Distributed Power and Channel Allocation for Cognitive Femtocell Network using a Coalitional Game Approach

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***Abstract*—The cognitive femtocell network (CFN) integrated with cognitive radio-enabled technology has emerged as one of the promising solutions to improve wireless broadband coverage in indoor environment for next-generation mobile networks. In this paper, we study a distributed resource allocation that consists of subchannel- and power-level allocation in the uplink of the two-tier CFN comprised of a conventional macrocell and multiple femtocells using underlay spectrum access. The distributed resource allocation problem is addressed via an optimization problem, in which we maximize the uplink sum-rate under constraints of intra-tier and inter-tier interferences while maintaining the minimum rate requirement of the served femto users. Specifically, the aggregated interference from cognitive femto users to the macrocell base station is also kept under an acceptable level. We show that this optimization problem is NP-hard and propose a distributed framework to maximize the sum-rate of network based on coalitional game in partition form. The proposed framework is tested based on the simulation results and shown to perform efficient resource allocation.**

Keywords*—Cognitive femtocell network, resource allocation, power allocation, subchannel allocation, coalitional game, game theory.

I. Introduction

In recent years, the number of mobile applications demanding high-quality communications have tremendously increased. For instance, high-quality video calling, mobile high-definition television, online gaming, and media sharing services always have connections with high-quality of services (QoS) requirements among devices and service providers [1]. In order to adapt to these requirements, the Third Generation Partnership Project (3GPP) Long-Term Evolution Advanced (LTE-Advanced) standard has been developed to support higher throughput and better user experience. Moreover, in order to accommodate a large amount of traffic from indoor environments, the next mobile broadband network uses the heterogeneous model, which consists of macrocells and smallcells [2], [3]. The smallcell model (such as femtocells) is one way of increasing coverage in dead zones in indoor environments, reducing the transmit power and the size of cells and improving spectrum reuse [4]. A two-tier femtocell network can be implemented by spectrum-sharing between tiers, where a central macrocell is underlaid with several femtocells [5]. This network model is also called the cognitive femtocell network (CFN) [6], [7]. In this paper, we focus on the resource allocation in underlay CFN where the channel usages are based on the underlay cognitive transmission access paradigm [7], [8].

In the CFN deployment, interference is a major challenge caused by overlapping area among cells in a network area and co-channel operations. The interference can be classified as: intra-tier (interference caused by macro-to-macro and femto-to-femto) or inter-tier (interference caused by macro-to-femto and femto-to-macro) [9]. In order to mitigate interference, some works have studied the downlink direction [10]. However, the CFN uplink using the underlay paradigm is also an important challenge that needs to be considered [3], [4]. In the uplink direction, the uplink capacity and interference avoidance for two-tier femtocell network were developed by Chandrasekhar *et al.* [6]. In [11], an interference mitigation was proposed by relaying data for macro users via femto users, based on the coalitional game approach and leasing channel. The power control under QoS and interference constraints in femtocell networks was studied in [12]. However, most of the above mentioned works only focus on single-channel operation and do not mention the channel allocation to the femto users. In [13], the uplink interference is considered in OFDMA-based femtocell networks with partial co-channel deployment without the femtocell users power control. Additionally, channel allocations are based on an auction algorithm for macrocell users and femtocell users. Clearly, the channel allocation in [13] is not efficient where users can reuse the channels by power control.

In this paper, we study a distributed resource allocation for the CFN uplink in two-tier networks to overcome the drawbacks of the existing. The main contributions of this paper are summarized as follows:

- We investigate an efficient resource allocation for the underlay CFN uplink that is addressed via a NP-hard optimization problem.

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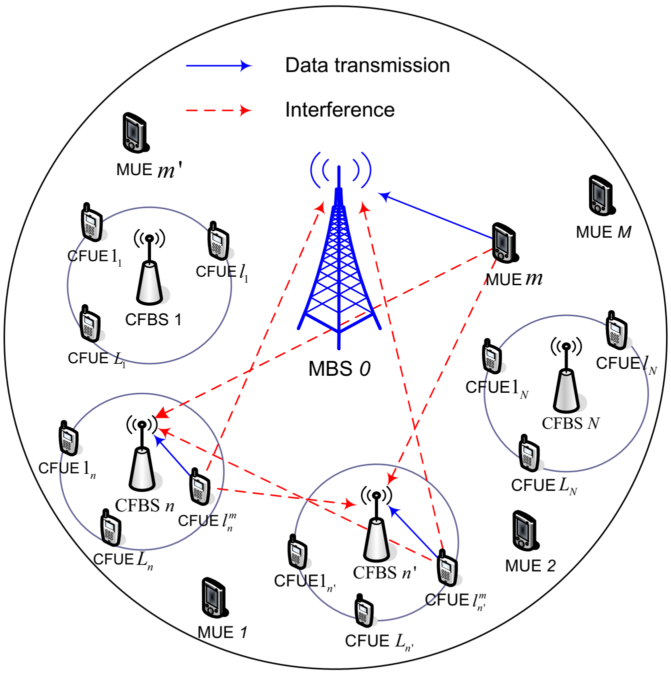

Fig. 1: System architecture of a cognitive femtocell network.

- We formulate the optimization problem as a coalition game in a partition form.
- We propose algorithms to allocate resources in a distributed way, in which the CFN implementation is self-organized and self-optimized.

The rest of the paper is organized as follows. In section II, we explain the system model and problem formulation. In section III, we address the solutions to solve this optimization problem based on a coalitional game in the partition form approach. Section IV provides simulation results. Finally, conclusions are drawn in section V.

II. System Model and Problem Formulation

Firstly, we provide the system model followed by the problem formulation of primary network protection. Then, we consider the data transmission model in the uplink of CFUEs. Next, we present CFUE's QoS demand. Finally, we formulate the resource allocation as an NP-hard optimization problem.

A. System model

We consider an uplink CFN based on the underlay spectrum access paradigm, in which N CFBSs are deployed as in Fig. 1. These CFBSs are under-laid to the macrocell frequency spectrum and reuse the set of licensed subchannels of the uplink OFDMA macrocell. In the primary macrocell, there exist M subchannels which are correspondingly occupied by M macrocell user equipments (MUEs) in the uplink direction. Let $\mathcal{N} = \{1, ..., N\}$ and $\mathcal{M} = \{1, ..., M\}$ denote a set of all CFBSs and MUEs, respectively. Every CFBS $n \in \mathcal{N}$ is associated to the same L number of CFUEs. Let $\mathcal{L}_n = \{1, ..., L\}$ denote the set of CFUEs served by a CFBS $n \in \mathcal{N}$. CFUEs and CFBSs are integrated cognitive modules that support self-organization, self-optimization and estimating channel state information (CSI) as in [7]. Moreover, CFUEs and CFBSs exchange information via dedicated reliable feedback channels or wired back-hauls.

B. Primary network protection

In the underlay CFN, the MBS of the macrocell needs to be protected against overall interference from CFUEs, as in [14], [15]. The protection on subchannel m at the MBS is addressed as follows:

$$\sum_{l \in \mathcal{L}_n, n \in \mathcal{N}} \alpha_{ln}^m h_{ln,0}^m P_{ln}^m \le \zeta_0^m, \quad \forall m \in \mathcal{M}, \tag{1}$$

where $\alpha_{ln}^m = \{0, 1\}$ is a subchannel allocation binary indicator; $h_{ln,0}^m$ denotes the channel gain between CFUE $l \in \mathcal{L}_n$ and the the primary MBS, P_{ln}^m is the power level of CFUE $l \in \mathcal{L}_n$ using subchannel m, and ζ_0^m is the interference threshold at the primary receiver MBS on subchannel m.

C. Data transmission model in uplink

In our considered model, the data transmission of CFUEs is affected by the interference from the MUE and other CFUEs in other femtocells. Each CFUE is assumed to be assigned to one subchannel for a given time. The transmission rate of CFUE $l \in \mathcal{L}_n$ on subchannel m follows the Shannon capacity as follows:

$$R_{ln}^m = B_w \log\left(1 + \frac{h_{ln}^m P_{ln}^m}{I_n^m + n_0}\right), \tag{2}$$

where B_w is the bandwidth of subchannel m, $\forall m \in \mathcal{M}$; I_n^m denotes the total interference at CFBS n on subchannel m:

$$I_n^m = \sum_{l' \in \mathcal{L}_{n'}, n' \in \mathcal{N}} h_{l'n}^m P_{l'n'}^m + h_{mn}^m P_{m0}^m, \tag{3}$$

where $n' \ne n$; h_{ln}^m, $h_{l'n}$ and h_{mn}^m are the channel gains between CFUE l and CFBS n, CFUE $l' \in \mathcal{L}_{n'}$ and CFBS n, and MUE m and CFBS n, respectively; n_0 is the noise variance of the symmetric additive white Gaussian noise; $h_{mn}^m P_{m0}^m$ is the inter-tier interference at CFBS n from MUE m; and $\sum_{l' \in \mathcal{L}_{n'}, n' \in \mathcal{N}} h_{l'n}^m P_{l'n'}^m$ is total intra-tier interference from CFUEs at the other CFBSs that use the same subchannel m.

D. CFUE's QoS demand

Assuming that, at the beginning of each time slot, the minimum data rate requirement for each CFUE $l \in \mathcal{L}_n$ for running high quality of services is given by R_{ln}^{th}, the condition

$$R_{ln}^m \ge R_{ln}^{\text{min}} \tag{4}$$

has to be guaranteed.

From (2) and (4), we have the constraint of total interference to guarantee the minimum data rate requirement of each CFUE as follows:

$$I_n^m + n_0 \le h_{ln}^m P_{ln}^m \chi_{ln}, \tag{5}$$

where $\chi_{ln} = (2^{\frac{R_{ln}^{\text{min}}}{B_w}} - 1)$.

In order to illustrate the subchannel and power allocation efficiently and optimally, we address an optimization problem in the next subsection.

E. Problem formulation

The objective is to maximize the uplink sum-rate of the whole CFN. The constraints include minimization of the intra-tier and inter-tier interference levels with similarly minimal rate requirements for connected CFUEs. Specifically, the total interference at the MBS is also kept under acceptable levels. Moreover, the subchannels are efficiently reused among CFUEs. From the discussion of our considered problems in section II, the optimization problem is formulated as follows:

$$\text{OPT1:} \quad \max_{(\alpha_{ln}^m, P_{ln}^m)} \quad \sum_{m\in\mathcal{M}} \sum_{n\in\mathcal{N}} \sum_{l\in\mathcal{L}_n} \alpha_{ln}^m R_{ln}^m \tag{6}$$

$$\text{s.t.} \quad (1), (5),$$

$$0 \le \sum_{m\in\mathcal{M}} \alpha_{ln}^m \le 1, \quad n\in\mathcal{N},\ l\in\mathcal{L}_n, \tag{7}$$

$$\alpha_{ln}^m = \{0,1\}, \quad m\in\mathcal{M}, n\in\mathcal{N}, l\in\mathcal{L}_n, \tag{8}$$

$$P_{ln}^{m,\min} \le P_{ln}^m \le P_{ln}^{m,\max}, \quad \forall m,n,l. \tag{9}$$

The purpose of OPT1 is to allocate the optimal subchannels and power levels for CFUEs in order to maximize the CFN uplink sum-rate. The constraint (1) are addressed in section II. Moreover, some conditions of subchannel allocation indicator α_{ln}^m are represented in (5) and (7). Constraint (8) shows that each CFUE $l \in \mathcal{L}_n$ is only assigned one subchannel at a given time. Constraint (9) represents the power range of each CFUE $l \in \mathcal{L}_n$, which has to be within the threshold range.

Clearly, OPT1 is a mixed integer linear program, which is NP-hard in general [16]. In order to solve OPT1, we propose a distributed solution that is based on the the coalitional game approach. CFUE cooperates with other CFUEs to choose subchannel and power levels in order to form stable coalitions using 1 (described in section III.C).

III. Resource allocation based on coalitional game in partition form.

Herein, the problem OPT1 is solved based on coalition game approach where CFUEs are players as follows. Firstly, the OPT1 is formulated as a coalitional game in partition form in which CFUEs are players. Secondly, we present the recursive core method to solve the proposed game. Thirdly, we address an implementation of the recursive core method to determine the optimal subchannel and power allocation in a distributed way. Finally, we consider the convergence and existence of the Nash-stable coalitions in the game.

A. Formulation OPT1 as a coalitional game in partition form

The coalitional game is a kind of cooperative game that is denoted by $(\mathcal{L}, U)$, in which individual payoffs of a set of players $\mathcal{L} = \cup_{n\in\mathcal{N}}\mathcal{L}_n$ are mapped in a payoff vector U. The players have incentives to cooperate with other players, in which they seek coalitions to achieve the overall benefit or worth of the coalitions. The coalitional game in partition form is one such game expression, which is studied and applied in [17], [18]. The worth of coalitions depend on how the players outside of the coalition are organized and on how the coalitions are formed. In the coalitional game, the cooperation of players to form coalitions is represented as the *non transferable utility* (NTU) game which is defined as follows [17]:

Definition 1: A coalitional game in partition form with NTU is defined by the pair $(\mathcal{L}, U)$. Here, U is a mapping function such that every coalition $\mathcal{S}_m \subset \mathcal{L}$, $U(\mathcal{S}_m, \phi_\mathcal{L})$ is a closed convex subset of $\Re^{|\mathcal{S}_m|}$, which contains the payoff vectors available to players in $\mathcal{S}_m$.
The mapping function U is defined as follows:

$$U(\mathcal{S}_m, \phi_\mathcal{L}) = \left\{ x \in \Re^{|\mathcal{S}_m|} | x_{ln}(\mathcal{S}_m, \phi_\mathcal{L}) = R_{ln}^m(\mathcal{S}_m, \phi_\mathcal{L}) \right\}, \tag{10}$$

where $x_{ln}(\mathcal{S}_m, \phi_\mathcal{L})$ is the individual payoff of player $l \in \mathcal{L}_n$, which corresponds to the benefit of a member in $\mathcal{S}_m$ in partition form $\phi_\mathcal{L}$; $R_{ln}^m(\mathcal{S}_m, \phi_\mathcal{L})$ is data rate of FUE ln in coalition $\mathcal{S}_m$ of network partition $\phi_\mathcal{L}$. The CFUE $l \in \mathcal{L}_n$ belongs to coalition $\mathcal{S}_m$ depending on the partition $\phi_\mathcal{L}$ in a feasible set $\Phi_\mathcal{L}$ of players joining coalitions. The singleton set $U(\mathcal{S}_m, \phi_\mathcal{L})$ is closed and convex [19].

In summary, the players make individual distributed decisions to join or leave a coalition to form optimal partitions that maximize their utilities and bring the overall benefit of coalitions. Based on the characteristics and principles of this game, we model the OPT1 as a coalitional game in partition form. Instead of finding the global optimal that cannot be solved directly, CFUEs will cooperate with other CFUEs to achieve sub-optimal solution of the optimization problem OPT1.

Proposition 1: The optimization problem OPT1 can be modeled as a coalitional game in partition form $(\mathcal{L}, U)$.

Proof: CFUE $l \in \mathcal{L}_n$ and its data rate R_{ln}^m in $\mathcal{L}$ are considered as player $l \in \mathcal{L}_n$ and individual payoff $x_{ln}(\mathcal{S}_m, \phi_\mathcal{L})$ in the game, respectively. A set of CFUEs is represented as $\mathcal{L}$. The data rate R_{ln}^m is mapped in a payoff vector U as in (10). In order to address formation of a certain coalition $\mathcal{S}_m$, we assume that there are only $M+1$ candidate coalitions $\mathcal{S}_m$ that CFUEs can join, $m \in \mathcal{M} \cup \{0\}$. Here, S_0 means that CFUEs in this coalition are not allocated to any subchannel. Furthermore, each joining or leaving coalition of CFUEs has to satisfy the constraints of the optimization problem OPT1. The total data rate of CFUEs using the same subchannel bring the overall benefit or worth of a coalition. In order to find a sub-optimal value in OPT1, CFUEs have incentives to cooperate with other CFUEs. The cooperation information consists of the subchannels and power levels allocated to CFUEs. Intuitively, if CFUEs do not exchange their information with other CFUEs, the system performance will be degraded due to unsatisfied constraints in OPT1. Hence, in order to improve the individual payoff value of CFUEs, incentives to cooperate among CFUEs are necessary [17], [20]. Therefore, the OPT1 can be solved based on modeling as a coalitional game in partition form. ■

Then, we apply the recursive core method that is introduced in [18] to solve this proposed game as following subsections.

B. Recursive core solution

Herein, we apply the recursive core method to solve our proposed game. In order to overcome the challenge of the

NTU game in partition form, we transform the NTU game into a transferable utility (TU) game, as discussed in [18]. In the TU game, the benefit of a coalition is captured by a real function. Because (10) is a singleton set, we define an adjunct coalitional game as $(\mathcal{L}, v)$. When $\mathcal{S}_m$ belongs to $\phi_{\mathcal{L}}$, the function value $v(\mathcal{S}_m, \phi_{\mathcal{L}}) \in v$ is determined as follows:

$$v(\mathcal{S}_m, \phi_{\mathcal{L}}) = \begin{cases} \sum_{ln \in \mathcal{S}_m} x_{ln}\left(\mathcal{S}_m, \phi_{\mathcal{L}}\right), & \text{if } |\mathcal{S}_m| \geq 1, \\ 0, & \text{otherwise.} \end{cases} \tag{11}$$

We can see that the mapping vector of the individual payoff value of CFUEs in (10) is uniquely given from (11) and the core in TU game is non-empty [18]. Thus, we are able to exploit the recursive core as a solution concept of the original game $(\mathcal{L}, U)$ by solving the game $(\mathcal{L}, v)$ while restricting the transfer of payoffs according to the unique mapping in (10). Here, the value $v(\mathcal{S}_m, \phi_{\mathcal{L}})$ is the sum-rate of CFUEs allocated to the same subchannel m in partition $\phi_{\mathcal{L}}$. Through cooperating and sharing the payoff among CFUEs in the coalition m, CFUEs achieve their optimal power allocation to maximize each coalition $\mathcal{S}_m$ to which they belongs. Then, based on the results in each coalition, the optimal subchannel allocations are determined by finding the core of the game using the recursive core definition.

Before describing the recursive core definition, we define a residual game that is an important intermediate problem. The residual game $(\mathcal{R}, v)$ is a coalitional game in partition form that is defined on a set of CFUEs $\mathcal{R} = \mathcal{L} \backslash \mathcal{S}_m$. CFUEs outside of $\mathcal{R}$ are deviators, while CFUEs inside of $\mathcal{R}$ are residuals [18]. The residual game is still in partition form and can be solved as an independent game, regardless of how it is generated [17]. The residual game of CFUEs forms a new game that is a part of the original game. CFUEs in the residual game still have the possibility to divide any coalitional game into a number of residual games which, in essence, are easier to solve. The solution of a residual game is known as the residual core, which can be found by recursively playing residuals games, which are defined as follows (mentioned in [18], definition 4):

***Definition** 2:* The recursive core $C\left(\mathcal{L}, v\right)$ of a coalitional formation game $(\mathcal{L}, v)$ is inductively defined as follows:

1) *Trivial Partition.* The core of a game with $\mathcal{L}$ is only an outcome with the trivial partition.
2) *Inductive Assumption*. Proceeding recursively, consider all CFUEs belonging to $\mathcal{L}$, and suppose the residual core $C(\mathcal{R}, v)$ for all games with at most $|\mathcal{L}|$-1 CFUEs has been defined. Now, we define $A(\mathcal{R}, v)$ as follows: $A(\mathcal{R}, v) = C(\mathcal{R}, v)$, if $C(\mathcal{R}, v) \neq \emptyset$; $A(\mathcal{R}, v) = \Omega\left(\mathcal{R}, v\right)$, otherwise. Here, let $\Omega\left(\mathcal{R}, v\right)$ denote a set of all possible outcomes of game $(\mathcal{R}, v)$.
3) *Dominance*. An outcome $(\boldsymbol{x}, \phi_{\mathcal{L}})$ is dominated via coalition S_m if at least one $(\boldsymbol{y}_{\mathcal{L}\backslash \mathcal{S}_m}, \phi_{\mathcal{L}\backslash \mathcal{S}_m}) \in A(\mathcal{L}\backslash \mathcal{S}_m, v)$ there exists an outcome $((\boldsymbol{y}_{\mathcal{S}_m}, \boldsymbol{y}_{\mathcal{L}\backslash \mathcal{S}_m}), \phi_{\mathcal{S}_m} \cup \phi_{\mathcal{L}\backslash \mathcal{S}_m}) \in \Omega(\mathcal{L}, v)$, such that $(\boldsymbol{y}_{\mathcal{S}_m}, \boldsymbol{y}_{\mathcal{L}\backslash \mathcal{S}_m}) \succ_{\mathcal{S}_m} \boldsymbol{x}$. The outcome $(\boldsymbol{x}, \phi_{\mathcal{L}})$ is dominated if it is dominated via a coalition.
4) *Core Generation*. The recursive core of a game of $|\mathcal{L}|$ is a set of undominated partitions, denoted by $C(\mathcal{L}, v)$.

Corresponding to each network partition, the individual payoffs of all CFUEs in the game are uniquely determined and undominated. Furthermore, the coalitions in the recursive core are formed to provide the highest individual payoffs or data rates of CFUEs, as detailed in Step 4.

C. Implementation of the recursive core at each coalitional game formation in partition form

We address implementation of the recursive core method to solve the proposed game. According to the transformation from a NTU game into a TU game, the coalition $\mathcal{S}_m$ in a partition $\phi_{\mathcal{L}}$ is represented by a real function $v(\mathcal{S}_m, \phi_{\mathcal{L}})$ as in (11). Corresponding to the subchannel allocation of CFUEs, some CFUEs can be allocated into the same subchannel m, which forms a coalition $\mathcal{S}_m$. Then, CFUEs optimize their individual payoffs by sharing with other CFUEs in the same coalition $\mathcal{S}_m$. In this case, CFUEs cooperate with others in coalition m to maximize the individual payoff and value $v(\mathcal{S}_m, \phi_{\mathcal{L}})$. Sharing is achieved by finding optimum power values of each CFUE in the following optimization problem:

$$\text{OPT1}_{\mathcal{S}_m, \phi_{\mathcal{L}}}: \ \max_{P_{ln}^m} \quad v(\mathcal{S}_m, \phi_{\mathcal{L}}) \tag{12}$$

s.t.

$$\sum_{ln \in \mathcal{S}_m} h_{ln,0}^m P_{ln}^m \leq \zeta_0^m, \tag{13}$$

$$Z_n^m h_{mn}^m P_{m0}^m + n_0 \leq h_{ln}^m P_{ln}^m \chi_{ln}, \ l \in \mathcal{L}_n, ln \in \mathcal{S}_m, \tag{14}$$

$$P_{ln}^{m,\min} \leq P_{ln}^m \leq P_{ln}^{m,\max}, \ ln \in \mathcal{S}_m, l \in \mathcal{L}_n. \tag{15}$$

The constraint (14) is taken from (5) in which $Z_n^m = \sum_{l' \in \mathcal{L}_{n'}, n' \in \mathcal{N}} h_{l'n}^m P_{l'n'}^m$ denote the intra-tier interference from other CFUEs to CFBS m on subchannel m. When CFUE $l \in \mathcal{L}_n$ belongs the coalition $\mathcal{S}_m$, α_{ln}^m is set to 1, otherwise is set to 0. Therefore, without loss of generality, we ignore parameter α_{ln}^m in $\text{OPT1}_{\mathcal{S}_m, \phi_{\mathcal{L}}}$. By finding the optimal power allocation to CFUEs, they will achieve an optimum individual payoff value that maximizes the worth of coalition $\mathcal{S}_m$. The optimal solution of $\text{OPT1}_{\mathcal{S}_m, \phi_{\mathcal{L}}}$ can be found in a centralized or distributed way. We find the optimal solution in a distributed way. We solve the optimization problem by modeling as a geometric convex programming problem [21].

Corresponding to the optimal transmit power levels in $\text{OPT1}_{\mathcal{S}_m, \phi_{\mathcal{L}}}$, in general, coalition $\mathcal{S}_m$ guarantees the optimal sharing payoffs among members CFUEs. Simultaneously, we also find the optimum worth $v(\mathcal{S}_m, \phi_{\mathcal{L}})$ of coalition $\mathcal{S}_m$. Based on the steps in the Definition 2, we propose Algorithm 1 to find recursive core which leads to the distributed subchannel and power allocation.

The algorithm is repeated until convergence to stable partitions $\phi_{\mathcal{L}}^{(k)*}$, which results in a set of undominated partitions in the recursive core. Whenever undominated partition $\phi_{\mathcal{L}}^{(k)*}$ is updated at time k, the network coordinator updates allocation subchannel to CFUEs (Step 9). In addition, observing value $v(\mathcal{S}_m, \phi_{\mathcal{L}})$ are done by network coordinator such as the femtocell gateway [20]. We note that, in our algorithm, subchannel and power allocation of CFUEs are updated whenever network partition is transfered from partition $(k-1)$ to partition (k),

Algorithm 1 Distributed algorithm for subchannel and power allocation in cogntive femtocell network.

* **Initialization:**

$\phi_{\mathcal{L}}^{(0)} = \{\{1\},\{2\}...,\{|\mathcal{L}|\}\}$ in which CFUEs are randomly allocated subchannel and transmit power with non-cooperative among FUEs.

* **Coalition formation**:

CFUEs operate in cooperative mode and join into potential coalitions $\phi_{\mathcal{L}} = \{\{0\},\{1\}...,\{|\mathcal{M}|\}\}$.

for player $\{nl\} \in \mathcal{L}$ **do**

  for $\mathcal{S}_m \in \{\phi_{\mathcal{L}}^{(k-1)*} \backslash \{nl\}\}$ **do**

    Set $\phi_{\mathcal{L}}^{(k)} := \{\phi_{\mathcal{L}}^{(k-1)*} \backslash \mathcal{S}_m, \mathcal{S}'_{m,g} = \mathcal{S}_m \cup \{nl\}\}$.

    Calculate $v(\mathcal{S}'_{m,g}, \phi_{\mathcal{L}}^{(k+1)})$.

    if $\sum\limits_{m\in\mathcal{M}\cup\{0\}} v(\mathcal{S}'_{m,g}, \phi'_{\mathcal{L}}) > \sum\limits_{m\in\mathcal{M}\cup\{0\}} v(\mathcal{S}_m, \phi_{\mathcal{L}})$, **then**:

      Set $\phi_{\mathcal{L}}^{(k)*} = \phi_{\mathcal{L}}^{(k)}$.

      Update α_{ln}^{m*}, P_{ln}^{m*}.

    end if

  end for

end for

* **Output:** Output the stable core of game $(\mathcal{L}, v)$ consisting of both the final partition $\phi_{\mathcal{L}}^{*}$, subchannel allocation decision α_{ln}^{m*}, and transmit power level P_{ln}^{m*}.

which produces Pareto dominates $\mathcal{S}_m^{(k)}$. The convergence and Nash-stable coalition in Algorithm 1 are discussed in the next subsection.

D. Convergence and stability analysis of the proposed game

The convergence of the proposed game through four steps of the recursive core method is guaranteed as follows:

Propriety 1: Starting from any initial partition $\phi_{\mathcal{L}}$, using the Algorithm 1, coalitions of CFUEs merge together by Pareto dominance, which results in network partition stable and lies in the non-empty recursive core $C(\mathcal{L}, v)$.

Proof: Every transfer operation from partition $(k-1)$ to partition (k) is an inductive step, which produces Pareto dominates $\mathcal{S}_m^{(k)}$ as follows:

$$\sum_{\mathcal{S}_m^{(k)} \in \phi_{\mathcal{L}}^{(k)}} v(\mathcal{S}_m^{(k)}, \phi_{\mathcal{L}}^{(k)}) > \sum_{\mathcal{S}_m^{(k-1)} \in \phi_{\mathcal{L}}^{(k-1)}} v(\mathcal{S}_m^{(k-1)}, \phi_{\mathcal{L}}^{(k-1)}). \tag{16}$$

We note that, each CFUEs gradually selects the coalitions based on conditions (7) and (8). Hence, the value of coalition will set to zero if conditions of the formed coalition is violated, and the value of other coalitions remains unchanged. Therefore, given any two successive algorithm steps $k-1$ and k, we have $v(\phi_{\mathcal{L}}^{(k)}) = \sum_{\mathcal{S}_m^{(k)} \in \phi_{\mathcal{L}}^{(k)}} v(\mathcal{S}_m^{(k)}, \phi_{\mathcal{L}}^{(k)})$ is Pareto dominated by $\phi_{\mathcal{L}}^{(k)}$.

Therefore, the Algorithm 1 ensures that the overall network utility sequentially increases by Pareto dominance. In addition, the sum of values of the coalitions in each group g increases without decreasing the payoffs of the individual CFUEs and the whole network as well. The number of partitions of $\mathcal{L}$ CFUEs into $M+1$ coalitions is a finite set given by the Bell number [18], the number of transmission steps is finite. Hence, the sequence of step transmissions will terminate after a finite number of inductive steps and will converge to a final partition. ■

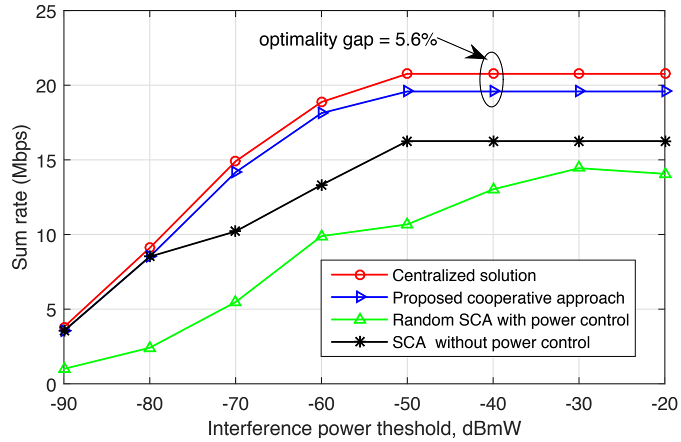

Fig. 2: Average throughput in uplink CFN versus interference threshold at MBS when N = 4 FBSs, K = 3 subchannels.

Obviously, the recursive core method applied to our proposed game always converges to a final network partition. Moreover, the network partition based on residual game always converges to a Nash-stable partition.

IV. Simulation Results

We simulate an MBS and a group of 4 CFBSs with the coverage radii of 500 m and 30 m, respectively. In order to allocate subchannels to the femtocells, we utilize three SC-FDMA licensed subchannels, which are allocated to uplink transmission of three MUEs, each with bandwidth B_w = 360 kHz (by using two sub-carriers for each licensed subchannel) and a fixed power level of 500 mW. Moreover, the interference threshold at the MBS for each licensed subchannel equals to -70 dbmW. Each CFBS has two CFUEs, a pilots signal with power equals to 500 mW. Each CFUE has a minimum data rate equals to 2 Mb/s. In addition, each CFUE has a maximum power level constraint (P^{max}) of 100 mW.

We estimate the sum rate of CFUEs versus the interference threshold at the MBS. As shown in Fig.2, the average throughput in our proposed approach increases with the interference threshold value of each subchannel at MBS increase. However, this value is saturated as the interference threshold value becomes sufficiently large (-50 dBm). Moreover, we compare the average throughput under two other methods, i.e., SCA without power control and Random SCA with power control. The “SCA without power control” approach performance is based on the algorithm 1 given fixed transmit power levels. For the “Random SCA with power control” approach, CFUEs are randomly allocated subchannels. Fig.2 shows that for any interference threshold at the MBS, the sum rate of the proposed approach is always higher than those of the (Random SCA with power control) and (SCA without power control) schemes. Further, in Fig.2, we have compared the proposed approach to

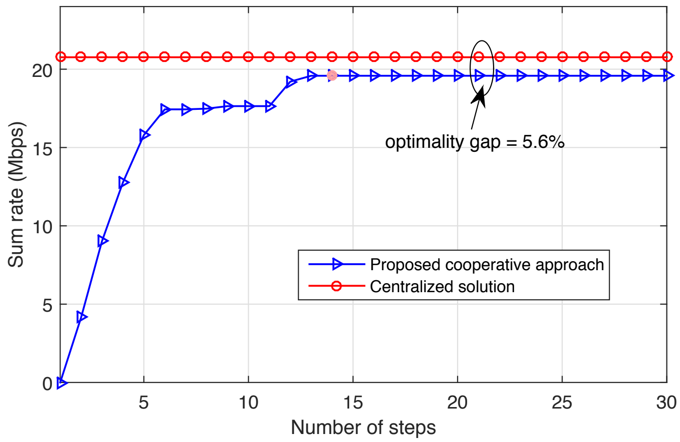

Fig. 3: The optimality game between the proposed approach and centralized solution .

an optimal solution, in which CFUEs are allocated subchannel and transmit power in a centralized fashion. The comparison shows that the proposed approach is close to centralized solution. In Figure 2 and Figure 3, we show the optimality gap between the optimal centralized approach and proposed cooperative approach, with a gap of 5.6% for a network with value -50dBmW of interference threshold at MBS. Moreover, in Figure 3, our algorithms converge after around 14 time steps.

V. Conclusions

In this paper, we investigated an efficient distributed resource allocation scheme for uplink underlay CFN. The efficient resource allocation is characterized via an optimization problem. We identified the optimal subchannels and power levels for CFUEs to maximize the sum-rate. The optimization problem guaranteed the inter-tier and inter-tier interference thresholds. Specifically, the aggregated interference from femtocell users to the MBS and the minimum rate requirement of the connected CFUE are kept under the acceptable level. In order to solve the optimization problem, we suggested a formulation optimization problem as a coalitional game in partition form. The convergence of algorithms was also carefully investigated. The efficient resource allocation has tested via simulation results, with the sum-rate of the proposed framework has closed to optimal solution and better than those of the other frameworks.

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