A New Model for Cooperative Cognitive Radio Network Using Coalitional Game

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Abstract. In this paper we study the resources access problem in cognitive radio networks, especially we are interested in the large number of secondary users (SUs) present in the system. We propose a model based on channel access process when the PU is active, respecting the level of interference authorized by the operator. In this paper, we take secondary users as positive potential cooperators for the primary users. SUs negotiate with PUs for the acquisition of underutilized channels with exceeded interference caused to the PU. The PU will support additional interference Δ but will benefit from the cooperation of SUs to relay its data. In each transmission frame, one or more secondary users are selected to act as a relay for the primary user and also transmit its own data. We model this cooperation as coalitional game. The utility function considers various factors such as transmission power and noise level. A distributed coalition formation algorithm is also proposed, which can be used by SUs to decide whether to join or leave a coalition. Such a decision is based on whether it can increase the maximal coalition utility value. The objective of this work is to demonstrate that the proposed scheme is able to enhance the network throughput while increasing the opportunity that SUs can access the licensed spectrum owned by PUs.

Keywords: Cognitive radio · Dynamic spectrum access
Cooperative relaying · Coalitional game

1 Introduction

Cognitive radio is an innovative approach to wireless communication, which can improve spectrum utilization by spectrum sharing between primary users (PUs) and secondary users (SUs). Cognitive radio has been proposed in recent years to promote the spectrum utilization by exploiting the existence of spectrum holes [1]. According to Federal Communications Commission (FCC)[1,2], the secondary users would sense the activities of the primary users periodically.

When a channel is not occupied by a primary user, a secondary user can use the channel opportunistically after sensing. In a cognitive radio network, the SUs are allowed to access the spectrum in overlay or underlay model [3–5]. In underlay spectrum sharing scenario, the SU and the PU can access a licensed spectrum simultaneously as long as the interference caused to PU is kept below a predefined threshold [2]. SUs' transmission power is constrained strictly. Accordingly, the SUs' quality of service (QoS) can not be guaranteed and enhancing the SUs' performance becomes a challenging issue.

For better exploitation of spectrum resources, and with the evolution of cognitive radio technologies, dynamic spectrum access [2,3] becomes a promising approach to increase the efficiency of spectrum use, allowing an unauthorized wireless users (secondary users) to dynamically access the bands of spectrum holders (primary users). This efficiency can be improved considerably when dynamic spectrum access is associated with spectrum leasing. Dynamic spectrum leasing (DSL) [6] is proposed on the basis of DSA. In DSL model, spectrum licensees (called primary users) have the rights to sell or trade their spectrum to the third party. So primary users can lease their owned spectrum resources for a fraction of time to the secondary users to exchange reasonable remuneration. The authors in [9] proposed an improved cognitive radio (CR) model in which the secondary system can harvest energy from the primary system and access the spectrum of the primary system to transmit its own data in an underlay mode.

In this paper, we study the cooperation between PU and SU where PU use SUs to relay their message in exchange for spectrum access. We focus on designing an effective cooperation strategy for SUs to form a coalition so that the overall system performance (primarily, the throughput) can be improved. A distributed coalition formation algorithm for each SU is proposed in this paper to decide whether to join or leave a coalition based on the split and merge rules [7]. Such a decision is based on whether it can increase the maximal coalition utility value.

The rest of this paper is organized as follows. The network model and the cooperative transmission mechanism are illustrated in Sect. 2. We formulated the relay selection problem as coalitional game with transferable utility in Sect. 3 and also proposed the distributed game formation algorithm. In the Sect. 4, we analyze the performance of our proposed cooperative cognitive framework. Finally the Sect. 4 concludes the paper.

2   System Model

In our proposed framework, we assume that:

- The network is dense where many SUs have the objective to access the channel.
- The PU is willing to cooperate with the SUs and grant to a subset of secondary transmitters in exchange for cooperation (relaying) in the form of transmission.
- The messages exchanged between the PU and the SU during the negotiation phase are not addressed in this paper.

- Most of the SUs have best effort traffics (like web surfing, mails,...), these users will be authorized by the PU to share the canal with it even if the interference threshold is not respected. They will not waste time in sensing to check the presence of the PU and will leave the spectrum holes for SUs with real time services.
- In the secondary network, each transmitter has information to deliver to a given secondary receiver (interference channel).

In this paper, we explore the ability of cognitive radio to provide sufficient capacity to support additional interference for the PU in exchange for cooperation. The PU will be willing to support additional noise level Δ *(presented in* Fig. 1*)* in his owned bandwidth for a fraction of time if, in exchange for this concession, they will benefit from enhanced quality of service (e.g., in terms of rate and also of outage probability). When the PU is active, he decides its strategy on the level of the additional noise level that he can support from the SUs, and also the number of successive time slots **X** granted of SUs in this cooperation. This cooperation is modeled as a game, specifically, as a ***coalitional game***.

The proposed system involves N Primary Network (owner of the spectrum rights) and M Secondary Users. The set of PUs and SUs are denoted by $\mathcal{N} = \{1, 2, ..., N\}$ and $\mathcal{M} = \{1, 2, ..., M\}$, respectively (Fig. 2).
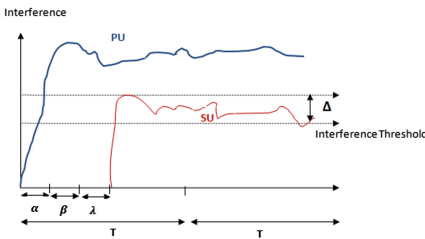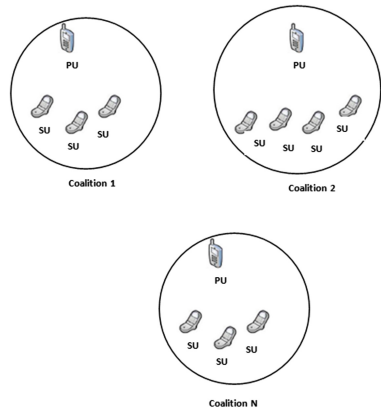

Fig. 1. Cooperative spectrum sharing

Fig. 2. Coalition formation for collaborative spectrum access

In this paper, we consider a model where the SUs act as cooperative relays to assist the PUs transmission in exchange for spectrum accesses in overlay or underlay mode. The PU can coexist with one or more secondary systems and sharing the same frequency band. Both these two networks operate autonomously. Thus, the Primary Network is aware of the spectrum occupancy by PUs and the same for the Secondary Network. SUs can make use of free

channels, or use the occupied channels under SINR constraints. Every PU in the $\mathcal{N} = \{1, 2, ..., N\}$ will form a collation with one or more SUs, The coalition head is represented by the PU. The number of coalitions formed in our proposed model is equal to N.

The PU has two transmission modes: direct transmission and cooperative transmission. If PU selects direct transmission mode, it sends the data to its receiver directly over the entire primary portion.

In our proposed system, the time resource is partitioned into discrete time slots (Fig. 1). We suppose every channel is slot Rayleigh channel which means that the channel coefficient is constant in a slot and all transmissions are assumed to be slot synchronized. During the primary time slot, each PU may use the entire slot for direct transmission or to employ cooperation with SUs which determined by the coalition algorithm described in the next section.

The data transmission slot is divided into four portions, α, β, λ and $T - \alpha - \beta - \lambda$.

- The Sensing phase with duration: α.
- The Reporting phase with duration: β.
- The Negotiation phase with duration: λ (Coalition Formation).
- The Data Transmission Phase with duration: $T - \alpha - \beta - \lambda$.

The contributions of this paper can be summarized as follows:

(1) We present a cooperation framework between primary users and secondary users.
(2) Coalitional game theoretic model of spectrum access/sharing is presented.
(3) We investigate the coalition formation and discuss the NE solution for our coalition game.

Algorithm 1. Coalition Formation Algorithm

1: **Initial Coalition Formation:**
2: PU broadcasts pilot traffic to each SU, and select candidate relays based on the geographic location
3: Initial coalition formation $C_{j_{initial}} = \{PU_j, SU_1, ..., SU_i, ...SU_{q_{initial}}\}$
4: The PU sets a value for the additional accepted interference Δ and the number of time slots X granted for SUs' access using the underlay mode.
5: **Coalition Transformation:**
6: SUs get the value of Δ
7: Apply merge-split rules on coalitions
8: Repeat after X time slot
9: $\Pi' =$ merge (Π), Coalitions in C merge into a new coalition based on the merge rules
10: Repeat until no more merge possible
11: $\Pi =$ split (Π'), Coalitions in F split into different coalitions based on the split rule
12: Repeat until no more split possible $C_j = \{PU_j, SU_1, ..., SU_i, ...SU_q\}$
13: SUs calculate the transmission power's value

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3 Proposed Cooperative Relay System

3.1 Coalition Game Overview

Coalition formation is a branch of game theory that investigates algorithms for studying the coalitional structures that form in a network. It's recognized as an important tool in many fields, such as social sciences, biology, engineering, political science [13]. Coalitional games approaches can achieve better results in terms of performance and stability in cooperative communications networks. Coalitional games was classified in a tutorial paper [7] into three categories: canonical (coalitional) games, coalition formation games, and coalitional graph games.

3.2 Framework Conception

In this section, an algorithm for the coalition formation of our proposed framework is presented. The SU will start by sensing the canal in the sensing phase α (presented in Fig. 1). If the PU is idle, then the SU will access the canal in its free spectrum holes using the Overlay Mode. The access will be granted for the current time slot. Otherwise, if the PU is active in the canal, the SU will share the same spectrum with the PU using the Underlay access mode. In our proposed model, SUs are authorized to exceed the predefined threshold with an additional interference Δ. In turn, they will collaborate with the PU by relaying its data to their destinations. When the PU is active, one or more SUs can coexist with the PU in the same canal for X time slots. The values of Δ and X are defined by the PU during the negotiation phase λ. In this case, for the next X time slots, the SUs will not waste energy in the sensing and the reporting phases, and will use the whole time slot with duration T.

Incorporating cooperation into cognitive radio networks, the SUs not only look for idle time slots to transmit their own data, but they may also relay the PUs' packets. Thus, cooperation in cognitive radio networks can be regarded as a win-win situation. In our paper, the cooperation between the PU and the SUs is used when the PU is present in the canal and is willing to support additional interference. In general, the more SUs in the selected coalition, the less spectrum's portion access. In turn, each SU may obtain less access time for its own data transmission. On the other hand, each SU may acquire more access time for its own data transmission if there is a fewer number of SUs in the coalition. Consequently, each SU in the game has the incentive to team up with the best partners so as to produce the maximal coalition utility value. This value depends also on the value Δ fixed by the PU at the beginning of the negotiation phase λ. The coalition formation algorithm is detailed in Algorithm 1 based on the split and merge rules.

3.3 Throughput Calculation/Coalition's Utility

As presented in the paper [11], a coalitional game G is uniquely defined by the pair $(K; U)$, where K is the set of players (PU and his SUs relay nodes),

any non-empty subset $\mathscr{C} \subseteq N$ is called a coalition, and U is the coalition value, it quantifies the worth of a coalition in a game. The strategy of each player is to decide on which coalition to join, and the payoff is the function $U(\mathscr{C}_j; \Pi_i)$.

The utility (denoted by U) is the aggregated utility value of a coalition. Specifically, $U(\mathscr{C}_j)$ denotes the total coalition utility value of the coalition $\mathscr{C}_j$, where $j \in \{1, 2, ..., N\}$ and $\mathscr{C}_j \subseteq (N \cup M)$, which is defined as below:

$$U(\mathscr{C}_j) = \sum_{i=1}^{q_j+1} U_i \tag{1}$$

Where $q_j + 1$ denotes the number of players in the coalition $U(\mathscr{C}_j)$: one PU and q_j SUs.

The utility value U_i of each player is the difference between reward and cost, which is defined as:

$$U_i = R_i - C_i \tag{2}$$

Where R_i and C_i represent respectively the reward and the cost given to SU_i/PU_i.

In our proposed coalition game, the throughput is considered as reward of the PU_j and SU_{ij} $(1 \le i \le q_j)$ in the coalition.

The cardinal of the coalition $\mathscr{C}_j$ is equal to $q_j + 1$, so we have:

$$U(\mathscr{C}_j) = \sum_{i=1}^{q_j+1} (R_i - C_i) \tag{3}$$

The aggregated utility value of each coalition is composed of the utility of the PU and the other SUs in his coalition. Then, after substitution:

$$U(\mathscr{C}_j) = (R_{PU_j} - C_{PU_j}) + \sum_{i=1}^{q_j} (R_i - C_i) \tag{4}$$

Then we have :
The primary transmission rate is giving by :

$$R_{PU} = \begin{cases} R_{Direct(PU)} & , no\ cooperation \\ R_{Direct(PU)} + R_{Coop(PU)} & , with\ cooperation \end{cases} \tag{5}$$

In the equations below, W denotes the communication bandwidth, P_s and P_p the transmission power for the SU and the PU respectively, G_i^j the channel gain between node i and j and is modeled as independent zero mean complex Gaussian random variable with variance σ^2.

The achievable rate from PU transmitter-receiver over the channel on the direct link (without using the SU for relaying its data) is:

$$R_{Direct(PU)} = W * log_2 \left(1 + \frac{P_p G_p^p}{\sigma^2} \right) \tag{6}$$

We assume that when the PU is active in the canal, it has many services in his queue to send to their destinations. He will benefit from cooperation with SUs and transmit some services to his coalition in order to relay them to their destinations. The achievable rate from Primary transmitter (PT) to Primary receiver (PR) over the channel with cooperative relay is:

$$R_{Coop(PU)} = L_j * \delta_{Succ(j)} * R_{Coop(SUij)} \tag{7}$$

Where L_j denotes the packet length delivered by the PU of the coalition $\mathscr{C}_j$ to its SUs in his coalition in order to deliver it (the packet) to PU's receiver, and $\delta_{Succ(j)}$ denotes the probability of successful delivery of a message by the SUs of the coalition $\mathscr{C}_j$. According to [13], we have:

$$\delta_{Succ(j)} = 1 - \Pi.Q_{SUij} \tag{8}$$

Where is the Q_{SUij} probability that a $SUij$ fails to deliver the copy of the PU's packet to the destination. Thus, the throughput of SU_{ij} when relaying the PU's data is:

$$R_{Coop(SUij)} = (T - \alpha - \beta - \lambda) * W * log_2\left(1 + \frac{P_s G_s^s}{\sigma^2}\right) \tag{9}$$

The achievable rate from ST to SR over the channel in the overlay mode for **one time slot** is ($\lambda = 0$ in this case because there is no negotiation on the value of X between the PU and the SU):

$$R_O(SU) = \frac{T - \alpha - \beta}{T} * W * log_2\left(1 + \frac{P_{si} G_{si}^{si}}{\sigma^2}\right) \tag{10}$$

As explained above, the PU will grant access to his formed coalition for X time slots in the underlay mode. In the first time slot, SUs will negotiate with the PU in the negotiation phase λ on the value of X and the additional value Δ. At the remaining time slots $X - 1$, SUs will exploit the whole time slot (without the sensing, the reporting and the negotiation phases). Then, the achievable rate from ST (Secondary Transmitter) to SR (Secondary Receiver) for all the SU_{ij} ($1 \leq i \leq q_j$) in the coalition in the underlay mode for X **time slot**s is:

$$R_U(SU_i, X) = \frac{T - \alpha - \beta - \lambda}{T} W log_2\left(1 + \frac{P_{si} G_{si}^{si}}{\sigma^2 + \Delta}\right) + (X - 1)W \sum_{i=1}^{q_j} log_2\left(1 + \frac{P_{si} G_{si}^{si}}{\sigma^2 + \Delta}\right) \tag{11}$$

Then we have the average throughput for the SU in the underlay mode for the X time slot :

$$R_U(SU_i Avrg) = \frac{1}{X} * R_U(SU_i, X) \tag{12}$$

Thus,

$$R_U(SU_iAvrg) = \frac{T - \alpha - \beta - \lambda}{T * X} * W * log_2\left(1 + \frac{P_{si}G_{si}^{si}}{\sigma^2 + \Delta}\right)$$
$$+ \frac{X - 1}{X} * W * \sum_{i=1}^{q_j} log_2\left(1 + \frac{P_{si}G_{si}^{si}}{\sigma^2 + \Delta}\right)$$

$$(13)$$

The SU will access in Overlay mode if the PU is idle in the canal and access in Underlay mode of he's active. Let's denote Π_p, the probability of the presence of the PU in a given band, and Y the number of time slots when SU access in the Overlay mode. Thus, the total average throughput of the SU in our proposed model is presented below:

$$R_{Total(SU_i,Avrg)} = \frac{Y}{X + Y} * (1 - \Pi_p) * R_O(SU_i) + \frac{X}{X + Y} * \Pi_p * R_U(SU_iAvrg)$$

$$(14)$$

3.4 Existence of Nash Equilibirum

The Nash equilibrium [15] is an important concept to measure the outcome of a non-cooperative game, which is a set of strategies, one for each player, such that no selfish player has incentive to unilaterally change his/her action.

According to [8], a Nash equilibrium exists if it satisfies the following conditions: $\forall i \in N$:

(1) The action strategy profile (A_i) is a nonempty, convex, and compact subset of some Euclidean space.
(2) The utility function (U_i) is a continuous and quasi-concave function over the strategy set of the players.

Proof: this can be achieved by showing the two conditions offered are met and the poof can be shown according to:

– Since each CR user has a strategy profile that is defined by a spectrum access type with some transmission power, thus the first condition is readily satisfied.
– To prove the second condition is also satisfied, we have to show that the given price based utility function (A_i) is quasi-concave $\forall i \in N$.

The utility function is continuous and strictly concave because we have:

$$\frac{\partial^2 U_{ab}^\gamma}{\partial p_\gamma} > 0 \qquad (15)$$

Nash equilibrium of a game G is a strategy profile $s^* \in S$ such that $\forall i \in I$ we have the following
$U_i(s_i^*, s_{-i}^*) >= U_i(s_i, s_{-i}^*)\forall s_i \in S_i, s_i \neq s_i^*, \forall i \in I$

4   Simulations and Numerical Results

In this section, we provide and discuss numerical results about the system performance for $N = 2$ and $M = 5$. We aim to show by these simulations that both the PU and the SU can achieve reasonable throughput in our proposed cooperative model. For our simulations, we choose the default parameters as follow: $K = 200\,kHz$, $Pp = 10\,mW$, $Ps(underlay) = 0.1\,mw$, $n0 = 10^{-15}\,W$; $SINR = 10\,dB$.

In Fig. 3, we plot the throughput's variation for both PU and SU as a function of the variation of the Δ. We note that the throughput of the PU without the cooperation decreases if the value of the Δ is increased, while it increases if the PU cooperates with SU. We can clearly see that the SU's throughput is enhanced for higher value of Δ.

In our game, every player is a general entity individual and uses a strategic learning algorithm to learn the best coalition and finally the system converge to Nash equilibrium. We use the imitative Boltzmann-Gibbs weighted strategy [11,13]. In our paper, we are interested in SU's strategies. Those of the PU will be studied in a future work.
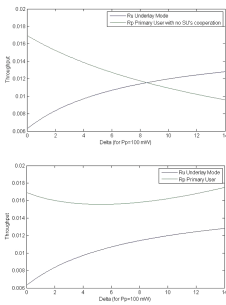
Fig. 3. SU's and PU's throughput variation without and with cooperation
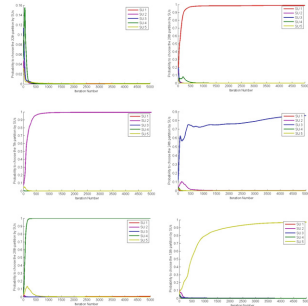
Fig. 4. Convergence of partition choice for five SUs

In Fig. 4, we plot the probability of partition's convergence ($N = 2$, $M = 5$). It shows that each SU can make a good decision on which partition to choose. SU1 to SU5 choose respectively partitions: Π_{28}, Π_7, Π_{24}, Π_{28} and Π_{13}. For the strategy Π_{32}, no user converge to this strategy, because the reward for this one is the lowest one (all the SUs with the same PU that offers the lowest value of Δ).

From these simulations we can conclude that having a maximum utility (throughput) for players is due to the partition's choice, which takes into account the value of Δ predefined by the PU and the number of the SUs present in the current coalition with the PU (Table 1).

Table 1. Possible Coalitions Structure for $N = 2$ and $M = 5$

$\Pi_1 = \{\{PU_1, SU_1\}, \{PU_2, SU_2, SU_3, SU_4, SU_5\}\}$	$\Pi_{17} = \{\{PU_1, SU_1, SU_2, SU_4\}, \{PU_2, SU_3, SU_5\}\}$
$\Pi_2 = \{\{PU_1, SU_2\}, \{PU_2, SU_1, SU_3, SU_4, SU_5\}\}$	$\Pi_{18} = \{\{PU_1, SU_1, SU_2, SU_5\}, \{PU_2, SU_3, SU_4\}\}$
$\Pi_3 = \{\{PU_1, SU_3\}, \{PU_2, SU_1, SU_2, SU_4, SU_5\}\}$	$\Pi_{19} = \{\{PU_1, SU_1, SU_3, SU_4\}, \{PU_2, SU_2, SU_5\}\}$
$\Pi_4 = \{\{PU_1, SU_4\}, \{PU_2, SU_1, SU_2, SU_3, SU_5\}\}$	$\Pi_{20} = \{\{PU_1, SU_1, SU_3, SU_5\}, \{PU_2, SU_2, SU_4\}\}$
$\Pi_5 = \{\{PU_1, SU_5\}, \{PU_2, SU_1, SU_2, SU_3, SU_4\}\}$	$\Pi_{21} = \{\{PU_1, SU_1, SU_4, SU_5\}, \{PU_2, SU_2, SU_3\}\}$
$\Pi_6 = \{\{PU_1, SU_1, SU_2\}, \{PU_2, SU_3, SU_4, SU_5\}\}$	$\Pi_{22} = \{\{PU_1, SU_2, SU_3, SU_4\}, \{PU_2, SU_1, SU_5\}\}$
$\Pi_7 = \{\{PU_1, SU_1, SU_3\}, \{PU_2, SU_2, SU_4, SU_5\}\}$	$\Pi_{23} = \{\{PU_1, SU_2, SU_3, SU_5\}, \{PU_2, SU_1, SU_4\}\}$
$\Pi_8 = \{\{PU_1, SU_1, SU_4\}, \{PU_2, SU_2, SU_3, SU_5\}\}$	$\Pi_{24} = \{\{PU_1, SU_2, SU_4, SU_5\}, \{PU_2, SU_1, SU_3\}\}$
$\Pi_9 = \{\{PU_1, SU_1, SU_5\}, \{PU_2, SU_2, SU_3, SU_4\}\}$	$\Pi_{25} = \{\{PU_1, SU_3, SU_4, SU_5\}, \{PU_2, SU_1, SU_2\}\}$
$\Pi_{10} = \{\{PU_1, SU_2, SU_3\}, \{PU_2, SU_1, SU_4, SU_5\}\}$	$\Pi_{26} = \{\{PU_1, SU_2, SU_3, SU_4, SU_5\}, \{PU_2, SU_1\}\}$
$\Pi_{11} = \{\{PU_1, SU_2, SU_4\}, \{PU_2, SU_1, SU_3, SU_5\}\}$	$\Pi_{27} = \{\{PU_1, SU_1, SU_3, SU_4, SU_5\}, \{PU_2, SU_2\}\}$
$\Pi_{12} = \{\{PU_1, SU_2, SU_5\}, \{PU_2, SU_1, SU_3, SU_4\}\}$	$\Pi_{28} = \{\{PU_1, SU_1, SU_2, SU_4, SU_5\}, \{PU_2, SU_3\}\}$
$\Pi_{13} = \{\{PU_1, SU_3, SU_4\}, \{PU_2, SU_1, SU_2, SU_5\}\}$	$\Pi_{29} = \{\{PU_1, SU_1, SU_2, SU_3, SU_5\}, \{PU_2, SU_4\}\}$
$\Pi_{14} = \{\{PU_1, SU_3, SU_5\}, \{PU_2, SU_1, SU_2, SU_4\}\}$	$\Pi_{30} = \{\{PU_1, SU_1, SU_2, SU_3, SU_4\}, \{PU_2, SU_5\}\}$
$\Pi_{15} = \{\{PU_1, SU_4, SU_5\}, \{PU_2, SU_1, SU_2, SU_3\}\}$	$\Pi_{31} = \{\{PU_1\}, \{PU_2, SU_1, SU_2, SU_3, SU_4, SU_5\}\}$
$\Pi_{16} = \{\{PU_1, SU_1, SU_2, SU_3\}, \{PU_2, SU_4, SU_5\}\}$	$\Pi_{32} = \{\{PU_1, SU_1, SU_2, SU_3, SU_4, SU_5\}, \{PU_2\}\}$

5   Conclusion

In this paper, we study the cooperation strategy for SUs in a CRN based on the coalition formation game theory. We focused on designing an effective cooperation strategy between PU and SU to form a coalition so that the overall system performance (primarily, the throughput) can be improved. We formulate the problem of cooperative spectrum access as a coalition game, which is solved by a proposed distributed coalition formation algorithm utilizing the split and merge rules. The simulation results showed that networks performances increase with the proposed scheme especially in terms of the throughput enhancement.

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