Channel Norm-Based User Scheduler in Coordinated Multi-Point Systems

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***Abstract*—In this paper, we address the problem of user scheduling in downlink coordinated multi-point transmission (CoMP) systems, where multiple users are selected and then served with zero forcing beamformer simultaneously by several cooperative base stations (BSs). To reduce the enormous overhead led by obtaining full channel state information at the transmitter, a low-feedback user scheduling method called channel norm-based user scheduler (NUS), is proposed by exploiting the asymmetric channel feature of CoMP systems. Simulation results show that the channel norm provides sufficient information for user scheduling when each BS has one antenna, where the performance gap between the NUS and the greedy user selection (GUS) is negligible with respect to both the cell average throughput and the cell edge throughput. When each BS has multiple antennas, NUS is inferior to GUS, but still significantly outperforms the uncoordinated systems.**

I. INTRODUCTION

Inter-cell interference is one of the major bottlenecks to improve system performance in future cellular networks, where universal frequency reuse is employed for high spectral efficiency. Except for various interference mitigation techniques, recently a concept of coordinated multi-point transmission (CoMP) has attracted much attention. As a promising transmit strategy of CoMP, coherent transmission with coordinated base stations (BSs) can significantly improve both the cell average throughput and the cell edge throughput [1]. Such a CoMP system can be regarded as a single super cell multiple-input multiple-output (MIMO) system. Either single user or multi-user (MU) MIMO techniques can be applied to serve multiple users from difference cells, where MU-MIMO schemes can approach the upper bound of the system throughput. One of the fundamental differences between CoMP MU MIMO systems and single-cell MU MIMO systems lies in the per base station power constraint (PBPC). The optimal linear beamforming for CoMP subject to PBPC is studied in [2] by using a convex optimization method. To reduce its complexity, a suboptimal zero-forcing beamforming (ZFBF) is proposed in [1], which is often used for performance analysis and evaluation of CoMP systems.

Apart from beamforming, user scheduling is critical, which selects multiple users located in different cells to be served by several cooperative BSs. Existing channel aware user scheduling methods are applicable for a centralized CoMP system. Nevertheless, the unique channel characteristic in these systems provides new opportunities to improve the performance of user scheduling. The composite channel consisting of both large and small scale fading experienced by heterogeneous users in CoMP systems provides an increased multiuser diversity gain of $\sqrt{2\log K}$ rather than the well-known $\log\log K$, where K is the total user number [3]. However, as will be discussed in Section III, the channel aware scheduling needs enormous feedback overhead to obtain channel state information at the transmitter (CSIT) even for CoMP time division duplexing (TDD) systems. In this study, we strive for reducing the feedback for user scheduling by exploiting the asymmetry channels in CoMP systems, where the average gain from different BSs to each user differs significantly.

Low feedback user scheduling has been investigated in single-cell MU-MIMO systems [4,5]. In [4], the authors point out that both channel direction information and channel quality information are necessary to achieve multiuser diversity. In [5], it is shown that the combination of channel norm with long term channel statistics in the form of channel mean and covariance matrix is enough for both beamforming and scheduling.

In this paper, we propose a channel norm-based user scheduler (NUS) for CoMP MU-MIMO systems where ZFBF [1] is used as a collaborated precoding. Multi-user precoding requires the full CSIT of the selected users. Since the number of selected users is usually a small fraction of the total user number, the feedback overhead can be significantly reduced.

To illustrate the performance of our NUS, we generalize it to consider a short term fairness in a round-robin fashion [6]. Then we use the cell average and cell edge throughput as performance metrics to compare our method with existing methods requiring full CSIT. Simulation results showed that channel norm information is sufficient for user scheduling in CoMP systems with single-antenna BS, otherwise full CSIT of users from their local serving BS is necessary for NUS to achieve comparable performance to the greedy user selection (GUS) [7].

II. SYSTEM MODEL

Consider a CoMP system consisting of M coordinated cells, each of which includes one BS equipped with N_t antennas and

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K uniformly distributed users equipped with one antenna. Let (M, N_t, K) denote such a network layout, and i_{km} denote the index of the *k-th* user located in cell m, $i_{km} = K(m-1)+k$, $m = 1, \ldots, M$, $k = 1, \ldots, K$. We define $\mathbf{h}_{i_{km}} = [\mathbf{h}_{i_{km}1} \ldots \mathbf{h}_{i_{km}M}] \in \mathbb{C}^{1 \times MN_t}$ as the downlink channel vector of user i_{km}, where $\mathbf{h}_{i_{km}n} \in \mathbb{C}^{1 \times N_t}$ is the channel vector from BS n to user i_{km}, $n = 1, \ldots, M$.

For linear beamforming, at most MN_t users can be served simultaneously in the considered system. Let $\mathcal{T} = \{i_{11}, \ldots, i_{KM}\}$ denote the total user pool, and $\mathcal{S} = \{s_1, \ldots, s_L\}$ denote the set of indices of the L selected users. $\mathcal{S}$ is a subset of $\mathcal{T}$, *i.e.*, $\mathcal{S} \subset \mathcal{T}$. Then the signal received by user s_l is

$$y_{s_l} = \mathbf{h}_{s_l}\mathbf{W}\mathbf{x} + z_{s_l}, \tag{1}$$

where $\mathbf{x} \in \mathbb{C}^{L \times 1}$ is information symbols of the users in $\mathcal{S}$, z_{s_l} is the additive white Gaussian noise at user s_l with zero mean and variance σ^2, and $\mathbf{W} \in \mathbb{C}^{MN_t \times L}$ is a linear precoding matrix. For ZFBF, $\mathbf{W}$ can be expressed as [1]

$$\mathbf{W} = \mathbf{G}\mathbf{P}^{\frac{1}{2}}, \tag{2}$$

where $\mathbf{G} = \mathbf{H}_{\mathcal{S}}^H \left(\mathbf{H}_{\mathcal{S}}\mathbf{H}_{\mathcal{S}}{}^H\right)^{-1}$, $\mathbf{H}_{\mathcal{S}} = [\mathbf{h}_{s_1}^T \ldots \mathbf{h}_{s_L}^T]^T$ and $\mathbf{P}$ is a diagonal power allocation matrix whose *l-th* diagonal element is p_l, $l = 1, \ldots, L$. The optimal user set $\mathcal{S}$ based on ZFBF can be chosen to maximize the sum rate as follows,

$$\max_{\mathcal{S},\mathbf{P}} \sum_{l=1}^{L} \log(1 + \frac{p_l}{\sigma^2}) \tag{3a}$$

$$s.t. \sum_{j=(m-1)N_t+1}^{mN_t} [\mathbf{G}\mathbf{P}\mathbf{G}^H]_{j,j} \leq P_m,\ m = 1, \ldots, M, \tag{3b}$$

$$p_l \geq 0, \quad l = 1, \ldots, L,$$

$$\mathcal{S} \subset \mathcal{T},$$

where P_m is the maximal transmit power of *m-th* BS and (3b) reflects the PBPC in CoMP systems.

This is a joint optimization problem of $\mathcal{S}$ and $\mathbf{P}$, which can be solved alternatingly. Given a user set $\mathcal{S}$, the optimization with respect to $\mathbf{P}$ is convex, which can be solved numerically by using optimization software packages like CVX [8]. Given $\mathbf{P}$, however, finding the optimal $\mathcal{S}$ needs exhaustive searching over $\sum_{L=1}^{MN_t} \binom{MK}{L}$ possible user sets, which will result in a huge computational complexity.

If we relax the PBPC in (3) into a sum power constraint, CoMP systems can then be treated as single-cell MU-MIMO systems, where many low-complexity user scheduling methods have been proposed like GUS [7]. With the knowledge of full CSIT, GUS combined with ZFBF performs almost as well as the exhaustive searching method, and can achieve a sum rate that asymptotically grows with the number of users in the same way as dirty paper coding [9]. GUS is a successive procedure initialized by selecting the user with maximum channel gain. Based on the selected users, each new user will be selected iteratively from the remaining users, until adding one more user reduces the sum rate. Considering its excellent performance and low complexity, we will use GUS with PBPC ZFBF as a benchmark for the performance evaluation of the proposed user scheduling scheme in next section.

III. CHANNEL NORM-BASED USER SCHEDULER

A. *Obtaining CSIT in CoMP Networks*

It is believed that TDD is more suitable for CoMP systems than frequency division duplexing (FDD), because the latter will lead to a prohibitive overhead of CSIT feedback. However, even though the downlink channel can be estimated at BS by exploiting uplink-downlink channel reciprocity in single-cell TDD systems, it may be infeasible to apply the same method in CoMP TDD systems due to the following reasons. First, since orthogonal training sequences for all users are required for uplink channel estimation, the resulting training overhead in CoMP systems including M cells increases by a factor of M compared to single-cell systems. Second, since the transmission power at the user side is limited, the uplink channels from adjacent cells users that experience very large path loss are hard to estimate in practice. Third, the calibration between the uplink and downlink channels among multiple BSs is not an easy task.

The downlink channel estimation facilitating data demodulation at the user side is much easier to obtain. On one hand, since the number of BSs in CoMP systems is typically far smaller than the number of users, the overhead led by orthogonal training sequences for the cooperative BSs is acceptable. On the other hand, the BS transmission power is generally large enough in order to perform the coordinated transmission. Thus the downlink channel estimation at the user side will not be power-constrained. Considering these facts, a feasible way to get CSIT for CoMP downlink transmission is to combine TDD and FDD mechanisms as follows. The channels from the users in its own cell can be estimated at the BS by exploiting channel reciprocity, while the channels from the users in other cells are first estimated at the user side and then fed back to the BSs. Nevertheless, one can see that the overhead is still not affordable. Next we will propose a low-feedback user scheduling scheme, which only requires channel norm information instead of the full CSIT.

B. *Channel Norm-Based User Scheduler*

NUS is inspired by the semi-orthogonal user selection (SUS) [10], which is also a successive user scheduling scheme like GUS. With the assumption of full CSIT, in each iteration SUS only calculates the norm of the orthogonal projection of each remaining channel vector onto the subspace spanned by the channel vectors of the selected users, instead of computing the sum rate in GUS. Then the user with largest orthogonal projection norm will be selected. The iteration will stop if the maximal number of selected users is reached or there is no user left that meets the semi-orthogonal limitation. SUS has a lower complexity than GUS at the expense of sum rate.

Considering the unique asymmetry feature of channels in CoMP systems, where the channel gain from different BSs to each user differs significantly, we can derive the upper bound of the norm of remaining channel vector onto the subspace spanned by the channel vectors of the selected users and the angle between them. This finally leads to the NUS scheduler.

In the *(l+1)-th* iteration of SUS, the following orthogonal projection norm of $\mathbf{h}_{i_{km}}$ onto $\mathbf{H}_{\mathcal{S}_l}$ is computed,

$$\nu_{\mathcal{S}_l i_{km}} = \mathbf{h}_{i_{km}} \left(\mathbf{I} - \mathbf{H}_{\mathcal{S}_l}^H (\mathbf{H}_{\mathcal{S}_l} \mathbf{H}_{\mathcal{S}_l}^H)^{-1} \mathbf{H}_{\mathcal{S}_l}\right) \mathbf{h}_{i_{km}}^H, \quad (4)$$

where $\mathbf{H}_{\mathcal{S}_l} = [\mathbf{h}_{s_1}^T \dots \mathbf{h}_{s_l}^T]^T$, $\mathbf{h}_{s_i} = [\mathbf{h}_{s_i 1} \dots \mathbf{h}_{s_i M}]$, $1 \le i \le l$, $i_{km} \in \mathcal{T}_{l+1}$, $\mathcal{T}_{l+1}$ is the user pool in the *(l+1)-th* iteration and $\mathcal{S}_l$ is the scheduling result before the *(l+1)-th* iteration. Considering the fact that the orthogonal projection norm of $\mathbf{h}_{i_{km}}$ onto $\mathbf{H}_{\mathcal{S}_l}$ is smaller than the orthogonal projection norm of $\mathbf{h}_{i_{km}}$ onto any vector $\mathbf{h}_{s_i}$ included in $\mathbf{H}_{\mathcal{S}_l}$, $\nu_{\mathcal{S}_l i_{km}}$ can be upper bounded by

$$\nu_{\mathcal{S}_l i_{km}} \le \min_i \mathbf{h}_{i_{km}} \left(\mathbf{I} - \frac{\mathbf{h}_{s_i}^H \mathbf{h}_{s_i}}{\mathbf{h}_{s_i} \mathbf{h}_{s_i}^H}\right) \mathbf{h}_{i_{km}}^H \triangleq \min_i \nu_{s_i i_{km}}, \quad (5)$$

where $\nu_{s_i i_{km}}$ is defined as the orthogonal projection norm of $\mathbf{h}_{i_{km}}$ onto $\mathbf{h}_{s_i}$. It can be upper bounded by (see Appendix)

$$\begin{aligned}\nu_{s_i i_{km}} \le & \frac{\sum_{\substack{j,n=1 \\ j \neq n}}^{M} \left(\|\mathbf{h}_{i_{km}n}\| \|\mathbf{h}_{s_i j}\| + \|\mathbf{h}_{i_{km}j}\| \|\mathbf{h}_{s_i n}\|\right)^2}{2 \sum_{n=1}^{M} \|\mathbf{h}_{s_i n}\|^2} \\ & + \frac{\sum_{n=1}^{M} \|\mathbf{h}_{i_{km}n}\|^2 \|\mathbf{h}_{s_i n}\|^2}{\sum_{n=1}^{M} \|\mathbf{h}_{s_i n}\|^2}. \quad (6)\end{aligned}$$

Substituting (6) into (5), an upper bound of $\nu_{\mathcal{S}_l i_{km}}$ can finally be obtained as

$$\begin{aligned}\nu_{\mathcal{S}_l i_{km}}^{ub} = \min_i & \left(\frac{\sum_{\substack{j,n=1 \\ j \neq n}}^{M} \left(\|\mathbf{h}_{i_{km}n}\| \|\mathbf{h}_{s_i j}\| + \|\mathbf{h}_{i_{km}j}\| \|\mathbf{h}_{s_i n}\|\right)^2}{2 \sum_{n=1}^{M} \|\mathbf{h}_{s_i n}\|^2} \right. \\ & \left. + \frac{\sum_{n=1}^{M} \|\mathbf{h}_{i_{km}n}\|^2 \|\mathbf{h}_{s_i n}\|^2}{\sum_{n=1}^{M} \|\mathbf{h}_{s_i n}\|^2} \right). \quad (7)\end{aligned}$$

One can see that $\nu_{\mathcal{S}_l i_{km}}^{ub}$ only depends on the norm of the channels from all BSs. When only channel norms are available at transmitter, the users can be selected by replacing the exact $\nu_{\mathcal{S}_l i_{km}}$ in SUS with its upper bound $\nu_{\mathcal{S}_l i_{km}}^{ub}$. We will analyze the tightness of $\nu_{\mathcal{S}_l i_{km}}^{ub}$ in our future works.

A stopping criterion is necessary for the successive user scheduler. In other words, the number of selected users needs to be optimized, since it is generally not optimal to serve as many users as possible. Due to the lack of full CSIT, it is impossible to use the sum rate as the stopping criterion. Analogous to SUS, we control the scheduling procedure by introducing a constraint on the orthogonality between the selected users. The angle θ between $\mathbf{h}_{i_{km}}$ and $\mathbf{h}_{s_i}$ can be obtained as

$$\cos\theta = \frac{|\mathbf{h}_{i_{km}} \mathbf{h}_{s_i}^H|}{\|\mathbf{h}_{i_{km}}\| \|\mathbf{h}_{s_i}\|}, \ 0 \le \theta \le \frac{\pi}{2}, \quad (8)$$

which is upper bounded by

$$\cos\theta \le \frac{\sum_{n=1}^{M} \|\mathbf{h}_{i_{km}n}\| \|\mathbf{h}_{s_i n}\|}{\sqrt{\sum_{n=1}^{M} \|\mathbf{h}_{i_{km}n}\|^2} \sqrt{\sum_{n=1}^{M} \|\mathbf{h}_{s_i n}\|^2}} \triangleq \mu_{i_{km} s_i}^{ub}. \quad (9)$$

Here we give an upper bound of $\cos\theta$, which is equivalent to define a lower bound on θ. Then a specific threshold ϵ can be introduced to ensure $\mu_{i_{km} s_i}^{ub} \le \epsilon$. Based on the above analysis, our NUS is summarized as follows.

Let $\mathcal{T}_l$ and $\mathcal{S}_l$ denote the user pool and the scheduling result at *l-th* step, $1 \le l \le \min(MN_t, MK)$. Set $\mathcal{S}_l = \{s_1, \cdots, s_l\}$, $\mathcal{T}_0 = \{1, 2, \dots, MK\}$.

1) Initialize by selecting a user with the maximum channel norm as the first user,

$$s_1 = \arg\max_{i_{km} \in \mathcal{T}_0} \|\mathbf{h}_{i_{km}}\|. \quad (10)$$

Set $\mathcal{S}_1 = \{s_1\}$ and $l = 1$.

2) When $l \le \min(MN_t, MK)$, obtain the user pool $\mathcal{T}_l$ as

$$\mathcal{T}_l = \left\{ i_{km} \in \mathcal{T}_{l-1}, i_{km} \notin \mathcal{S}_l \mid \mu_{i_{km} s_l}^{ub} \le \epsilon \right\}, \quad (11)$$

where $\mu_{i_{km} s_l}^{ub}$ is defined by (9).
If $\mathcal{T}_l = \phi$ (empty set), the iteration will stop. Otherwise, compute the upper bound $\nu_{\mathcal{S}_l i_{km}}^{ub}$ of the orthogonal projection norm of each remaining channel vector onto the subspace spanned by the channel vectors of the selected users, and select the user with largest $\nu_{\mathcal{S}_l i_{km}}^{ub}$,

$$s_{l+1} = \arg\max_{i_{km} \in \mathcal{T}_l} \nu_{\mathcal{S}_l i_{km}}^{ub}, \quad (12)$$

where $\nu_{\mathcal{S}_l i_{km}}^{ub}$ is defined by (7). Set $\mathcal{S}_{l+1} = \mathcal{S}_l \cup \{s_{l+1}\}$ and $l = l + 1$, where $\cup$ denotes the union between two sets.

To implement NUS in the network (M, N_t, K), each user only needs to feedback M real scalars to the cooperative BSs, while to implement GUS each user needs to feedback MN_t complex scalars. The ratio of the feedback overhead of NUS over GUS is $1/(2N_t)$, which linearly decreases with the number of antennas at each BS.

C. Round-robin NUS

When a scheduler is designed for maximizing the sum rate, only users at the cell center will be served, which contradicts to the goal of CoMP to improve the cell edge throughput. This can be solved by simply combining NUS and a fair scheduling scheme like Round-robin (RR) or proportional fair scheduler. In [10] a fair scheduling scheme combining RR and SUS is proposed. To illustrate the performance of a coherent CoMP transmission using NUS, we extend NUS in a RR fashion, namely RR-NUS, which assigns equal transmission time slots to all the users. The idea is similar to the short term fairness scheduler as presented in [6]. RR-NUS is a combination of TDMA and SDMA, which achieve spatial multiplexing gains by SDMA and provide fairness among users by TDMA. In RR-NUS, it is a group of users rather than one user that are served at each time slot. The selected users will be removed from the user pool at next time slot. Let Q denote the total number of user groups. Then a scheduling period for RR-NUS will contain Q time slots.

IV. SIMULATION ANALYSIS

In this section we evaluate the performance of NUS via simulations. Except for RR-NUS, two relevant user scheduling schemes, RR-NOC (No Cooperation) and RR-GUS, are also considered for comparison. RR-NOC is a RR scheduling scheme for uncoordinated networks, where BS in each cell independently selects users in a TDMA fashion thus inter-cell interference exists. RR-GUS is similar to RR-NUS, where the user group at each time slot is selected according to GUS [6].

The simulation setup is based on [11]. In particular, we consider a CoMP system with a 1 km BS-to-BS distance and a 10 MHz channel bandwidth. The BSs transmit with a maximal power of 40 W and with an antenna gain of 14 dBi. The path loss exponent is 3.76, the shadowing standard deviation is 8 dB, the mean power loss at the reference distance of 1 m is 36.3 dB, and the minimum distance between user and BS is 35 m. The users are placed randomly. Each user has a receiver noise figure of 9 dB. For each drop of users, the *i.i.d.* Rayleigh fading channels with variance 1 are assumed among transmit and receive antennas. All the results are averaged over 100 drops.

We use the cell average throughput and the cell edge throughput that each individual user achieves as the performance metrics, which are denoted by $R_{cell-aver}$ and $R_{cell-edge}$[1], respectively. Different network layouts, represented by (M, N_t, K), are considered to analyze their influence on NUS. For a fair comparison, we fix the total user number $MK = 40$ and the total BS antenna number $MN_t = 8$, which essentially decides the multiuser diversity and spatial multiplexing gain. Then, the following three network layouts will be evaluated: (2,4,20), (4,2,10) and (8,1,5).

Fig. 1 shows the influence of the threshold ϵ on the performance of NUS in networks with layouts (4,2,10) and (8,1,5). We can see that both the cell average throughput and the cell edge throughput per user are not a monotonic function of ϵ. This is led by the entangled influence of ϵ on the short term performance (the throughput at each time slot) and the scheduling period. Specifically, the short term performance depends on the spatial multiplexing gain and the multiuser diversity. ϵ will not only affect the spatial multiplexing gain by controlling the orthogonality between the selected users, but also affect the multiuser diversity gain by determining the size of user pool at each time slot. These two effects of ϵ on the short-term performance are counteracting, which should be considered for the selection of ϵ. On the other hand, for a given total user number, the scheduling period is related to the number of selected users at each time slot, which is determined by ϵ. Moreover, one can see from Fig. 1 that the optimal ϵ is different for the cell average throughput and the cell edge throughput. For instance, in the network with layout (8,1,5), the optimal values of ϵ for these two metrics are respectively 0.8 and 0.6. Therefore, the selection of ϵ is not explicit and easy. The optimal value of ϵ depends on the system parameters.

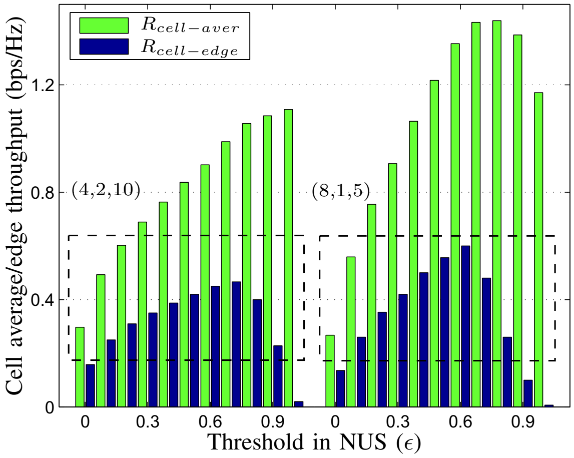

Fig. 1. Cell average and cell edge throughput versus threshold ϵ in NUS.

Fig. 2 and Fig. 3 compare the performance of RR-NOC, RR-GUS and RR-NUS with respect to the cell average throughput and the cell edge throughput per user. From Fig. 3 we can see a poor cell edge throughput of RR-NOC due to the strong interference. Compared with RR-NOC, RR-GUS and RR-NUS show the benefit of CoMP in terms of both $R_{cell-aver}$ and $R_{cell-edge}$. RR-GUS has the highest throughput due to the best user scheduling based on full CSIT. The gap between RR-GUS and RR-NUS depends on the network layout. For the single-antenna BS scenario like the network with layout (8,1,5) where each cell can generally serve at most 1 user at each time slot[2], RR-NUS has a very little performance loss compared with RR-GUS. With an increasing number of antennas at the BS, e.g., in the layout (4,2,10) and (2,4,20), the gap between RR-NUS and RR-GUS increases. In this case, the scheduling among the users located in the same cell plays an important role on the performance. Therefore, we can conclude that channel norm information is sufficient for user scheduling when each BS has only one antenna, otherwise the full CSIT of users from their own serving BS (which is much easier to get in practice) is necessary to achieve a comparable performance to GUS.

V. CONCLUSIONS AND FUTURE WORK

In this paper we proposed a low-feedback user scheduling method, channel norm-based scheduler, for downlink CoMP systems. It was demonstrated that the channel norm provides sufficient information to select users when each BS has one antenna, but full CSIT of the users from their own BS is still necessary when each BS has multiple antennas. In our future works, we will exploit the knowledge of full CSIT from local BS to reduce the performance gap between NUS and GUS.

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[1] $R_{cell-edge}$ is defined as the 5% point of the cumulative distribution function (CDF) of the user throughput normalized by channel bandwidth [12]. In the simulations, the normalized user throughput is obtained via the Shannon capacity formula.

[2] Although theoretically it may happen that more than 1 users are selected in one cell when some other cells do not serve any users, it happens with extremely low probability when using RR-NUS.

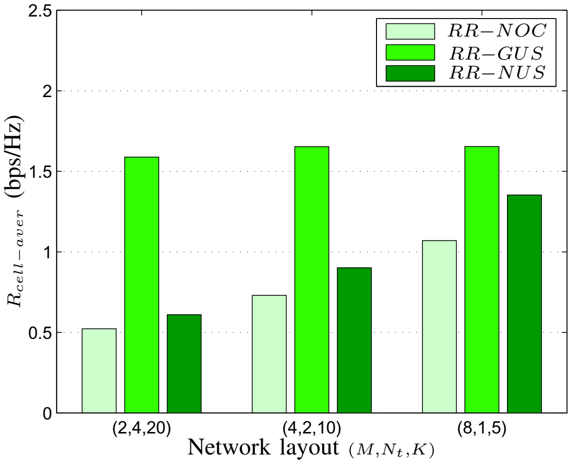

Fig. 2. $R_{cell-aver}$ in different network layout, $\epsilon = 0.6$ in NUS.

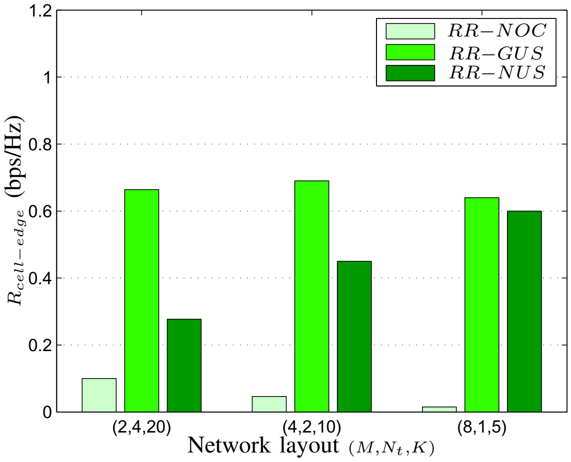

Fig. 3. $R_{cell-edge}$ in different network layout, $\epsilon = 0.6$ in NUS.

APPENDIX
PROOF OF (6)

From (5) we can get that

$$\nu_{s_i i_{km}} = \frac{\mathbf{h}_{i_{km}}\mathbf{h}_{i_{km}}^H\mathbf{h}_{s_i}\mathbf{h}_{s_i}^H - \mathbf{h}_{i_{km}}\mathbf{h}_{s_i}^H\mathbf{h}_{s_i}\mathbf{h}_{i_{km}}^H}{\mathbf{h}_{s_i}\mathbf{h}_{s_i}^H}. \tag{13}$$

Define $\mathbf{h}_{i_{km}n} = \|\mathbf{h}_{i_{km}n}\|\mathbf{v}_{i_{km}n}$, where $\mathbf{v}_{i_{km}n}\mathbf{v}_{i_{km}n}^H = 1$. Then $\nu_{s_i i_{km}}$ can be further expressed as

$$\nu_{s_i i_{km}} = \frac{1}{\sum_{n=1}^M \|\mathbf{h}_{s_i n}\|^2} \sum_{j,n=1}^{M} \Big(\|\mathbf{h}_{i_{km}n}\|^2\|\mathbf{h}_{s_i j}\|^2 - \|\mathbf{h}_{i_{km}n}\|$$
$$\|\mathbf{h}_{s_i n}\|\|\mathbf{h}_{i_{km}j}\|\|\mathbf{h}_{s_i j}\|\mathbf{v}_{i_{km}n}\mathbf{v}_{s_i n}^H\mathbf{v}_{s_i j}\mathbf{v}_{i_{km}j}^H\Big) \tag{14a}$$
$$\leq \frac{1}{\sum_{n=1}^M \|\mathbf{h}_{s_i n}\|^2} \sum_{\substack{j,n=1\\ j\neq n}}^{M} \Big(\|\mathbf{h}_{i_{km}n}\|^2\|\mathbf{h}_{s_i j}\|^2 - \|\mathbf{h}_{i_{km}n}\|$$
$$\|\mathbf{h}_{s_i n}\|\|\mathbf{h}_{i_{km}j}\|\|\mathbf{h}_{s_i j}\|\mathbf{v}_{i_{km}n}\mathbf{v}_{s_i n}^H\mathbf{v}_{s_i j}\mathbf{v}_{i_{km}j}^H\Big)+$$
$$\frac{\sum_{n=1}^M \|\mathbf{h}_{i_{km}n}\|^2\|\mathbf{h}_{s_i n}\|^2}{\sum_{n=1}^M \|\mathbf{h}_{s_i n}\|^2} \tag{14b}$$
$$\leq \frac{1}{\sum_{n=1}^M \|\mathbf{h}_{s_i n}\|^2} \sum_{\substack{j,n=1\\ j\neq n}}^{M} \Big(\|\mathbf{h}_{i_{km}n}\|^2\|\mathbf{h}_{s_i j}\|^2 + \|\mathbf{h}_{i_{km}n}\|$$
$$\|\mathbf{h}_{s_i n}\|\|\mathbf{h}_{i_{km}j}\|\|\mathbf{h}_{s_i j}\|\Big) + \frac{\sum_{n=1}^M \|\mathbf{h}_{i_{km}n}\|^2\|\mathbf{h}_{s_i n}\|^2}{\sum_{n=1}^M \|\mathbf{h}_{s_i n}\|^2} \tag{14c}$$
$$= \frac{1}{2\sum_{n=1}^M \|\mathbf{h}_{s_i n}\|^2} \sum_{\substack{j,n=1\\ j\neq n}}^{M} \Big(\|\mathbf{h}_{i_{km}n}\|^2\|\mathbf{h}_{s_i j}\|^2 + 2\|\mathbf{h}_{i_{km}n}\|$$
$$\|\mathbf{h}_{s_i n}\|\|\mathbf{h}_{i_{km}j}\|\|\mathbf{h}_{s_i j}\| + \|\mathbf{h}_{i_{km}j}\|^2\|\mathbf{h}_{s_i n}\|^2\Big)+$$
$$\frac{\sum_{n=1}^M \|\mathbf{h}_{i_{km}n}\|^2\|\mathbf{h}_{s_i n}\|^2}{\sum_{n=1}^M \|\mathbf{h}_{s_i n}\|^2} \tag{14d}$$
$$= \frac{\sum_{\substack{j,n=1\\ j\neq n}}^M \left(\|\mathbf{h}_{i_{km}n}\|\|\mathbf{h}_{s_i j}\| + \|\mathbf{h}_{i_{km}j}\|\|\mathbf{h}_{s_i n}\|\right)^2}{2\sum_{n=1}^M \|\mathbf{h}_{s_i n}\|^2}+$$
$$\frac{\sum_{n=1}^M \|\mathbf{h}_{i_{km}n}\|^2\|\mathbf{h}_{s_i n}\|^2}{\sum_{n=1}^M \|\mathbf{h}_{s_i n}\|^2}. \tag{14e}$$

Note that $|\mathbf{v}_{i_{km}n}\mathbf{v}_{s_i n}^H\mathbf{v}_{s_i j}\mathbf{v}_{i_{km}j}^H| \leq 1$ is used in the step from (14b) to (14c).

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