

Three novel opportunistic scheduling algorithms in CoMP-CSB scenario

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Abstract Coordinated scheduling/beamforming (CSB), which belongs to the coordinated multi-point (CoMP) transmission, has received lots of attention recently due to its great potential to mitigate inter-cell interference (ICI) and to increase the cell-edge throughput, and meanwhile it only requires limited base station cooperation and is easy to implement. However, to the best of our knowledge, there are no effective scheduling algorithms with low complexity and overhead in CoMP-CSB scenario as yet. Thus, in this paper, we propose three novel opportunistic scheduling algorithms in CoMP-CSB scenario. All of them jointly consider the intended channel condition of the scheduled user from its serving cell and the orthogonality between the intended channel and the corresponding interference channels to concurrently scheduled users in nearby cells, thus exploiting multi-user diversity (MUD) and mitigating ICI at the same time. Algorithm 1 cooperatively chooses the most orthogonal user pair within a candidate user set in which all users have a large local channel feedback, while Algorithm 2 concurrently schedules the user pair with the largest ratio between the local channel feedbacks and the aforementioned orthogonality within the same candidate user set. Algorithm 3 performs in the way similar to the proportional fairness scheduling, while making a proper modification for its usage in CoMP-CSB scenario. The performance of the proposed scheduling algorithms are evaluated through simulation. Results show that, they all can significantly enhance the received signal to interference plus noise ratio (SINR) with relatively good fairness guarantee, thus achieving larger throughputs and utilities than several well-known scheduling algorithms. Algorithm 2 even outperforms Algorithm 1 when the aforementioned candidate user set is big enough in size and has a bit more overhead/complexity. Furthermore, Algorithm 3 is the best one among all the three proposed algorithms, but it requires more overhead/complexity than Algorithm 1 and 2. Finally, we give the optimal parameter for all of the three proposed algorithms, which can make a good tradeoff between performance and overhead/complexity.

Keywords coordinated multi-point (CoMP), coordinated scheduling/beamforming (CSB), inter-cell interference (ICI), multi-user diversity (MUD), opportunistic scheduling.

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1 Introduction

Coordinated multi-point (CoMP) transmission has received a lot of attention recently [1–5] due to its great potential to increase the coverage of high data rates and the cell-edge throughput. There are mainly

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two categories of cooperation with different backhaul requirements and overheads, i.e., joint processing and coordinated scheduling/beamforming (CSB). In the former, user data is available at each base station (BS) and the multiple antennas across multiple BSs can be seen as a large antenna array, which is theoretically similar to the distributed multi-input multi-output (MIMO) system and has been exhaustively researched [6–8]. Furthermore, sharing user data among BSs requires high-capacity backhaul communication which brings about a huge overhead to the practical system. In this paper, we focus on the second category, in which user data is only available at the serving BS but user scheduling/beamforming decisions are made with coordination among cells. The second category clearly requires much less backhaul communication than the first one and therefore is much easier to implement in a practical deployment.

Communication in the CoMP-CSB scenario has been considered in many papers. For example, joint design of beamforming among multiple cells has been considered in [9–12] while inter-cell scheduling has been considered in [13–16]. Yu et al. [17] have done a solid work on joint optimization among scheduling, beamforming and power allocation. However, it is time consuming to converge to the optimal solution since more than five iterations among scheduling decision, beamforming design and power adjustment are to be done under each channel condition. Thus, to the best of our knowledge, effective scheduling algorithms with limited complexity and overhead in the CoMP-CSB scenario are still lacking. In traditional scheduling algorithms in the single-cell scenario, such as, round robin scheduling (RRS), max rate scheduling (MRS) and proportional fairness scheduling (PFS) [18], users are scheduled according to the feedbacks from their serving cell to exploit multi-user diversity (MUD), which comes from the effective utilization of the frequency selective channel among different users and is especially useful in orthogonal frequency-division multiple access (OFDMA) systems [19,20]. However, traditional scheduling algorithms may have poor performance if the scheduled user suffers from severe inter-cell interference (ICI), especially the cell-edge users in the CoMP-CSB scenario. Thus, in the CoMP-CSB scenario, how to cooperatively schedule users to exploit MUD and mitigate ICI simultaneously with limited complexity and overhead becomes an important question. Good scheduling algorithms should schedule a user with a reasonably good channel gain from its own BS and at the same time require that the scheduled user should not cause too much interference to the users scheduled in nearby cells.

In this paper, we propose three novel scheduling algorithms (abbreviated to Alg. 1, Alg. 2 and Alg. 3 for short), all of which construct a candidate set of users with large values of the cumulative distribution function (CDF) of the norm of the local intended channel and schedule users from this set that has a higher orthogonality between local intended channel and the corresponding interference channels. The effectiveness of our algorithms is verified by simulation, in which all of the three proposed algorithms can significantly enhance the CDF of received signal to interference plus noise ratio (SINR) with relatively good fairness guarantee, thus achieving larger throughputs and utilities than several existing scheduling algorithms. Furthermore, we evaluate the three algorithms with various parameters which capture the tradeoff between MUD exploitation and ICI mitigation. The results show that, Alg. 2 performs better than Alg. 1 when the aforementioned candidate user set is big enough in size. And Alg. 3 is the best among all the three proposed algorithms, having more overhead/complexity than Alg. 1 and Alg. 2. Finally, we also give the optimal operation parameter for all of the three proposed algorithms, which can make a good tradeoff between performance and overhead/complexity.

The remainder of this paper is organized as follows. In Section 2, we give the system model. Then we naturally extend the single-cell RRS, MRS and PFS in the CoMP-CSB scenario and propose three novel algorithms in Section 3 with overhead/complexity analysis. Using zero-forcing beamforming, we compare the performance of the above algorithms in Section 4. The whole paper is concluded in Section 5.

2 System model

2.1 Network model

A typical three-cell cooperation scenario within a multi-cell wireless network is considered, where each BS has N_t antennas and each user has a single antenna. As shown in Figure 1, each cell is controlled by

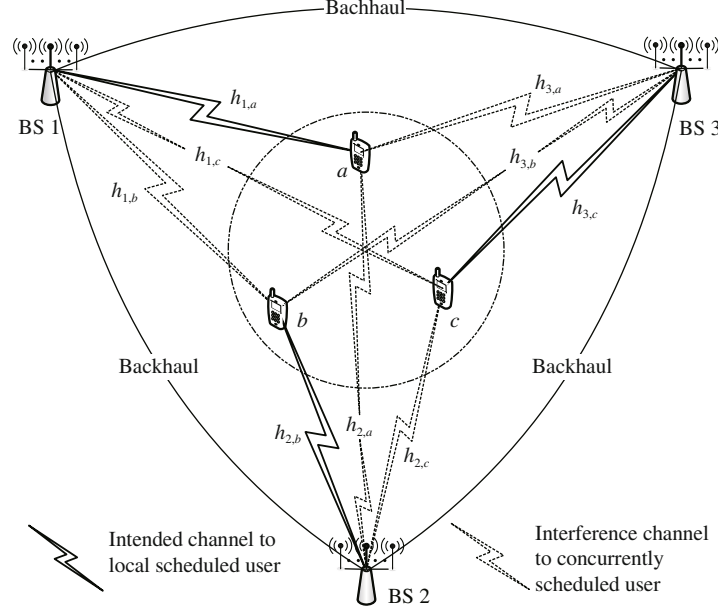


Figure 1 A typical three-cell cooperation scenario within a multi-cell networks.

a BS and the data for a user is only stored in its serving BS. For convenience, cell and BS are used interchangeably throughout this paper. For ease of presentation, inner region of the rotundity represents the cooperation area. In reality, its shape would be irregular due to network topology, BS configuration, shadow fading and the criterion of choosing CoMP-CSB users.

C , U and U_i are used to represent the set of CoMP-CSB cells, CoMP-CSB users and CoMP-CSB users served by cell i , respectively. It is obvious that $C = \{1, 2, 3\}$ and $U = U_1 \cup U_2 \cup U_3$. Each user is assumed to feed back the instantaneous channel status to its serving BS on each scheduling unit, and all the three cooperative BSs can exchange the channel information of all users on error- and delay-free backhauls. Then, on a certain scheduling unit, if users a , b and c are scheduled by cells 1, 2 and 3, respectively, the received SINR of user a from cell 1 is given in the following equation as an example while omitting that of users b and c due to similarity.

$$\text{SINR}_{1,a} = \frac{P_{1,a} |h_{1,a}^* w_{a,bc}^1|^2}{P_{2,a} |h_{2,a}^* w_{b,ac}^2|^2 + P_{3,a} |h_{3,a}^* w_{c,ab}^3|^2 + P_{\text{IN}_{1,a}}}, \quad (1)$$

where h^* is the conjugate transpose of a vector (or matrix) h , and

- $P_{i,k}$ is the average received power at user $k \in U$ from cell $i \in C$, which is determined by the transmit power, path loss and shadow fading.
- $h_{i,k}$ is the $N_t \times 1$ channel vector of user k from cell i . We assume each component of $h_{i,k}$ is independent and identically distributed (i.i.d.) circular symmetric complex Gaussian variable with zero mean and unit variance.
- $w_{k,mn}^i$ is the $N_t \times 1$ beamforming vector for cell i when users $k \in U_i$, $m \in U_j$ and $n \in U_l$ are chosen by their respective cells. It is normalized, i.e. $\|w_{k,mn}^i\|^2 = 1$, and its design will be discussed later in this section.
- $P_{\text{IN}_{1,a}}$ is the power of interference and noise signal, which contains two part: 1) received interference signal power from neighboring two-tier non-cooperation cells of user a 's serving cell 1, which is a location-dependent variable and can be treated as background noise; 2) thermal noise power, which equals the product of the thermal noise power spectral density and the bandwidth of a scheduling unit.

Given $\text{SINR}_{1,a}$, the achievable rate of user a in cell 1 is

$$r_{1,a} = B_w \cdot \log_2(1 + \text{SINR}_{1,a}), \quad (2)$$

where B_w is the bandwidth of a scheduling unit. For convenience, we use the Shannon capacity as the communication rate in Eq. (2) for theoretical analysis while ignoring the influence of the quantization error from practical modulation and coding schemes.

2.2 Beamforming strategy

In typical three-cell cooperation scenario within a practical wireless network, it is difficult to define the optimal beamforming strategy [21], which is also out of the scope of this paper. Then we take the well-known zero-forcing beamforming (ZFBF) as an example in this work.

ZFBF can precancel interference for $N_t - 1$ neighboring cells with N_t antennas each BS [22]. Taking cell 1 as an example, to cancel its interference to concurrently scheduled user $b \in U_2$ and $c \in U_3$, the beamforming vector $w_{a,bc}^1$ needs to satisfy the orthogonality condition $h_{1,b}^* w_{a,bc}^1 = 0$ and $h_{1,c}^* w_{a,bc}^1 = 0$ simultaneously. Furthermore, we also want to maximize the desired signal power $|h_{1,a}^* w_{a,bc}^1|^2$. This corresponds to choosing the beamforming vector $w_{a,bc}^1$ in the direction of the projection of vector $h_{1,a}$ on the null space of vectors $\mathbf{H} = [h_{1,b}, h_{1,c}]$ [23], i.e. the beamforming vector is the normalized version of the following vector:

$$w_{a,bc}^1 = (\mathbf{I} - P_{\mathbf{H}})h_{1,a}, \quad (3)$$

where $P_{\mathbf{H}}$ is the projection on $\mathbf{H}$, given as $P_{\mathbf{H}} = \mathbf{H}(\mathbf{H}^* \mathbf{H})^{-1} \mathbf{H}^*$. $\mathbf{I}$ is the unit matrix which has the same dimension as $P_{\mathbf{H}}$.

3 Three novel opportunistic scheduling algorithms

In this section, we first extend the three well-known scheduling algorithms in the single-cell scenario to the CoMP-CSB scenario. Then, we propose three novel scheduling algorithms.

3.1 Three single-cell scheduling algorithms in the CoMP-CSB scenario

There are a large number of scheduling algorithms proposed in the single-cell scenario, in which RRS, MRS and PFS are the most widely researched. Resources are allocated to users in a round robin way in RRS, and to users with the maximum instantaneous rate in MRS. In PFS, the user with the highest ratio of instantaneous rate to average throughput is scheduled.

In the CoMP-CSB scenario, RRS remains the same as in the single-cell scenario, in which each cell independently schedules users one by one. However, MRS and PFS need to be adapted in the CoMP-CSB scenario since the instantaneous rate of each user is hard to obtain, because, by Eqs. (1)–(3), the instantaneous rate of a user depends on the concurrently scheduled users in the other two cooperative cells and their respective beamforming vectors. Thus, user scheduling, beamforming vectors design and the instantaneous rates of scheduled users get combined.

In the following, we use the feedback only from the serving cell to simplify the coupled problem, which is also similar to the method used in [24,25]. First we revise the $\text{SINR}_{1,a}$ in Eq. (1) for any user $k \in U_1$ when only considering local feedback:

$$\text{SINR}'_{1,k} = \frac{P_{1,k} \|h_{1,k}\|}{P_{2,k} \|h_{2,k}\| + P_{3,k} \|h_{3,k}\| + P_{\text{IN}_{1,k}}}. \quad (4)$$

Since all of the components in Eq. (4) can be obtained by each user independently through pilot detection, each cell could get all $\text{SINR}'_{1,k}, k \in U_1$ through user feedback. Then using Eq. (2), each cell could obtain the estimated instantaneous rate $r'_{1,k}$ of all its users which is indispensable in MRS or PFS procedure.

Then MRS and PFS in each cell $i \in C$ become

$$\text{MRS} : k = \arg \max_{k \in U_i} r'_{i,k} \quad (5)$$

and

$$\text{PFS: } k = \arg \max_{k \in U_i} r'_{i,k} / \widetilde{R}_{i,k}, \quad (6)$$

where $\widetilde{R}_{i,k}$ is the long-term average throughput of user k in cell i over past t_c scheduling units, updated as

$$\widetilde{R}_{i,k}^+ = \begin{cases} \left(1 - \frac{1}{t_c}\right) \widetilde{R}_{i,k} + \frac{1}{t_c} r_{i,k}, & \text{if scheduled,} \\ \left(1 - \frac{1}{t_c}\right) \widetilde{R}_{i,k}, & \text{else,} \end{cases} \quad (7)$$

where $\widetilde{R}_{i,k}^+$ is the long-term average throughput after one scheduling, which is updated by practical instantaneous rate $r_{i,k}$ from Eqs. (1)–(3) rather than the estimated rate $r'_{i,k}$. To avoid confusion, in the following, we rename MRS and PFS which utilize the estimated rate $r'_{i,k}$ in Eqs. (5) and (6) as local MRS (LMRS) and local PFS (LPFS), respectively.

3.2 Three novel scheduling algorithms

RRS, LMRS and LPFS consider only the local feedback from the serving BS, while ignoring the corresponding interference signal to concurrently scheduled users in neighboring cells. Thus, all of them exploit only MUD while ignoring the ICI completely. In the following, we propose a novel scheduling algorithm, which jointly considers MUD exploitation and ICI mitigation,

Three novel scheduling algorithms.

On each scheduling unit, each cell $i \in C$ performs:

Step 1: Sorts the values of the CDF of the norms of all the users' instantaneous channel feedback $F(\|h_{i,k}\|), k \in U_i$ in descending order.

Step 2: Chooses the largest M feedbacks, asks the corresponding users to feed back the interference channel $h_{j,k}, k \in U_{i_M}, j \in C, j \neq i$ from neighboring CoMP-CSB cells, where U_{i_M} represents the set of users within the M selected users in cell i .

Step 3: For each user $k \in U_{i_M}$, sends its necessary channel information to all of the other CoMP-CSB cells.

Step 4: Having all the channel information, chooses the most favorable user pair $\{a, b, c\}$, where $a \in U_{1_M}, b \in U_{2_M}$ and $c \in U_{3_M}$ as follows:

$$\text{Alg. 1: } \{a, b, c\} = \arg \max L_{1 \rightarrow 2,3} + L_{2 \rightarrow 1,3} + L_{3 \rightarrow 1,2},$$

$$\text{Alg. 2: } \{a, b, c\} = \arg \max \frac{F(\|h_{1,a}\|)}{L_{1 \rightarrow 2,3}} + \frac{F(\|h_{2,b}\|)}{L_{2 \rightarrow 1,3}} + \frac{F(\|h_{3,c}\|)}{L_{3 \rightarrow 1,2}},$$

where $L_{1 \rightarrow 2,3}, L_{2 \rightarrow 1,3}$ and $L_{3 \rightarrow 1,2}$ represent the orthogonality between the intended channel from local serving cell and the corresponding interference channel to concurrently scheduled user in nearby cells, which are

$$\begin{aligned} L_{1 \rightarrow 2,3} &= \frac{|h_{1,a} \cdot h_{1,b}|}{\|h_{1,a}\| \cdot \|h_{1,b}\|} + \frac{|h_{1,a} \cdot h_{1,c}|}{\|h_{1,a}\| \cdot \|h_{1,c}\|}, \\ L_{2 \rightarrow 1,3} &= \frac{|h_{2,b} \cdot h_{2,a}|}{\|h_{2,b}\| \cdot \|h_{2,a}\|} + \frac{|h_{2,b} \cdot h_{2,c}|}{\|h_{2,b}\| \cdot \|h_{2,c}\|}, \\ L_{3 \rightarrow 1,2} &= \frac{|h_{3,c} \cdot h_{3,a}|}{\|h_{3,c}\| \cdot \|h_{3,a}\|} + \frac{|h_{3,c} \cdot h_{3,b}|}{\|h_{3,c}\| \cdot \|h_{3,b}\|}. \end{aligned}$$

$$\text{Alg. 3: } \{a, b, c\} = \arg \max \frac{r_{1,a}}{\widetilde{R}_{1,a}} + \frac{r_{2,b}}{\widetilde{R}_{2,b}} + \frac{r_{3,c}}{\widetilde{R}_{3,c}},$$

where $r_{1,a}, r_{2,b}$ and $r_{3,c}$ are defined in Eq. (2), also jointly decided by Eqs. (1) and (3). And $\widetilde{R}_{1,a}, \widetilde{R}_{2,b}$ and $\widetilde{R}_{3,c}$ are updated through Eq. (7), respectively.

Step 5: For the scheduled user pair $\{a, b, c\}$, uses intended beamforming strategy to transmit, end.

Remark 1. The above scheme is not limited to a three-cell cooperation scenario. For any X -cell cooperation, the algorithm still works with different complexities and overheads.

Remark 2. The parameter M in step 2 should be chosen carefully, which decides the weight we put on MUD exploration and ICI mitigation. For example, only choosing the user with the largest feedback ($M=1$) in step 2 means that we pay all attention to exploiting the MUD while ignoring ICI mitigation completely, thus achieving the same scheduling results for all the three algorithms. This is an extension from the user scheduling criterion in [26] when BS has multiple antennas or is the same as the first user selection criterion in a multi-user scheduling algorithm proposed in [16]. Meanwhile, a bigger M means that we pay more attention to ICI mitigation when exploiting MUD.

3.3 Overhead/complexity analysis and practical application

In this subsection, a brief analysis on overhead and complexity is given for all of the three algorithms. The overhead mainly comes from the channel information exchange in Step 3. In the following, we take user $a \in U_{1M}$ as an example. For Alg. 1, the local channel $h_{1,a}$ and the interference channels $h_{2,a}$ and $h_{3,a}$ are necessary for both cells 2 and 3. If we simply define the overhead of one channel information transfer through the backhaul as 1, then the overhead brought from user a is 3×2 , which means that all the channel information of user a , i.e., $h_{1,a}$, $h_{2,a}$ and $h_{3,a}$, should be sent to the other two CoMP-CSB cells b and c . Generally, if there is X -cell cooperation, the overhead brought from one user is $X \times (X - 1)$, then the overhead of one cell is $M \times X \times (X - 1)$ and the total overhead of the network is $X \times M \times X \times (X - 1)$. Alg. 2 needs one more extra information than Alg. 1, i.e., the CDF of local channel feedback $F(\|h_{1,a}\|)$, to be exchanged. Then the overheads brought from a user, a cell and the network are $(X + 1) \times (X - 1)$, $M \times (X + 1) \times (X - 1)$ and $X \times M \times (X + 1) \times (X - 1)$, respectively. Alg. 3 needs more extra information exchange than Alg. 1, i.e., averaged received power $P_{1,a}$, $P_{2,a}$ and $P_{3,a}$, interference and noise power $P_{N_{1,a}}$ and user a 's long-term average throughput $\widehat{R}_{1,a}$. Then the overhead brought from a user, a cell and the network are $(2X + 2) \times (X - 1)$, $M \times (2X + 2) \times (X - 1)$ and $X \times M \times (2X + 2) \times (X - 1)$, respectively. Then, we can find that the total overhead of the network increases with the number of cooperative BSs and the number of selected users in Step 2 for all the three algorithms. And the overhead of Alg. 2 is larger than that of Alg. 1, while the overhead of Alg. 3 is the largest among all the three proposed algorithms.

The difference in complexity among the three proposed algorithms mainly comes from the algorithms themselves defined in Step 4. Ignoring the same "argmax" operation in all the three proposed algorithms, we simply compare the three different metrics defined in Step 4. It is obvious that the complexity of Alg. 2 is slightly higher than that of Alg. 1 since it requires three more division operations. The complexity of Alg. 3 is the highest since its metric is jointly decided by Eqs. (1)–(3), which bring a high complexity in the calculation.

All of the proposed algorithms can be easily applied to the cellular OFDMA system with a bit more backhaul overheads. On each scheduling unit in cellular OFDMA system, all the CoMP-CSB cells cooperatively choose the most favorite users pair for transmission with necessary channel information exchange among them. Furthermore, the scheduling procedure can be performed on all scheduling units independently and simultaneously.

4 Simulation

4.1 Simulation setup

One scheduling unit here is consistent with the definition of one physical resource block in the 3rd generation partnership project (3GPP) long term evolution (LTE), i.e., $180 \text{ kHz} \times 1 \text{ ms}$ [27]. The international telecommunication union (ITU) urban micro-cell scenario (Umi) [28] is adopted for modeling the multi-cell networks, which is also strongly recommended by 3GPP LTE [1]. The network considered here is hexagonal grid layout with 19 sites, and 3 sectors (cells) per site. The inter-site distance is 200 m. The path loss model is $36.7 \log_{10}(d) + 22.7 + 26 \log_{10}(f_c)$, where d is the distance from BS to user (in meters) and $f_c = 2.5 \text{ GHz}$ is the carrier frequency. BSs and users are equipped with 3D and omni-direc-

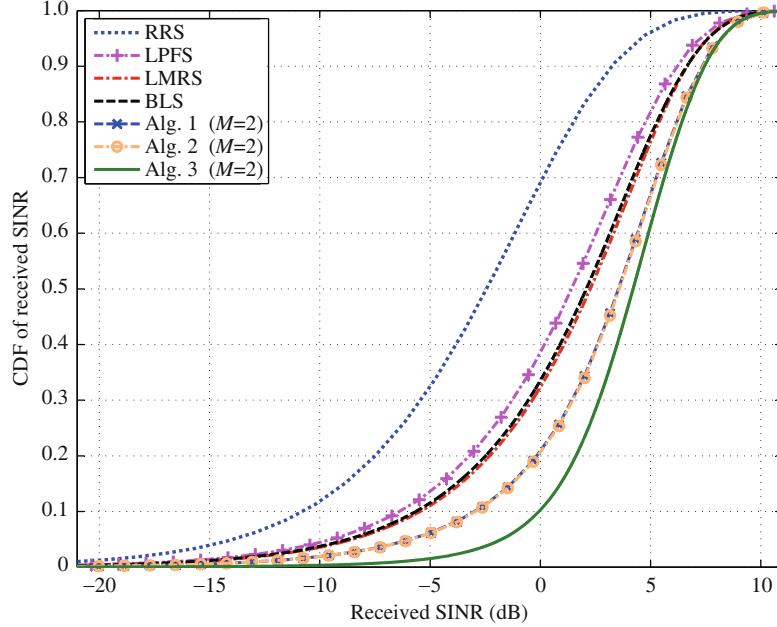


Figure 2 CDF of received SINR of all CoMP-CSB users.

tional antenna, respectively. Users are randomly and uniformly distributed. t_c in Eq. (7) is set at 1000 scheduling units and the thermal noise level is -174 dBm/Hz.

First, users in each cell are chosen to be the CoMP-CSB users if the following condition is satisfied:

$$|P_{i,k} - P_{j,k}| \leq \Delta, \quad \forall i, j \in C, \quad (8)$$

where Δ is the threshold of the maximal difference of average received power from different CoMP-CSB cells. We set it at 5 dB here. And $N_t = 3$ is chosen to satisfy the minimum antenna requirement for ZFBF in a three-cell cooperation scenario.

4.2 Simulation results

In the following, we compare all the aforementioned scheduling algorithms through the metrics of the CDF of the received SINR and that of the scheduled times of all users. The first metric represents the efficiency, while the second metric represents the fairness of scheduled times among users which is also similar to the time-share fairness. For the three proposed algorithms, we take $M = 2$ in Step 2 as an example. We also give the same performance of the three proposed algorithms when $M = 1$ and call it best local scheduling (BLS).

In each simulation, we give each CoMP-CSB user 1000 scheduling units but the actual scheduling units one user can get depends completely on the practical scheduling process. And we randomly perform the simulation 100 times to get the average performance of all of the scheduling algorithms.

The CDF of received SINR of all CoMP-CSB users are shown in Figure 2. We can find that the performance of RRS is the worst since it chooses user one by one independently without taking into account MUD exploration or ICI mitigation. Since LMRS always schedules the user with the largest local channel feedback, LMRS performs much better than RRS. Similar to the single-cell scenario, LPFS can make a tradeoff between efficiency and fairness so as to exploit MUD with certain fairness guarantee, and the received SINR of LPFS is a bit worse than that of the LMRS. The performance of BLS lies in between LPFS and LMRS, which is slightly worse than LMRS and a bit better than LPFS. That is reasonable since BLS exploits the MUD more efficiently than LPFS as in the single-cell scenario [29]. All of the three proposed algorithms perform much better than the aforementioned four scheduling algorithms

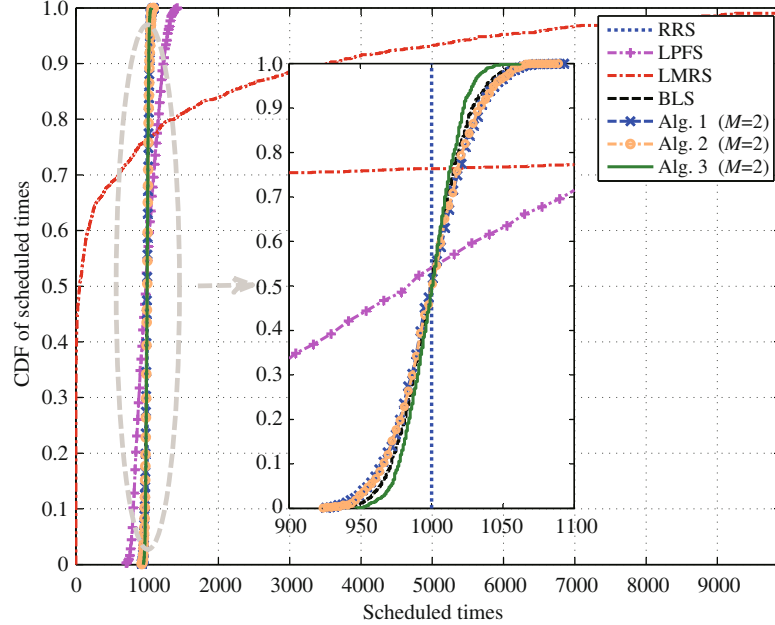


Figure 3 CDF of scheduled times of all CoMP-CSB users.

Table 1 Total throughput & network utility

Scheduling schemes	Total throughput (kbps)	Network utility
RRS	421.3771	50.4044
LMRS	774.7759	N/A
LPFS	704.2178	63.3909
BLS	762.8516	66.6784
Alg. 1 ($M=2$)	905.0508	71.3457
Alg. 2 ($M=2$)	908.9973	71.4591
Alg. 3 ($M=2$)	1002.3430	74.1923

which only consider local feedback even if there is only one more extra candidate user (the case $M = 2$). In Figure 2, we find that the curves of Alg. 1 and Alg. 2 almost overlap with each other and surpass that of LMRS by 1.8 dB on average, which means that jointly considering MUD exploration and ICI mitigation in scheduling process is helpful to selecting “good” users pair with high received SINRs. We can also find that the efficiency of Alg. 3 is the best, the SINR of 10% and 40% users in Alg. 3 are higher than that in Alg. 1 and Alg. 2 by about 2.9 dB and 0.9 dB, respectively.

The CDF of users’ scheduled times of all scheduling algorithms are shown in Figure 3. Once a user is scheduled and gets a scheduling unit, the scheduled time of this user adds one, and this metric represents the fairness of a scheduling algorithm. We see that RRS is fairest because each user gets an equal number of scheduling units. LMRS is most unfair since it always select users with the largest local feedback to transmit and therefore give more scheduling opportunities to “center” users. As in the single-cell scenario, LPFS can make a good tradeoff between efficiency and fairness and thus the curve of LPFS is much closer to the mean value (1000) than LMRS. In the enlarged figure of Figure 3, we see that all the proposed algorithms, i.e., BFS, Alg. 1, Alg. 2 and Alg. 3, achieve a better fairness than LPFS. All of the four scheduling algorithms could guarantee the fairness to a significant extent, which inherits the bonus from CDF based scheduling (in Step 2) as in the single-cell scenario [29]. Furthermore, the performance of Alg. 3 is slightly better than that of Alg. 1 and Alg. 2.

In Table 1, we give two more metrics of the seven scheduling algorithms, i.e, total throughput and network utility. Total throughput is the sum of the long-term average throughput of each CoMP-CSB user $i \in U$, i.e.,

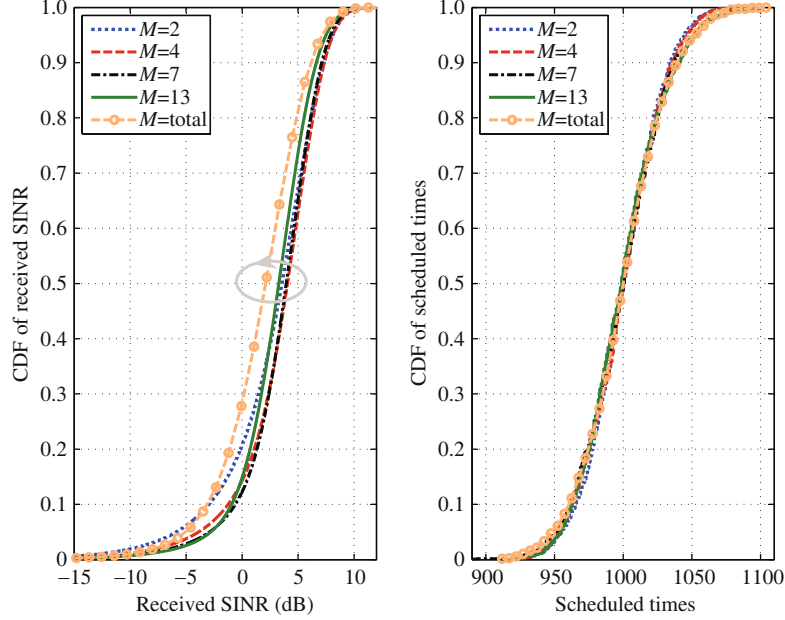


Figure 4 CDF of received SINR and scheduled times with different M of Alg. 1.

$$\text{Total throughput} = \sum_{i \in U} \widetilde{R}_i. \quad (9)$$

Network utility is the sum of the widely used log utility of the long-term average throughput of each CoMP-CSB user $i \in U$, i.e.,

$$\text{Network utility} = \sum_{i \in U} \log(\widetilde{R}_i), \quad (10)$$

where $\widetilde{R}_i$ is in kbps.

As shown in Table 1, all of the three proposed scheduling algorithms achieve larger throughput and utility simultaneously than RRS, LMRS, LPFS and BLS. The utility of LMRS is N/A since about 45% users have not been scheduled as shown in Figure 3. And the performance of Alg. 3 is the best with the largest total throughput and network utility.

In the following, we evaluate the performance for different M in our proposed algorithms. The parameter M decides the weight we put on MUD exploration and ICI mitigation. A smaller M means that we pay more attention to exploiting the MUD while a bigger one means that we pay more attention to ICI mitigation.

The CDF of the received SINR and scheduled times of all CoMP-CSB users of Alg. 1, Alg. 2 and Alg. 3 are shown in Figures 4, 5 and 6, respectively. For clarity, we only show parts of the performance with different M . From the three figures, we see that the CDF of received SINR of Alg. 1 do not get better with the increasing M . That is because with increasing M in Step 2, more and more users are considered for ICI mitigation. Meanwhile, we pay less and less attention to MUD exploitation, which could not be ignored in a typical three-cell CoMP-CSB scenario within a practical multi-cell network. And the two CDF curves of the received SINR of Alg. 2 and Alg. 3 enhance marginally with the increased M after $M > 4$. Besides, the fairness of Alg. 1 and Alg. 2 can be guaranteed perfectly with arbitrary M as shown in Figures 4 and 5, in which the CDF of scheduled times with different M overlap with one another in both of the two figures. Although the fairness of Alg. 3 deteriorates with increasing M , it is quite slight and brings little influence on the algorithm. From the three figures, $M = 4$ and 7 may be two good choices for all the three proposed algorithms.

In Figure 7, we show the total throughput and network utility with increasing M of all the three proposed algorithms. We see that both of the two metrics achieve their own maximum with $M = 5$, $M = 7$ and $M = \text{total}$ for Alg. 1, Alg. 2 and Alg. 3, respectively. Since the complexity and overhead

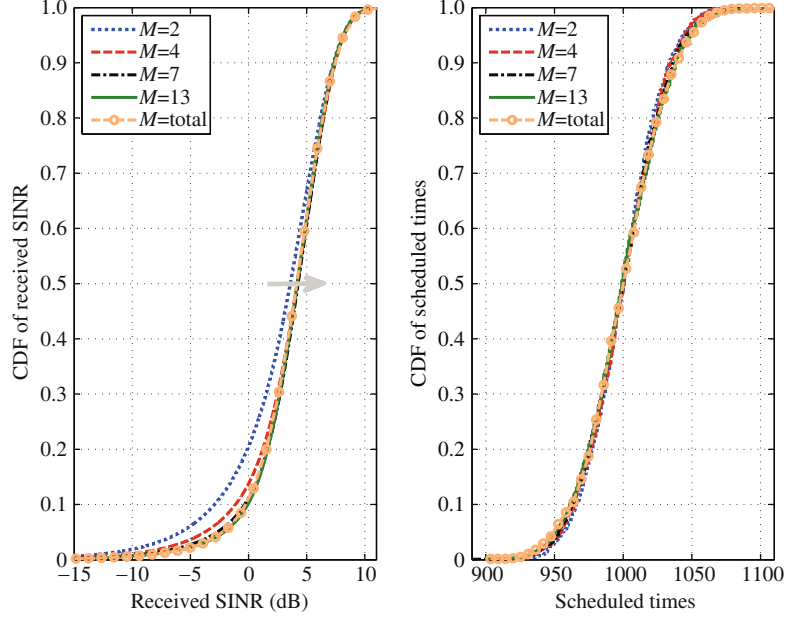


Figure 5 CDF of received SINR and scheduled times with different M of Alg. 2.

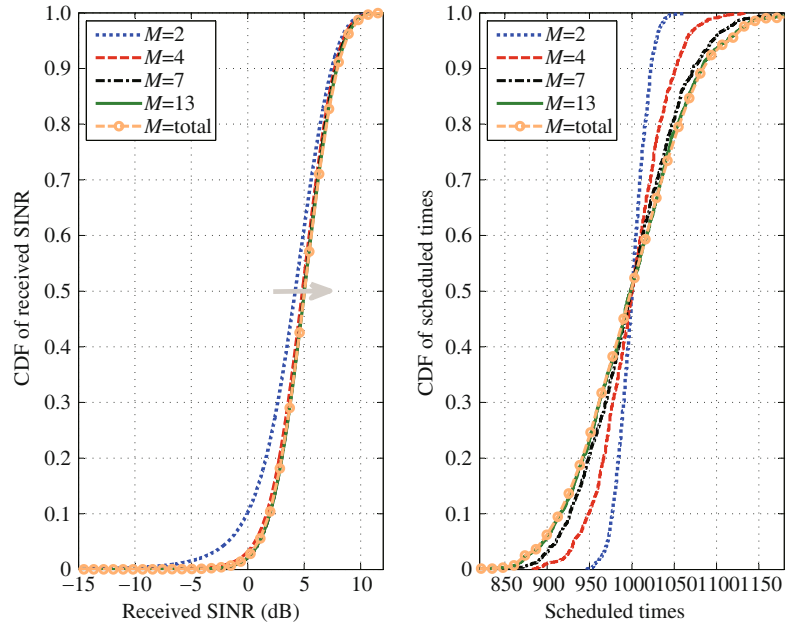


Figure 6 CDF of received SINR and scheduled times with different M of Alg. 3.

increase exponentially with M and the two metrics deteriorate slightly with $M = 4$ comparing to their maximum, i.e., 0.40% deterioration in total throughput and 0.15% deterioration in network utility for Alg. 1, 1.76% deterioration in total throughput and 0.65% deterioration in network utility for Alg. 2, 2.61% deterioration in total throughput and 0.98% deterioration in network utility for Alg. 3. $M = 4$ is chosen as the optimal operating parameter for all of the three proposed algorithms.

From all of the above results, we find that Alg. 2 outperform Alg. 1 when the candidate user set in Step 2 is big enough in size and has a bit more overhead and complexity. Besides, Alg. 3 is the best one among all the three proposed algorithms, but it requires more overhead/complexity than Alg. 1 and Alg. 2 at the same time.

Finally, we would like to mention that we have evaluated all the three proposed algorithms with

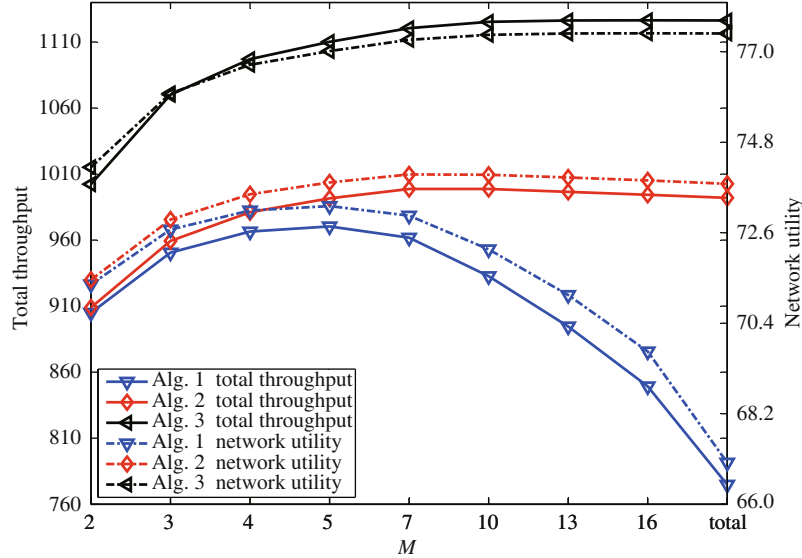


Figure 7 Total throughput & network utility with increasing M of all the three proposed algorithms.

eigenmode beamforming and leakage based beamforming [30], and all of them achieve similar superiority as that with ZFBF. The exact performances are not shown due to space limitation.

5 Conclusions

In this paper we propose three novel scheduling algorithms for users in the CoMP-CSB scenario within a practical multi-cell network. The proposed algorithms jointly consider the intended channel condition of the local scheduled user and the orthogonality between that and the corresponding interference channels to concurrently scheduled users in nearby cells so as to exploit MUD and mitigate ICI simultaneously. Our algorithms achieves better SINRs than RRS, LMRS, LPFS and BLS, and with relative good fairness guarantee. As a result, they achieve larger throughputs and utilities. Simulation results also show that $M = 4$ is a reasonable choice with good performance and limited overhead and complexity for all the three proposed algorithms. Furthermore, the performance of Alg. 2 is better than Alg. 1 with slightly more overhead/complexity, and Alg. 3 achieves the best performance with the largest overhead/complexity.

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