Sub-channel and Power Allocation in Uplink Cognitive Small Cell Network: A Game Theoretic Approach

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Abstract

In this paper, we provide a novel framework of the sub-channel and power allocation in uplink cognitive small cell network (CSN). In our model, the CSN reuses sub-channels of a macro cell using underlay spectrum access paradigm. The problem of sub channel and power allocation is formulated as an optimization problem. We maximize sum rate in uplink data transmission while protecting the macro base station (MBS) and guaranteeing minimum data rate requirement of served cognitive small cell users (CSUE). To solve this problem, a framework based on the one-to-many matching game is proposed to enable the CSN to make decisions on sub-channel and power allocation. Simulation results show that the proposed approach has efficient performance with a stable matching.

I. Introduction

Recently year, the small cell networks deployment is a promising technique to improve the capacity, and enhance the coverage for indoor in next-generation wireless cellular network [1]. To improve the limited radio resource utilization, a two-tier network is proposed in which small cells reuse the same radio resources with the macro cell network [2]. However, this two-tier network lead to challenges of co-channel interference, thus requiring a smart adaptation of scheduling algorithms. Several recent studies have considered the sub-channel and power allocation [3], [4]. However, none of these works studies resource allocation in which small cell users and small cell network management's decision selfishly and rationally interference in a way that maximizing their utilities.

Our contributions can be summarized as follows:

- We investigate the joint sub channel and power allocation problem in the uplink of an underlay CSN, which become an NP-hard optimization problem in centralized solution.
- We formulate the NP hard problem as a one-to-many matching game in which CSUEs and CSM are players.
- We design a distributed algorithm to allocate sub channels and power level to CSUEs in stable matching.

II. System model and formation problem

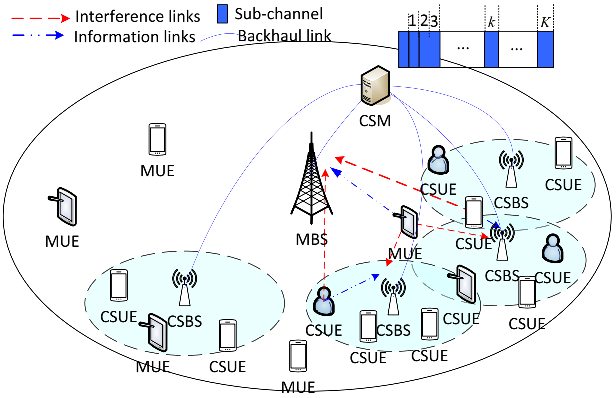

Figure 1: system model

System model. We consider an uplink cognitive small cell network composed of a set $\mathcal{M} = \{1 \ldots M\}$ CSBSs. Each CSBS m has the set $\mathcal{N}_m$ of CSUEs as in Fig.1. Denote $\mathcal{N} = \bigcup_{m \in \mathcal{M}} \mathcal{N}_m$ by a set of all CSUEs in the network. There is a set $\mathcal{K} = \{1, 2 \ldots K\}$ of sub-channels which are utilized from the MBS. We assume that have no interference among small cells. Each CSUE is only permitted to access at most a sub-channel. A cognitive small cell management (CSM) is deployed to manage the MBS protection and CSUEs' QoS. Additionally, the predefined interference power threshold on each sub channel k at the MBS is $I_{0,k}^{th}$. Each the CSUE has minimum data rate requirement $R_n^{\min}$.

Problem formulation.

When CSUE n in CSBS m using sub channel k, the data rate of CSUE n is given by

$$R_{nm}^k = B_k \log_2\left(1 + \frac{g_{nm}^k P_{nm}^k}{g_{km}^k P_{k0}^k + \sigma^2}\right) \quad (1),$$

where B_k is the bandwidth of sub-channel k; g_{nm}^k is channel gain between n-th CSUE and m-th CSBS on sub-channel k; $g_{km}^k P_{k0}^k$ is interference level of MUE k to CSBS m; σ^2 is Gaussian Noise at CSBS.

To protect MBS protection and to guarantee FUEs' QoS, the problems of sub-channel and power allocation are formulated as follows: (OPT-1)

$$\begin{aligned}
&\max_{Y,P} \quad \sum_{m=1}^{M}\sum_{n=1}^{N_m}\sum_{k=1}^{K} y_{nmk} R_{nm}^k \qquad (2)\\
&C1: \quad \sum_{m=1}^{M}\sum_{n=1}^{N_m} y_{nmk} g_{nm}^k P_{nm}^k \le I_{0,k}^{th}, \ \ \forall k\\
&C2: \quad \sum_{k=1}^{K} y_{nmk} R_{nm}^k \ge R_n^{\min}, \ \ \forall n, m\\
&C3: \quad \sum_{n=1}^{N_m} y_{nmk} \le 1, \ \ \forall m, k\\
&C4: \quad y_{nmk} = \{0,1\}, \ \ \forall m, n, k\\
&C5: \quad P_{nmk} \in [\mathrm{P}_n^{\min}, \mathrm{P}_n^{\max}], \ \ \forall m, n, k\\
&C6: \quad Stability
\end{aligned}$$

The objective (1) represents the overall network throughput in the uplink CSN; the MBS protection is constrained in (C1); the minimum data rate requirement of each CSUE is addressed in (C2); the constraint (C3) shows that a CSUE is allocated at most a sub channel; in condition (C4), the sub channel index y_{nmk} = 1 means that sub channel k is assigned to CSUE n in FBS m and y_{nmk} = 0 otherwise; and condition (C6) guarantees that the final matching is group stable as defined in the next section.

Clearly, the optimization problem is NP hard in centralized fashion. In order to solve it, we propose a novel solution which based on one-to-many matching game approach.

III. Sub-channel and power allocation as

In this section, we design a distributed algorithm based on one-to-many matching game [5]. We transform finding variable **Y** by using matching one-to-many between two sets $\mathcal{N}$ and $\mathcal{K}$ which satisfy constraints (C1)-(C6).

Proposition 1: The problem OPT-1 is formulated as the one-to-many matching game.

Proof: A matching-based sub-channel allocation problem is defined by the tuple as a function from $(\mathcal{N}, \mathcal{M}, \succ_n, \succ_k, q_n = 1, q_k = N_k)$. Here q_k is quota of sub channel k at CSM which represents maximum number of CSUEs can be assigned sub channel k. The q_k value is dynamic quota that depend on constraints (C1), (C2), (C5), (C6). Parameter q_n is quota of CSUE n which addresses as condition (C3). The sought solutions is a matching function a matching game $\mu_{SCA}: \mathcal{N} \cup \mathcal{K} \to \mathcal{N} \cup \mathcal{K}$ which provides the final allocation between CSUEs and CSBSs based on preference functions $\succ_n$ and $\succ_k$.

In the proposed matching game, the two preference relation $\succ_n$ and $\succ_k$ are formulated based on following utility functions:

CSUE utility. The utility function of each CSUE n forms its preference relation on each sub channel k which is determined as follows:

$$U_{nm}(k) = R_{nm}^k . \qquad (3)$$

CSM utility on each sub channel. At the CSM side, the CSM estimates the utility value on each sub channel k given the requested CSUE n in FBS m as follows:

$$U_{nm}(k) = \frac{R_{nm}^k - R_n^{\min}}{R_n^{\min}} - \beta P_{nm}^k g_{nm,0}^k \max\left(0, \frac{\sum_{\forall n}\sum_{\forall m} y_{nmk} P_{nm}^k g_{nm,0}^k - I_{0,k}^{th}}{I_{0,k}^{th}}\right) (4)$$

In which, the second term in (4) is the measurement which quantities degree of violation of constraint (C1); the first term in (4) is the measurement which quantities degree of satisfaction of the condition (C2).

In the proposed matching game, value N_k is dynamic quota which depends on the CSM demand as follows:

CSM demand. Given a set $\mathcal{N}_k^{req}$ of requested CSUEs on sub channel k, CSM has a sub channel and power allocation strategies to maximize the total data rate on the sub channel k while guaranteeing MBS protection and CSUEs' minimum rate. From the OPT-1, the demand function of CSM is formulated as follows: (OPT-2)

$$\max_{Y,P} \sum_{(n,m)\in N_k^{req}} R_{nm}^k \qquad (1)$$

$$C1': \sum_{(n,m)\in N_k^{req}} g_{nm}^k P_{nm}^k \le I_{0,k}^{th}, \ \forall k$$

$$C2': \ R_{nm}^k \ge R_n^{\min}, \ \forall n,m \in N_k^{req}$$

$$C5': \ P_{nmk} \in [\mathrm{P}_n^{\min}, \mathrm{P}_n^{\max}], \ \forall m,n,k$$

$$C6': \ Stability$$

We can see that given feasible solution of the OPT-2 is a concave problem in variable P. Therefore, OPT-2 can be solved using some solvers such as the CVX toolbox in *matlab* software. In the proposed game, if the OPT-2 is infeasible, the CSUE in the set $\mathcal{N}_k^{req}$ will be removed by the CSM with lowest value $U_{nm}(k)$.

From above setups, we propose a distributed algorithm based on the one-to-many matching game to solve OPT-1 as in Algorithm 1.

Algorithm 1: Join sub channel and power allocation in CSN

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Input: $\mathcal{N}, \mathcal{M}, \mathcal{K}$
Repeat
Algorithm at the CSUE:
1. Form preference relation $\succ_n$ for all sub channels in the set $\mathcal{K}$.
2. Send a request to access sub channel k = $\arg\max$ ($\succ_n$) to the CSM
At the CSM:
1. Collect requested CSUE into the set $\mathcal{N}_k^{req}$.
2. Form preference relation $\succ_k$ for all CSUE in the set $\mathcal{N}_k^{req}$.
    While (the OPT-2 is infeasible solution)
        Remove CSUE n = $\arg\min \succ_k$.
    End
    Update $y_{nm}^{k*} = 1$ if (n, m) ∈ $\mathcal{N}_k^{accepted}$.
    Solve OPT2 based on CVX to find optimal transmit power.
    Update $P_{nm}^{k*}$.
Until have no change for two consecutive iterations $\mathcal{N}_k^{accepted}$
Output: Stable groups $\mathcal{N}_k^{accepted}$.
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IV. Simulation results

In this section we present our simulation with Matlab to evaluate the performance of our proposals. We consider a two-tier network, where M= 5 CSBSs are located with a MBS. Some parameters are installed as follows: $P_{nm}^{\max}$ = 100 mW; I_0^{th} = -75 dBmW; σ^2 =-105 dBm; B_k =360 kHz; K = 5 sub-channels. The channel gain is assumed to be iid Rayleigh random variables with mean value h(d) = $h_0(d/15)^{-4}$ where h_0 is a reference channel gain at a distance 15 m. In Fig. 2, we compare the proposed approach with other four schemes: Greedy scheme, random scheme, no admission control scheme, and fixed power scheme. Fig.2 illustrates the average overall network throughput and average outage probability versus the number of CSUEs. We can see that our proposal outperforms other schemes in term of total throughput and outage probability.

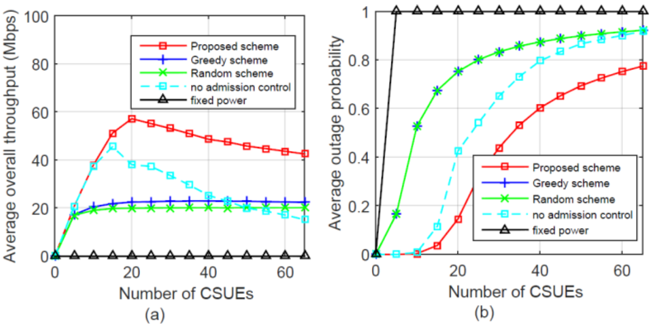

Fig.2. The average total throughput and average outage probability in the CSN.

V. Conclusions

In this paper, we have provided a novel framework of the sub-channel and power allocation in uplink cognitive small cell network. The problem of sub channel and power allocation have formulated as an optimization problem. We have maximized the sum rate in uplink data transmission while protecting the macro base station and guaranteeing minimum data rate requirement of served small cell users. Simulation results showed that the proposed approach has efficient performance with a stable matching.

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