Paper

Cooperative Games with Incomplete Information for Secondary Base Stations in Cognitive Radio Networks

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Abstract—Cognitive radio (CR) technology is considered to be an effective solution for enhancing overall spectrum efficiency. Using CR technology fully involves the providing of incentives to Primary Radio Networks (PRNs) and revenue to the service provider so that Secondary Base Stations (SBSs) may utilize PRN spectrum bands accordingly. In this paper, a cooperative games with incomplete information for SBSs in a CR network is presented. Each SBS can cooperate with neighboring SBSs in order to improve its view of the spectrum. Moreover, proposed game-theory models assume that the devices have incomplete information about their components, meaning that some players do not completely know the structure of the game. Using the proposed algorithm, each SBS can leave or join the coalition while maximizing its overall utility. The simulation results illustrate that the proposed algorithm allows us to reduce the average payoff per SBS up to 140% relative to a CR network without cooperation among SBSs.

Keywords*—*Bayesian equilibrium, cognitive radio networks, game theory, wireless communication.

1. Introduction

Cognitive radio (CR) was first proposed by J. Mitola [1] as a way of ”scavering” fragments of unused spectrum and designing signals accordingly. In the United States, the Federal Communications Commission (FCC) later come up with its Spectrum Policy Task Force (SPTF) report [2] that opened up the television band as a start for CR purposes. Moreover, the most recent FCC measurement [3] concludes that 70% of allocated spectrum is not utilized in the United States. Because of this, CR technology is considered one of the most attractive candidates to tackle such challenge [4].

Node cooperation is fundamental to ensure acceptable performance in CR networks. Cooperation in CR networks has been studied by, among others, A. Ghasemi *et al*. In their work, the authors showed that the collaboration among SUs (Secondary Users) and the effects of the hidden terminal problem can be reduced and the probability of detecting the PU (Primary User) can be improved [5]. Moreover, Zhang [7] has proposed that collaborative spectrum-sensing spatial diversity techniques for improving collaborative spectrum-sensing performance by detecting means of combating error probability caused by fading the reporting channel between the SUs and the central fusing center. Thus, it is obvious that the deployment of all available PUs in the exploration and use of the spectrum is a key technology for the development of cognitive radio systems. It allows to improve the quality and the amount of information transmitted over radio channels. Unfortunately, the PUs may belong to different service providers, and they interact with each other by means of the cooperation between the management centers.

In the literature, the Cognitive Pilot Channel (CPC) has been proposed by P. Houz *et al*. [8] and M. Filo *et al*. [9] as a means of providing frequency and geographical information to cognitive users. As explained in these papers, the CPC concept is based on control channels that carry information such as available spectrum opportunities and existing frequencies. Additionally, Sallent has proposed a broadcast and on-demand method for delivering the CPC data to the SUs [10]. According to this approach, each SU can exchange its own information about the entire spectrum to identify spectrum holes and available PUs. Collaboration between the SBSs can lead to a significant decrease of the costs of use and can improve the network structure’s stability. In other words, a network of SBSs in every CR network is responsible for gathering all information about new PUs (the view of the spectrum, the position change detection, etc.). Recently, W. Saad has proposed a coalition formation among SBSs that can account for the tradeoffs between the costs of receiving inaccurate information and the benefit from learning about new channels through coalition members [11].

Game theory is an essential tool for CR networks. Most games considered in these systems are games with complete information. For example, games with complete information have been studied in the distributed collaborative spectrum sensing [12], for the sake of a dynamic spectrum sharing [13], interference minimalization in the CR networks [14], designing independent parallel channels (i.e., OFDM) [15], etc. However, there are no existing methods of calculating the equilibrium policy in a general game with incomplete information. The imperfect information or partial Channel State Information (CSI) means that the CSI is not perfectly estimated/observed at the transmitter/receiver side. This is a common situation which usually happens in a real wireless communication, since it may be too ”expensive” for every radio receiver/transmitter to keep the information from the channels of all other devices.

Harsanyi and Selten [18] at first proposed an extension of the Nash solution to Bayesian bargaining problems. A new generalization of the Nash bargaining solution for two player games with incomplete information was presented by Myerson [19].

The main contributions of this paper are twofold. Firstly, the coalition formation among SBSs with incomplete information in the CR networks is studied. A Bayesian equilibrium which allows to formulate the study of the coalition formation among SBSs with incomplete information in CR network is given. Secondly, an algorithm for building a coalition of SBSs is formulated. Each SBS decides to enter or leave the coalition for the sake of maximizing its utility function. Finally, the system model is validated through simulation.

The remainder of this paper is organized as follows. In Section 2 the system model is presented in details. Section 3 is devoted to the coalition formation among the SBSs with incomplete information. In Section 4, an algorithm for the coalition formation of SBSs with incomplete information is described. Section 5 presents some simulation results. The paper and its possible extensions are summarized in the concluding remarks of Section 6.

2. The System Model

In this section, the model of the CR system consisting of the PUs and the SUs is presented. Assuming that to the CR network also belong N secondary base stations (SBSs). Each i-th SBS can service number L_i of SUs in a specific geographical area. It means that each SBS provides coverage area for a given cell or mesh. Let $\mathscr{N}$ be the set of all SBSs and $\mathscr{K}$ be the set of all PUs. Each PU can use a number of admissible wireless channels. We assume that each SU can employ the k-th channel of PU, if the k-th channel is not transmitting and this channel is available for the SU. According to the approach given by D. Niyato [21] each i-th SBS can be characterized by accurate statistics regarding a subset $\mathscr{K}_i \in \mathscr{K}$ of PUs during the period of time the channels remain stationary.

Let each i-th SBS use energy detectors which belong to the main practical signal detectors in the CR network. Assuming the Raleigh fading, the probability that the i-th SBS accurately received the signal from PU $k \in \mathscr{K}$ is given by [5]

$$P^i_{det,k} = e^{-\frac{\lambda_{i,k}}{2}} \sum_{n=0}^{m-2} \frac{1}{n!}\left(\frac{\lambda_{i,k}}{2}\right)^n + \left(\frac{1+\overline{\gamma}_{k,i}}{\overline{\gamma}_{k,i}}\right)^{m-1} \times \left[e^{-\frac{\lambda_{i,k}}{2(1+\overline{\gamma}_{k,i})}} - e^{-\frac{\lambda_{i,k}}{2}} \sum_{n=0}^{m-2} \frac{1}{n!}\left(\frac{\lambda_{i,k}\overline{\gamma}_{k,i}}{2(1+\overline{\gamma}_{k,i})}\right)^n\right], \quad (1)$$

where $\lambda_{i,k}$ is the energy detection threshold selected by the i-th SBS for sensing the k-th channel, m is the time bandwidth product. $\overline{\gamma}_{k,i}$ is the average SNR of the received signal from the k-th PU and is given by $\overline{\gamma}_{k,j} = \frac{P_k g_{k,i}}{\sigma^2}$, where P_k is the transmit power of the k-th PU, $g_{ki} = \frac{1}{d^{\mu}_{k,i}}$ is the path loss between the k-th PU and the i-th SBS, d_{ki} is the distance between the k-th PU and the i-th SBS, σ^2 is the Gaussian noise variance.

Thus, as was shown in [5] the false alarm probability perceived by the i-th SBS $i \in \mathscr{N}$ over the k-th channel, $k \in \mathscr{K}$, belonging to PU, is given by

$$P^i_{fal,k} = P_{fal} = \frac{\Gamma(m, \frac{\lambda_{i,k}}{2})}{\Gamma(m)}, \quad (2)$$

where $\Gamma(.,.)$ is the incomplete gamma function and $\Gamma(.)$ is the gamma function.

The non-cooperative false alarm probability depends on the position of SU. Thus, the index k in Eq. (2) could be dropped, and the missing probability perceived by the i-th SBS, is [5], [6]

$$P_{mis,i} = 1 - P_{det,i}. \quad (3)$$

Assuming a non-cooperative collaboration for every i-th SBS, $i \in \mathscr{N}$ the amount of information which is transmitted to the SUs served by it over its control channel can be obtain from

$$\begin{aligned} v(\{i\}) \quad = \quad & \sum_{k\in\mathscr{K}_i}\sum_{j=1}^{L_i}[(1-P^i_{fal,k})\theta_k\rho_{ji} - \alpha_k(1-P^i_{det,k}) \\ & (1-\theta_k)(\rho_{kr_k} - \rho^j_{kr_k})], \end{aligned} \quad (4)$$

where L_i is the number of SUs served by the i-th SBS, α_u is the penalty factor imposed by the k-th PU for the SU that causes the interference. $(1-P^i_{det,k})$ defines the probability that the i-th SBS treated channel k as available while the PU is actually transmitting. The probability $(\rho_{kr_k} - \rho^j_{kr_k})$ indicates the reduction of a successful transmission at its receiver r_k of the k-th PU at its receiver r_k caused by the transmission from the j-th SU over k-th channel. It means the probability that the SNR received by the i-th SBS is given by [22]

$$\rho_{ji} = e^{-\frac{v_0}{\overline{\gamma}_{j,i}}}, \quad (5)$$

where v_0 is the target SNR for all PUs, SUs, SBSs, $\overline{\gamma}_{j,i}$ is the average SNR received by the i-th SBS from all SUs with the transmit power P_j of the j-th SU. It is defined as

$$\overline{\gamma}_{ji} = \frac{P_i g_{kr_k}}{\sigma^2 + g_{ji}P_j}, \quad (6)$$

where P_i gives PU i's probability of successful transmission at its receiver r_i, g_{ji} is the channel gain between the j-th SU and the i-th SBS.

Assuming Rayleigh fading and BPSK modulation within each coalition, the probability of reporting error between the i-th SBS and the j-th SU [7] is given by

$$P_{e,i,j} = \frac{1}{2}\left(1 - \sqrt{\frac{\overline{\gamma}_{j,i}}{2+\overline{\gamma}_{j,i}}}\right). \quad (7)$$

Inside a coalition C by a collaborative sensing, the missing and the false alarm probabilities of a coalition is given by:

$$Q_{mis,C} = \prod_{i\in C}[P_{mis,i}(1-P_{e,i,j}) + (1-P_{mis,j})P_{e,i,j}], \tag{8}$$

$$Q_{fal,C} = 1 - \prod_{i\in C}[(1-P_{fal})(1-P_{e,i,j}) + P_{fal}P_{e,i,j}]. \tag{9}$$

3. The Coalition Formation Among Secondary Base Stations with Incomplete Information in the CR Networks

In this section the SBS game with incomplete information in CR network is presented.

The problem can be formulated with the help of using a cooperative game theory [16]. More formally, we have a (Ω, u) coalition game, where Ω is the set of players (the SBSs) and u is the utility function or the value of the coalition.

Following the coalition game of Harsanyi [18], a possible definition for a Bayesian game [17] is as follows.

Definition 1 (Bayesian game)

A Bayesian game $\mathscr{G}$ is a strategic-form game with incomplete information, which can be described as follows

$$\mathscr{G} = \langle \Omega, \{\mathscr{T}_k, \mathscr{A}_k, \rho_k, u_k\}_{k\in\mathscr{K}} \rangle \tag{10}$$

which consists of:

- a player set: $\Omega = \{1,\dots,N\}$,
- a type set: $\mathscr{T}_n(\mathscr{T} = \mathscr{T}_1 \times \mathscr{T}_2 \times \dots \times \mathscr{T}_N)$,
- an action set: $\mathscr{A}_n(\mathscr{A} = \mathscr{A}_1 \times \mathscr{A}_2 \times \dots \mathscr{A}_N)$,
- a probability function set: $\rho_n : \mathscr{T}_n \rightarrow \mathscr{F}(\mathscr{T}_{-n})$,
- a payoff function set: $u_n : \mathscr{A} \times \mathscr{T} \rightarrow \mathscr{R}$, where $u_n(a,\tau)$ is the the payoff of player n when action profile is $a \in \mathscr{A}$ and type profile is $\tau \in \mathscr{T}$.

The set of strategies depends on the type of the player. Additionally, it is assumed that the type of the player is relevant to his decision. The decision is dependent on information which it possesses. A strategy for the player is a function mapping its type set into it action set. The probability function ρ_k represents the conditional probability $\rho_k(-\tau_k|\tau_k)$ that is assigned to the type of profile $\tau_{uk} \in \mathscr{T}_{-k}$ by the given τ_k.

The payoff function of player k is a function of strategy profile $s(.) = \{s_1(.),\dots,s_K(.)\}$ and the type profile $\tau = \{\tau_1,\dots,\tau_K\}$ of all players in the game and is given by

$$u_k(s(\tau),\tau) = u_k(s_1(\tau_1),\dots,s_N(\tau_N),\tau_1,\dots,\tau_N). \tag{11}$$

In a strategic-form game with complete information, each player chooses one action. In a Bayesian game each player chooses a set or collection of actions, strategy $s_k(.)$.

A definition for a payoff of player in the Bayesian game as follows:

Definition 2 (The player's payoff)

The player's payoff in a Bayesian game is given by

$$\begin{aligned} u_k(\tilde{s}_k(\tau_k), s_{-k}(\tau_{-k}),\tau) = u_k(s_1(\tau_1),\dots,\tilde{s}_k(\tau_k),\\ s_{k+1}(\tau_{k+1}),\dots,s_N(\tau_N),\tau), \end{aligned} \tag{12}$$

where $\tilde{s}_k(.), s_{-k}(.)$ denotes the strategy profile where all players play $s(.)$ except player k.

Next, we define the Bayesian equilibrium (BE) as follows:

Definition 3 (Bayesian equilibrium)

The strategy profile $s^*(.)$ is a Bayesian equilibrium (BE), if for all $k \in \mathscr{N}$, and for all $s_k(.) \in S_k$ and $s_{-k}(.) \in S_{-k}$

$$E_\tau[u_k(s_k^*(\tau_{-k}),\tau)] \geq E_\tau\left[u_k(s_k(\tau_k), s^*_{-k}(\tau_{-k}),\tau)\right], \tag{13}$$

where

$$\begin{aligned} E_\tau[u_k(x_k(\tau_k), x_{-k}(\tau_{-k}),\tau)] \overset{\triangle}{=} \sum_{\tau_{-k}\in\mathscr{T}_{-k}} \rho_k(\tau_{-k} \mid \tau_k),\\ u_k(x_k(\tau_k), x_{-k}(\tau_{-k}),\tau), \end{aligned} \tag{14}$$

is the expected payoff of player k, which is averaged over the joint distribution of all players' types.

For the proposed game the false alarm probabilities for the i-th and j SBSs over channel k are given by $P^i_{fal,k}$ and $P^j_{fal,k}$. Thus, the utility function or the value of the coalition is given by $u(C)$, namely

$$u(C) = (1-Q_{mis,C}) - Cost(Q_{fal,C}), \tag{15}$$

where $Q_{mis,C}$ is the missing probability of coalition C.

For the cooperation problem the following definition can be provided [16].

Definition 4 (Transferable utility of coalitional game)

A coalitional game (Ω, u) is said to have a transferable utility if value $u(C)$ can be arbitrarily apportioned between the coalition players. Otherwise, the coalitional game has a non-transferable utility and each player will have their own utility within coalition C.

Based on these concerns, it is important to say, that the utility of coalition C is equal to the utility of each SBS in the coalition. Thus, the used (Ω, u) coalitional game model has a non-transferable utility. In the coalitional game the stability of the grand coalition of all the players is generally assumed and the grand coalition maximizes the utilities of the players. Then, player i may to choose the randomized strategy s which maximizes his expected utility. Informally, we could provide a Nash equilibrium here.

Assuming the perfect coalition of SBS C_{per}, the false alarm probability is given by

$$Q_{fal,C_{per}} = 1 - \prod_{i \in C_{per}} (1 - P_{fal}) = 1 - (1 - P_{fal})^{|C_{per}|} . \quad (16)$$

4. The Coalition Formation Algorithm

In this section, an algorithm for the coalition formation of SBS with incomplete information in CR networks is proposed. The algorithm works on two levels: the possible coalition formation and the grand coalition formation. The first level is the basis for all the coalitions formation. Each member of group C cooperates so as to maximize their collective payoff. At this level a maximum number of SBSs per coalition is defined. At the second level the grand coalition is formed. Firstly, the utility function of the formed coalition is calculated. If the utility function of formed coalition reaches the maximum value, the Bayesian equilibrium (BE) is tested for the coaltion. Finding the Bayesian equilibrium (BE) finishes the operation of the algorithm. If two or more coalitions possess the Bayesian equilibrium with the same value of the payoff, the normalized equilibrium introduced by Rosen [20] is proposed here exists, where it is shown that a unique equilibrium exists if the payoff functions satisfy the condition of the diagonal strictly concave.

Algorithm 1 shows the pseudo-code of the proposed algorithm.

Algorithm 1: BSSs coalition formation

```
   Input: False alarm probability for each coalition
1  $|C_{perf}| := 1$;
2  compute $Q_{fal,C}$;
3  while $Q_{fal,C} > Q_{fal,C_{perf}}$ do
4      for $i = 1$ to $N$ do
5          compute $Q_{fal,C}$;
6          if BE exists for given $|C_{perf}|$ then
7              $|C_{perf}| := i$; go to 10;
8          else
9              $|C_{perf}| := i + 1$
10         end
11     end
12     label 10;
13 end
```

5. Simulation Results

A simulation was used to confirm the above given algorithm for the coalition formation among the SBSs with incomplete information. The simulation of the CR network has a four square with the PU at the center. Each square is equal to 1 × 1 km. In each square 4 SBSs and 8 SUs were randomly deployed. Initially, it was assumed that each SBS is non-cooperative and detects information from its neighbors by means of the common channels. The energy detection threshold $\lambda_{i,k}$ for an i-th SBS over channel k was chosen following the false probability $P^i_{f,k} = 0.05$, $\forall i \in \mathcal{N}$, $k \in K$. The transmit power of all the SU was assumed as equal to to 10 mW, the transmit power of all the PUs was equal to 100 mW, the noise variance $\sigma^2 = -90$ dBm.

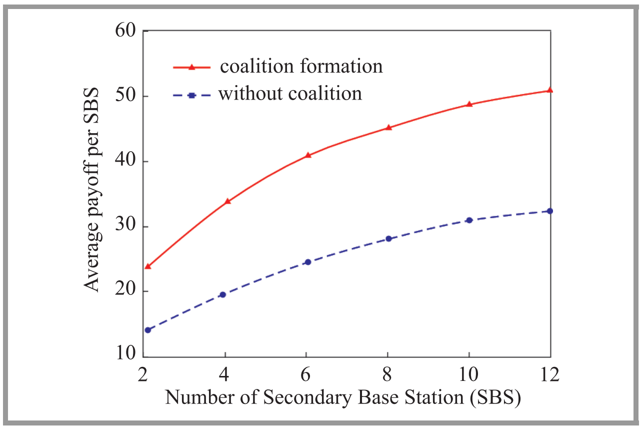

Fig. 1. The average payoff per SBS versus the number of SBSs.

Figure 1 presents the average payoff per SBS versus the number of SBSs for both the organization of the CR network with a coalition of SBSs and the non-cooperation of SBSs. Both results are averaged over random positions of all the nodes (SUs and PUs). In the case of non-cooperation game of SBS the average payoff per SBS has a smaller value than for the cooperation game of SBS. The proposed algorithm significantly increases the average payoff up to 140% relative to the non-cooperative case at the number of 15 SBSs. Figure 2 shows the number of SBSs versus the average maximum coalition number. The graph shows that the number of SBSs increases with the maximum average coalition number. It is due to the fact that as N increases, the number of potential members of the coalition increases. The graph indicates that the typical size of the SBS coalition is proportional to the num-

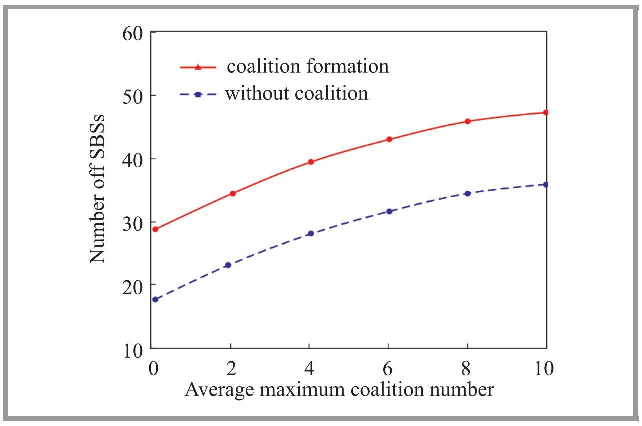

Fig. 2. The number of SBSs versus the average maximum coalition number of SBSs.

ber of SBSs for the certain value. A large number of SBSs does not allow for the formulation of a relatively large coalition.

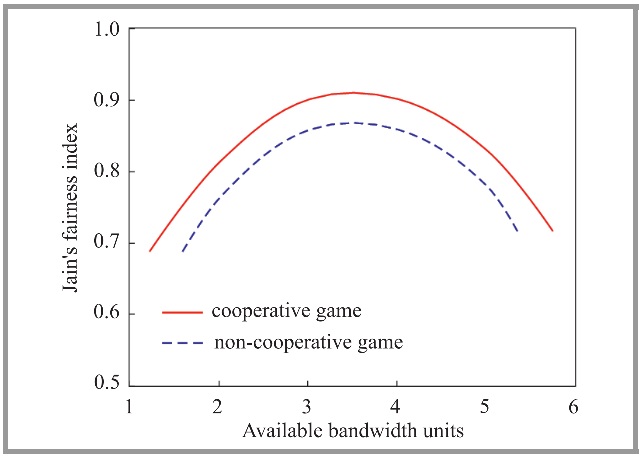

Fig. 3. Jain's fairness index (JFI) for available bandwidth units for cooperative and non-cooperative games.

Figure 3 shows that the coalition among SBSs allows us to obtain a higher value of Jain's fairness index for available bandwidth units. Jain's fairness index is defined as [23]

$$JFI = \frac{(\sum_i^{N_b} x_i)^2}{N_b \sum_{i=1}^{N_b} x_i^2}, \tag{17}$$

where x_i denotes a bandwidth unit and N_b is the number of all bandwidth units. The results show that all cooperation games take the maximum values of the JFI index.

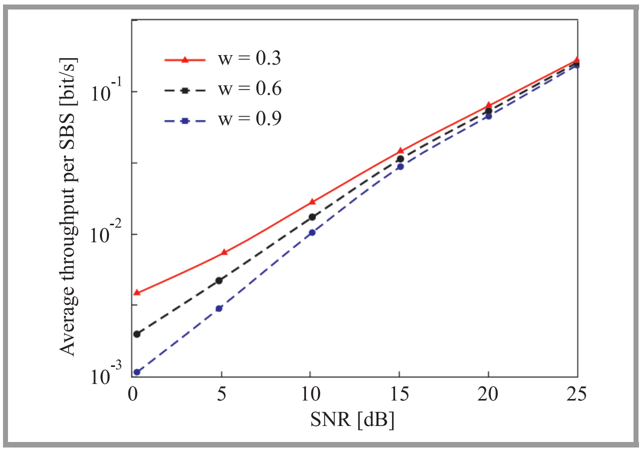

Fig. 4. Maximum achieved throughput for various value of the utility contribution weighting factor *w*.

Figure 4 shows the results of the average transmissions of SBSs coalition in terms of achieved throughput per SB (the player's achieved throughput in the coalition divided by the total available bandwidth) for various values of the utility-component weighting factor w $(w \in [0.3, 0.6, 0.9])$, and for assumed SNR value. Here, it can be seen that the transmitted power exceeds the power limit for small SNR value and for $w = 0.3$. Thus, a higher throughput is achieved due to the lack of noise. If $w = 0.9$, the opposite results are obtained because the SB is forced to be more power efficient. By assuming $w = 0.6$ in the game, the optimal curve of the achieved throughput and the bandwidth can be obtained.

6. Conclusion

In this paper, a new scheme for the coalition game among the SBSs in CR networks was proposed. The main advantage of the presented solution lies in the coalition formation of the SBS with incomplete information and the conveyed knowledge of the spectrum for all the SUs in the system. The proposed algorithm allows to ensure cooperation among the SBSs. The payoff of every coalition of the SBSs allows to decide to join or leave the coalition. Finally, using showed algorithm, the SBSs can reach a Bayesian equilibrium. The results of the simulation also confirm that proposed algorithm improved the average payoff of the SBSs coalition with incomplete information up to 140% in comparison to the non-cooperative case.
The future work should consider the confrontation of the proposed algorithm with that of an centralized solution.

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