Coalitional Game Theoretic Approach for Cooperation in Heterogeneous Cognitive Wireless Networks

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ABSTRACT

Heterogeneous cognitive wireless networks (HeCoNets)) are consisted of macrocells that are overlaid by small cells (e.g, femtocells, picocells). These small cells operate over the cognitive radio paradigm. In this paper, we consider a cooperative model in the uplink of HetCoNets, that includes picocell and famtocells networks that are using unlicensed channels from the macrocesll network. In our cooperative model, cognitive picocell users' equipments (CPUEs) and cognitive femtocell users (CFUEs) get incentives from cooperating with each other to improve the unlicensed channels usage and mitigate inter-tier and intra-tier interference while maximizing sum-rate of users in the HetCoNet. We apply a coalition game approach in which CPUEs and CFUEs are considered as players of the game. We have intensively simulated the proposed idea in matlab. Our simulation results show the effectiveness of our proposed compared with non-cooperative model.

Keywords

Heterogeneous Cognitive Wireless Network; Femtocell Network; Coaltional Game; Cognitive Radio Network.

1. INTRODUCTION

The HeCoNet is a wireless network that is consisted of heterogeneous cell networks, in which channel usages are based on cognitive radio paradigm [2, 7]. In HeCoNet there may be coexistence of two type of networks: primary network and secondary network. Secondary network utilizes the licensed channels of the primary network in such a way that it doesn't disturb the primary network's communication . Additionally, the channel access of the *secondary user equipments* (SUs) in secondary networks have lower priority than *primary user equipments* (PUs) in accessing the channel [2,5,7,8]. On the basis of channel usage, the CR network can be divided into overlay, underlay and mixed network [8]. According to underlay access strategy, the SU always has access to the channel subjected to the interference threshold constraint [13]. The interference threshold or interference temperature constraint indicates the tolerable interference level at the primary receiver [10]. Details about channels access strategies are discussed in [8, 13].

According to aforementioned problem, our considered HetCoNets is composed of heterogeneous cognitive cellulars network and and primary network. The primary network contains the licensed *Orthogonal Frequency Division Multiple* (OFDM) channels that leasing from spectrum hole [2]. The cognitive heterogeneous cells network comprises a two-tier network with coexistence of a cognitive picocell and cognitive femtocell network.

In order to improve the licensed channel utilization, sharing the channels among cognitive femtocell and cognitive picocell are deployed as in [1, 4]. Sharing the licensed channel poses some challenges: 1) How to overcome the interference problem in a two-tiers secondary network i.e. intra-tier, inter-tier interference? 2) How to mitigate the licensed channels usage by avoiding harmful interference to the primary macrocell as in [1, 4, 5, 7]? Furthermore, deployment of cognitive femtocell network has to overcome some challenges: covering the dead zone, sharing traffic-load between a heavy-load cell and a lightly loaded cell, providing high quality of data connection to mobile users which lie outside or at border of the coverage area of the femtocells or macrocell base stations [1, 4–7]. We have given more attention to these challenges in our proposed communication framework.

In order to overcome the above challenges, [1] has proposed a model in which secondary user play the role of a relay. However, the authors have only focused on how to avoid interference in traditional femtocell network by using coalitional game approach. Characteristics like, self-organizing, self-optimizing, distributed manner are emergence of coop-

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IMCOM (ICUIMC) 2016. January 4-6, Danang, Vietnam.

DOI: 10.1145/1235

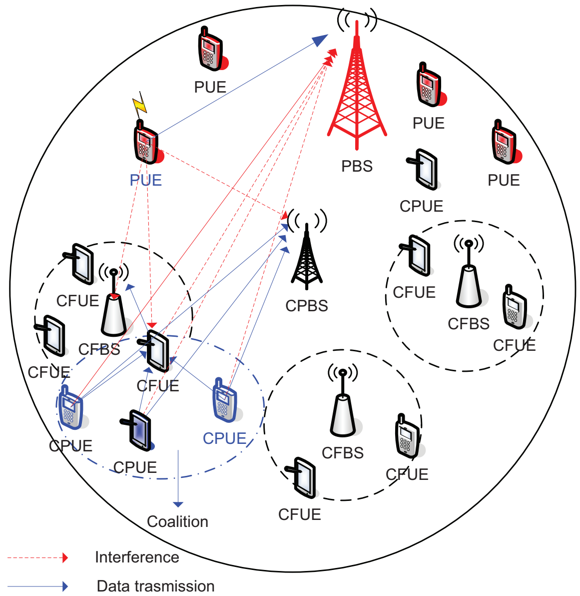

Figure 1: The system model

eration are becoming very critical in future wireless network. The coalitional game has become imperative to seek suitable game theoretical tools that allows to analyze and study the behaviors and interactions of the mobile users in the future wireless mobile network [11, 12]. In our framework, we study these limited points in the HeCoNet by using coalitional game approach. We have solved the problems in a distributed way along with self-organization and self-optimization in HeCoNet. The coalitional game in partition form composed of *cognitive femtocell user equipments* (CFUEs) and *cognitive picocell user equipments* (CPUE) as players in the game. Players in the game form cooperative model in which the CPUEs have an incentive to join coalition to maximize the worth of the coalitions and its own utility as well. Briefly, in our work we focus on:

1. Improve the capacity of the CPUE connection in cognitive picocell network.
2. Improve the channels utilization of secondary network in the HeCoNet.
3. Propose a distributed algorithm for coopering among secondary users in secondary system.

The remaining of this paper is organized as follows: Section II provides the system architecture. Next, our problem is formulated as a coalitional game in section III. The solution and algorithms are presented in section IV. The simulation results are illustrated in section V. Finally, the paper is concluded in section V.

2. SYSTEM MODEL AND COOPERATIVE ARCHITECTURE

We consider an uplink OFDMA HeCoNet as shown in Fig. 1. The HeCoNet is composed of a cognitive picocell base station and a set $M = \{1, 2, ..., \}$ cognitive femtocell base stations that utilizes a set of $\mathcal{L} = \{1, 2, ..., L\}$ OFDMA licensed channels. These channels belongs to L

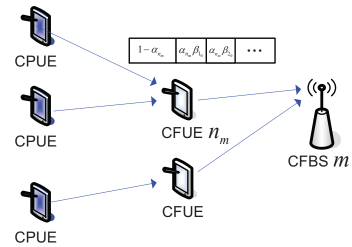

Figure 2: The transmission time of CFUEs

primary user equipments (PUEs) in the uplink primary network. In the HeCoNet, each CFBS is composed of a set of $\mathcal{N}_m = \{1, ..., N_m\}$ cognitive femtocell users (CFUEs), and the CPBS has a set $\mathcal{N}_0$ cognitive pico users (CPUEs). These cognitive femtocells are situated at different locations that guarantees avoiding interference among themselves. The HeCoNets are synchronized following time-slotting via wire-backhaul network. In the data transmission model, CPUEs can have direct transmission to the CPBS, or handover the data to femtocells. The CPUE can directly transmit the data to the CPBS or it can use another CPUE as a relay for transmitting the data to the CPBS. This phenomenon can be observed in the Fig. 1 In next subsections we discuss about two data transmission modes: cooperative and non-cooperative model.

Data transmission in non-cooperative model: In this model, each CPUE transmits data to the CPBS or direct handover to the cognitive femtocell network via CFBS. The n_0-th CPUE uses l-th channel for its data transmission offering a link wireless capacity as follows:

$$R_{n_0}^{l(NC)} = B_l \log\left(1 + \frac{|h_{n_0,0}|^2 P_{n_0}^l}{|h_{l,0}|^2 P_l + \sigma^2}\right) \qquad (1)$$

where $n_0 \in \mathcal{N}_0$, B_l is the bandwidth of channel l, $|h_{n_0,0}|^2$ is the channel gain between the CPUE n_0 and CFBS, $P_{n_0}^l$ is the transmission power of the CPUE n_0 on channel l, $|h_{l,0}|^2 P_l$ is the interference power from PMUE l using l-th channel, σ^2 is the Gaussian noise.

Data transmission using relay-aided cooperative model: In the uplink data transmission, CPUEs faraway from CPBS or have low channel gain need to increase their transmission power to increase SINR at the receiver. Unfortunately, these actions increase harmful interference to PBS. In order to protect primary transmission in PBS and still guaranteeing SINR threshold demand of CPUEs, CPUEs need to shift its transmission to CFBSs which get SINR higher than direct transmit to the PBS. Fortunately, we can achieve this data transmission with the cooperative CPUEs model by forming Relay-aided cooperative model to shift data of CPUEs to CFBS.

The cooperative model of CPUE n_0 shifts to CFBS m using relay-aided cooperative modeling is described in Fig. 2. In Fig. 2, α_{n_m} represents the time faction of the CFUE n_m's data transmission, $(1 - \alpha_{n_m})$ is the time fraction for relaying data of the CPUEs joined to coalition contain CFUE n_m, $\beta_{n_0}(1 - \alpha_{n_m})$ is the fraction of time of CPUE n_0 when relaying data via CFUE n_m. In cooperative approach, the CFUE will be considered as a relay for CPUE. By using amplify and forward approach [12] and interference model as shown in Fig 1, the data rate of the CPUE n_0 belonging to coalition k_n is calculated as follows:

$$R^{l(C)}_{m,k_n} = (1-\alpha_{n_m})\beta_{n_0} B_l \log\left(1 + SINR^{l(C)}_{n_0,m}\right), \quad (2)$$

where, the Signal to Interference plus Noise Ratio (SINR) when the CPUE m using CFUE k_n as a relay user is computed according to equation (2). In equation (2), $|h_{m,n}|^2$, $|h_{m,k_n}|^2$, $|h_{k_n,n}|^2$ and $|h_{l,n}|^2$ are channel gains between CPUE m and CFUE n_k, CPUE m and CFUE k_n, CFUE k_n and CFBS n and PMUE l and CFBS n, respectively; P_m, P_{k_n} and P_l are transmission power of CPUE m, CFUE k_n and PMUE l, respectively; $\sum\limits_{m'} P^l_{m'}|h_{m',k_n}|^2$ is the total interference of CPUEs using the same channel of other femtocells.

Consequently, in the underlay CR paradigm, in order to protect primary system, the transmission of CPUEs and CFUEs have to satisfy:

$$\begin{cases} P^l_m = [0, P^{l(\max)}_m]; P_{k_n} = [0, P^{l(\max)}_{k_n}];\ \text{Idle channel} \\ P^l_m = [0, \frac{\gamma_{\text{PMBS}}}{|h_{m,\text{PMBS}}|^2}]; P_{k_n} = [0, \frac{\gamma_{\text{PMBS}}}{|h_{k_n,\text{PMBS}}|^2}];\ \text{Busy channel} \end{cases} \quad (4)$$

The problem is how CPUEs and CFUEs form stable coalitions to maximize the total throughput of coalition S is discussed in section III.

3. COALITIONAL GAME FORMULATION AND ANALYSIS

In this section we present the formulation of cooperation among CFUEs and CPUEs as a coalitional game in partition form. After that we discuss th solution of coalitional game in partition form problem.

3.1 The cooperation among CPUEs and CFUEs as a coalitional game

Coalitional game is the game that contains a set of players $\mathcal{N} = \mathcal{M} \cup \{\cup \mathcal{N}_k\}$, who seeks to form cooperative groups, i.e., the players can form coalitions and make a collective decision. Any coalition $S_{k_n} \in \mathcal{N}$ represents an agreement between the players in S_{k_n} to act as a single entity. In our problem, coalition S_{k_n} is formed by a CFUE and $(S_{k_n} - 1)$ CPUEs which get incentive by joining the S_{k_n} in the form of improving licensed channel utilization, reduce transmission power as well as avoiding interference among tier in the HeCoNet meanwhile guaranteeing data rate requirements of the CPUEs and CFUEs. With respect to the formulation of the coalitions, due to cochannel interference, the rate achieved by the members of any coalition of S_{k_n} that forms in the network is affected by the cooperative behavior of coalitions outside S_{k_n},i.e coalition $\mathcal{N}\backslash S_{k_n}$. Hence, the performance of a coalition depends on the partition of the network $\pi_{\mathcal{N}}$. Therefore, one suitable framework for modeling the femtocell cooperation problem is that of a coalition game in partition form with nontransferable utility (NTU) [11] which is defined as follows:

Definition 1: A coalition game in partition form with NTU is defined by a pair $(\mathcal{N}, v)$ with v is a value function that assigns for every partition form $\pi_{\mathcal{N}}$ and coalition $S_{k_n} \in \pi_{\mathcal{N}}$, and a real number that represents the total utility that each player in S_{k_n} can achieve.

In cooperation among CPUEs and CFUEs, each players can increase its own individual rate until the total benefit of $v(S_{k_n}, \pi_{\mathcal{N}})$ is maximal, which is defined as follows:

$$v(S_{k_n}, \pi_{\mathcal{N}}) = \sum_{m=1}^{S_{k_n}-1} (1-\alpha_{k_n})\beta_{m,k_n} R^l_{m,k_n} + \alpha_{k_n} R^l_{k_n} \quad (5)$$

in which, the individual payoff is determined by:

$$U(S_{k_n}, \pi_{\mathcal{N}}) = \left\{x \in \mathcal{R}^{|S_{k_n}|} | x_i(S_{k_n}, \pi_{\mathcal{N}}) = \tilde{R}^l_i\right\} \quad (6)$$

where, $\tilde{R}^l_i$ is individual payoff of each player i in coalition S_{k_n}, U is a mapping payoff value for all players. $i = 1$, correspond to $\tilde{R}^l_1 = \alpha_{k_n} R^l_{k_n}$, $i \neq 1$ correspond to $\tilde{R}^l_i = (1-\alpha_{k_n})\beta_{m,k_n} R^l_{m,k_n}$, U is a mapping such that for every coalition S_{k_n}, $U(S_{k_n}, \pi_{\mathcal{N}})$ is a closed convex subset of $\mathcal{R}^{|S_{k_n}|}$, that contains the payoff vectors of players in coalition S_{k_n}.

In order to solve this problem, we use the concept of a recursive core introduced in [9]. The recursive core is one of the key solution concepts for coalition game that have dependence on external, in partition form. The payoff value of each player in (5) has an unique individual payoffs as mapped in (6). net We can exploit the recursive core as a solution when restricted in the transformation of payoffs according to the unique mapping of (6).

3.2 Recursive Core as a Solution for the CFUEs and CPUEs Cooperation Game

In this section we find an optimal network partition which is a challenging task and is very interesting in game theory [9].

3.2.1 Recursive Core Discussion

In our work, recursive core is suitable outcome of a coalition formation process that the processing takes into account external across coalitions, which are represented by effects of mutual interference among coalitions. The recursive core solution can be found by recursively playing residual games $\mathcal{R}$ which is computed as follow expressions [9]:

DEFINITION 3.1. *The recursive core $C(\mathcal{N}, v)$ of a coalitional game is inductively defined in four steps:*
1. Trivial partition is the recursive core which is composed of individual players i: $C(\{i\}, v) = (i, v(i))$.
2. Inductive assumption. We assume that the residual $C(\mathcal{R}, v)$ is defined by at most $N-1$ players. And $A(\mathcal{R}, v) = C(\mathcal{N}, v)$, if $C(\mathcal{N}, v) \neq \emptyset$; $A(\mathcal{R}, v) = \Omega(\mathcal{R}, v)$, otherwise. Here, $\Omega(\mathcal{R}, v)$ is one of the possible partitions of $\mathcal{R}$. Specifically, the residual game $(\mathcal{R}, v)$ is partitioned via the residual core $C(\mathcal{R}, v)$.
3. Dominance. An outcome $(\boldsymbol{x}, \pi_{\mathcal{N}})$ is dominated via a coalition S_{k_n} if the resulting partition $\pi_{S_{k_n}} \cup \pi_{\mathcal{N}\backslash S_{k_n}}$, $\pi_{S_{k_n}} \in A(S_{k_n}, v)$ leads to a higher payoff: $(\boldsymbol{y}_{S_{k_n}}, \boldsymbol{y}_{\mathcal{N}/S_{k_n}}) >_{S_{k_n}} \boldsymbol{x}$. In this step, the coalitions in the residual cores $C(\mathcal{R}, v)$ which guarantee the highest payoff, become part of the recursive core of the larger game on $\mathcal{N}$, $C(\mathcal{N}, v)$.
4. Core generation. The recursive core $C(\mathcal{N}, v)$ of the game with $\mathcal{N}$ CFUEs and CPUEs is the set of undominated outcomes. Equivalently, the recursive core of the entire game is consisted of the optimal coalitions emerged from the residual cores $C(\mathcal{R}, v)$, each one representing solution of the generic reduced game $\mathcal{R} \subset \mathcal{N}$

$$SINR_{m(k_n)}^{l(C)} = \frac{P_m^l |h_{m,n}|^2}{\sum_{m'} P_{m'}^l |h_{m',n}|^2 + |h_{l,n}|^2 P_l + n_0} + \frac{P_m^l P_{k_n}^l |h_{m,k_n}|^2 |h_{k_n,n}|^2}{n_0 \left(\sum_{m'} P_{m'}^l |h_{m',k_n}|^2 + P_{m'}^l |h_{m',n}|^2 + P_m^l |h_{m,k_n}|^2 + P_{k_n}^l |h_{k_n,n}|^2 + |h_{l,n}|^2 P_l + n_0 \right)}, \tag{3}$$

Here, the residual game $\mathcal{N}\backslash S_{k_n}$ is a coalitional game in partition form defined on a set of players $\mathcal{R} = \mathcal{N}\backslash S_{k_n}$. Players in S_{k_n} are called deviators, while players in $\mathcal{R}$ are called residuals. The residual core is consisted of a set of residual games that are smaller than the original one and the complexity is lower than the original game. Particularly, the recursive core is formed with a set of partitions that allows the players to organize themselve in stable coalitions and get highest payoff. Moreover, the deviation in residual core has to guarantee balance i.e., the CPUEs will not break away from the current partition . Furthermore, similar to many game theoretic concepts such as the core or Nash Equilibrium (NE), the existence of a recursive core for a coalitional game is a key issue.

Proposition: Given a set of players $\mathcal{N}$ of game $(\mathcal{N}, v)$, existence of a recursive core of the game or at least one residual core to be nonempty.

PROOF. 1) The residual core is non-empty because at least a subset of the players in the network must have defined a preference on how to organize and partition the network. 2) An empty residual core corresponds to residual game that does not identify any preferred network partition of players. Correspondingly, in our work the cooperative scenario can equivalently choose to cooperate or not. 3) The recursive core is evaluated through a sequence of residual games over subset of players. When residual core is empty, it is still possible to solve a larger game which contains all the players. □

Based on the definition of recursive core, we present an algorithm in next section to further explain optimal solution of our problem.

3.2.2 Implementation of the Recursive Core

When a coalition S_{k_n} is formed, the CFUE k_n has to optimize its own payoff by deciding segment of time α_{k_n} for accessing channel to satisfy its power constraint and data rate requirement. This performance must be taken into account before joining a cooperation. After that through a sequence of residual games over a subset of CPUEs consider the CFUE k_n as a relay, the recursive core is evaluated with constraints of transmission power to avoid harmful interference to primary system and the fraction of time $(1-\alpha_{k_n})\beta_{m,n_k}$. The spectrum leasing and transmission power can be *tuned to achieve highest payoff or maximizing the payoff of each member in the coalition*. Therefore, after the coalition formation, given α_{k_n}, the CFUE jointly optimizes the transmission power and the parameter β_{m,k_n},

Algorithm 1 The coalition formation in uplink HeCoNet

Initial State: The network is partitioned by $\pi_{\mathcal{N}}$ under trivial partition. The CFUEs, CPUEs, CFBSs, CPBSs collect primary network information.

repeat

Phase I: *Interference Discovery (through RSSI)*

a) Each CFUE detects nearby CPUEs, active on the same sub-channel, and vice versa.

b) For each of the occupied sub-channel, each CFUE sorts the interfering CPUEs from the stronger to the weaker interference level from primary network and power transmission range from (4).

c) Each CPUEs m in $\mathcal{M}$ sorts the sensed CFUEs from the supposedly closer to the farther.

Phase II: *Coalition formation*

for all mutually interfering CPUEs and CFUEs in $\mathcal{N}$ **do**

a) Each CPUE and CFUE consequently engages in pairwise negotiations with the strongest discovered interfer, to identify potential coalition partners.

b) Each CPUE and CFUE in $\mathcal{N}$ estimates the achieved rate and computes its utility as in (6).

c) CFUEs and CPUEs engage in a coalition formation that ensures the maximum payoff.

end for

until Converging to a stable partition in the recursive core.

Phase III: *Spectrum leasing and cooperative transmission.*

a) With each coalition, the CPUEs notify the serving CPBS, and connect to the serving CFUE through AF operation.

b) Each CFUEs $k_n \in S_{k_n}$ by optimizing its payoff based on (7)

by solving the following problem:

$$\text{Max} \qquad x_i(S_{k_n}, \pi_{\mathcal{N}}) \tag{7}$$

Subject to:

$$0 \le \beta_{k_n} \le 1 \tag{8}$$

$$(1), (2), (3), (4).$$

In performance, the CFUE gets feedback from the CPUEs m outside the coalition with the estimation of the aggregated interference, which can be either measured by its own belonging CFBS, or estimated by considering the CPUEs in the proximity. The problem in (7) can be solved using some optimization techniques such as those in [3]. In a nutshell, the players in game play a game that use Algorithm 1 to reach a partition in the recursive core as in [12].

4. SIMULATION RESULTS

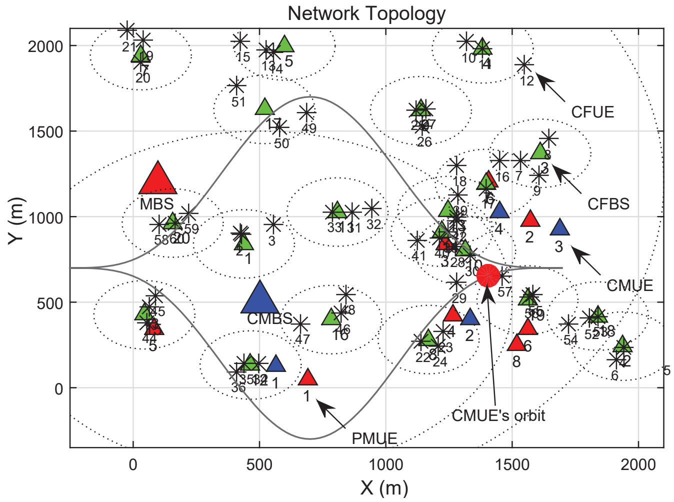

Figure 3: Simulation model

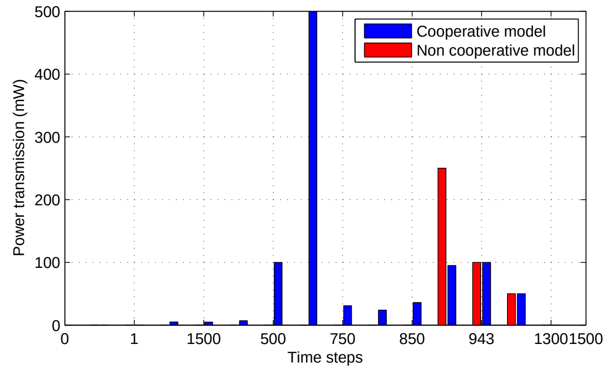

Figure 4: The power allocation in the cooperative model and the non-cooperative model

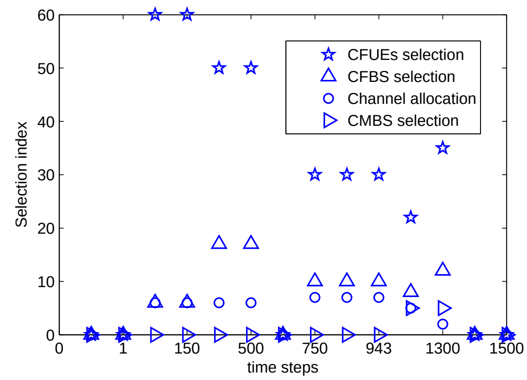

Figure 5: The CFUE and channel selection of the CPUE

For the analysis we consider a heterogeneous cognitive radio network with a total of 8 licensed channels ($L = 8$ PMUEs), the number of CFBSs equals to 20, each CFBS has 3 CFUEs. In order to see formation coalition, we assume a mobile CPUE is moving in a radius of its CPBS. The cognitive radius equal 20m and $B = 128$ kHz. The noise power is $n_0 = 10^-10$ at the receiver, and transmission power of PMUE is 1W. The power level of CPUEs and CFUE always changes in each time period to avoid interference to CPBS. The maximum value of transmission powers of CPUE and CFUE are $P_l^{\max} = 0.5$ W, $P_k^{\max} = 0.01$W, respectively. The SINR threshold for PMBS is set to 5 dBm, SINR threshold for CPBS and CFBS are set to 20dBm. The minimum data rate of CPUE is 1.6 Mb/s.

In our simulation, we divide the transmission time period into 1500 segments. Moreover, we set the movement path of CPUE as shown in Figure 3. We can see that, in CFBS 17, we fixed the channel 8 to CFUE 17, CFUE 60, channel 6 for CFUE 49, channel 4 to CFUE 51 in uplink transmission, channel 5 to CFUE 10, to form a coalition by CFUE 30, we fix channel 4 for user CPUE 4, CPUE 3 and CPUE 2. Other users are allocated channels 4. There is one CPUE moving and randomly selects channels to avoid interference to PMBS.

In our simulation, we setup $\alpha_k = 1$, which means that there is no traffic generated by CFUEs. By consider in 1500 time steps. We first estimate the transmission power by comparing two schemes, non-cooperative and cooperative. Fig. 5 is showing the results of time periods of 1,500 stamps. We can see that, the total allocated power saved in cooperative model more than 57 %. Fig. 5, shows that when an CPUE is moving, it always selects the best channel to avoid interference to MBS. Moreover, it always joins coalitions to increase its data rate. When an CPUE joins a coalition, it runs four steps to form recursive core. Then, after solving optimization problem (7), CFUE determines power level and fraction of time for its data transmission.

Fig. 6 represents the CPUE's data rate of cooperative and non-cooperative model. Here we observe that the cooperative method is performing better than non-cooperative method. We can see that, in step 11, the cooperative model becomes the best solution because it always guarantees the QoS for CPUE with minimum power level. At this point, the power allocated for cooperative model is smaller than the allocated power level in non-cooperative model it can be observed in Fig. 4. Finally, Fig. 6 shows the optimal payoff value of coalition. Moreover, we observe that, when the CPUE joins a coalition, it always runs recursive core algorithm, where each step is based on equation (7) to compute optimal solution. By this way, the CFUE always achieves the optimum payoff value in its coalition. We come back to the Fig. 3, when the CPUE runs on its route, it forms coalition for relaying data as follow: S60 = {CFUE60, CPUE}, S50 = {CFUE50, CPUE}, S30= {CPUE, CPUE4, CPUE3, CPUE2, CFUE30}.

Finally, we estimate our proposal by increasing number of CPUEs in system. CPUEs are located at nearby CFBSs which can communicate to nearby CFUEs of femtocells which support decode and forward scheme. We compare our proposed scheme with scheme without using cooperative model, and a scheme in which CPUEs randomly choose channels. The results are shown in Fig. 7, clearly, our scheme improves data rate of CPUEs which is better than non-cooperative scheme and random scheme. We can see that, when number of CPUEs in system is increasing the total data rate increase due to increasing number of connec-

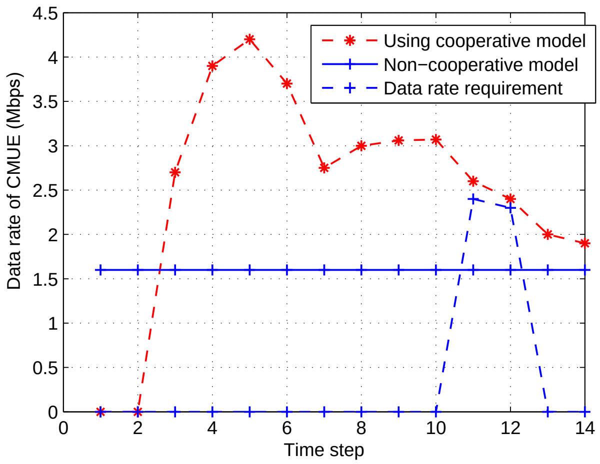

Figure 6: The data rate of the CPUE

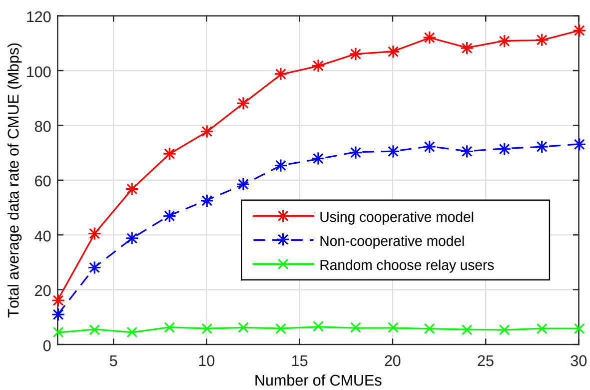

Figure 7: The average total data rate of CPUEs

tion and coalition formation among CPUEs and CFUEs.

5. CONCLUSIONS AND FUTURE WORKS

In this paper, we analyzed a scenario of cooperation in cognitive heterogeneous wireless network among the secondary macrocell, secondary femtocells and multiple primary users. Specifically, by applying the coalitional game approach, we formulated cooperation among secondary users in secondary network as players. Based on principle of recursive core method we assigned channels, transmission time and power in cooperating model in uplink data transmission. Then, we achieve maximum payoff for players in uplink mode of secondary users in heterogeneous cognitive wireless network. But restriction of the above problem is not yet find optimal solution in stochastic optimization that secondary users cooperate with other to achieve optimal solution in a long term in stochastic environment. Therefore, in the future we aim to analyze this problem in stochastic environment.

6. ACKNOWLEDGMENTS

This research was supported by Basic Science Research Program through National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2014R1A 2A2A01005900). *Dr. CS Hong is the corresponding author.

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