A Hierarchical Stackelberg-Coalition Formation Game Theoretic Framework for Cooperative Spectrum Leasing

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***Abstract*—The problem of cooperative spectrum leasing among multiple primary users (PUs) and secondary users (SUs) is considered. A hybrid Stackelberg-coalition formation game theoretic algorithm is proposed that enables the PUs to identify a group of cooperative SUs by looking at the reputation history of their cooperative behavior. The coalition formation approach also promotes collaboration among the SUs to provide them with a higher chance of spectrum access. The Stackelberg game determines the optimum time allocation among the PUs and SUs individual transmission as well as cooperation time. The results show the performance enhancement of spectrum leasing model, particularly in mobile and dynamic network with a diverse range of SUs initial credits and channel conditions.**

Index Terms- Coalition formation, cognitive radio, spectrum leasing, Stackelberg game.

I. Introduction

Cognitive radio (CR) has emerged as a promising technology to enhance the efficiency of radio spectrum utilization. These techniques are generally categorized into two main approaches of *commons model* and *property right* model [1]. Despite the commons model, where secondary users (SUs) are required to constantly sense the spectrum in an individual or cooperative manner to detect possible transmission opportunities, in the property right model, the primary users (PUs) are aware of SUs presence and can willingly lease a portion of their spectrum in exchange for remuneration or a physical compensation such as relaying service. This may eliminate the chance of harmful interference to the PUs as well as power wastage to SUs due to continuous sensing of the spectrum, while monetary or cooperative relaying benefits are obtained for PUs.

In [1], the spectrum is leased to a secondary ad hoc network, who were assumed to be trustworthy, in exchange for cooperative relaying. The selection of SUs was solely based on channel state information (CSI). However, cooperation is not a natural tendency of selfish users and they may deviate from cooperation after granted with the spectrum. To overcome this, a reputation-based Stackelberg game model was proposed in [2], for cooperative spectrum leasing between a PU and a SU. Both, the PUs and SUs were able to monitor their opponent's cooperative behavior which was taken into account to find the optimum time allocation strategy. In [3], a reputation-based Stackelberg game is proposed that monitors the behavior of the SUs in terms of the power they assign to relaying the PUs' message compared to the power they use for their individual transmission. This model filters out the selfish SUs over the course of time and results in improving the PU's transmission rate. In [4], a Stackelberg-matching game approach was proposed in a multiple PUs- multiple SUs network, where each user can select the best partner for collaboration among the other group noting their cooperation credit.

However, in the previously reported models, the SUs that are present in a neighborhood of PUs for a long time could accumulate a higher credit and are more likely to be selected to occupy the spectrum, while new SUs who have a low initial cooperation credit have a slight chance of being selected. To address this, we propose a Stackelberg-coalition formation model, in which the spectrum is leased to a coalition of SUs, where the members obtain a time portion of spectrum access in a fair manner given their contributions. In this model, the cooperative relaying service for the PUs is guaranteed through the coalition of SUs, while the new SUs will also have the opportunity to access the spectrum by cooperating with other SUs.

Cooperative relaying through a network of SUs, to enhance the transmission performance of the PUs, has been studied in many papers. In [5], the SUs were used as a cooperators that can increase the PUs transmission performance. The available SUs were selected based on their short term effective bit rate and long term expected throughput using an optimum stopping rule, where the first SU with the expected throughput was selected as the cooperative relay. In [6], the PU selects a SU which is not transmitting or receiving at the time, to relay its data and in return the SUs can transmit whenever they are not interfering with the PU. Based on optimum power ratio between the PU and SU, the maximum achievable transmission capacity of SU under outage constraints for both PU and SU with and without cooperative relaying was compared and it was shown that a higher transmission rate can be achieved by cooperative relaying.

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Coalition formation (CF) is a class of game theory, where an agreement is made among a set of players to act as a single entity in order to strengthen their position in interaction with other players of the game [7]. CF games have been used to optimize the performance of cooperative networks [8]. In [9], distributed cooperation with cost among single antenna users to study the gains resulting from fair cooperation among them for virtual MIMO formation is modeled. With the aim to find an ultimate transmitter coalition structure which maximized the utility of cooperating users while accounting for the cost of CF, a simple distributed merge and split algorithm for CF was proposed. This algorithm allowed them to self organize into stable disjoint coalitions [9]. CF games have been also utilized to model spectrum sensing in CR networks (CRN). A similar merge and split algorithm for CF was used in [10], where the trade-off between topology and dynamics of a network of SUs in a commons CR model was studied. The study has shown to reduce the missing probability per SU while maintaining a certain false alarm rate.

In [11], a cooperative spectrum sensing and accessing (CSSA) scheme was formulated as a CF game and a distributed algorithm was proposed to form stable coalitions. The utility function of each coalition accounted for sensing accuracy and energy efficiency. The distributed CSSA allowed the maximization of aggregate utility of all coalitions in the system compared to a non-cooperative sensing and accessing scheme. In [12], sensing- throughput trade-off problem was formulated using CF game in common CR model. The paper proposed coalitions based on increasing individual gains (selfish) and increasing the overall gain of the group (altruistic) and a comparison between them in spectrum sensing was presented. The altruistic game provided significant gain in terms of reducing false alarm probability and increasing the throughput per user compared to the selfish approach.

In this paper, we address the problem of cooperative spectrum leasing, where a portion of spectrum access is leased to a coalition of SUs as opposed to a single user using a reputation based mechanism. A record of SUs contribution in providing relaying service for the PUs is stored in a cooperative credit parameter. All SUs are assigned with an initial credit that can be improved over the course of time, noting their cooperative behavior as well as their channel conditions. The PUs prefer to select a SU or a group of SUs with higher credit to ensure that they will receive a better relaying service. Therefore, the SUs may prefer to join a coalition to have a higher chance of spectrum access while considering the cost of participating in a coalition.

To the best of our knowledge, the proposed model is the first work to consider, a reputation-based CF for cooperative spectrum leasing. The proposed model increases the PU's performance through cooperative relaying via a coalition of SUs with the highest cooperative credit, while it also enables the SUs with a wider range of cooperative credits to get a chance of spectrum access. This could provide a practical solution to facilitate a reliable cooperative relaying in a highly dynamic network.

The rest of this paper is organized as follows: the system model is described in Section II. The proposed hybrid Stackelberg-Coalition formation game model is defined in Section III. Section IV presents the numerical results followed by the concluding remarks in Section V.

II. System Model

Consider a CRN consisting of M PUs, with orthogonal channels and N SUs, $SU_1, SU_2, \ldots, SU_N$. Shadowing can cause a poor quality link between a Primary Transmitter (PT) and Primary Receiver (PR) which may prompt the PU to take advantage of cooperative communication and use the SUs as relays in exchange for spectrum access.

Assume that s_p and s_{s_i} are the PU's and SU_i's messages where $E\{s_p s_p^*\} = E\{s_{s_i} s_{s_i}^*\} = 1$ for $i = 1, \ldots, N$. P_{P_t} is the power required by the PT to send the message s_p. P_{iP_R} represents the power utilized by the SU_i to relay the s_p and P_i represents the power used by the i^{th} SU for its own transmission. The total available power at SUs is represented by P_{i_T}. The noise spectral density is represented by N_0.

The channels among all the users are modeled as slow Rayleigh fading channels, that are invariant during one time slot. The parameters $h_{P_T i}$ and h_{iP_R}, $i = 1, \ldots, N$, represent the complex channel coefficient between PT and SU_i and between SU_i and PR, respectively. The channel coefficients between SU_i, $i = 1, \ldots, N$ and their destinations are represented by h_i. The parameters related to the system model are summarized in Table I.

TABLE I
Parameter Definition

P_{P_T}	PU Transmission power
P_{iP_R}	Relaying Power for i^{th} SU
P_i	Transmission power for i^{th}SU
P_{i_T}	Total Power for i^{th} SU
$\|h_{iP_R}\|$	Channel gain between i^{th} SU and PR
$\|h_{P_T i}\|$	Channel gain between PU and i^{th} SU
$\|h_i\|$	Channel gain between i^{th} SUs transmitter and receiver

A cooperative credit, C_i is assigned to each SU to keep a record of its participation in providing relaying service for PUs. The PUs prefer to select a SU or

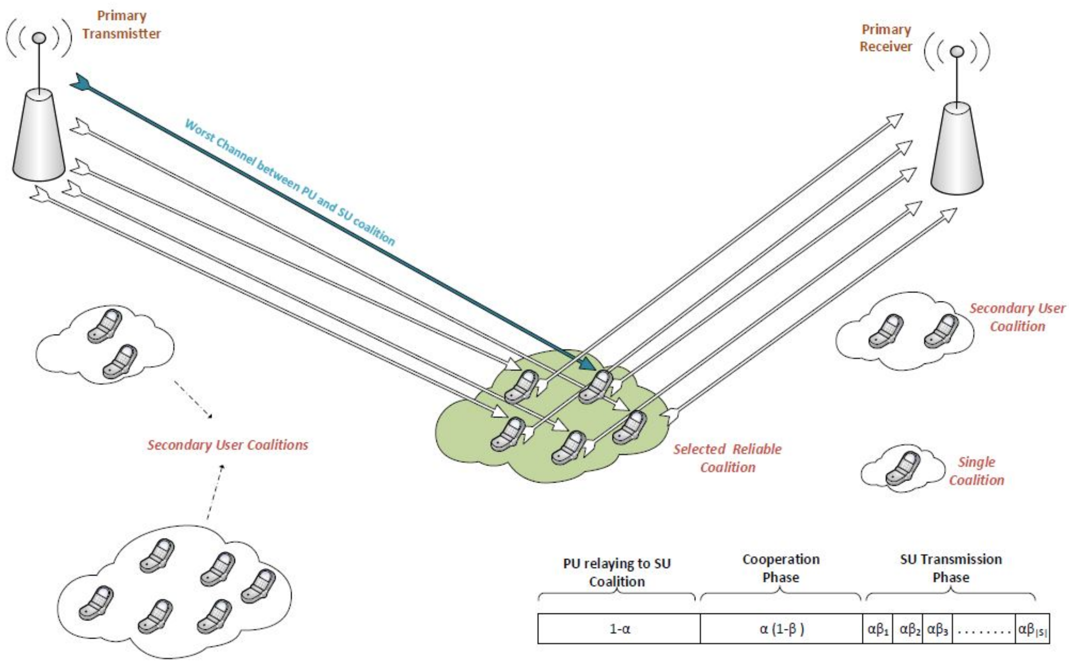

Fig. 1. An illustrative example of coalition formation for cooperative spectrum leasing and associated time slot allocation among the users.

a group of them with the highest credit. This can encourage the SUs to form coalitions, to increase their chance of being selected by the PU for cooperation in exchange for spectrum access, while providing a better quality of service for the PU through cooperation. A detailed description of CF is provided in section III. In the proposed Stackelberg- CF game, the PU is the game leader and selects a coalition of SUs with the highest sum of individual credits as the winning coalition, $\mathcal{C}^{opt}$.

Stackelberg game is utilized to allocate time portions of spectrum access to PU and SUs. For generalization, we assume that the length of total time slot is 1. The total time slot is divided into three time phases, where in the first portion $(1-\alpha)$, PT broadcasts its message and the SUs receive and fully decode the PU message utilizing a Decode and Forward (DF) method. In the second portion $\alpha(1-\beta)$, the selected relay coalition forwards the decoded PUs message to the PR. As a compensation for the DF relaying by $\mathcal{C}^{opt}$, the PU allows the SUs in $\mathcal{C}^{opt}$ to access the spectrum in the remaining portion of the time slot i.e., $\alpha\beta$. This portion of time slot, is fairly partitioned among the SUs in $\mathcal{C}^{opt}$ based on their credits into $\alpha\beta_1, \ldots, \alpha\beta_{|\mathcal{C}^{opt}|}$, where $|\mathcal{C}^{opt}|$ represents the number of SUs in $\mathcal{C}^{opt}$. Hence the SUs in $\mathcal{C}^{opt}$ can transmit their messages to their own destinations in a Time Division Multiple Access (TDMA) manner. After the s_p is relayed by $\mathcal{C}^{opt}$, the PU updates the cooperative credit of the SUs in $\mathcal{C}^{opt}$ by ΔC. The Credit encapsulates the truthfulness of a user in cooperation, reflecting the amount of power assigned to cooperation in previous time slots. Every SU is initialized by a Credit C_i^0, which can be improved over time by the PU after relaying its data. This can encourage cooperation among SUs and also allow the PU to keep track of their cooperative behavior.

III. Game Definition

In this section, we define the proposed distributed Stackelberg-coalition formation game for spectrum leasing. Dynamic coalitions with transferable utility are formed and represented by $\mathcal{C}_{\mathcal{J}}$ where J varies from 1 to the number of SU coalitions. The proposed game is not super additive, since the portion of spectrum received by each user after relaying reduces, as the number of users in the coalition increases. The SUs will follow a merge and split algorithm, to form coalitions. In the following subsection, the corresponding payoffs and the merge and split algorithm for coalition formation are discussed in detail.

A. Coalition Formation

In the proposed model, the PU selects the coalition with the highest summed credit as the winning coalition. Therefore, the SUs prefer to form the coalitions with maximum possible summed credit. However, this coalition formation comes with the cost of extra signaling among the coalition members to exchange the essential information such as Credit. As the number of SUs in a coalition increases, it increases the summed credit of that coalition, but it will cause a decrease in the access time to the spectrum allocated to each SU. The complexity order of such signalings' is $\mathcal{O}(|\mathcal{C}|^2)$. Therefore, the following function is defined as a value of a coalition:

$$v(\mathcal{C}) = \sum_{i\in\mathcal{C}} C_i - \eta_C|\mathcal{C}|^2, \quad (1)$$

where η_C is a constant design parameter to ensure that both terms in the value function are in the same range and $|\mathcal{C}|$ represents the number of users in the coalition. Communication cost to SUs for broadcasting its Credit information is unavoidable, in order to form best coalitions.

The payoff function (1) is used in the merge and split algorithm as a joining or leaving criterion for the members to form coalitions. The merge and split algorithm starts from a partition of the SUs set where all SUs are disjoint i. e. $\{\{SU_1\},\{SU_2\},\ldots,\{SU_N\}\}$ as an initial state. It is worth mentioning that these initial coalitions are used only for the first run of the game. After the first run, the output of the merge and split algorithm is used as the initial state for the next run of the game. After initializing, the algorithm merges any two coalitions $\mathcal{C}_m$ and $\mathcal{C}_n$ that satisfy the condition $v(\mathcal{C}_m \bigcup \mathcal{C}_n) > v(\mathcal{C}_m) + v(\mathcal{C}_n)$. Later, the algorithm splits any coalition $\mathcal{C}$ with more than two members into $\mathcal{C}_1$ and $\mathcal{C}_2$ if $v(\mathcal{C} = \mathcal{C}_1 \bigcup \mathcal{C}_2) < v(\mathcal{C}_1) + v(\mathcal{C}_2)$. The CF process is summarized in Algorithm 1. The partitioning output of the above algorithm is $\mathcal{D}_{hp}$ stable since the algorithm allows the players to leave the partition only by means of merging or splitting [13]. After forming the coalitions, the PU will be notified of the coalition structures so that, it can select the coalition with highest summed credit i.e., $\mathcal{C}^{opt}$ as the relay coalition.

B. Primary Utility

The strategy of PU includes, selecting the best SU coalition, $\mathcal{C}^{opt}$ and calculating the corresponding time allocation parameters α and β. The SUs will select the power required to relay s_p, based on the value of α and β provided by the PU. Assuming $E\{s_p s_p*\} = 1$, the PUs' rate though cooperation with DF relaying can be expressed as the minimum of the down-link and up-link rates. On the other hand, the cost for obtaining this rate is the energy required by PU to transmit s_p to the relay coalition. Therefore, the PU's utility can be defined as:

$$\begin{aligned} U_P &= \log\left(\min\{R_{P_T i}, R_{iP_R}\}\right) \\ &- \frac{\eta_2}{N_0}(1-\alpha)P_{P_T} \end{aligned} \quad (2)$$

$$R_{PT_i} = (1-\alpha)\log_2\left(1 + \frac{P_{P_T}\min_{i\in\mathcal{C}^{opt}}|h_{P_T i}|^2}{N_0}\right) \quad (3)$$

$$R_{i_{PR}} = \alpha(1-\beta)\log_2\left(1 + \frac{\Sigma_{i\in\mathcal{C}^{opt}} P_{iP_R}|h_{iP_R}|^2}{N_0}\right) \quad (4)$$

where $R_{P_T i}$ represents the worst channel between PT and $\mathcal{C}^{opt}$, R_{iP_R} represents the channel between $\mathcal{C}^{opt}$ and PR, and η_2 is the design parameter to ensure that the cost to relay information to $\mathcal{C}^{opt}$, is in the range of communication rate. The PU selects the time allocation parameters, α and β in such a way that its utility is maximized. In order to find the optimal values for α and β, knowledge of P_{iP_R}, $i \in \mathcal{C}^{opt}$ is required. In the next subsection, the optimization problem to find the optimum cooperation power for each individual SU in $\mathcal{C}^{opt}$ is provided.

C. Optimal Cooperation Power for SUs

The strategy of the SUs is to select which coalition to join in order to have a higher chance of spectrum access, and the members of the winning coalition also need to determine their transmission power P_{iPR} considering the trade-off between obtaining a higher transmission rate and keeping a good cooperative credit. By assuming $E\{s_{s_i} s^*_{s_i}\} = 1$, the communication rate for SU_i is given by:

$$R_i = \alpha\beta_i \log_2(1 + P_i\frac{|h_i|^2}{N_0}), \quad (5)$$

where, P_i is the power required by SU_i for its own transmission. Considering the power constraint $P_i + P_{iP_R} \leq P_{i_T}$ for all $i = 1,\ldots,N$, maximizing the equation (5), suggests that each SU exhausts its total power, P_{i_T} for its transmission. However, this strategy may reduce the trustworthiness of the mentioned SU for later selections. Therefore, the smart SUs will try to increment their credit while optimizing their own communication rates. The incremented credit for each individual SU_i, $i \in \mathcal{C}^{opt}$ can be defined as:

$$\begin{aligned} \Delta C_i &= (1-\beta)P_{iP_R} - \beta_i P_i \\ &+ \eta_1 \min\{P_{P_T}|h_{P_T i}|^2, P_{iP_R}|h_{iP_R}|^2\}, \end{aligned} \quad (6)$$

where the first and second terms represent the energy consumed by SU_i for relaying and for own transmission, respectively. The third term, encompasses the effect of CSI provided by SU_i and η_1 is a design parameter to make sure that all parameters are in the same range.

As a result of the above discussion, each SU is willing to optimize a multi-objective problem (maximize R_i and maximize ΔC_i). In our design, we assume that the SUs select the optimal solution which maximizes $R_i \times \Delta C_i$ among all pareto optimals. In the next subsection, the optimization solution to find the optimal value of α, β and P_{iP_R}, $i \in \mathcal{C}^{opt}$, is provided.

D. Optimization Solution

The PU is responsible for calculating the variables α and β with the aim to increase its utility and the SUs in the coalition $\mathcal{C}^{opt}$ calculate the optimum values of P_{iP_R} in such a way that $R_i \times \Delta C_i$ is maximized, given the values of α and β from PU. Therefore, a solution should be provided to calculate the optimum values of both perspectives, simultaneously. The PU starts with initial values of P_{iP_R} and maximizes (2) using the interior point method while including the constraints that the variables α and β remain in the interval [0,1]. The optimal solutions α^1 and β^1 are used as parameters to optimize $R_i \times \Delta C_i$. The time slot $\alpha\beta$ is fairly distributed among all SU_i, $i \in \mathcal{C}^{opt}$, proportional to each members' credit, such that $\beta_i = \frac{C_i}{\sum_{j \in |\mathcal{C}^{opt}|} C_j} \beta$. Using these initials and including the constraint $0 \leq P_{iP_R} \leq P_{i_T}$, $R_i \times \Delta C_i$ of the SU_i will be maximized using the interior point method, whose solution is $P^1_{iP_R}$, $i \in \mathcal{C}^{opt}$. This routine is repeated and in n^{th} turn, the value of $P^{n-1}_{iP_R}$, $i \in \mathcal{C}^{opt}$ and later α^{n-1} and β^{n-1} are used as parameters for their corresponding optimization problems. A termination criterion is defined as $\frac{\|\mathbf{p}^n - \mathbf{p}^{n-1}\|}{\|\mathbf{p}^{n-1}\|} \leq \epsilon$, where $\mathbf{p}^n = [\alpha^n, \beta^n, P^n_{iP_R}, \ldots, P^{|\mathcal{C}^{opt}|}_{iP_R}]^T$ and ϵ is a small value.

IV. Numerical Analysis

For simulation, a CRN consisting of one PU and five SUs is considered. All channels among the nodes in the network are generated as complex zero-mean Gaussian random variables. An initial credit of 0.2 is assumed for each SU. A numerical experiment is performed for 300 runs of the game. At each run, after performing the merge and split algorithm, the coalition with highest sum credit is selected as a relay coalition, $\mathcal{C}^{opt}$. The game solution of the joint PU utility and $R_i \times \Delta C_i$ optimization is obtained and the SU_i's credit is incremented by ΔC_i, $i \in \mathcal{C}^{opt}$.

The value of α was calculated against different values of SNR between the PU and worst channel in $\mathcal{C}^{opt}$. Fig. 2 shows an increase in the value of α with the increase in SNR. This means that, the incentive of PU increases as the quality of relay links is improved.

Algorithm 1: CF game in the proposed model.

1. The partition of SUs, where all the SUs are disjoint is selected as the initial state.
2. Merge and split rules are applied in order to form coalitions as follows.

Input: η_C, η_1, η_2, $initalCredit$, Number of SUs (N).

Output: Coalitions Formed after a specific number of runs or time slots (R).

```
begin
  – Initially all the SUs are disjoint
  for x ← 1 to R do
    for i ← 1 to N do
      for j ← 1 to N do
        if value(i ∪ j) ≥ value(i) + value(j) then
          –Merge the two coalitions i and j
    for l ← 1 to N do
      for m ← 1 to N do
        if v(C = l ∪ m) < value(l) + value(m) then
          –Split the coalition
    3. The coalition with the highest sum of Credit is selected as the relay coalition
       by the PU. The parameters α and β are calculated by the PU for the selected
       coalition and P_{iP_R} is calculated by the SU_i using the described optimization process.
    4. The PU sends its data to the selected relay coalition in the time slot, (1 − α).
    5. The relays coalition relays PU's message to PR in the time slot, α(1 − β).
    6. The selected coalition is granted access to the spectrum in the time slot, αβ,
       which is divided among the relays proportional to its Credit.
    7. The PU increments the credit of the selected relay coalition based on the power
       they assigned for relaying and their individual transmission and their CSI.
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As the PU's energy cost of relaying information, η_2 increases, the value of α increases. The value of α assigned also increases with an increase in the effect of CSI on Credit, η_1.

The rate of PU by applying the CF game is compared to the scenarios in which a single relay is selected based on credit or knowledge of CSI.

Fig. 3 shows that our proposed method outperforms

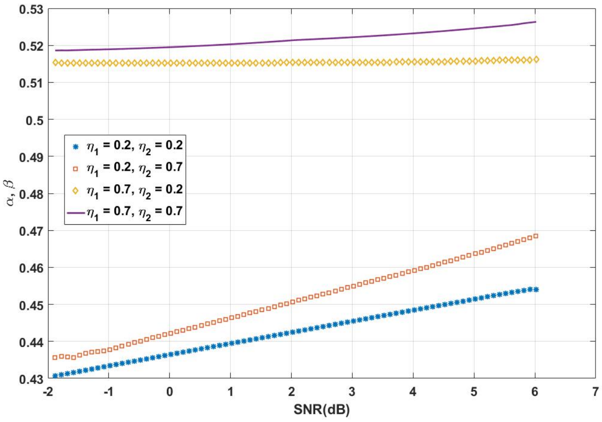

Fig. 2. The value of α plotted against the Signal to Noise Ratio of the worst channel between PU and $\mathcal{C}^{opt}$

the other two scenarios in which the best relay is selected only based on credit or solely based on the CSI. This figure shows that our proposed approach, allows us to take advantage of the diversity through reliable SUs and gain better performance over the other scenarios. Moreover, these three methods are compared to the case that the relay is selected randomly. A monte-carlo simulation is performed to obtain the average rate of the PU, see Fig. 3.

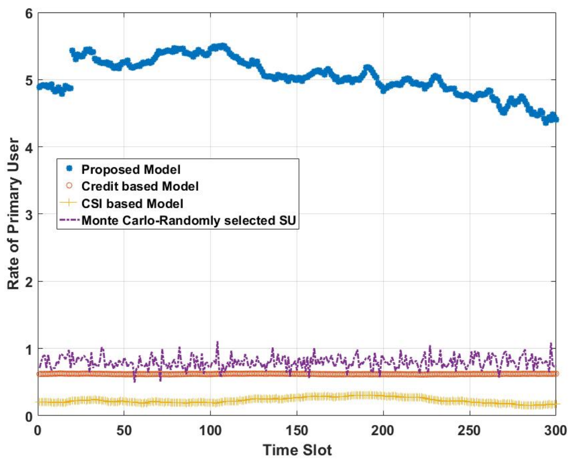

Fig. 3. Comparison of the PUs rate for the proposed game theoretic model versus selecting the SUs in a random manner, or only based on their credit or based on the knowledge of CSI.

V. Conclusions

The cooperative spectrum leasing among multiple primary users (PUs) and secondary users (SUs) is considered. A credit-based hybrid Stackelberg-coalition formation game theoretic model is proposed where a merge and split algorithm is used to form the coalitions. The results indicate that the proposed model provides the PU with a higher transmission rate through working with a group of reliable SUs. Moreover, this model enables a new SU with a potential low initial cooperation credit to get a chance of spectrum access by joining a coalition of SUs, while assuring a reliable relaying performance for the legitimate PU.

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