the performance with asymmetric system configurations where a different number of users and per BS power constraint are assumed at each BS. The simulation is carried out in seven cell networks with $N_t = 4$, $[K_1, K_2, ..., K_7] = [10, 15, 22, 5, 20, 9, 11]$ and $\alpha_i = \alpha m_i$ for $\forall i$ where K_i and m_i represent the number of users in cell i and the fraction of the received power for BS i. Here m_i is given by $[m_1, \cdots, m_7] = [0.5, 0.7, 1, 0.5, 0.7, 1, 0.6]$. In this plot, we see that there is a negligible performance gap between the proposed algorithm and the conventional algorithm regardless of system configurations. Thus we confirm that the proposed user scheduling scheme can be applied with much reduced CSI exchange overhead and computational complexity.

VII. Conclusions

In this paper, we have proposed a low complexity scheduling algorithm for the WSR maximization in MISO downlink CS/CB systems. Applying the SLNR-based selection technique, our proposed algorithm is implemented which requires only local CSI. Also, the overall computational complexity becomes substantially lower than the conventional GUS algorithm. We have shown from the simulation results that the proposed scheme exhibits the average sum rate performance

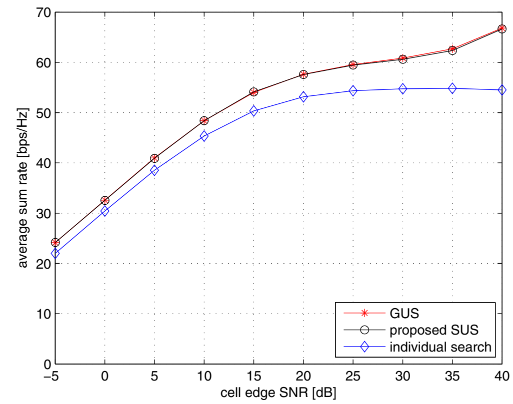

Fig. 4. Average sum rate performance of a seven cell network with asymmetric system configurations

almost identical to the conventional GUS scheme with substantially lower CSI requirements.

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