COORDINATED SCHEDULING AND BEAMFORMING FOR MULTICELL SPECTRUM SHARING NETWORKS USING BRANCH & BOUND

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ABSTRACT

We consider the downlink of a multicell network where neighboring multi-antenna base stations share the spectrum and coordinate their frequency and spatial resource allocation strategies to improve the overall network performance. The objective of the coordination is to maximize the number of users that can be scheduled, meeting their quality-of-service requirements with the minimum total transmit power. The coordinated scheduling and multiuser transmit beamforming problem is combinatorial; we formulate it as a mixed-integer second-order cone program and propose a branch & bound algorithm that yields the optimal solution with relatively low-complexity. The algorithm can be used to motivate or benchmark approximation methods and to numerically evaluate the gains due to spectrum sharing and coordination.

1. INTRODUCTION

We consider the downlink of a multicell wireless network with orthogonal frequency division multiple access, where the frequency reuse factor is one. The base stations (BSs) have multiple antennas enabling spatial multiplexing. Given the total amount of frequency and spatial resources of the network, how do we distribute them across the mobile stations (MSs) to improve the total network utility? This question is important in modern wireless systems, as they are increasingly deployed with hierarchical structure where cells can heavily overlap. We are interested in the scenario where several adjacent BSs coordinate their scheduling decisions and beamforming designs, but transmit the data streams independently. This is different from the coordinated multipoint transmission (CoMP), where multiple BSs form a large virtual array and jointly transmit and receive signals for multiple MSs [1, 2].

We assume that the total transmit power budget of each BS can be distributed among the frequency resources, hereafter called subchannels. A MS is scheduled when its quality-of-service (QoS) requirement, corresponding to a signal-to-interference-and-noise ratio (SINR) target, can be satisfied. Scheduling is a hard combinatorial problem; in order to reduce its complexity we constrain each MS to be scheduled in at most one subchannel. This may be interpreted as a fairness constraint when the total number of MSs requesting service exceeds the number of available subchannels. More than one MSs may be scheduled in a subchannel, by means of spatial multiplexing. In order to improve the network performance, the BSs coordinate the scheduling decisions and beamforming designs to effectively manage intracell and intercell interference. The primary objective of the coordination is to maximize the number of scheduled MSs and the secondary objective is to minimize the total transmit power.

SINR-constrained multiuser transmit beamforming for a given set of MSs, in a single cell and subchannel, is a convex problem; specifically, a second-order cone program (SOCP) [3]. In [4], this beamforming problem is extended to multicell networks. A joint formulation for the hard combinatorial problem of scheduling and beamforming, in a single subchannel and cell, is given in [5]. Therein, convex approximation algorithms are proposed that yield near-optimal solutions. In [6], a coordinated scheduling, beamforming, and power allocation scheme is proposed and the joint problem is decoupled and solved in an iterative fashion, but without considering SINR constraints. In [7], the single subchannel scheduling and power control problem is solved using the branch and bound (B&B) algorithm [8]. In [9], the beamforming and user maximization problem is considered in a single-cell cognitive radio network and a B&B algorithm is proposed where the lower bound is based on semidefinite relaxation but without considering an upper bound.

In this paper, we use integer variables to model the scheduling and formulate the coordinated scheduling and beamforming problem in the general multicell and multicarrier network setup as a mixed-integer SOCP (MI-SOCP). Such programs can be solved using general-purpose solvers, which implement the B&B algorithm and yield at each node a lower bound by relaxing a subset of the integer variables. These bounds are quite loose, motivating us to propose a customized B&B algorithm that avoids the relaxation and finds tighter lower and upper bounds with low complexity.

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2. SYSTEM MODEL AND FORMULATIONS

We consider a wireless network with L cells and K MSs per cell, where the kth ($k \in \mathcal{K} \triangleq \{1, \cdots, K\}$) MS in the lth ($l \in \mathcal{L} \triangleq \{1, \cdots, L\}$) cell is denoted as $\text{MS}_{l,k}$ [4]. Each BS has N_t antennas and each MS has a single antenna. Multiuser downlink beamforming is employed at each BS. The number of available subchannels is N (indexed by $n \in \mathcal{N} \triangleq \{1, \cdots, N\}$), which is assumed to be smaller than the total number of MSs in the network, i.e., $N < LK$. All the channel state information, i.e., from each BS to every MS in the network, is assumed to be known, and the channels are flat in each transmission interval.

We denote the beamforming vector for $\text{MS}_{l,k}$ in the nth subchannel as $\mathbf{w}_{l,k}^n \in \mathbb{C}^{N_t}$, and the channel from the BS of the jth cell to $\text{MS}_{l,k}$ in the nth subchannel as $\mathbf{h}_{j,l,k}^n \in \mathbb{C}^{N_t}$. We have $\mathbf{w}_{l,k}^n \neq \mathbf{0}$ if $\text{MS}_{l,k}$ is scheduled in the nth subchannel, and $\mathbf{w}_{l,k}^n = \mathbf{0}$ otherwise. The SINR for $\text{MS}_{l,k}$ in the nth subchannel can then be expressed as

$$\Gamma_{l,k}^n = \frac{|(\mathbf{w}_{l,k}^n)^H \mathbf{h}_{l,l,k}^n|^2}{\sum\limits_{b \neq k} |(\mathbf{w}_{l,b}^n)^H \mathbf{h}_{l,l,k}^n|^2 + \sum\limits_{j \neq l} \sum\limits_{b} |(\mathbf{w}_{j,b}^n)^H \mathbf{h}_{j,l,k}^n|^2 + \sigma_{l,k}^2}. \tag{1}$$

The QoS requirement to schedule $\text{MS}_{l,k}$ in the nth subchannel is $\Gamma_{l,k}^n \geq \gamma_{l,k}$, where $\gamma_{l,k}$ is the SINR target. Here, a single SINR target is chosen for different subchannels. Thus a MS can be scheduled in the subchannel which has the best channel and interference condition. Moreover, we assume the total transmit power at each BS can not exceed a maximum budget P_l, i.e., $\sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{K}} \|\mathbf{w}_{l,k}^n\|^2 \leq P_l$. This constraint allows the power to be distributed unevenly among the subchannels.

In our problem of interest, we have two objectives. The primary objective is to maximize the number of MSs that can be scheduled in the available subchannels while satisfying both the SINR constraints and the BS power constraints. The secondary objective is to find the optimal beamforming vectors for those scheduled MSs that minimize the total transmit power. We can describe this multi-objective optimization problem in two stages as in [5]. Let $\mathcal{S}_l^n \subseteq \mathcal{K}$ denote the subset of MSs in the lth cell that are scheduled in the nth subchannel, and $|\mathcal{S}_l^n|$ denote the cardinality of $\mathcal{S}_l^n$. The first stage is a combinatorial optimization problem given by

$$\max_{\mathcal{S}_l^n, \mathbf{w}_{l,k}^n} \sum_{n \in \mathcal{N}} \sum_{l \in \mathcal{L}} |\mathcal{S}_l^n| \tag{2a}$$

$$\text{s.t.} \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{S}_l^n} \|\mathbf{w}_{l,k}^n\|^2 \leq P_l, \quad \forall l \in \mathcal{L}, \tag{2b}$$

$$\Gamma_{l,k}^n \geq \gamma_{l,k}, \quad \forall n \in \mathcal{N}, \forall k \in \mathcal{S}_l^n, \forall l \in \mathcal{L}. \tag{2c}$$

$$\mathcal{S}_l^n \cap \mathcal{S}_l^m = \emptyset, \quad n \neq m, \forall n, m \in \mathcal{N}, \forall l \in \mathcal{L}. \tag{2d}$$

Constraint (2d) ensures that no MS can be scheduled in more than one subchannel. With the optimal sets $\{\mathcal{S}_l^n\}$ from (2), the second stage is a downlink beamforming problem,

$$\min_{\mathbf{w}_{l,k}^n} \sum_{n \in \mathcal{N}} \sum_{l \in \mathcal{L}} \sum_{k \in \mathcal{S}_l^n} \|\mathbf{w}_{l,k}^n\|^2, \quad \text{s.t.} \quad \text{(2b), (2c)}. \tag{3}$$

Problem (3) can be transformed into a SOCP problem [3] with complexity $\mathcal{O}(((\sum_n \sum_l |\mathcal{S}_l^n|)N_t)^{3.5})$ and solved efficiently by using general-purpose convex optimization toolboxes.

As an alternative to the two-stage formulation (2) and (3), we propose a joint formulation by introducing auxiliary binary variables $s_{l,k}^n \in \{0,1\}$. Let $s_{l,k}^n = 1$ if $\text{MS}_{l,k}$ is scheduled in the nth subchannel; and $s_{l,k}^n = 0$ otherwise. The joint formulation is given by

$$\min_{\mathbf{w}_{l,k}^n, s_{l,k}^n} \epsilon \sum_{n \in \mathcal{N}} \sum_{l \in \mathcal{L}} \sum_{k \in \mathcal{K}} \|\mathbf{w}_{l,k}^n\|^2 - \sum_{n \in \mathcal{N}} \sum_{l \in \mathcal{L}} \sum_{k \in \mathcal{K}} s_{l,k}^n \tag{4a}$$

$$\text{s.t.} \quad s_{l,k}^n \in \{0,1\}, \qquad \forall n \in \mathcal{N}, \forall l \in \mathcal{L}, \forall k \in \mathcal{K}, \tag{4b}$$

$$\sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{K}} \|\mathbf{w}_{l,k}^n\|^2 \leq P_l, \quad \forall l \in \mathcal{L}, \tag{4c}$$

$$\frac{|(\mathbf{w}_{l,k}^n)^H \mathbf{h}_{l,l,k}^n|^2 + M_{l,k}^n(1 - s_{l,k}^n)}{\sum\limits_{b \neq k} |(\mathbf{w}_{l,b}^n)^H \mathbf{h}_{l,l,k}^n|^2 + \sum\limits_{j \neq l} \sum\limits_{b} |(\mathbf{w}_{j,b}^n)^H \mathbf{h}_{j,l,k}^n|^2 + \sigma_{l,k}^2} \geq \gamma_{l,k},$$
$$\forall n \in \mathcal{N}, \forall l \in \mathcal{L}, \forall k \in \mathcal{K}, \tag{4d}$$

$$\sum_{n \in \mathcal{N}} s_{l,k}^n \leq 1, \qquad \forall l \in \mathcal{L}, \forall k \in \mathcal{K}. \tag{4e}$$

In (4a), the first term is the total transmit power scaled by a positive constant ϵ and the second term counts the total number of admitted MSs. Since the total transmit power is bounded by $\sum_{l \in \mathcal{L}} P_l$ and the second term is discrete with step size -1, we choose $0 < \epsilon < 1/(\sum_{l \in \mathcal{L}} P_l)$. This choice of ϵ implies that the maximum possible number of MSs will be scheduled and no other solution that schedules the same number of MSs can operate with less power [5]. Constraint (4d) defines N inequalities for each $\text{MS}_{l,k}$. When $s_{l,k}^n = 1$, the inequality is a standard SINR constraint; when $s_{l,k}^n = 0$, the inequality does not impose any constraint on $\{\mathbf{w}_{l,k}^n\}$ provided that $M_{l,k}^n$ is large enough to satisfy the inequality for all possible values of $\{\mathbf{w}_{l,k}^n\}$. By considering the power constraint (4c) and the Cauchy-Schwarz inequality, we choose the value of $M_{l,k}^n$ as $M_{l,k}^n \geq \gamma_{l,k} \sum_{j \in \mathcal{L}} P_j \|\mathbf{h}_{j,l,k}^n\|^2 + \gamma_{l,k}\sigma_{l,k}^2$. Constraint (4e) makes sure that each MS is scheduled in at most one subchannel. Note that, when all the binary variables $\{s_{l,k}^n\}$ are fixed, (4) is equivalent to (3) in the two-stage formulation.

Constraint (4d) can be formulated as a SOCP constraint:

$$\left\| [(\mathbf{u}_{l,k}^n)^T, \ \sigma_{l,k}] \right\| \leq \sqrt{(1 + 1/\gamma_{l,k})} (\mathbf{w}_{l,k}^n)^H \mathbf{h}_{l,l,k}^n +$$
$$\sqrt{M_{l,k}^n / \gamma_{l,k}} (1 - s_{l,k}^n), \quad \forall l \in \mathcal{L}, \forall k \in \mathcal{K}, \forall n \in \mathcal{N}, \tag{5}$$

where $\mathbf{u}_{l,k}^n$ is a $LK \times 1$ vector defined as $\mathbf{u}_{l,k}^n = [(\mathbf{w}_{1,1}^n)^H \mathbf{h}_{1,l,k}^n, \cdots, (\mathbf{w}_{L,K}^n)^H \mathbf{h}_{L,l,k}^n]^T$, and $(\mathbf{w}_{l,k}^n)^H \mathbf{h}_{l,l,k}^n$ is constrained to be real valued and positive. By replacing (4d) with (5), we can transform (4) into a MI-SOCP problem, which can be solved, e.g., by using the B&B solver CPLEX. The procedure of using CPLEX to solve this MI-SOCP problem is based on the relaxation of the binary variables. Specifically, constraint (4b) is relaxed as $0 \leq s^n_{l,k} \leq 1$. Thus the MI-SOCP problem changes into a SOCP problem of complexity $\mathcal{O}((LKNN_t)^{3.5})$. However, the lower bound found from relaxation in this problem is quite loose. This is because the chosen values of constants $\{M^n_{l,k}\}$ are much larger than the sum of interference and noise in (4d). Therefore, every constraint in (4d) can be satisfied with $\{s^n_{l,k}\}$ of such values that the equality in (4e) becomes valid for every MS, i.e., $\sum_{n\in\mathcal{N}} s^n_{l,k} = 1$. Thus the second term in the objective function (4a) will be LK, which seems like all the LK MSs are scheduled in the available subchannels, but in fact it is not. In the next section, we propose a customized B&B algorithm which avoids the relaxation. Our algorithm has tighter lower bound and also finds an upper bound with low complexity.

3. PROPOSED ALGORITHM USING B&B

In our B&B algorithm, we split the problem in (4) (i.e., the root) into subproblems (nodes) by fixing a subset of the binary variables. We define a $N \times 1$ binary vector $\mathbf{s}_i\,(i \in \{1,\cdots,LK\})$ for each MS, for example, $\mathbf{s}_i = [s^1_{j,b},\cdots,s^N_{j,b}]^T$ ($\forall j \in \mathcal{L}$, $\forall b \in \mathcal{K}$). Because of the constraint (4e), $\mathbf{s}_i$ can be either a column of the identity matrix $\mathbf{I}_{N\times N}$ or an all-zero vector, so it has $N+1$ possible combinations. We can generate a tree with LK levels, where each level corresponds to a specified MS. The original problem (4) can be split into $N+1$ nodes in the first level by fixing $\mathbf{s}_1$. Each of those nodes can be further split in the second level by further fixing $\mathbf{s}_2$, etc, thus generating $(N+1)^{LK}$ nodes in the last level. Solving the SOCP problem for each and every node at the last level corresponds to the enumeration method which has prohibitive complexity. For this reason, we would like to prune nodes in the tree early on without going all the way down to the last level and we show how to achieve this in the following.

For a node in the tree, we calculate a lower bound (LB) and an upper bound (UB) for the optimal value of (4a). If the LB of a node is higher than the global upper bound (GUB), i.e., the tightest UB from all nodes already examined, this node and all its children nodes can be safely pruned without loss of optimality. This is because all children nodes are further restrictions of their parent node (each child node has one more binary vector fixed relative to its parent node), implying that the LB of a child node must be greater than or equal to the LB of its parent node. This implicit elimination is the key to computational savings, and it can be very effective if substantial pruning happens early in the process.

In order to make the algorithm more efficient, we need to define a proper *order* to fix the binary vectors of the MSs, i.e., for which MS it is fixed in the first level, which is fixed in the second level, etc. Since our primary objective is to maximize the number of scheduled MSs within the limited total transmit power and satisfying the individual SINR constraints, we have an intuition that the MS requiring small transmit power to satisfy its SINR constraint is more likely to be admitted, so we fix the binary vector of such a MS in a early level. Although a SOCP has to be solved to determine the required transmit power $\|\mathbf{w}^n_{l,k}\|^2$ satisfying $\Gamma^n_{l,k} \geq \gamma_{l,k}$, we can find a LB for it by considering the interference-free case. The minimum transmit power satisfying the QoS constraint can be find through the maximum ratio transmission (MRT) as $p^n_{l,k} = \gamma_{l,k}\sigma^2_{l,k}/\|\mathbf{h}^n_{l,l,k}\|^2$ and the related beamforming vector is $\mathbf{v}^n_{l,k} = \sqrt{p^n_{l,k}}\mathbf{h}^n_{l,l,k}/\|\mathbf{h}^n_{l,l,k}\|$. We refer to $p^n_{l,k}$ and $\mathbf{v}^n_{l,k}$ as MRT power and MRT beamformer, respectively. We calculate every $p^n_{l,k}$ to get a $N \times LK$ matrix $\mathbf{P} = [\mathbf{p}_{1,1},\cdots,\mathbf{p}_{1,K},\cdots,\mathbf{p}_{L,1},\cdots,\mathbf{p}_{L,K}]$, where $\mathbf{p}_{l,k} = [p^1_{l,k},\cdots,p^N_{l,k}]^T$. Then we find the minimum element in each column of $\mathbf{P}$ and sort them into a $LK \times 1$ vector in an ascending order. This vector gives the *order* that we need, i.e., the MS corresponds to the i element of this vector will be fixed in the ith level.

Then we introduce how to calculate the UB. For a specified node in the ith level, we have a subset of i fixed binary vectors $\mathbf{s}_1\cdots\mathbf{s}_i$. By assuming all the other $\mathbf{s}_{i+1}\cdots\mathbf{s}_{LK}$ to be all-zero vectors (i.e., not scheduled in any subchannel), we get a fixed set of binary variables $\{s^n_{l,k}\}$, and the node corresponds to a SOCP problem (3). The complexity of this SOCP problem is $\mathcal{O}((iN_t)^{3.5})$, since there are only i SINR constraints (2c). However, if using the relaxation method as in CPLEX, the same node corresponds to a SOCP problem with complexity $\mathcal{O}(((i+N(LK-i))N_t)^{3.5})$, because of the additional $N(LK-i)$ constraints (4d) and variables. If the SOCP problem of the node is infeasible, this node can be pruned directly. Otherwise, we get a solution which can be used as a UB for this node. However, this UB is a *loose* one because we have assumed all the other unfixed MSs are not scheduled. We can tighten this UB by scheduling more MSs while keeping those already scheduled ones. We implement this by extending the low-complexity admission-control method in [10] into our multi-subchannel model. In each subchannel, we keep the spatial signatures of beamformers for the already admitted MSs, but adjust their power (under the power limit) to schedule a new MS, and the beamforming vector for the new MS is calculated while satisfying all the constraints. This process is repeated until no more MS can be scheduled. In this way, we find a relatively tight UB avoiding to solve additional SOCPs.

For the LB, we keep the solution from the *loose* UB. Since the beamforming vectors for those MSs with the fixed binary vectors $\mathbf{s}_1\cdots\mathbf{s}_i$ were calculated, we know how much power was spent in each cell. With the remaining power budget, we try to schedule as many other MSs as possible by considering their MRT power under the power constraint, i.e., assuming the interference-free case for the other MSs. Since the MRT power is the least power required to admit a MS, we get a LB for the node. This LB is tighter than that of the relaxation method.

We also find an initial LB and an initial UB before splitting the original problem into subproblems. We calculate the initial LB by minimizing the objective function (4a) under the constraints (4b), (4c) and (4e) while assuming $\|\mathbf{w}_{l,k}^n\|^2 = p_{l,k}^n$. For the initial UB, we first schedule one MS in each subchannel, which corresponds to the smallest element in each row of the MRT power matrix $\mathbf{P}$. Then we schedule more MSs with the same method as we do in tightening the UB.

Our proposed optimal algorithm using B&B is summarized in Algorithm 1. We denote the node that selected to be split as *s-node* and we use a *stack* to keep track of nodes that require further examination. In step 1, if the calculated initial LB and initial UB are equal, we terminate the algorithm, and the optimal solution to the problem is obtained from the initial UB. Otherwise, we initialize *s-node* to be the root and *stack* to be empty, set GUB to be equal to the initial UB and go to step 2. In step 2, we implement the depth-first search. Specifically, a node is split into $(N+1)$ children nodes, but only the one with the lowest LB is further split into the next level, while any other unpruned nodes are inserted in the stack. We repeat step 2 and 3 until the *stack* becomes empty. The final optimal solution is obtained from the GUB.

For large size problems, the complexity of Algorithm 1 can be very high because a large number of nodes might be generated in step 2 and 3. Therefore, we can find a sub-optimal solution by implementing a fixed number of depth-first searches in Algorithm 1. If Q searches are implemented, the maximum number of nodes generated is $(N+1)LKQ$.

Algorithm 1 Proposed optimal algorithm using B&B

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1. Calculate an initial LB and an initial UB.
   - If they are equal, terminate; else, initialize *s-node* $\leftarrow$ root, *stack* $\leftarrow \emptyset$, $GUB \leftarrow$ initial UB, and go to 2.
2. Implement the depth-first search one time.
   (a) Split *s-node* into $N+1$ new nodes. For every new node, solve a SOCP problem (3).
      - If it is infeasible, prune the node; else, calculate LB.
      - If $LB > GUB$, prune the node; else, tighten UB.
      - If $UB < GUB$, $GUB \leftarrow UB$.
   (b) *s-node* $\leftarrow$ the one has the lowest LB in the unpruned new nodes, insert the other ones in *stack*, go to (a).
   (c) Repeat (a) and (b) until all new nodes are pruned or the last level is reached.
      - If *stack* $= \emptyset$, terminate; else, go to 3.
3. Delete the nodes whose $LB > GUB$ in *stack*.
   - If *stack* $= \emptyset$, terminate; else, *s-node* $\leftarrow$ the node with the lowest LB in *stack*, go to 2.

We give an example to illustrate Algorithm 1 in Fig. 1, where 2 cells with 2 MSs in each cell and 2 subchannels are

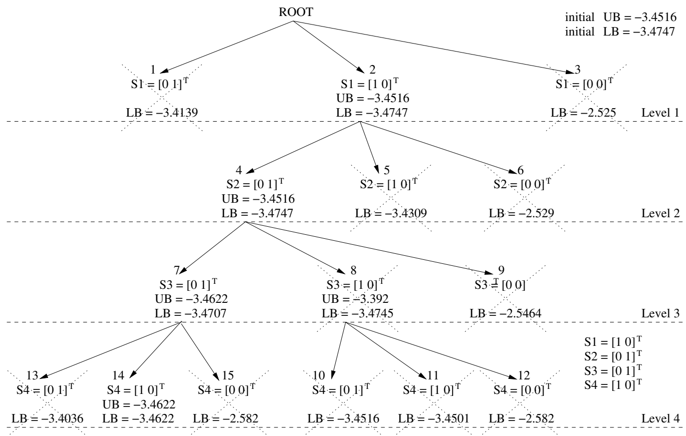

Fig. 1. An example for the B&B algorithm.

considered. The branching *order* is that, the binary vector for $\text{MS}_{1,1}$ is fixed in level 1, followed by $\text{MS}_{1,2}$ in level 2, $\text{MS}_{2,2}$ in level 3 and $\text{MS}_{2,1}$ in level 4. The nodes are numbered in the same order as they are generated. Since the initial UB and the initial LB are not equal to each other, we split the root into three nodes in level 1 by fixing $\mathbf{s}_1$. Then node 1 and 3 are pruned because their LB are higher than GUB and we do not need to tighten their UB. Since node 2 is the only node left, it is split in level 2 where $\mathbf{s}_2$ is further fixed. In level 2, node 5 and 6 are pruned and node 4 is split into level 3. In level 3, GUB is updated to be equal to the UB of node 7, node 9 is pruned, node 8 is split into level 4 and node 7 is inserted in *stack*. In level 4, nodes 10, 11, and 12 are all pruned since their LB are higher than the updated GUB, and therefore node 8 is also pruned. Next, take node 7 out of *stack* and split it. Then nodes 13 and 15 are pruned. Now all the nodes in the tree, except node 14 and its parents (nodes 7, 4, and 2), have been pruned and *stack* becomes empty. Therefore, the optimal binary vectors in this example are $\mathbf{s}_1 = [1\ 0]^T$, $\mathbf{s}_2 = [0\ 1]^T$, $\mathbf{s}_3 = [0\ 1]^T$ and $\mathbf{s}_4 = [1\ 0]^T$, and the optimal beamforming vectors are also obtained when calculating the GUB. In this example, we find the optimal solution by generating 15 nodes, while by using the relaxation method with CPLEX there are 26 nodes generated, and by brute-force searching we have to solve all 3^4 nodes. For larger size problems, we can even save more complexity, as shown in the next section.

4. NUMERICAL EXAMPLES

We consider a network with two cells as shown in Fig. 2. The distance between the two BSs is 500 m and five MSs are randomly placed in each cell. Ten realizations of the MSs positions are considered. Each BS has four antennas and each MS has one antenna. The mobility of the MSs is 3 km/h. The car-

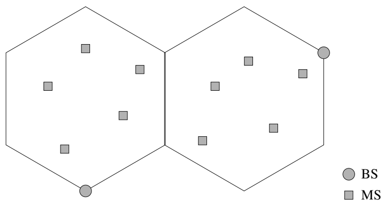

Fig. 2. A network with two cells and 5 MSs in each cell.

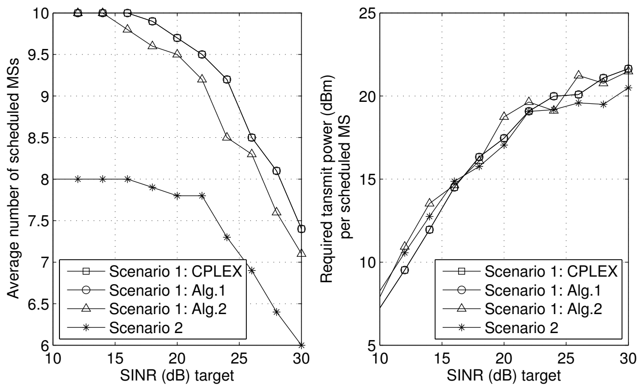

Fig. 3. Performance of the proposed algorithms.

rier frequency is 2.6 GHz and we consider two subchannels[1]. The path loss is $35.74\log(d) + 5.59 + 23\log(2.6)$, where d is the MS-BS distance in meter. The shadowing is log-normal distributed with a standard deviation of 8 dB. The power budget at each BS is 0.8 W and the noise power at every MS is -174 dBm/Hz. The SINR target for every MS has the same value. We consider two scenarios: in scenario 1 both cells share both subchannels; in scenario 2 each cell uses a different subchannel. In scenario 1, we show the optimal solution from Alg. 1 and CPLEX, and the sub-optimal solution with 2 depth-first searches (Alg. 2).

The average number of scheduled MSs and the average transmit power per scheduled MS versus various SINR targets are shown in Fig. 3. As expected, our optimal algorithm has the same result as using CPLEX. We can see a larger number of MSs are scheduled in scenario 1. The average transmit power in scenario 1 is close to that in scenario 2. In Fig. 4, we compare the average number of nodes generated in scenario 1. The number of nodes generated in Alg. 1 is smaller than CPLEX and it is even much more smaller in Alg. 2.

5. CONCLUSIONS

The coordinated scheduling and beamforming problem for multicell spectrum sharing networks has been formulated as a MI-SOCP and an algorithm using B&B has been proposed that yields the optimal solution. The proposed algorithm is more efficient than the generic relaxation-based B&B algorithm, since a smaller number of nodes is generated and lower complexity is required at each node to calculate lower and upper bounds. Moreover, when the complexity is bounded, the algorithm can be adapted to return a high-quality sub-optimal solution.

[1]Simulation results for larger numbers of subchannels and MSs are included in the journal version of this paper.

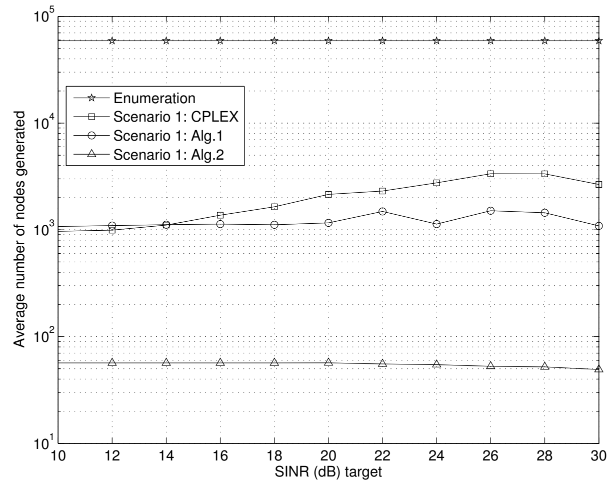

Fig. 4. Average number of nodes generated.

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