Mobile Networks and Applications (2018) 23:1436–1448
https://doi.org/10.1007/s11036-018-1078-z

A New Energy Efficiency/Spectrum Efficiency Model for Cooperative Cognitive Radio Network

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Published online: 6 October 2018

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). We establish a model based on channel access process when the PU (Primary User) is active, respecting the level of interference authorized by the operator. We study a system of cooperation between the SUs and the PUs to increase the performance of the system. SUs pass through an negotiation phase with the PUs for the acquisition of the 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. We model this cooperation as coalitional game.The utility function depends on two main parameters which are: 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. We consider also the trade off between energy efficiency and the target throughput in the proposed cooperative relay network. The objective of this work is to validate the expected enhancement of the overall throughput of the network and also the energy efficiency while increasing the opportunity for SUs to access the licensed spectrum owned by PUs.

Keywords Cognitive radio · Dynamic spectrum access · Cooperative relaying · Coalitional game · Energy efficiency.

1 Introduction

Cognitive radio is an innovative approach to wireless communication, which can lead to a better spectrum utilization using the opportunistically spectrum access and the spectrum sharing between primary users (PUs) and secondary users (SUs). Over the recent years, cognitive radio has been proposed to exploit the spectrum holes and improve the spectrum utilization [1]. According to Federal Communications Commission (FCC) [1, 2], many spectrum bands are underutilized for large period of times, and the Cognitive radio (CR) can play an important role to improve the spectrum efficiency of wireless networks [1]. This promising technology is based on spectrum sensing and opportunistic spectrum access which can improve the spectrum efficiency of wireless networks [1]. In a cognitive radio network, the SUs have two access modes to access PUs' spectrum which are: the overlay or the underlay mode [3, 12]. The characteristic of the latter is that the SUs can acces a licensed spectrum simultaneously with the PU without causing harmful interference to the him [2], SUs should maintain their transmission power. Unlike the first mode, in the overlay mode, the SUs are not authorized to coexist with the PUs in the same channel, SUs can only user the free channels not currently utilized by the spectrum holders.

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] has been proposed in complement to DSA. In DSL model, spectrum licensees (called primary

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users) can trade a portion of their spectrum to the other party in exchange for compensation and remuneration in return.

A cooperation framework was designed based on the coalition game. we established a distributed coalition formation algorithm wich can be used to form a coalition between one PUs and his SUs followers and to make a stable coalition based on the split and merge rules (a SU can leave his current coalition and join a new one with an other PU in order to increase his utility). We developed the utility function for our proposed game which considers many factors and parameters.

The authors in [10] proposed an improved cognitive radio (CR) model in which the secondary system can harvest energy from the primary system and access to transmit its own data in an underlay mode. The outage probability of the is evaluated as a function of the maximum transmit power at the secondary transmitter (ST) under a constraint of peak interference power at the primary receiver (PR), the energy harvesting period at ST, the channel's path loss between primary and secondary networks.

Our manuscript reports research on cognitive radio networks. It focuses on providing a novel mechanism for some SUs to participate in the primary user's transmission to ride on the bandwidth where the primary user also boosts its transmission through relaying. This mechanism offers the opportunity to SUs with best effort services to access the licensed spectrum at the same time with the spectrum holders which lead to a better spectrum efficiency. The center of the proposed mechanism is a coalition game. We studied the formation of the coalition, dressed the coalition's utility and the energy efficiency for our proposed model. Numerical simulation shows positive results.

The rest of this paper is organized as follows. The network model and the cooperative transmission mechanism are illustrated in Section 2. We formulated the cooperation behavior as coalitional game with transferable utility in Section 3 and also proposed the distributed game formation algorithm. In the Section 4, we analyze the performance of our cooperative cognitive framework. In Section 5, we analyze the fundamentals for EE (Energy Efficiency) and prove the enhancement of it in our proposed framework. Finally the Section 6 concludes the paper.

2 System model

Our proposed cognitive radio network involves multiple PUs and multiple SUs seeking to access the channel hold by the PUs in a cooperative model. We will prove that this cooperation can increase spectrum capacity and utilization.

Assumptions:

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.
– The primary link may grant to a group of secondary transmitters in exchange for cooperation (relaying).
– 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, mail sending ...), 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 if the PU is active or idle and will leave the free bands for SUs with real time services.

In this paper, we study the performance of the system when PU can support additional interference in exchange for cooperation. We study the cooperation between PU and SU using the spectrum sharing concept. The PU will be willing to support additional noise level Δ (presented in Fig. 1) for a number of successive time slots. In return for this concession, they will benefit from the cooperation with the SUs in order to enhance network parameters (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 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.

Algorithm 1 Coalition formation algorithm

1: **Initial Coalition Formation:**
2: PU broadcasts information to each SU, and select candidate relays according to the geographic location
3: Initial coalition formation $C_{j_{initial}} = \{PU_j, SU_1, ..., SU_i, ...SU_{qj}\}$
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 for $C_{j_{initial}}$
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 stable coalition $C_j = \{PU_j, SU_1, ..., SU_i, ...SU_q\}$
13: SUs calculate the transmission power's value

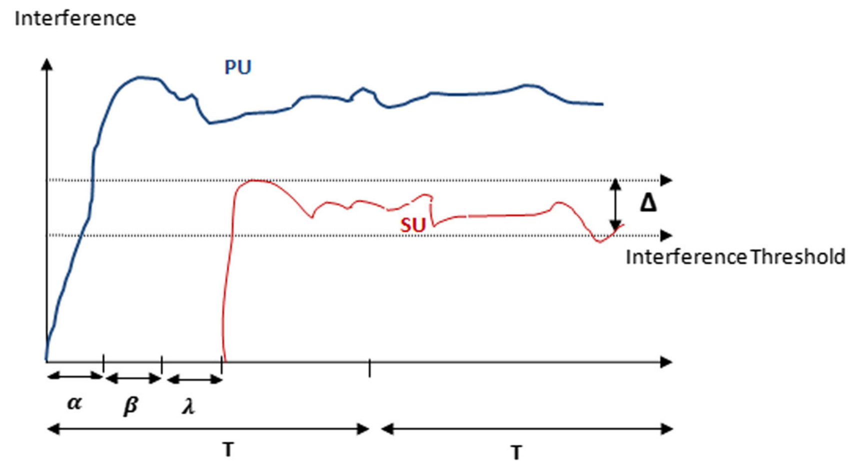

Fig. 1 Cooperative spectrum sharing

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). 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.

3 Proposed cooperative relay system

In this section, we first give a brief introduction of coalition game, then give a description of our proposed cooperative transmission mechanism.

3.1 Coalition game overview

Game theory have bee used as useful approach for many studies's decision in several axes like economy, telecommunications, social behavior,... In the vast and huge field of this theory, we can precisely exploit the properties of Coalitional Games [13], in this specific field of game theory, the formulation of the group of the formed coalition remains the important deal and the basic step to achieve a good result.

In a tutorial study for Coalitional game theory, the authors in [7] grouped this branch into three families: the first one is the canonical games(also known as the coalitional games), the characteristic of this first type is that: there's no group of players can do worse by joining a coalition than by acting non-cooperatively. The second family is the coalition formation games, wich bring better reward for the players but we have to take into consideration, the cost of coalition's formation. The last group is the coalitional graph games where the coalitional game is represented in a graph form.

And the interconnection between the players strongly affects the characteristic as well as the outcome of the game. In this paper, we use the second group as presented above wich refers to the Coalition formation games. As presnted in (Fig. 2), one PU can form a coalition with one or many SUs. The detailed framework conception is developped in the next paragraph.

3.2 Framework conception

In this section, an algorithm for the coalition formation of our proposed framework is presented in Fig. 3. 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,

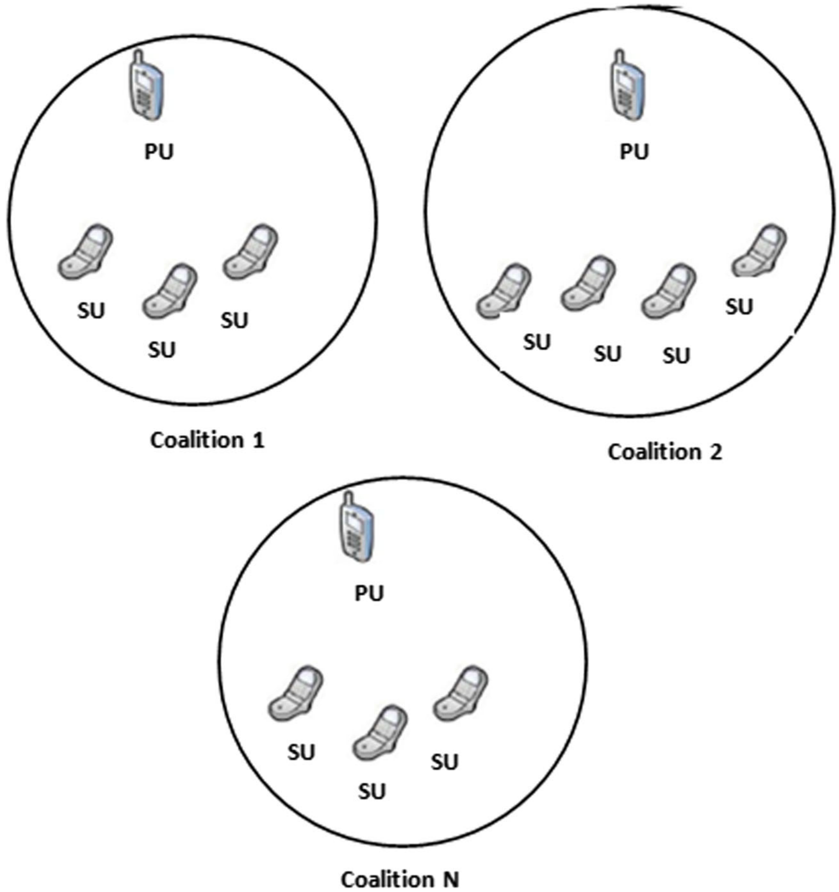

Fig. 2 Coalition formation for collaborative spectrum access

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.

In Wireless communications systems, making cooperation between PUs and SUs possible can improve the spectrum utilization and more opportunities to the unlicensed users to transmit their messages and data. We can consider the implementation of this cooperation as a win-win solution and can deal with the channel allocation problem. 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 exchange, he will benefit from the SUs in his current coalition to transfer messages to the PU receiver.

In general, taking into account the number of SUs in the formed coalition is primordial. if the number of SUs selected in the coalition is high, they will be benefit for small spectrum portion to transmit their data or they have to constraint their transmission power to respect the interference temperature. On the other hand, if the number of SUs forming the coalition is few, they we will be granted a large portion the channel and will transmit higher data.SU will be always seeking to join the coalition that brings the maximum benefit for it. 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 presented in Fig. 5. It's based on the split and merge rules. Every SU has the objective to form or leave a coalition in the aim to maximize its benefit. Next section details the utility calculation of the coalition.

3.3 Coalition's utility

As presented in the paper [13], a coalitional game G is uniquely defined by the pair $(K; U)$, where K is the set of

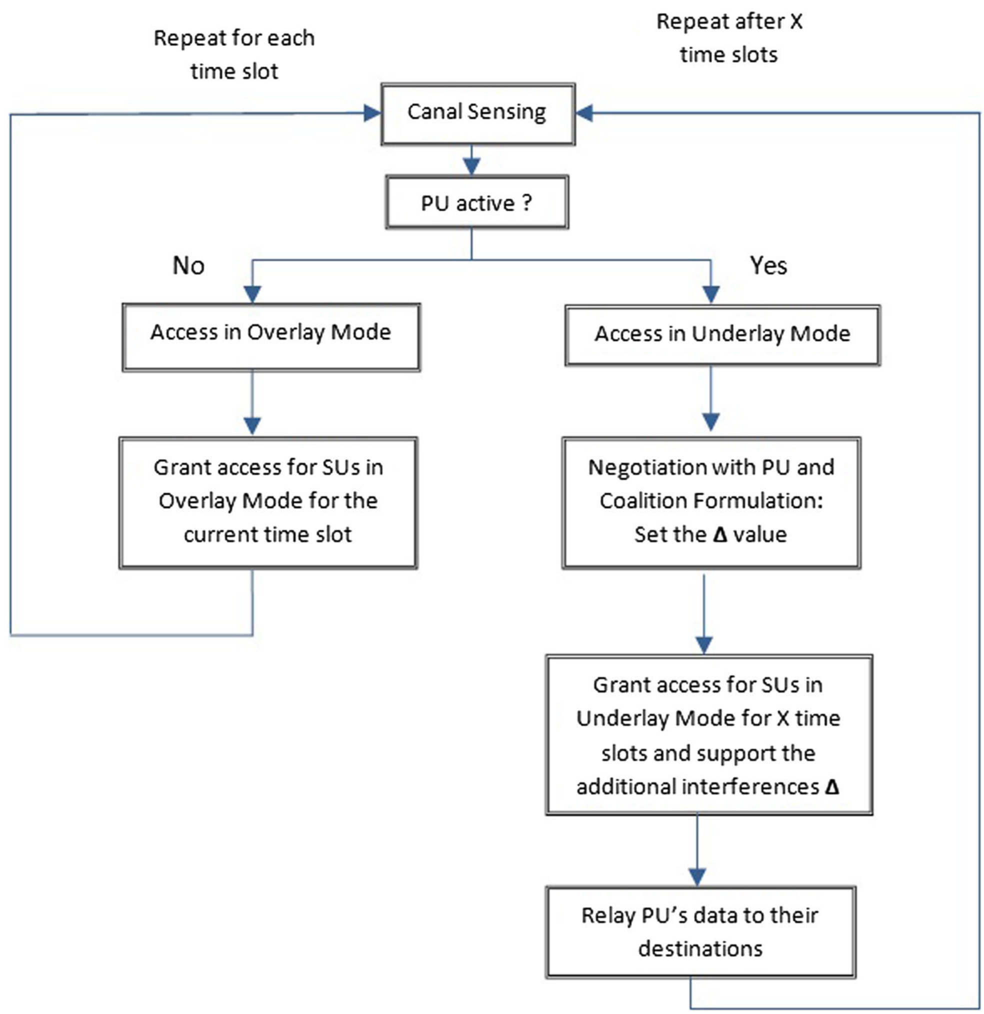

Fig. 3 Relay coalition access algorithm

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 $U(\mathscr{C}_j;\Pi_i)$. In this section, the utility calculation of the coalition will be presented.

In the following, we present our model where SUs act as cooperative relays for PU in order to help him to tramit his messages in exchange for a portion of his licensed spectrum.

In our spectrum sharing scenario SUs can access the radio frequency spectrum in the overlay mode or in the underlay mode simultaneously with primary user.

The value of the aggregated utility $U(\mathscr{C}_j)$ for a coalition C_j is the sum of the utility of each player in the formed coalition. where $j \in \{1, 2, ..., N\}$ and $\mathscr{C}_j \subseteq (N \cup M)$, we can express this aggreated utility value as below:

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

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:

$$U_i = R_i - C_i \qquad (2)$$

Where R_i represents the reward given to SU_i/PU_i and $U(\mathscr{C}_j)$ represents the cost of SU_i/PU_i.

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

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

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

Then, after substitution :

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

Then we have:

The primary transmission rate is giving by:

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

In the equations below, K denotes the communication bandwidth, n_0 is the power of the additive white Gaussian noise, P_s and P_p the transmission power for the SU and the PU respectively, G_s^s and G_p^s are respectively the channel gain for SU and the channel gain from PU's transmitter to SU's receiver.

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 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 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 negociation 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 to SR 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,

$$R_U(SU_i Avrg) = \frac{T - \alpha - \beta - \lambda}{T * X} * W * log_2\left(1 + \frac{P_{si} G_{si}^{si}}{\sigma^2 + \Delta}\right) + \frac{X-1}{X} * W * \sum_{i=1}^{q_j} log_2\left(1 + \frac{P_{si} G_{si}^{si}}{\sigma^2 + \Delta}\right) \tag{13}$$

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:

$$R_{Total(SU,Avrg)} = \frac{Y}{X+Y} * (1 - \Pi_p) * R_O(SU) + \frac{X}{X+Y} * \Pi_p * R_U(SU_i Avrg) \tag{14}$$

In this paper we are considering a scenario in which SUs are trying to transmit data in the uplink to the base station. As SUs are sharing the spectrum with PUs, SUs will cause interference to PUs. In this paper, we have considered N PU and M SUs scenario. SUs negotiate with PUs for the acquisition of underutilized channels with exceeded interference caused to the PU. The PU will support additional interference Δ (presented in the figure above). In turn, he will use the SUs as relays to transmit its messages. This is a win-win solution for both PUs and SUs. The main advantage for PU is that the SUs may either enhance the QoS performance (in our model, the throughput) of PU by relaying the PU's packets towards its destination, or to increase the monetary gain of PUs. Whereas, the main advantage for SU is that, the SUs enhance its QoS performance by obtaining guaranteed channel access (rather than opportunistic access) from PUs.

3.4 Existence of Nash equilibirum

In game theory, the Nash equilibrium is a solution concept of a non-cooperative game involving two or more players, in which each player is assumed to know the equilibrium strategies of the other players, and no player has anything to gain by changing only their own strategy. If each player has chosen a strategy and no player can benefit by changing strategies while the other players keep theirs unchanged, then the current set of strategy choices and the corresponding payoffs constitutes a Nash equilibrium. The Nash equilibrium [13] 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.

Proof Since each CR user has a strategy profile that is defined by a spectrum acces type with some transmission power, thus the first condition is readily satisfied. □

2) The utility function (U_i) is a continuous and quasi-concave function over the strategy set of the players.

Proof 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: □

Explanations: We have:

$$\frac{\partial^2 U_{ab}^{\gamma}}{\partial p_{\gamma}} > 0 \tag{15}$$

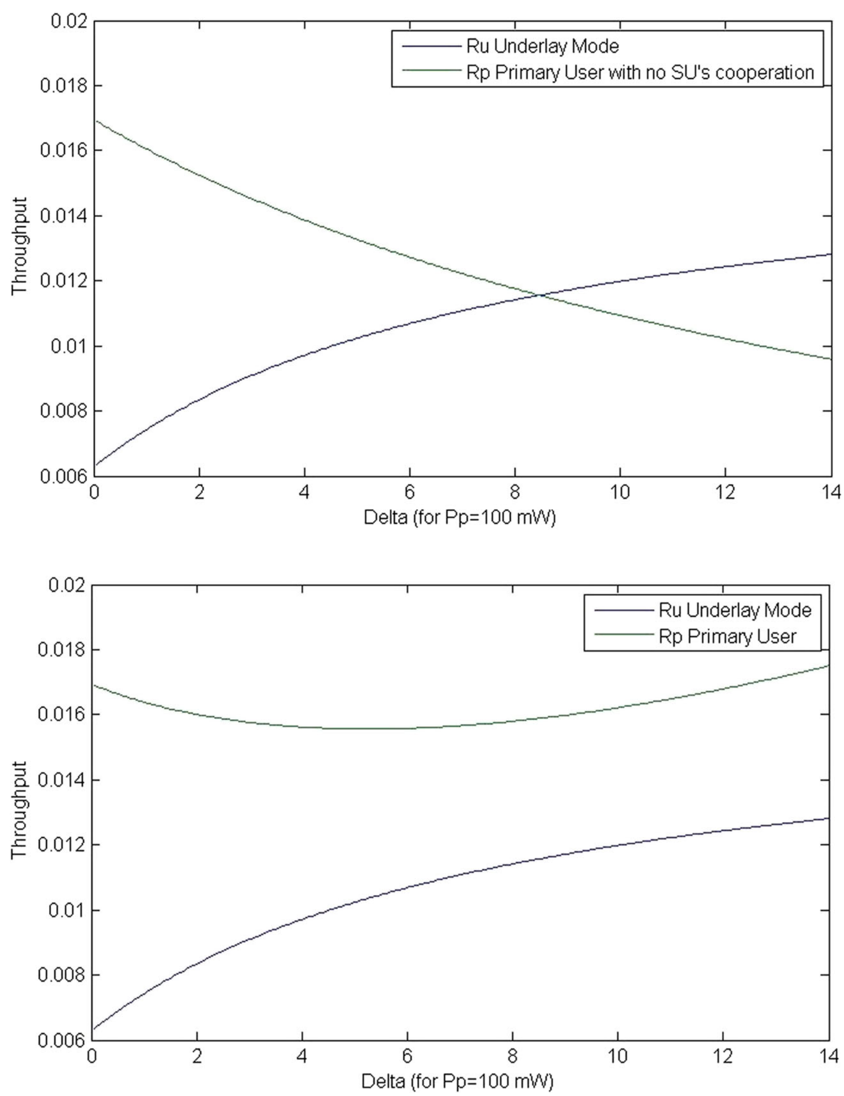

Fig. 4 SU's and PU's throughput variation for a predefined Δ interval without and with cooperation

Nash equilibrium of a game G is a strategy profile $s^* \in S$ such that $\forall i \in I$ we have the following

$$U_i(s_i^*, s_{-i}^*) >= U_i(s_i, s_{-i}^*) \forall s_i \in S_i, s_i \neq s_i^*, \forall i \in I$$

In the Simulations section, we will study the Nash Equilibrium for different values of N, M and Δ.

4 Energy efficiency improvement for the proposed cooperative model

Nowadays, energy efficiency is becoming an important research orientation in wireless network and green communications [16–20]. According to the technical report published by Ericsson [21], by 2020, the number of mobiles connected devices is growing rapidly and will reach more than 50 billion equipments.

In the previous section, we presented our cooperative model and demonstrated the improvement of the throughput for both the PU and the SU. In this section, we will formulate the problem of Energy Efficiency. As shown in Fig. 3, we consider the scenario that a SU accesses the channel in the Overlay Mode or the Underlay Mode (with cooperation with PU for relaying its data). We will evaluate the system energy efficiency to show trade-off metric of energy consumption and throughput. Performance results are presented to validate the cooperative relay framework. Our objective is to maximize the total energy efficiency and also the total throughput while keeping the interference to the PUs not exceeding their specified thresholds.

Nowadays, energy efficiency is an important objective in the analysis and design of wireless networks, in addition to the traditional interest in higher rates and quality of service. According to the technical report from Ericisson [21], by 2020, there will be more than 50 billion connected devices, including sensors, smart phones, IoT devices, etc...

According to [22], energy efficiency can be grouped into three types: circuit power energy consumption, spectrum sensing energy consumption and the last type is data transmission energy consumption. In our paper, we are interested in:

- The spectrum sensing energy consumption for the SU.
- The data ransmission energy consumption for the PU.
- The total energy efficiency for the cooperative relay system.

We will focus on optimizing these two energy consumption modes in order to maximize the energy efficiency of the presented system.

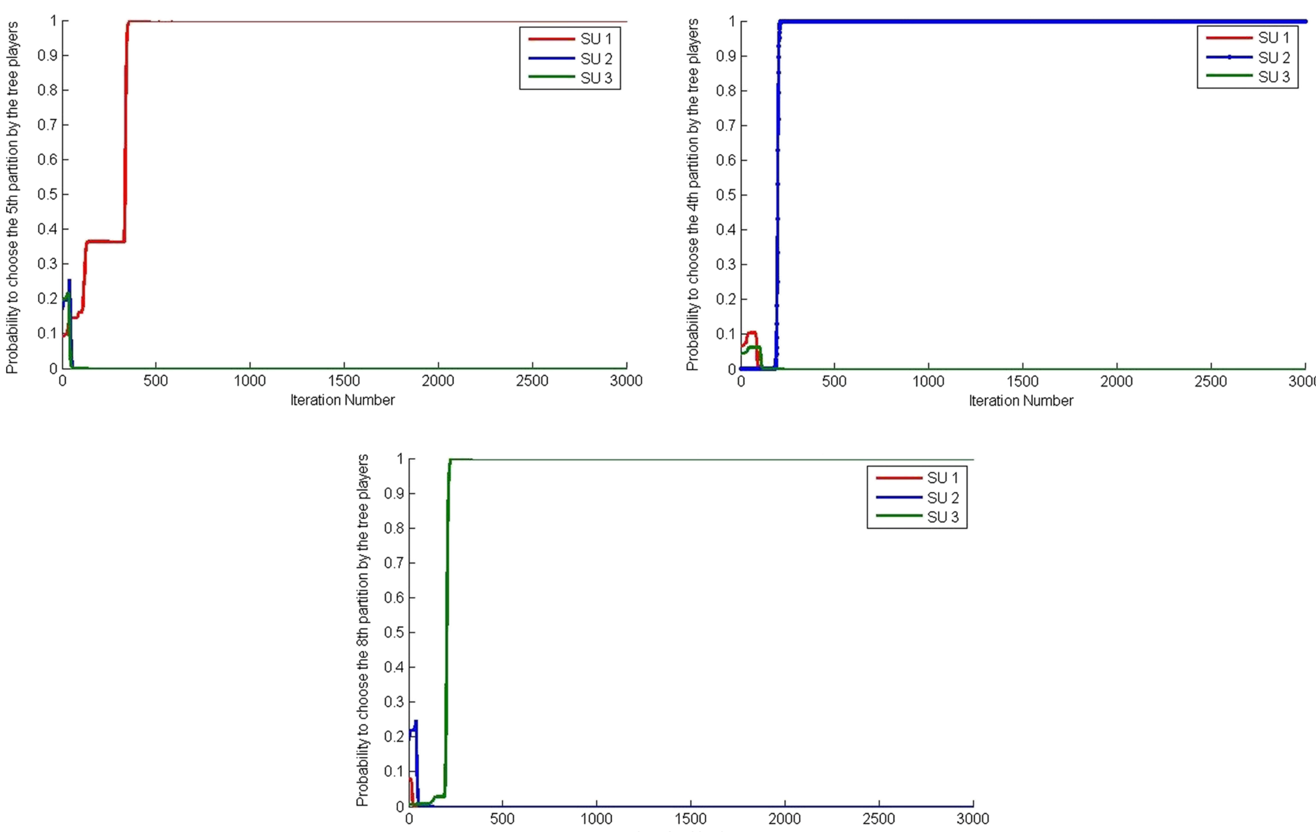

Fig. 5 Probability to choose strategy Π4 Π5 Π8 by the three players for $\Delta_{PU1} = 4$ and $\Delta_{PU2} = 16$

According to [23], the energy efficiency is given by:

$$\phi_{EE} = \frac{D}{E} \tag{16}$$

Where D and E denote respectively, the total amount of transmitted data and total consumption of energy.

In our system, the total energy efficiency for both the PU and SUs in the formed coalition $\mathscr{C}_j$ is expressed as follow:

$$\phi_{EE}^{\mathscr{C}_j} = \frac{D^{\mathscr{C}_j}}{E^{\mathscr{C}_j}} \tag{17}$$

Where:

$$D^{\mathscr{C}_j} = D^{PU} + \sum_{i=1}^{q_j} D^{SU_j} \tag{18}$$

And:

$$E^{\mathscr{C}_j} = E^{PU} + \sum_{i=1}^{q_j} E^{SU_j} \tag{19}$$

As explained above, the amount of transmitted data refers to the throughput of the User (PU or SU).

So we have:

$$D^{\mathscr{C}_j} = R^{PU} + \sum_{i=1}^{q_j} R^{SU_j} \tag{20}$$

The consumption energy can be expressed as:

For the Primary Network, the average energy consumption for $X + Y$ time slots is:

$$E_{Avrg}^{PU} = \Pi_p * (E_D^{PU}(PU) + E_R^{PU}(PU) + E_D^{PU}(BS) + E_{Coal}^{SU}). \tag{21}$$

Where Π_p denotes the probability of PU's presence; $E_D^{PU}(PU)$ represents the energy that the PU sends to his corresponding BS (Base Station) for transmitting its data; $E_R^{PU}(PU)$ represents the energy that the PU user spents to sent to his cooperative SUs for relaying its data; $E_D^{PU}(BS)$ represents the energy spent by the base station in the Primary Network ; and E_{Coal}^{PU} reprents the energy spent for the coalition formation phase.

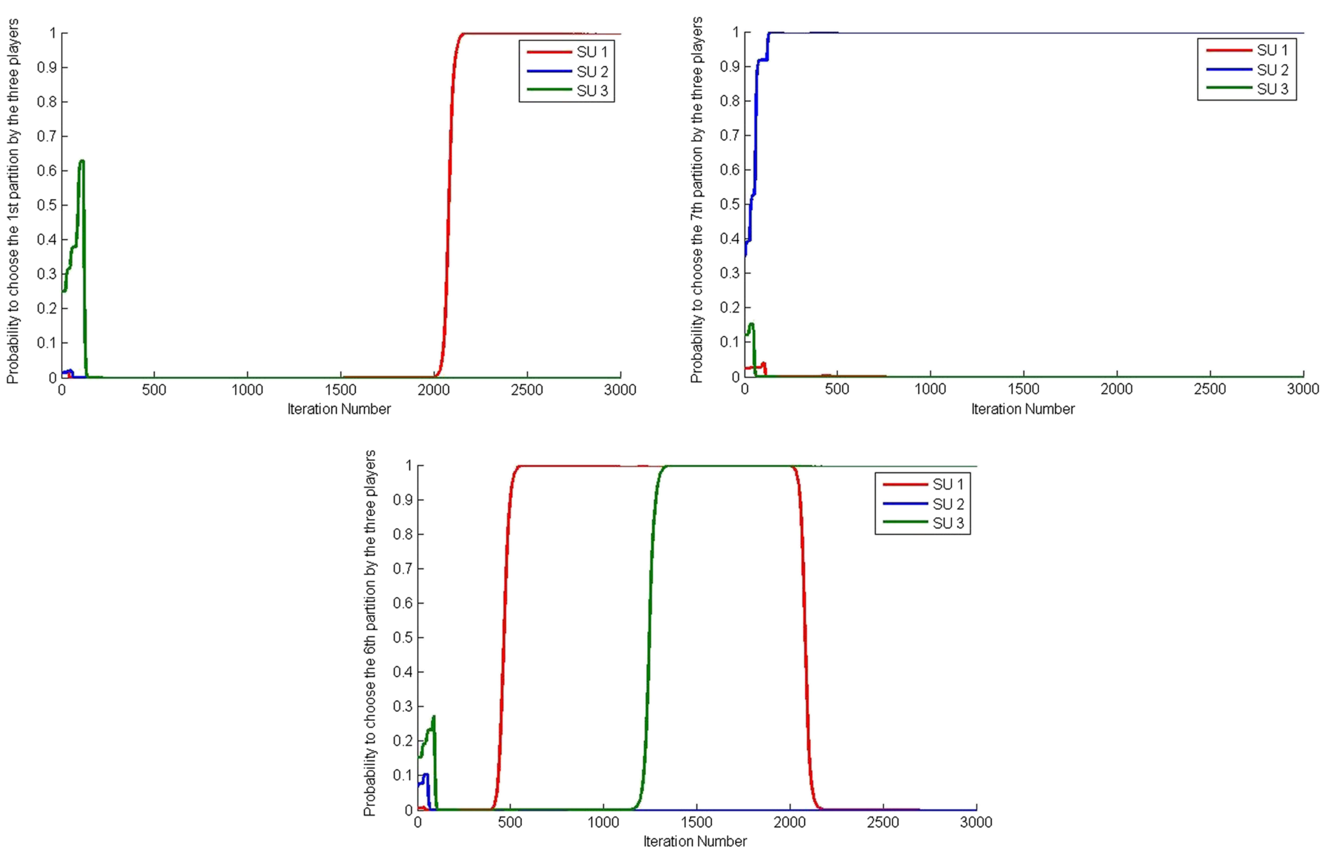

Fig. 6 Probability to choose strategy Π4 Π5 Π8 by the three players for $\Delta_{PU1} = 14$ and $\Delta_{PU2} = 16$

Table 1 Possible Coalitions Structure for $N = 2$ and $M = 3$

$\Pi_1 = \{\{PU_1, SU_1\}, \{PU_2, SU_2, SU_3\}\}$	$\Pi_5 = \{\{PU_1, SU_1, SU_3\}, \{PU_2, SU_2\}\}$
$\Pi_2 = \{\{PU_1, SU_2\}, \{PU_2, SU_1, SU_3\}\}$	$\Pi_6 = \{\{PU_1, SU_2, SU_3\}, \{PU_2, SU_1\}\}$
$\Pi_3 = \{\{PU_1, SU_3\}, \{PU_2, SU_1, SU_2\}\}$	$\Pi_7 = \{\{PU_1\}, \{PU_2, SU_1, SU_2, SU_3\}\}$
$\Pi_4 = \{\{PU_1, SU_1, SU_2\}, \{PU_2, SU_3\}\}$	$\Pi_8 = \{\{PU_1, SU_1, SU_2, SU_3\}, \{PU_2\}\}$

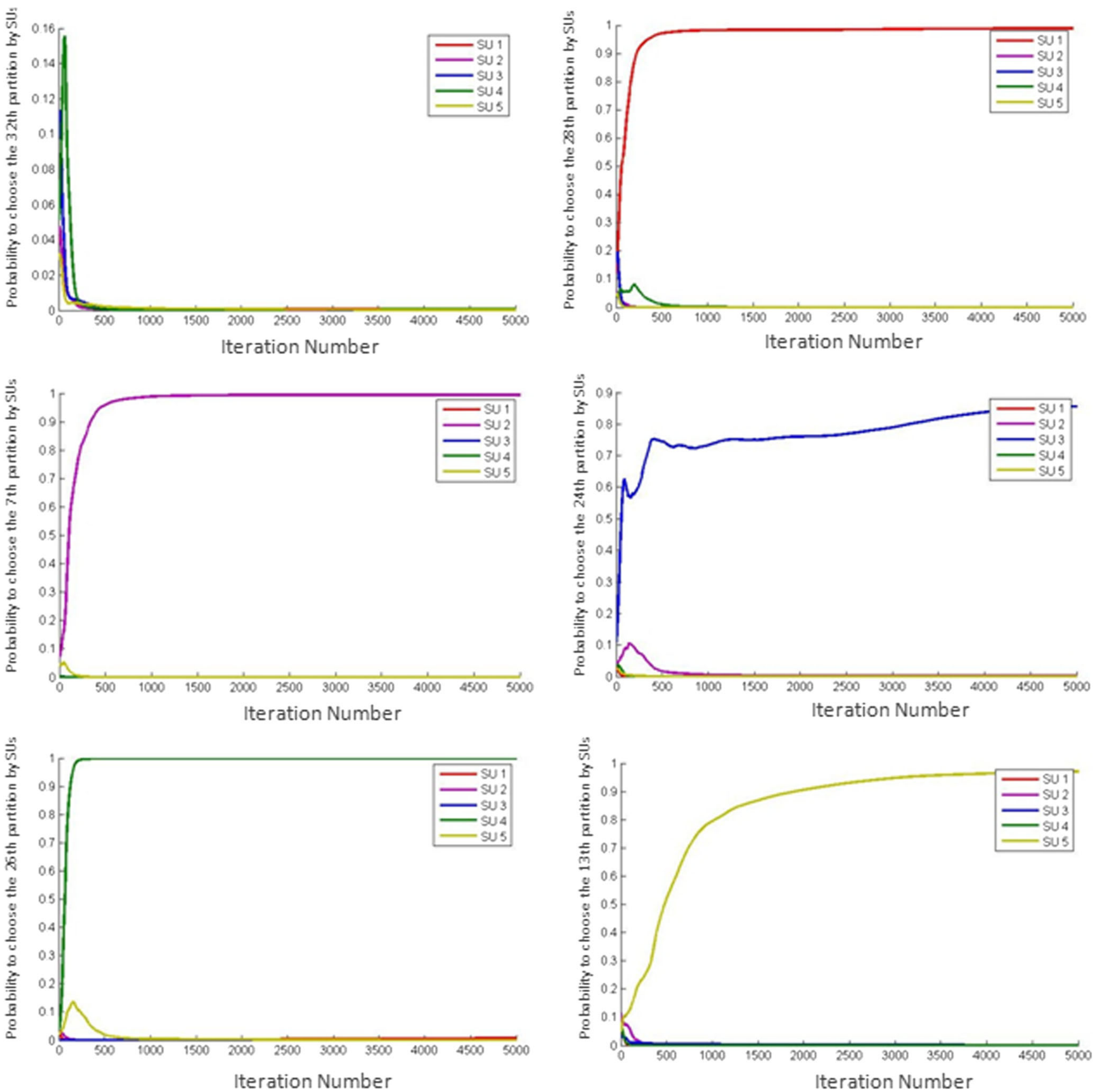

Fig. 7 Coalition formation for collaborative spectrum access

For the Secondary Network, the average energy consumption for $X+Y$ time slots is:

$$E^{SU}_{Avrg} = \frac{Y}{X+Y}E^{SU}_{Sensing} + E^{SU}_{D}(SU) + \frac{X}{X+Y}E^{SU}_{R}(SU) + \frac{1}{X+Y}E^{SU}_{Coal}. \quad (22)$$

Where $E^{SU}_{Sensing}$ represents the energy spent in the sensing phase; $E^{SU}_{D}(SU)$ represents the he energy that SU spents to send his data to his destinations; $E^{SU}_{R}(SU)$ represents the energy spent by the SU to relay PU's data; and E^{SU}_{Coal} reprents the energy spent for the coalition formation phase.

In the next section, extensive simulations are presented to explore and study the performance of the average energy efficiency and the average throughout in our proposed cooperative relay cognitive network (the average is calculated over $X+Y$ time slots).

5 Simulations

In this section, we provide and discuss numerical results about the system performance, to analyze the secondary user throughput. We aim to show by these simulations that both the PU and the SU can achieve reasonable throughput in our proposed cooperative model.

In the following simulations, it is assumed all the channels between every source and destination experience Rayleigh fading. For our simulations, we choose the default parameters as follow: $K = 200kHz$, $Pp = 10mW$, $Ps(underlay) = 0.1mW$, $n0 = 10^{-15}W$; $SINR = 10dB$.

In Fig. 4, 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 [13, 15]. In our paper, we are interested in SU's strategies. Those of the PU will be studied in a future work.

We use the Boltzmann-Gibbs learning Algorithm for two cases: ($N = 2$, $M = 3$) and ($N = 2$, $M = 5$).

For the first case, we plot the probability to converge to the best partition for according to two different values of Δ: $\Delta_{PU1} = 4$, and $\Delta_{PU1} = 16$ (Fig. 5), and for $\Delta_{PU1} = 14$, and $\Delta_{PU1} = 16$ (Fig. 6).

When the Δ value of the PUs are far away from each other, SUs can make decision on which partition to choose, SU_1 chooses partition Π_5, SU_2 chooses partition Π_4 and SU_3 chooses partition Π_8 (presented in Table 1). Whereas when the Δ values are close to each other, SUs can not make decision and the algorithm don't converge after the number of iteration.

In Fig. 7, 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 partition: Π_{28}, Π_7, Π_{24}, Π_{28} and Π_{13} (presented in Table 2). For the strategy Π_{32}, no user converge to this strategy, because the reward for this one is the lowest one : all SUs with the PU that offers the lowest value of Δ.

In Fig. 8, we plot the variation for the energy spent for both PU and SUs for q variation (q refers to the number of the SUs in the coalition). As we can see, when q increase,

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

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

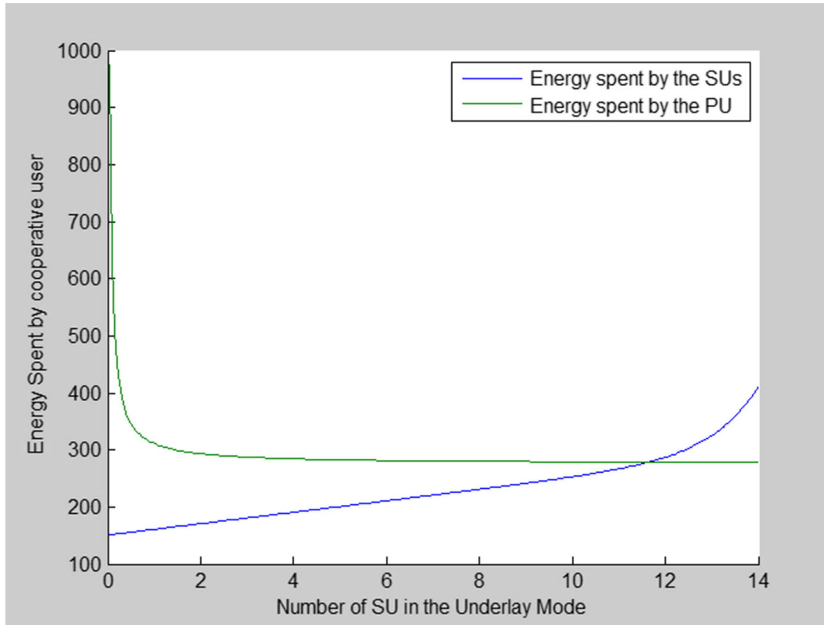

Fig. 8 Energy Spent by PU and SU Network

the energy spent by the all SUs in the coalition increase. On the other hand, the energy spent by the PU decreases; On explain this variation by the cooperative beahvir of the SUs to relay the PU's data.

Figure 9 illustrates energy efficiency for the PU network, the SU Network and for the proposed cooperative model versus the number of SUs in the underlay mode. it's observed from this figure that we get an improvement of the total average energy efficiency of our proposed system with cooperative users. The gain gap for the PU and the SU are also illustrated in this figure.

From these simulations we can say that having a maximum utility (throughput) for players is due to the choice of the partition, 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.

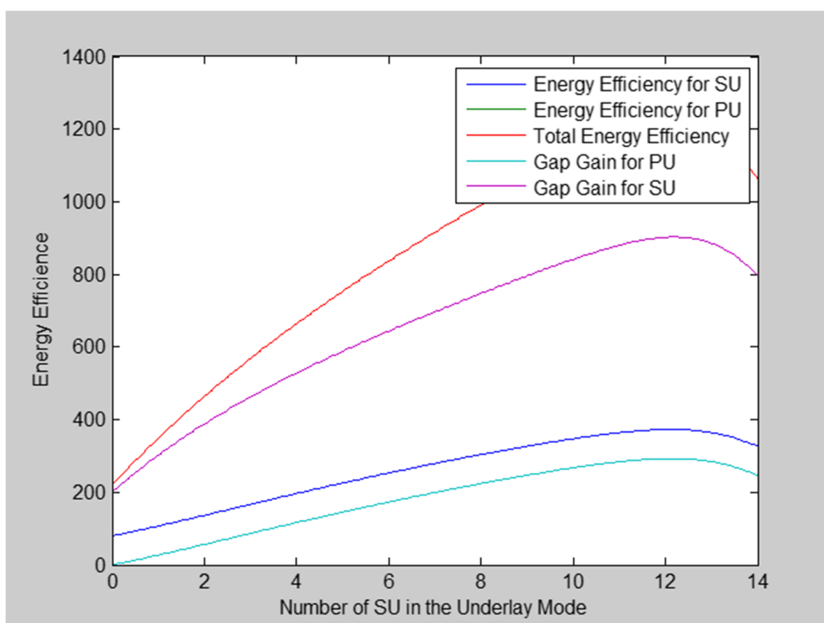

Fig. 9 Energy Efficiency variation

6 Conclusion

In this paper, we have studied the implementation of 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. We have shown that our proposed framework can make a gain and a profit for both the licensed and the unlicensed users. Thus, the performance of the network can be enhanced and improved. We formulate the problem of cooperative spectrum access as a coalition game, and we presented an algorithm for coalition formation used by SUs to choose the best coalition to join. We have also investigated the energy efficiency for both the PU and the SU Network in our cooperative framework wich leads to performance optimization. The simulation results showed that networks performances increase with the proposed scheme especially in terms of the throughput enhancement and energy efficiency and proved that the secondary network is more beneficial than harmful from the primary interference under power and interference constraints.

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