Hybrid Relay Forwarding and Interference Mitigation Mechanisms in Cooperative Cognitive Ad-Hoc Networks

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Abstract—In this paper, a cooperative cognitive ad-hoc network is considered where a primary user and secondary users coexist with an interference user. A hybrid cooperation mechanism is proposed which allows secondary users to cooperate with primary user by forwarding the interference user's data as well as conventionally forwarding the primary user's data. The proposed scheme provides a more flexible approach that the secondary user can select the relay method according to channel state information. The primary user would release a reasonable portion of spectrum in return for data relay (so the primary user could improves throughput), while the secondary users could earn more spectrum access rights. When there is an interference user, secondary users could choose a method to help primary users by relay forwarding or interference mitigation depending on its own channel quality. With an aim of maximizing primary user's rate and minimizing the secondary users' energy consumption, a Stackelberg game framework is introduced in which a primary user is modeled as the leader and multiple secondary users are modeled as followers. The secondary users control their power to cooperate with the primary user to optimize game utilization. The existence and uniqueness of the proposed game's equilibrium is proved and a distributed iterative algorithm is designed to reach the game equilibrium. Numerical results show that the proposed hybrid relay forwarding and interference mitigation mechanism outperforms the single cooperation scheme when an interference user exists.

Index Terms—cognitive ad-hoc networks, cooperative communication, relay forwarding, interference mitigation, game theory

I. INTRODUCTION

In recent years, the exhaustion of spectrum resources has become a serious problem due to the inefficiency of conventional spectrum allocation policies. Cognitive radio (CR) networks [1] and [2] which provide secondary users (SU) dynamic spectrum access to the spectrum holes of primary users (PU) have attracted significant research attentions because of its ability to improve the spectrum resource efficiency [3]-[6].

Cooperative communication is another emerging communication approach which has great potential to increase the capacity of communications and reduce the path loss and fading in wireless networks [7]-[9]. Cooperative communication allows relays to cooperate as a virtual antenna array and forms a virtual multi-input-multi-output (MIMO) system to transmit data from source to destination; the data of the source node is transmitted not only by itself, but also by the cooperative relay nodes. Cooperative communication can greatly increase the reliability of wireless communication.

To take advantage of the above two communication approaches, cooperative communication has been introduced into cognitive radio networks as cooperative cognitive network in recent researches [10]-[20]. There are three means of cooperation in cognitive radio networks [10]: i) cooperation among primary users; ii) cooperation among secondary users; and iii) cooperation between primary and secondary users. Classes i) and ii) can be regarded as conventional cooperative communications within the context of cognitive radio networks [11]-[15]. However, class iii) is infeasible in conventional cognitive radio for it requires consultations and interactions between PU and SU.

Several schemes have been proposed for the cooperation between primary and secondary users. In [16], the authors jointly encode PU and SU's data and transmit in the PU's spectrum in order to maximize the total transmission rate. However this approach assumes that SU have full knowledge of PU's data packet, an assumption that is not feasible in most of scenarios. The authors in [17] propose an improved scheme that SU forward PU's failed data packet and its own data in the spectrum holes at the same time using dirty-paper coding [18]. However, from the aspect of SU, helping PU's transmission with no profit is not reasonable, so in [19], the authors propose a spectrum leasing scheme in which PU releases its spectrum for a portion of time to SU and SU relays PU's data packet to PU's destination in another portion of time in return; a Stackelberg game is introduced to analyze the proposed problem. In [20], the authors import a relay node to forward PU and SU's data in order to improve the spectrum utilization. Comparing with the scheme in [19], the authors in [10] propose a protocol that SU can assist to relay PU's signals in exchange for spectrum released by PU in the frequency domain, provide a potentially continuous service for SU. These approaches above take SUs as relay nodes that help

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forward PU's data; this paper will refer to the above as "relay forwarding".

The current research in cognitive networks often assumes that no independent interference users (IU) exist. In many cases, however, an interference user (IU) with high transmission power that affects both PU and SU could exist. Recently, another form of cooperative communication technology called interference mitigation in which relay nodes forward the interference user's data instead of PU's data in order to help the destination node separate the interference user's signal more efficiently has been proposed. It has been shown in [21]-[23] that the performance of the interference mitigation approach can surpass relay forwarding in some cases especially when the channel quality from the interference node to the relay node is better than the quality from the source node to the relay node. However, [21], [22] considers only the cooperative communication system and the work in [23] mainly focuses on the outage performance in hybrid automatic repeat request (HARQ) processes with only one relay node.

This paper considers the scenario of a cognitive radio network where a primary user and multiple secondary users coexist with an interference user; a hybrid mechanism is proposed which allows secondary users to cooperate with the primary user by forwarding the interference user's data as well as conventionally forwarding the primary user's data. Different from [10]-[20], an interference user that affects both the primary user and secondary users is present in the network; different from [23], the proposed scheme provides a more flexible approach for secondary users to cooperate with the primary user since SU can choose its strategy to cooperate by relay forwarding or interference mitigation. Unlike previous works, this paper also takes into consideration the interference user in cognitive radio environment and introduces the hybrid cooperation relay method that combines data forwarding with interference mitigation.

More specifically: while in cooperation with secondary users, the primary user could improve its transmission rate by setting a reasonable portion of released spectra and secondary users could choose a way to help the primary user by relay forwarding or interference mitigation depending on its own channel quality. The secondary relay user could select the data forwarding or interference method according to the channel state information. A Stackelberg game with the aim of maximizing obtained spectrum bandwidths, and jointly maximizing primary user and secondary users' utilities, is formulated to decide SU's power consumptions. A Stackelberg game is formulated to decide SU's power consumptions, aiming at maximize obtained spectrum bandwidths, and jointly maximize primary user and secondary users' utilities. The primary user is modeled as the leader and secondary users are modeled as followers. Furthermore, the existence and uniqueness of the proposed game's equilibrium is proved and a distributed iterative algorithm is given to reach the equilibrium. Numerical results show that the proposed hybrid cooperation mechanism has a good performance when an interference user exists.

The rest of this paper is organized as follows: Section II describes the system model; Section III specifies the process of the proposed hybrid cooperation mechanism and formulates utility functions for the resource allocation problem; Section IV describes the resource allocation problem as a Stackelberg game and proposes an effective iterative update algorithm to reach the game equilibrium; Section V gives the simulation results; and Section VI concludes the paper.

II. System Model

The cooperative cognitive ad-hoc network model is shown in Fig. 1; it consists of a primary user pair composed of a primary transmitter (PT) and a primary receiver (PR), and K ad-hoc secondary user pairs $\{\mathrm{SU}_i\}_{i=1}^{K}$ composed of secondary transmitters $\{\mathrm{ST}_i\}_{i=1}^{K}$ and secondary receivers $\{\mathrm{SR}_i\}_{i=1}^{K}$ that are seeking for available spectrum resources from PU for their own data transmission. An interference user (IU) pair with an interference transmitter (IT) and an interference receiver (IR) which affects both the primary user and secondary users also exists at the same frequency band.

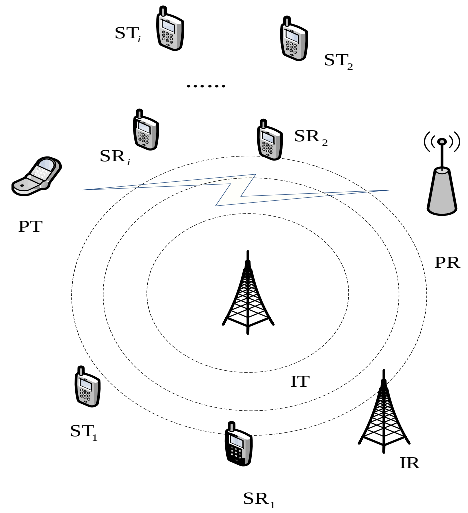

Fig. 1. System model with a PU pair, multiple SU pair seeking for available spectrum and an IU pair which affects both the primary user and the secondary users.

In order to reduce the effect caused by disturbance and improve the quality of the communication to its receiver, the primary user leases a portion of its spectrum to the secondary users for their own data transmissions in exchange for their cooperation. PU's time slot and bandwidth are normalized to T=1 and W=1 respectively, the procedures of cooperation in one full time slot of the primary node's transmission would be as follow:

First, PU leases a portion α $(0 \le \alpha \le 1)$ of its spectrum to a set S of secondary users for data transmissions. Then the rest of the primary user's spectrum $1-\alpha$ is divided into two parts in the time domain. The primary user only broadcast its data in the first time slot β $(0 \le \beta \le 1)$; at the second time slot $1-\beta$, the secondary users in set S cooperate with the primary user to promote its performance. The allocation is illustrated in Fig. 2.

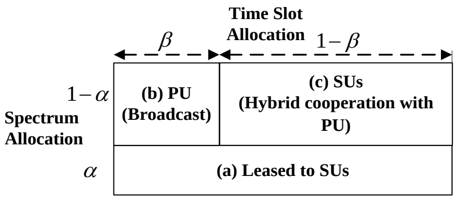

Fig. 2. Time and Spectrum allocation of one PU's slot when cooperating with SUs

Therefore the primary user's resources are split into three parts with aspects to time and spectrum, namely stages (a), (b) and (c).

The secondary users can cooperate with the primary user in two methods: *relay forwarding* and *interference mitigation*. If the SU chooses the method of relay forwarding, then in the second time slot $1-\beta$ of spectrum $1-\alpha$ (stage (c)), ST cooperates with primary user by forwarding primary user's packet to the PR; this is shown in Fig. 3. Moreover, if the SU choose the method of interference mitigation, ST cooperates with the primary user by forwarding the interfering user's packet to the PR rather than the primary user's packet; this is shown in Fig. 4. For simplicity, it is noted that each secondary user can only choose one method to cooperate with the primary user.

III. Problem Formulation

In this section, it is assumed that PU and SUs are all selfish network users in cognitive ad-hoc networks. Their objective is to improve their own utility. Based on this, the resource allocation problem is then formulated by defining each user's own utility functions.

Consider a basic network scenario with one communication user and interference user; the communication channel can be regarded as a multiple-access channel (MAC) where the signal from user's transmitter is received with signal-to-noise ratio (SNR) Γ_1 and the signal from interference's transmitter is received with SNR Γ_2. If the interference user transmits at rate r_2, then the achievable rate of the communication user is known to be [24]

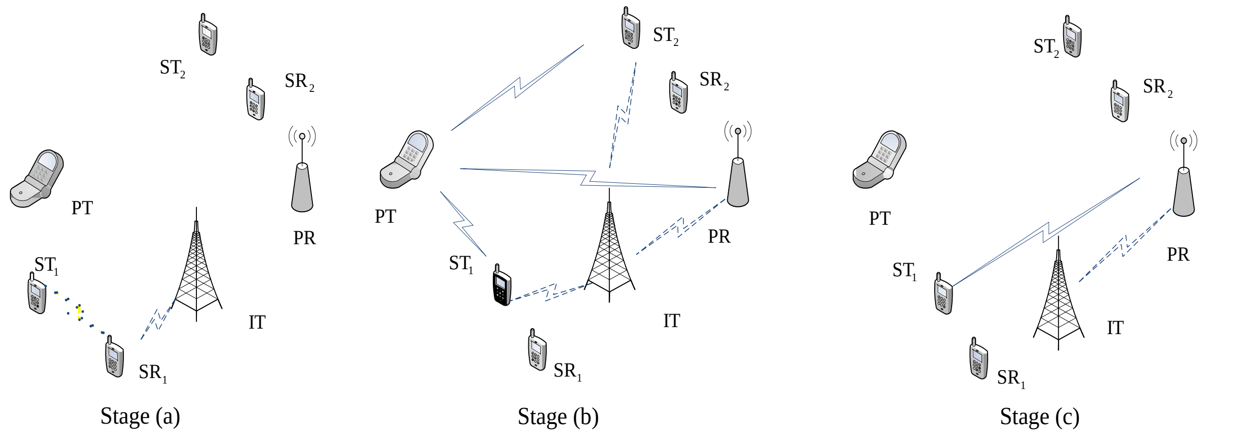

Fig. 3. SU_1 cooperates with the primary user by Relay Forwarding: in stage (a) SU_1 transmit its own data, in stage (b) PT broadcast its data, in stage(c) SU_1 cooperatively relay PT's data to PR.

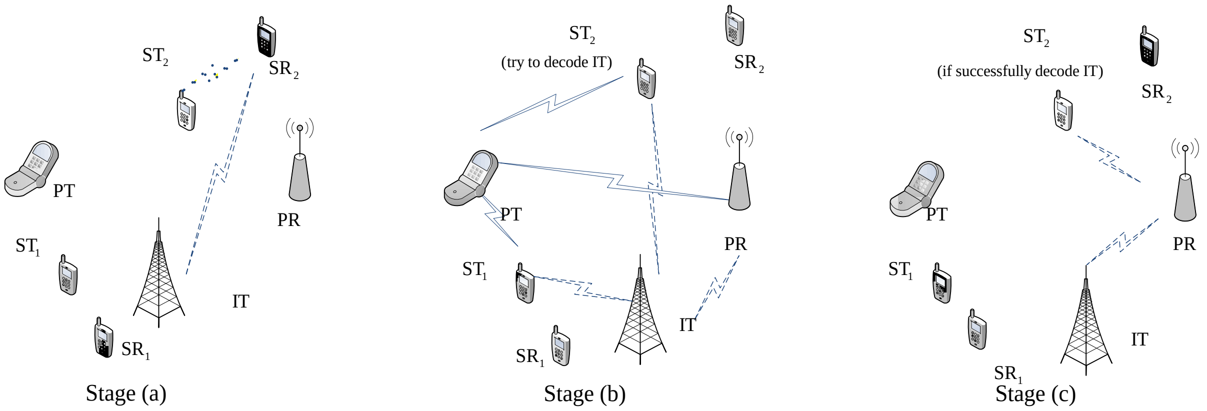

Fig. 4. SU_2 cooperates with primary user by Interference Mitigation: in stage (a) SU_2 transmit its own data, in stage (b) SU_2 try to decode IT's data packet, if successful, in stage(c) SU_2 relay IT's data to PR.

$$R(\Gamma_1,\Gamma_2,r_2,W)=\max(R_N(\Gamma_1,\Gamma_2,W),R_J(\Gamma_1,\Gamma_2,r_2,W)) \quad (1)$$

where

$$R_N(\Gamma_1,\Gamma_2,W)=W\log_2(1+\frac{\Gamma_1}{\Gamma_2}) \quad (2)$$

$$R_J(\Gamma_1,\Gamma_2,r_2,W)=\min\{W\log_2(1+\Gamma_1),W\log_2(1+\Gamma_1+\Gamma_2)-r_2\} \quad (3)$$

and W is the bandwidth of user's transmission; rate $R_N(\Gamma_1,\Gamma_2,W)$ is achieved if the receiver treats the signal of interference as noise (subscript "*N*" stands for "Noise"), whereas rate $R_J(\Gamma_1,\Gamma_2,r_2,W)$ is achieved if the receiver jointly decodes the primary and interference user's signals (subscript "*J*" stands for "Joint"). It's obvious that the user can get a larger achievable rate if the interference SNR becomes higher while the interference user's rate r_2 remains the same.

A. Primary User's Utility

Non Cooperation: in order to make a proper comparison, the case where the primary user transmits without the cooperation of secondary users is first discussed. In this scene, the SNR at PR caused by the direct transmission of PT and IT are as follows

$$\Gamma_{PP}=\frac{g_{PP}P_P}{\sigma^2} \quad (4)$$

$$\Gamma_{IP}=\frac{g_{IP}P_I}{\sigma^2} \quad (5)$$

where g represents the channel gain from transmitter to receiver and P the power of transmitter, respectively. For instance, the channel gain from PT to PR and the power of PT is g_{PP} and P_P respectively. So the achievable rate of PU without cooperation is

$$R_P=R(\Gamma_{PP},\Gamma_{IP},r_I,1) \quad (6)$$

Then consider the case where the primary user transmits with the cooperation of secondary users. In terms of the proposed system model, PU first leases a portion α of its spectrum to SUs. Due to the QoS requirement of PU, there should exist a maximum α to ensure that the remaining $1-\alpha$ bandwidth meets the QoS requirement; this is defined to be $\alpha_{\max}$. PU would then set α such that $0\le\alpha\le\alpha_{\max}$.

After PU releases a portion of the spectrum, SUs will join the hybrid cooperation with PU to make use of the leased bandwidths. For simplicity, it is assumed that the set S with a number of K_c SUs is composed of a set S_1 with a number of K_1 SUs cooperates by relay forwarding and a set S_2 with a number of K_2 cooperates by interference mitigation has already been selected where $K_1+K_2=K_c\le K$. How SUs decide to relay forwarding or interference mitigation will be discussed later. While in cooperation with secondary users, PU will first calculate the parameter β to broadcast its data in the first time slot in accordance to the following condition:

$$\beta R(\Gamma_{PP},\Gamma_{IP},r_I,1\text{-}\alpha)\ge L_p \quad (7)$$

where L_p is the data packet size of PU. If this inequality has a solution in which $0\le\beta\le1$, then the PU will deem that continuing this hybrid cooperation is feasible; otherwise PU will stop this cooperation and recalculate the α for the next cooperation step.

Next, the performance of PU with different cooperation policies is discussed.

Relay Forwarding: for conventional cooperative relay forwarding, decode-and-forward (DF) cooperation protocol is employed in order to implement the cooperation process between the primary user and SUs. Then, the SNR of each link can be calculated as follows.

In cooperation transmission stage (b), PT broadcasts packets to PR and all ST in relay set S_1; the SNR from PT to ST is dominated by the worst channel

$$\Gamma_{PS_i}=\frac{(\min_{i\in S_1} g_{PS_i})P_P}{\sigma^2},\ i\in S_1 \quad (8)$$

In cooperation transmission stage (c), STs transmit primary data packet to PR. Should PR use the Maximum-Ratio Combining (MRC) to combine before decoding the data, then effective SNR would be equal to the sum of each transmitter's SNR. Therefore the effective SNR of the cooperative link ST to PR is given by

$$\Gamma_{SP}=\sum_{i\in S_1}\frac{g_{S_iP}P_{S_i}}{\sigma^2} \quad (9)$$

Based on DF and space-time coding, the overall achievable SNR of the PU with the Relay Forwarding method is equal to the minimum SNR of the two stages

$$\Gamma_{\text{Relay Forwarding}}=\min\{\beta\sum_{i\in S_1}\Gamma_{PS_i},(1-\beta)\Gamma_{SP}\} \quad (10)$$

Interference Mitigation: for cooperative interference mitigation, decode-and-forward (DF) cooperation protocol is still employed in order to implement the interference mitigation process between the interfering user and SUs. Reference [23] shows that ST has a probability to successfully decode IT's data packet; when ST decodes IT's packet, it will informs PU to start interference mitigation. However, for simplicity, it is assumed that the above procedures have already been completed, which means that in cooperation transmission stage (b), all ST in relay set S_2 has decoded IT's packet and informed PU to start interference mitigation. The mechanism of interference mitigation is that ST forwards IT's packet to PR; the analysis process for interference mitigation is similar to that for relay forwarding.

The SNR from IT to ST is dominated by the worst channel:

$$\Gamma_{IS_i}=(\min_{i\in S_2} g_{IS_i})\ \frac{P_I}{\sigma^2},\ i\in S_2 \quad (11)$$

In cooperation transmission stage (c), STs transmit interference data packets to PR. With MRC to combine before decoding the data, the effective SNR is equal to the sum of each transmitter's SNR. Therefore the effective SNR of the ST to PR link is given by

$$\mathit{\Gamma}_{SP} = \sum_{i \in S_2} \frac{g_{S_i P} P_{S_i}}{\sigma^2} \quad (12)$$

Based on DF and space-time coding, the overall achievable SNR of the IU with Interference Mitigation method equals to the minimum SNR of the two stages

$$\mathit{\Gamma}_{\text{Interference Mitigation}} = \min\{\beta \sum_{i \in S_2} \mathit{\Gamma}_{IS_i}, (1-\beta)\mathit{\Gamma}_{SP}\} \quad (13)$$

After importing these two methods in hybrid cooperation, PU's utility, or the achievable rate of PU with hybrid cooperation, is:

$$\begin{aligned} & R_{\text{Hybrid Cooperation}} \\ & = R(\mathit{\Gamma}_{\text{Relay Forwarding}}, \mathit{\Gamma}_{\text{Interference Mitigation}}, r_I, 1-\alpha) \end{aligned} \quad (14)$$

Since the primary user's strategy is to maximize its achievable rate, then, on the one hand, if the spectrum parameter α is too little, the spectrum leased to SUs would be too small, the SUs would make less effort for cooperation and in turn the power SUs used to cooperate with PU would be relatively small. On the other hand, if α is too large, the achievable rate of the primary user would also be low because its own transmission bandwidth would decrease. Therefore, PU needs to find an optimal α to attract SUs to employ higher power levels while maintaining enough transmission bandwidth for itself at the same time in order to maximize its achievable rate. This is obtained by solving the following problem

$$\max_{0 \le \alpha \le 1} R_{\text{Hybrid Cooperation}} \quad (15)$$

B. Secondary Users' Utility

In order to join in hybrid cooperation with PU, SUs will first decide whether to choose relay forwarding or interference mitigation. The decision is made by the link quality of each SU, based on DF; the achievable SNR is equal to the minimum SNR of the two relay stages, so if $\min\{\beta g_{PS_i}, (1-\beta) g_{S_i P}\} \ge \min\{\beta g_{IS_i}, (1-\beta) g_{S_i P}\}$, SU$_i$ will decide to cooperate by Relay Forwarding expressed as $M_r = 1$, otherwise it will choose the Interference Mitigation expressed as $M_i = 1$.

After joining the hybrid cooperation, since each SU has a different ability to help PU, therefore the PU would independently lease each SU different spectra. The spectrum leased to secondary user *i* is

$$\alpha_i = \begin{cases} \alpha \dfrac{\min\{\beta \Gamma_{PS_i}, (1-\beta)\Gamma_{S_i P}\}}{\Upsilon}, & i \in S_1 \\ \alpha \dfrac{\min\{\beta \Gamma_{IS_i}, (1-\beta)\Gamma_{S_i P}\}}{\Upsilon}, & i \in S_2 \end{cases} \quad (16)$$

where

$$\begin{aligned} \Upsilon = & \sum_{k \in S_1} \min\left\{\beta \mathit{\Gamma}_{PS_k}, (1-\beta)\mathit{\Gamma}_{S_k P}\right\} + \\ & \sum_{k \in S_2} \min\left\{\beta \mathit{\Gamma}_{IS_k}, (1-\beta)\mathit{\Gamma}_{S_k P}\right\} \end{aligned} \quad (17)$$

SUs are regarded as energy limited users; they consider not only the bandwidths that can be obtained from PU, but also the energy cost in cooperation with PU. So the utility function of the SU$_i$ consists of two parts, profit and cost, defined as follows

$$U_i = \alpha_i - \theta P_{s_i}, \quad \text{s.t } P_{s_i} \le P_{\max,i} \quad (18)$$

where $P_{\max,i}$ is the maximum power of SU$_i$ and θ is the normalized weighting coefficient of the energy consumption for each SU. It is observed from (18) that on the one hand, the more spectra that are leased, the more profit SU would obtain. On the other hand, with an increase of leased spectra, the SU would definitely increase the energy cost. Therefore each SU needs to reach equilibrium by choosing a suitable cooperate method and a reasonable power cost. For each SU, this problem can be formulated as

$$\max_{P_{S_i} \le P_{\max,i}} U_i \quad (19)$$

IV. SU and PU's Game Analysis

Based on the utilities function derived above, the process of decision optimization is analyzed as a Stackelberg game; a Stackelberg game is a strategic game that consists of a leader who acts firstly and several followers who act subsequently, all parties competing with each other on certain resources. In our proposed hybrid cooperative transmission scenario, PU attempts to increase its utility by leasing the spectrum to the SUs, so, the PU is formulated as the leader and the SUs are formulated as the followers. The primary user (leader) decides an α on per unit of its time slot. Then, the SUs (followers) choose their power allocation strategies to maximize their individual utilities based on the leased spectrum α.

A. SU(Follower)'s game Analysis

At the follower's level, the game is consist of the secondary users set *S*$_1$, *S*$_2$, their strategies $\{P_{s_i}\}$ and their utilities $\{U_i\}$, the follower's game can be formulated as $G = [\{S_1, S_2\}, \{P_{s_i}\}, \{U_i\}]$. It is necessary to prove the existence and uniqueness of the equilibrium of the proposed game and then find the equilibrium point. First, to prove the existence of a Nash Equilibrium, it is equivalent to prove that the game $G = [\{S_1, S_2\}, \{P_{s_i}\}, \{U_i\}]$ satisfies the following conditions [25]

- User strategy is a non-empty convex and compact subset of some Euclidean space $\Re^N$.

- User utility is continuous and concave.

Proof: For condition 1, it's obviously that SUs' strategy P_{s_i} is a non-empty, convex and compact subset of the Euclidean space $\Re^N$.

To prove condition 2, first it is obvious that the SNR of DF replay reaches the optimal value if the SNR of source-to-relay is equal to the SNR of relay-to-destination. So $\beta\Gamma_{PS_i} = (1-\beta)\Gamma_{S_iP}$ and $\beta\Gamma_{IS_i} = (1-\beta)\Gamma_{S_iP}$; then the derivative of U_i over P_s is

$$\frac{\partial U_i}{\partial P_{s_i}} = \frac{\alpha\sigma^2\Upsilon}{(P_{s_i} + \frac{\sigma^2\Upsilon}{(1-\beta)g_{s_ip}})^2(1-\beta)g_{s_ip}} - \theta \quad (20)$$

where

$$\Upsilon = \sum_{k\in S_1, k\neq i} \min\{\beta\Gamma_{PS_k}, (1-\beta)\Gamma_{S_kP}\} + \sum_{k\in S_2, k\neq i} \min\{\beta\Gamma_{IS_k}, (1-\beta)\Gamma_{S_kP}\} \quad (21)$$

the 2nd-derivative of U_i is:

$$\frac{\partial^2 U_i}{\partial P_{s_i}^{\ 2}} = \frac{-2\alpha\sigma^2\Upsilon}{(P_{s_i} + \frac{\sigma^2\Upsilon}{(1-\beta)g_{s_ip}^{\ 2}})^3(1-\beta)g_{s_ip}} < 0 \quad (22)$$

which means that the utility function U_i is continuous and concave, thus proving the existence of the Nash Equilibrium.

Then, to find the best-response function of SUs, make (20) equal to 0

$$\frac{\partial U_i}{\partial P_{s_i}} = \frac{\alpha\sigma^2\Upsilon}{(P_{s_i} + \frac{\sigma^2\Upsilon}{(1-\beta)g_{s_ip}})^2(1-\beta)g_{s_ip}} - \theta = 0 \quad (23)$$

from (23), it have

$$P_{s_i}^{\ *} = \sqrt{\frac{\alpha\sigma^2\Upsilon}{\theta(1-\beta)g_{s_ip}}} - \frac{\sigma^2\Upsilon}{(1-\beta)g_{s_ip}} \quad (24)$$

whether (24) is the uniqueness best-response depend on if it's a standard function [25]. A function is said to be standard if it satisfies the following properties:

- Positivity
- Monotonicity
- Scalability

When is (24) greater than zero, $\theta < \frac{\alpha(1-\beta)g_{s_ip}}{\sigma^2\Upsilon}$ and the derivation of (11) is less than zero, which means that $P_{s_i}^{\ *}$ is monotonically decreasing and $\theta > \frac{\alpha(1-\beta)g_{s_ip}}{4\sigma^2\Upsilon}$. So if $\frac{\alpha(1-\beta)g_{s_ip}}{4\sigma^2\Upsilon} < \theta < \frac{\alpha(1-\beta)g_{s_ip}}{\sigma^2\Upsilon}$, the best response $P_{s_i}^{\ *}$ satisfies positivity and monotonicity.

For any $t > 1$, it's obvious that

$$tP_{s_i}^{\ *}(\mathbf{P}) - P_{s_i}^{\ *}(t\mathbf{P}) = t\sqrt{\frac{\alpha\sigma^2\Upsilon}{\theta(1-\beta)g_{s_ip}}} - \sqrt{\frac{t\alpha\sigma^2\Upsilon}{\theta(1-\beta)g_{s_ip}}} > 0$$

which means that $P_{s_i}^{\ *}$ is scalable. Thus $P_{s_i}^{\ *}$ meets the positivity, monotonicity and scalability conditions and therefore the proposed game $G = [\{S_1, S_2\}, \{P_{s_i}\}, \{U_i\}]$ has a unique Nash Equilibrium and can be reached by solving the equation set for all $i \in S_1 \cup S_2$ from (24). However, this equation set is hard to have an analytical solution due to its complex form. So $P_{s_i}^{\ *}$ will be obtained by an iterative update algorithm instead which will be shown later.

B. PU(Leader)'s game Analysis

Based on the optimal power allocation of SU, PU as the leader of the Stackelberg game will give strategy α to maximize its utility. So substitute (11) into (5), and the result is the following:

$$\max_{0\leq\alpha\leq 1} R(\Gamma_{\text{Relay Forwarding}}(P_{s_i}^{\ *}), \Gamma_{\text{Interference Mitigation}}(P_{s_k}^{\ *}), r_1, 1-\alpha) \quad (25)$$

where $i \in S_1, k \in S_2$. Recalling the definition in (1), (25) has three analytic expressions in terms of different conditions. However, in the proposed system model, the interfering user affects both the primary user and secondary users, so it's assumed that both the SNR and data rate of IU is relatively high and therefore only

$$R_{\text{Hybrid Cooperation}} = (1-\alpha)\log_2(1 + \Gamma_{\text{Relay Forwarding}}(P_{s_i}^{\ *}) + \Gamma_{\text{Interference Mitigation}}(P_{s_k}^{\ *})) - r_I$$

will be considered later.

It has been analyzed that there exists an optimal tradeoff to maximize (25). To get this tradeoff, make a derivation of (25) and set it to zero; that is:

$$\frac{\partial R(\Gamma_{\text{Relay Forwarding}}(P_{s_i}^{\ *}), \Gamma_{\text{Interference Mitigation}}(P_{s_k}^{\ *}), r_1, 1-\alpha)}{\partial\alpha} = -\left[\Lambda + (\alpha-1)\frac{\partial\Lambda}{\partial\alpha}\right] = 0 \quad (26)$$

where

$$\Lambda = \log_2[1 + \Gamma_{\text{Relay Forwarding}}(P_{s_i}^{\ *}) + \Gamma_{\text{Interference Mitigation}}(P_{s_k}^{\ *})] \quad (27)$$

by solving (26), it becomes clear that

$$\alpha^* = \alpha^*(\{g_{PS_i}\}, \{g_{S_iP}\}, \{g_{PS_k}\}, \{g_{S_kP}\}), \quad i \in S_1,\ k \in S_2 \quad (28)$$

C. Algorithm and Implementation

Both equation (28) and the equation set for all $i \in S_1 \cup S_2$ from (24) is hard to have an analytical solution, so an iterative update algorithm is proposed for each SU to update its P_{s_i} to $P_{s_i}^{\ *}$ and PU to update α until it reaches α^* in this sub-section. The proposed algorithm is as follows: at first, all SUs decide their initial cooperate power $P_{s_i}{}^1$ and PU gives an initial released spectrum α^1. With this, SUs will update its strategy for a higher utility for any t=2,…N

$$P_{s_i}{}^t = \sqrt{\frac{\alpha^{t-1}\sigma^2\Upsilon}{\theta(1-\beta)g_{s_iP}}} - \frac{\sigma^2\Upsilon}{(1-\beta)g_{s_iP}} \tag{29}$$

here SU i uses the last strategy of other game players known from PU to calculate its utility for this time period; this in turn implies that

$$\Upsilon = \sum_{k\in S_1,k\neq i}\min\{\beta\Gamma_{PS_k},(1-\beta)\Gamma_{S_kP}P_{s_k}{}^{t-1}\} + \sum_{k\in S_2,k\neq i}\min\{\beta\Gamma_{IS_k},(1-\beta)\Gamma_{S_kP}P_{s_k}{}^{t-1}\} \tag{30}$$

After followers change their strategies, the leader, PU, will also change strategy for its own benefit. From (13), the iterative function of α is

$$\alpha^t = 1 - \frac{\Lambda(P_{s_i}{}^t, P_{s_k}{}^t)}{\left.\dfrac{\partial\Lambda(P_{s_i}{}^{t-1}, P_{s_k}{}^{t-1})}{\partial\alpha}\right|_{\alpha=\alpha^{t-1}}} \tag{31}$$

where

$$\Lambda(P_{s_i}{}^t, P_{s_k}{}^t) = \log_2[1+\Gamma_{\text{Relay Forwarding}}(P_{s_i}{}^t) + \Gamma_{\text{Interference Mitigation}}(P_{s_k}{}^t)] \tag{32}$$

Equation (32) is also calculated from the last strategy of PU and SU. For the given iterative update algorithms (29) and (31), all PU and SUs will reach the equilibrium after a few iterations.

V. Simulation and Results Analysis

In order to evaluate the validity and the performance of the proposed hybrid cooperation based algorithm with a Stackelberg game, the simulation results of the convergence of the proposed iterative algorithm will be shown first. Then the strategy and utility performance against SU's cooperation method and its location will be shown. Finally, a performance comparison of our proposed hybrid cooperation scheme to other cooperation schemes in cognitive radio networks will be made. For simplicity, the simulation consisted of one primary user pair, two secondary user pairs and a single interference user. The node distribution of the simulation is as shown in Fig. 5: One PU pair, where PT is at coordinate (0, 0) and PR is at coordinate (5, 5); IT is located in (6, 3), two of SU pairs where the transmitters of SU_1 and SU_2 have a fixed y-coordinate 2 and 2.5 respectively and their x-coordinate can vary from 0 to 10; the black line in Fig.5 represents the trajectory of STs. The transmission power of PU and IU are set as $P_P = 100$ mW and $P_I = 300$ mW, respectively, the noise power is σ^2 =10^{-5}mW, and the normalized weighting coefficient is set to be θ =10^{-4}. Channel gain is set to be $E|g| = 1/d^2$, where d is the distance between transmitter and receiver.

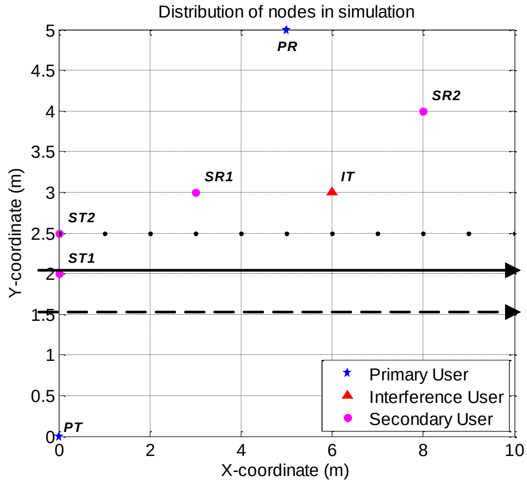

Fig. 5. Nodes distribution and movement trajectory of STs in the simulation

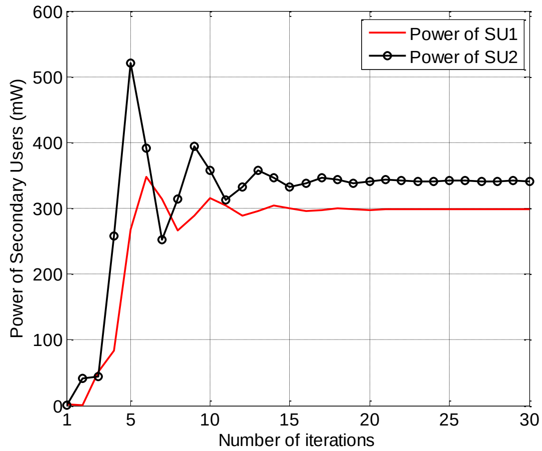

Fig. 6. Convergence speed of the SUs' power consumption

A. Convergence Speed of the Proposed Algorithm

In this section, the convergence speed of the proposed algorithm is given. For intuitive observation, SU_1 is set to use interference mitigation and has a fixed coordinate (7.5, 2) and SU_2 is set to use relay forwarding and has a fixed coordinate (4, 2.5). Initial strategies for each game players are $P_{s_1}{}^1 = 9$ mW, $P_{s_2}{}^1 = 0.1$ mW and α^1 =0.05, and then the proposed algorithm is executed with 30 iterations. Fig. 6 and Fig. 7 show the convergence of strategies and utilities of SUs; it can be seen that after 20 iterations, both strategies and utilities become stable. Fig. 8 shows the convergence speed of PU's utility is about 15 iterations; this is faster than SUs because there is only one PU(leader) in our proposed network and therefore the primary user has no competitors.

B. Performance of SUs

In order to study strategy and utility performance against SU's cooperation method and location, several numerical results are shown in this simulation. SU_1 is still set to use interference mitigation and SU_2 is still set to use relay forwarding. Both x-coordinate of ST_1 and ST_2 vary from 0 to 10 simultaneously and 30 iterations are implemented for each position to ensure convergence. Fig. 9 shows the optimal power consumption and Fig. 10 shows the optimal utility of SUs with different positions; it can be seen in the simulation that when *x*-coordinate varies from 0 to 5, which is close to PT and PR and suitable for relay forwarding, the power consumption of SU_1 is relatively low and its utility is higher than SU_2. However, when the x-coordinate varies from 5 to 10, SU_1 no is longer near PT but is closer to IT; in this case the opposite situation occurs and SU_2 has a relatively lower power consumption but higher utility than SU_1.

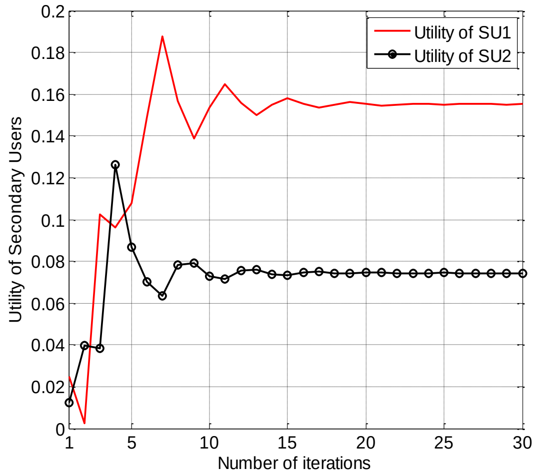

Fig. 7. Convergence speed of SUs' utility

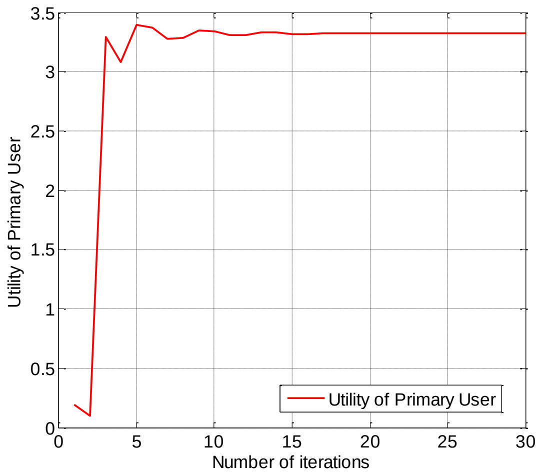

Fig. 8. Convergence speed of PU's utility

In Fig. 9, the optimal utility of SU changes a lot as its position moves, consequently, the SU's channel quality changes as well. The proposed scheme enables SU to choose different cooperation methods according to the channel state information, which providing a flexible approach for secondary users to earn available spectrum as much as possible.

C. Performance of PU

In order to evaluate the proposed scheme performance to PU, let *x*-coordinate of ST_1 and ST_2 still vary from 0 to 10 simultaneously and four simulation groups are set respectively: 1) Direct Transmission: PU transmit without the cooperation of SUs; 2) Relay Forwarding X2: SU_1 and SU_2 all cooperate with relay forwarding; 3) Interference Mitigation X2: SU_1 and SU_2 all cooperate with interference mitigation; 4) Relay Forwarding and Interference Mitigation: SU_1 and SU_2 cooperate with interference mitigation and relay forwarding respectively.

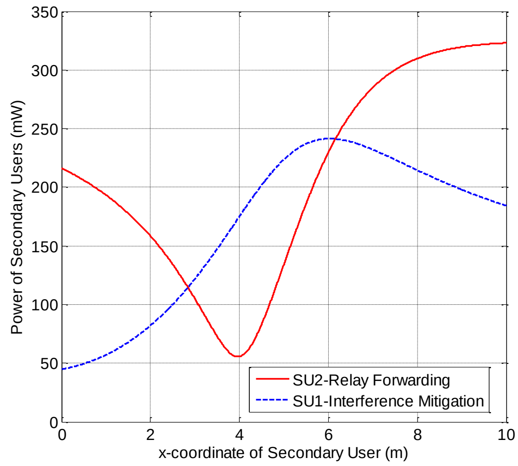

Fig. 9. Optimal power consumption of SUs with different positions

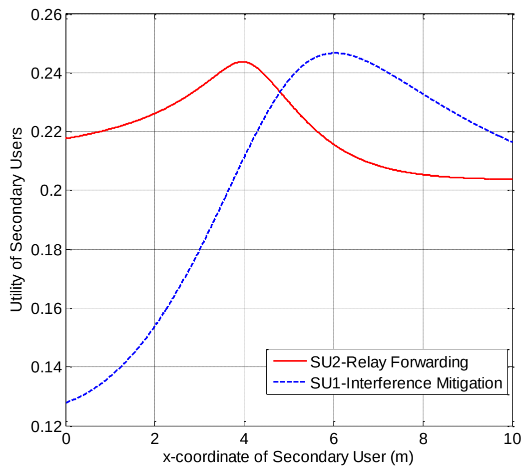

Fig. 10. Optimal utilities of SUs with different positions

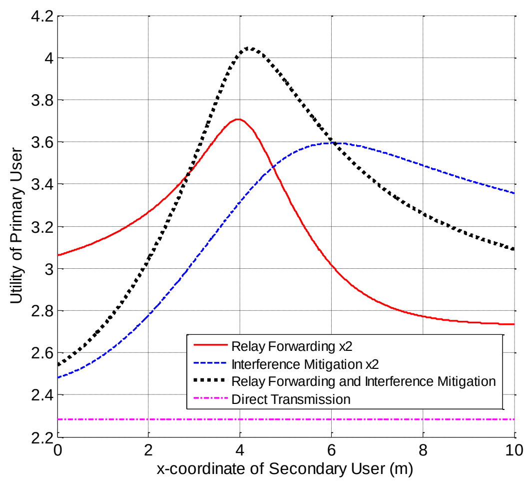

Fig. 11. Optimal utilities of PU with different positions of SUs

In Fig.11, the performance of above groups have been compared, demonstrating the advantage of the proposed mechanism over the following: the direct method, the data forwarding relay method and the interference mitigation relay method. It can be observed that when an interference user exists, direct transmission has a relatively low utility for PU and the utility is basically a horizontal line which does not change with the position of the SUs, whereas other groups have advantages due to the secondary user cooperation. But when the position of secondary user has been changed, the channel quality of the primary user to relay user and channel quality of the interference user to relay user will vary in different trends. Both the sole data forward relay and the sole interference mitigation relay method could not adapt to the change. However, by automatically choosing a suitable method of cooperation, The proposed mechanism could let both PU and SUs reach a higher utility.

VI. Conclusions

In this paper, a hybrid cooperation mechanism is proposed which allows secondary users to cooperate with primary users by relay forwarding as well as interference mitigation in exchange for available spectra for secondary users. The proposed scheme provides for secondary users in different locations a more flexible cooperation approach to the primary user. By automatically choosing a suitable method of cooperation, both SUs and PU can reach a higher utility. A Stackelberg game in which the primary user is modeled as the leader and secondary users are modeled as followers is used to jointly maximize both the primary and secondary users' utilities. The existence and uniqueness of the game's equilibrium is proved and a convergent iterative algorithm is given in order to reach that equilibrium. Analytical and numerical results show that the proposed hybrid cooperation mechanism has a preferable performance in the changing communications environment and outperforms the single cooperation scheme.

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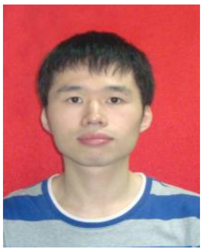

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