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Incentivize Spectrum Leasing in Cognitive Radio Networks by Exploiting Cooperative Retransmission

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Abstract

This paper addresses the spectrum leasing issue in cognitive radio networks by exploiting the secondary user's cooperative retransmission. In contrast with the previous researches that focuses on cancellation-based or coding-based cooperative retransmissions, we propose a novel trading-based mechanism to facilitate the cooperative retransmission for cognitive radio networks. By utilizing the Stackelberg game model, we incentivize the otherwise non-cooperative users by maximizing their utilities in terms of transmission rates and economic profit. We analyze the existence of the unique Nash equilibrium of the game, and provide the optimal solutions with corresponding constraints. Numerical results demonstrate the efficiency of the proposed mechanism, under which the performance of the whole system could be substantially improved.

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1. Introduction

Spectrum has become the scarcest resource in wireless communications due to the emerging wireless services and products in past decade. The current fixed spectrum allocation scheme is recognized to be very inefficient due to the exclusive use to licensed services (e.g., less than 20% on average in Chicago across all bands [1]). With the development of cognitive radio technologies [2], dynamic spectrum access has been suggested as a promising technique to improve the spectrum utilization efficiency. By dynamic spectrum access, an unlicensed user is capable of accessing the licensed spectrum dynamically and serving its own traffic.

The dynamic spectrum access schemes can be classified into two categories: *opportunistic spectrum access* [3–6] and *negotiated spectrum access* [7–12]. In opportunistic spectrum access, the Primary Users (PUs) are oblivious of the presence of the Secondary Users (SUs). The SUs are allowed to access the channel only in the spectrum holes (e.g., interwave schemes [3, 4]) or under a certain interference constraint (e.g., overlay schemes [5, 6]). In negotiated spectrum access, instead, the PUs are aware of the existence of the SUs. The PUs and SUs explicitly communicate with each other to reach a spectrum sharing arrangement. Specifically, PU leases part of the spectrum resources to the SU (i.e., spectrum leasing) in exchange for the improved transmission quality or appropriate economic profit.

In the context of dynamic spectrum access, most of the previous researches focused on spectrum access in the whitespace or during the PU's transmission slot [3, 4, 6–10]. However, there is a growing body of work recently that investigates the spectrum access during the PU's retransmission slot [5, 11, 12]. These work has shown that nontrivial rates for PU and SU can be achieved by careful retransmission resource management, in spite of the retransmission may be relatively infrequent. Specifically, Tannious *et al.* [5] proposed a cancellation based retransmission scheme for cognitive radio networks. This scheme allows the SU to opportunistically access the spectrum by transmitting with the PU simultaneously during the PU's retransmission period. The interference at both PU and SU sides could be canceled or mitigated by

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utilizing the knowledge of primary packet. However, the throughput of SU is extracted at the cost of reduced PU's transmission rate, which is undesired. Since PU has higher priority in cognitive radio networks, it is unrealistic to assume that PU is willing to share the spectrum if it cannot obtain any profit or at least be compensated. To incentivize the cooperation at both PU and SU sides, Stanojev *et al.* proposed an auction-based negotiated spectrum access scheme to reassign the retransmission slot. In this scheme, in exchange for the cooperative retransmission from the SU, PU yields part of the retransmission duration for the aided SU's own traffic. The competition of the multiple SUs are modeled by auction theory. This scheme, however, needs every SU has a minimum tolerated reliability, thus cannot be applied in a network with SUs using best-effort transmission. Our previous work [12] also investigated the negotiated spectrum access issue for cooperative retransmissions. we proposed a cooperative coding-based retransmission protocol for the cognitive radio networks. In the proposed protocol, SU relays the primary packet and serves its own traffic simultaneously. To realize that, Network Coding (NC) scheme MIMO_NC [13] is applied in the physical layer, by which the original packets can be retrieved by the corrupted and redundant packets. However, the success probability of this scheme relies on the SINR threshold of MIMO_NC, and it potentially increases the processing complexity of the wireless terminals.

In this paper, we propose a novel *trading-based* spectrum leasing mechanism for cooperative retransmission in cognitive radio networks. The proposed trading framework involves both *resource-exchange* and *money-exchange*. The resource-exchange refers to the exchange between licensed spectrum and SU's cooperating expense, and the money-exchange is executed in the form of *charge* and *reimbursement*. Motivated by the proposed trading model, a PU is willing to lease the licensed spectrum to SUs during the retransmission slot, if it can benefit from enhanced retransmission quality or considerable economic profit. And SUs may compete to access the licensed spectrum for their own transmissions in a best-effort manner, if the cost is reasonable. Under the assumption that both PU and SU are rational, we formulate the network to a Stackelberg game, which characterizes the hierarchical feature of the system. With the objective to maximizing respective utilities, we derive the optimal strategies for both PU and SU.

The main contributions of this paper are summarized as follows.

- We propose a novel trading-based spectrum leasing mechanism for cognitive radio networks by exploiting the cooperative retransmissions.
- We formulate the considered problem as a Stackelberg game, where PU and SU have their selfish objectives in terms of transmission rates and economic return.
- We analyze the unique Nash equilibrium of the game, and derive the optimal solutions with corresponding constraints. The solutions give reliable predictions of the system outcome, and are easy to implement.
- We show the efficiency of the proposed mechanism by numerical results, and analyze the impacts of different parameter settings.

The rest of the paper is organized as follows. We present the system and trading models in Section 2. In Section 3, we formulate the problem by game theory, and analyze its Nash equilibrium. Numerical results are addressed in Section 4. And finally Section 5 draws the conclusions.

2. System and Trading Models

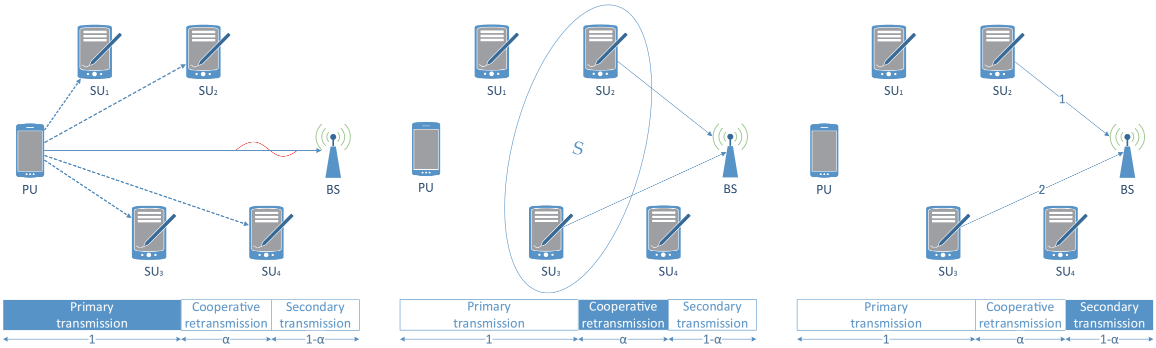
2.1. System Model

As depicted in Fig. 1, we consider a cognitive radio network, where a PU communicates with the Base Station (BS). In the same spectrum band, a secondary network with multiple SUs tries to exploit best-effort transmissions with BS[1] by taking advantage of the opportunities that arise during PU's retransmission period (with normalized duration 1). In the case of a failed primary transmission, the SUs may hear the primary packet and be able to decode it (Fig .1(a)). Upon receiving the negative feedback message from the BS, PU involves a subset $\mathcal{S}$ of capable SUs[2] to perform cooperative retransmission by employing orthogonal Space-Time Codes (STCs) scheme [15] in an α fraction of the retransmission interval (Fig. 1(b)). And as a reward, the remaining $1-\alpha$ fraction of the retransmission interval is allocated to the cooperating SUs for their own data transmissions in a Time-Division Multiplexing Access (TDMA) mode (Fig. 1(c)). The cooperation between PU and SU are incentivized by the trading model addressed in next subsection.

We assume that the channel is subject to Rayleigh fading, and is invariant within a coherence interval. The channel gain between PU and BS is denoted as h_p, and

[1] The considered network focuses on the primary network access, i.e., the SU accesses the primary base station through the licensed spectrum. However, it will not restrict the implementation of the proposed scheme to other scenarios, such as the secondary network access, i.e., the SU accesses the secondary base station or other SUs.

[2] Capable SU refers to the SU that can correctly decode the primary data during the transmission interval. And in implementation, this information is reported by the individual SU to PU after a random backoff time.



(a) In the primary transmission interval with normalized length 1, PU transmits data to BS, which might fail due to bad channel conditions.

(b) In the α fraction of the retransmission interval, multiple capable SUs retransmit the primary data to BS cooperatively by using orthogonal STCs.

(c) In the remaining $1-\alpha$ fraction of the retransmission interval, cooperating SUs access the channel to transmit their own data in a TDMA mode.

Figure 1. Transmission model for cooperative retransmission based spectrum leasing for cognitive radio networks

the channel gains between SU i ($\mathrm{SU_i}, i \in \mathcal{S}$) and BS is denoted as h_i. It is assumed that the channel coefficient follows the Gaussian zero mean distribution, and the noises at the receivers are normally distributed as N_0.

By the cooperation of SU subset $\mathcal{S}$ using orthogonal STCs, PU's retransmission rate could be expressed as

$$R_p(\mathcal{S}) = \alpha \overline{R_p(\mathcal{S})} = \alpha \log_2 \left(1 + \frac{\sum\limits_{i \in \mathcal{S}} \left(|h_i|^2 P_i \right)}{N_0} \right), \qquad (1)$$

where $\overline{R_p(\mathcal{S})}$ denotes the retransmission rate over normalized time slot, and P_i is the transmitting power at $\mathrm{SU_i}$. And the transmission rate for each cooperating $\mathrm{SU_i}$ is expressed as

$$R_i = t_i \overline{R_i} = t_i \log_2 \left(1 + \frac{|h_i|^2 P_i}{N_0} \right), \qquad (2)$$

where $\overline{R_i}$ denotes $\mathrm{SU_i}$'s transmission rate over normalized time slot, and t_i is the time duration granted for $\mathrm{SU_i}$ to access the spectrum.

2.2. Trading Model

To incentivize the user cooperation, we propose a trading model involving both resource-exchange and money-exchange. For the resource-exchange, PU leases part of the retransmission interval to the cooperating SUs in exchange for the improved retransmission quality, and SU spends its transmitting energy in cooperating behavior in exchange for the opportunity to access the licensed spectrum. However, only using resource-exchange is inadequate for the considered system. Since PU has strong position in cognitive radio network, and will always prefer to allocate the whole retransmission interval to cooperative retransmission, which leads to a non-cooperation result. To encourage the cooperation for both PU and SU sides, market mechanisms in spectrum sharing has been exploited recently [16]. In this paper, we propose a novel money-exchange model involving both *charge* and *reimbursement*. Charge is paid by the SUs for the access right of spectrum resource, and reimbursement is paid by the PU for the cooperative retransmission. Specifically, SU is charged by the amount of time that it accesses the spectrum. Since the cooperating SUs split the accessing time $1-\alpha$ in TDMA mode, the time duration t_i granted for $\mathrm{SU_i}$ to access the spectrum is defined proportional to its charge c_i as

$$t_i = \frac{c_i}{\sum\limits_{j \in \mathcal{S}} c_j} (1-\alpha). \qquad (3)$$

The reimbursement to SU is defined as the product of its cooperation time and the amount of services it provided. Specifically, the cooperation time is the allocated retransmission time α, and the amount of provided services refers to its contribution to the cooperative retransmission rate. We define the reimbursement r_i for $\mathrm{SU_i}$ as

$$r_i = \frac{\alpha |h_i|^2 P_i \left(R_p(\mathcal{S}) \right)}{\sum_{j \in \mathcal{S}} \left(|h_j|^2 P_j \right)} \lambda, \qquad (4)$$

where $|h_i|^2 P_i \Big/ \sum_{j \in \mathcal{S}} \left(|h_j|^2 P_j \right)$ is the SNR contribution of $\mathrm{SU_i}$ to the total received SNR at BS, and λ is the reimbursement unit price.

3. Game Theoretical Framework for Spectrum Leasing in Cooperative Retransmission

In this section, we address the spectrum leasing issue in PU's retransmission by utilizing Stackelberg game.

Based on the proposed trading model, we firstly define the utility functions for both PU and SU. Then we propose a Stackelberg game based framework, where the leader (PU) optimizes its strategy based on the knowledge of the effects of its decision on the behavior of the followers (SUs).

3.1. Utility Functions

In the considered system, PU intends to maximize its retransmission rate plus the economic profit, i.e., the total charges it earned minus the total reimbursements it paid. Therefore, the natural utility U_p for PU is defined as the cooperative retransmission rate plus the economic profit as

$$U_p = R_p(\mathcal{S}) + \sum_{j\in\mathcal{S}} c_j - \sum_{j\in\mathcal{S}} r_j. \tag{5}$$

Notice that in Eqn. (5), the equivalent economic profit per unit data rate contributes to the overall utility is set to 1 for simplicity.

Similarly, the utility U_i for $\mathrm{SU_i}$ is defined as its transmission rate plus the received reimbursement from PU, and minus the charge it pays. We have

$$U_i = R_i + r_i - c_i. \tag{6}$$

3.2. Stackelberg Game Based Framework

The considered system is characterized by a hierarchical structure, in which PU holds the strong position and can impose its own strategy upon the SUs. This structure could be formulated to a *Stackelberg game* [17], which consists of a leader (PU) and multiple followers (SUs). In Stackelberg game, *the leader optimizes its strategy based on the knowledge of the effects of its decision on the behavior of the followers*. Therefore, with the target to maximize its utility U_p, the leader PU declares its strategy first in terms of the time fraction α and the cooperation subset $\mathcal{S}$. Then with the objective to maximize its utility U_i, the follower $\mathrm{SU_i}$ reacts to the PU's declared α and $\mathcal{S}$ by deciding how much it is willing to be charged for the channel access. We solve this typical leader-follower game by backward induction as follows. Firstly, we derive the optimal solution for the SUs' non-cooperative payment decision game. Then based on this outcome, we derive the optimal strategy for the PU.

SU's Optimal Strategy. Given the time fraction α and cooperation subset $\mathcal{S}$ that decided by PU, SUs in $\mathcal{S}$ compete with each other to maximize their utilities by deciding a reasonable charge for the channel access. The payment decision game is denoted as $G = \langle \mathcal{S}, \{C_i\}_{i\in\mathcal{S}}, \{U_i\}_{i\in\mathcal{S}} \rangle$, where C_i is the strategy set, and U_i is the utility of $\mathrm{SU_i}$ given in Eqn. (6). For the Nash Equilibrium (NE) existence of the payment decision game G, we have

Lemma 1. A NE exists in game G.

Proof. According to [17], A NE exists in $G = \langle \mathcal{S}, \{C_i\}_{i\in\mathcal{S}}, \{U_i\}_{i\in\mathcal{S}} \rangle$, if $\forall i \in \mathcal{S}$:

- C_i is a nonempty, convex, and compact subset of some Euclidean space R^N.
- $U_i(\mathbf{c})$ is continuous in $\mathbf{c}$ and concave in c_i.

Notice that $\mathbf{c} = (c_i, \mathbf{c}_{-i})$ is the strategy profile, where $\mathbf{c}_{-i}$ denotes the vector of strategies of all players except i. It is obvious that the first requirement in ***Lemma* 1** is satisfied, and $U_i(\mathbf{c})$ is continuous in $\mathbf{c}$. We prove the concavity by taking the second order derivative of U_i with respect to c_i as

$$\frac{\partial U_i}{\partial c_i} = \frac{(1-\alpha)\,\overline{R_i}\left(\sum\limits_{j\in\mathcal{S}} c_j - c_i\right)}{\left(\sum\limits_{j\in\mathcal{S}} c_j\right)^2} - 1, \tag{7}$$

$$\frac{\partial^2 U_i}{\partial^2 c_i} = \frac{2\,(1-\alpha)\,\overline{R_i}\left(c_i - \sum\limits_{j\in\mathcal{S}} c_j\right)}{\left(\sum\limits_{j\in\mathcal{S}} c_j\right)^3}. \tag{8}$$

Obviously, $\frac{\partial^2 U_i}{\partial^2 c_i}$ is always less than 0, thus $U_i(\mathbf{c})$ is concave in c_i. Therefore, two requirements are both satisfied and, a NE exists in game G. □

Next, we analyze the uniqueness of the NE in game G and, derive the NE solution with corresponding constraint.

Theorem 1. The NE of the SUs' payment decision game G is unique, and the optimal charge is

$$c_i^* = (1-\alpha)(|\mathcal{S}|-1)\frac{\sum\limits_{j\in\mathcal{S}} \frac{1}{\overline{R_j}} - \frac{|\mathcal{S}|-1}{\overline{R_i}}}{\left(\sum\limits_{j\in\mathcal{S}} \frac{1}{\overline{R_j}}\right)^2}, \tag{9}$$

under constraint

$$\sum_{j\in\mathcal{S}} \frac{1}{\overline{R_j}} > \frac{|\mathcal{S}|-1}{\overline{R_i}}. \tag{10}$$

Proof. By definition, a strategy profile $\mathbf{c}^* = (c_i^*, \mathbf{c}_{-i}^*)$ is a NE if and only if every player's strategy is a *best response* to the other players' strategies, i.e., $c_i^* \in b(\mathbf{c}_{-i}^*)$ for every player $\mathrm{SU_i}$. Due to the concavity of U_i, the best response function $b(\cdot)$ can be obtained when the first derivative of U_i with respect to c_i is zero. By solving Eqn. (7) = 0, we have

$$b(\mathbf{c}) = c_i^* = \sqrt{(1-\alpha)\overline{R_i}\left(\sum_{j\in\mathcal{S}} c_j - c_i\right)} - \left(\sum_{j\in\mathcal{S}} c_j - c_i\right), \quad (11)$$

under constraint

$$\sum_{j\in\mathcal{S}} c_j - c_i < (1-\alpha)\overline{R_i}. \quad (12)$$

Notice that for the cases that constraint Eqn. (12) does not hold, c_i^* is 0.

According to [17], if the best response functions of a non-cooperative game are *standard functions* for all players, then the game has a unique NE. The function $b(\cdot)$ is said to be standard if is has the following properties:

- *Monotonicity*: $\mathbf{c} \leq \mathbf{c}' \Rightarrow b(\mathbf{c}) \leq b(\mathbf{c}')$
- *Scalability*: $\forall \theta > 0, b(\theta \mathbf{c}) \leq \theta b(\mathbf{c})$.

Eqn. (11) can be easily proved to be monotonic and scalable. Finally, the best response function is proved to be a standard function and thus, there exists a unique NE for game G. However, Eqn. (11) cannot be directly used in real implementation, since $\mathrm{SU_i}$ is unaware of the charges of other SUs, i.e. c_j. To derive a practical formula for c_i^*, we solve the Eqn. (11) set with $i = (1, 2, \cdots, |\mathcal{S}|)$. By removing the term c_j, we can express c_i^* as Eqn. (9) in ***Theorem*** 1. Substituting Eqn. (9) into constraint Eqn. (12), we can rewrite the new constraint as Eqn. (10), which *will be used by the PU to select the optimal cooperation subset* $\mathcal{S}$. □

Notice that in ***Theorem*** 1, to calculate c_i^*, the values of α, $|\mathcal{S}|$, $\overline{R_i}$, and $\sum_{j\in\mathcal{S}} \frac{1}{\overline{R_j}}$ are needed at SU. For implementation, besides $\overline{R_i}$, the other 3 parameters are piggybacked by PU. It is assumed that PU is aware of the individual SUs' channel conditions by periodically reporting (e.g. like BS handles the D2D link in 4G cellular systems). Thus, the value of $\sum_{j\in\mathcal{S}} \frac{1}{\overline{R_j}}$ could be easily computed by PU. Since in Eqn. (9), instead of every other $\overline{R_j}$, only the sum of all the inverse of SUs' normalized rate $\sum_{j\in\mathcal{S}} \frac{1}{\overline{R_j}}$ is required. It makes the proposed framework easy to implement and avoid large number of exchanging information. By one broadcast message with short length, every SU can calculate its optimal charge c_i^* based on Eqn. (9).

PU's Optimal Strategy. Being aware of its strategy will affect the strategy selected by $\mathrm{SU_i}$ (follower of the Stackelberg game), the PU (leader of the Stackelberg game) optimizes its strategy $(\alpha, \mathcal{S})$ in order to maximize its utility U_p. Substituting Eqn. (9) into Eqn. (5), the utility of PU can be expressed as

$$U_p = (1-\alpha\lambda)\,\alpha\overline{R_p}(\mathcal{S}) + \frac{(1-\alpha)(|\mathcal{S}|-1)}{\sum_{j\in\mathcal{S}} \frac{1}{\overline{R_j}}}. \quad (13)$$

Regarding to PU's optimal strategy, we have

Theorem 2. The PU maximizes its utility when α is set to

$$\alpha^* = \frac{\overline{R_p(\mathcal{S})}\sum_{j\in\mathcal{S}} \frac{1}{\overline{R_j}} - |\mathcal{S}| + 1}{2\lambda\overline{R_p(\mathcal{S})}\sum_{j\in\mathcal{S}} \frac{1}{\overline{R_j}}}, \quad (14)$$

under constraint

$$\lambda > \frac{1}{2} - \frac{|\mathcal{S}|-1}{2\overline{R_p(\mathcal{S})}\sum_{j\in\mathcal{S}} \frac{1}{\overline{R_j}}}. \quad (15)$$

Proof. By calculating the first order derivative of U_p in respective with α, we can obtain the optimal α^* given in Eqn. (14). Notice that α^* should lie in the range $[0, 1]$. Given the constraint Eqn. (10), $\alpha^* \geq 0$ is always satisfied, since

$$\overline{R_p(\mathcal{S})}\sum_{j\in\mathcal{S}} \frac{1}{\overline{R_j}} - |\mathcal{S}| + 1 > \overline{R_p(\mathcal{S})}\frac{|\mathcal{S}|-1}{\overline{R_i}} - |\mathcal{S}| + 1 \geq 0. \quad (16)$$

And to ensure $\alpha^* \leq 1$, we have the constraint Eqn. (15). In implementation, Eqn. (15) is used for setting the parameter λ in the system. Specifically, we notice that Eqn. (15) is *strictly lower bounded by* 0.5, thus setting $\lambda \geq 0.5$ is appropriate regardless of the SUs' transmission rates and the size of $\mathcal{S}$. If λ is too small to satisfy Eqn. (15), PU will allocate all the retransmission interval to the cooperative retransmission (i.e., $\alpha = 1$), which results in a non-cooperation outcome. □

To select the optimal cooperation subset $\mathcal{S}^*$, PU enumerates all the possible subset $\mathcal{S}$ which satisfy the constraint Eqn. (10). Based on different $\mathcal{S}$, the optimal α^* and corresponding utility U_p^* can be calculated. From all possible subsets, the $\mathcal{S}^*$ that maximizes the U_p is selected.

3.3. Implementation Details

For the network with multiple PUs transmit with one base station via distinct channels, multiple SUs could listen all the channels and randomly choose one candidate PU to cooperative, or randomly choose one channel to listen and cooperative it if possible. We give the operating details of the proposed mechanism as follows:

1. The PU transmits the primary packet to the BS, while SUs listen and store this packet. If BS

successfully decodes the packet, it sends back an ACKnowledgement (ACK) frame. Upon receiving the ACK, PU handles the next packet in the buffer if any. And SUs will discard the received primary packet.

2. If BS cannot decode the primary packet, it sends back a Negative ACK (NACK) frame. This message could be heard by SUs, who tries to decode the stored primary packet. If the decoding succeeds, it sends an Able-To-Help (ATH) frame to PU, which only consists of its identity. To avoid collision, ATH frame could be sent after a random generalized backoff time t $(0 < t < T)$, or in a particular predefined time point over time T.

3. Upon receiving the NACK frames, PU waits for $T + \delta$ time duration, where δ is the maximum propagation delay. If no transmission is overheard, PU assumes that no SU is available to provide cooperative retransmission and thus, retransmits the primary packet by itself. Otherwise, PU calculates the optimal time fraction α^* by using Eqn. (14) and determines the optimal cooperating SU set $\mathcal{S}^*$ by using Eqn. (10) over the SUs that send ATH. Then, PU could also predict the optimal charge c_i^* for $\mathrm{SU_i}$ by using Eqn. (9) and calculate the reimbursement r_i by Eqn. (8). Finally, SU splits the rewarding $1 - \alpha^*$ time slot to multiple durations based on Eqn. (3). PU writes α^*, $\mathcal{S}^*$, c_i^*, r_i and time splitting information (including the identity, start time, end time) into a Clear-To-Send (CTS) frame, and broadcasts it to SUs.

4. Upon receiving the CTS, selected $\mathrm{SU_i}$ performs the cooperative retransmission by using STCs scheme, and transmits its own message during the allocated time duration. Noted that the proposed protocol involves an extra waiting time $T + \delta$ when the secondary retransmission is unavailable. However, compared to the long payload transmission time, $T + \delta$ is extremely small and with negligible influence on the whole system.

4. Numerical Results

In this section, we show the efficiency of the proposed mechanism by numerical results. We consider the scenario that the primary transmission fails since the mutual information between PU and BS cannot support the required data rate. The network model is similar as the one in [8], where the set of SUs are all placed at approximately the same normalized distance d $(0 < d < 1)$ from the BS, and $1 - d$ from the PU. The average channel gains between $\mathrm{SU_i}$ and BS are assumed to be $E[|h_i|^2] = 1/d^\eta$, where $\eta = 2$ is the path loss coefficient.

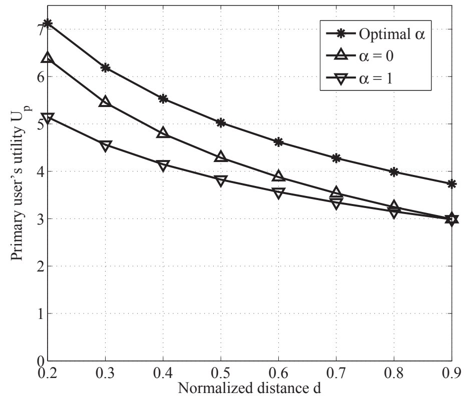


Figure 2. PU's utility by different α vs. normalized distance d, with the size of the cooperation subset $|\mathcal{S}| = 5$ and the reimbursement unit price $\lambda = 0.5$.

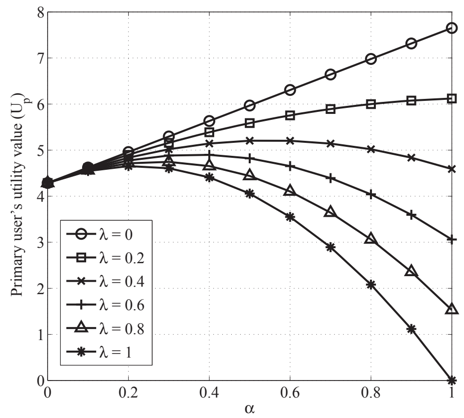


Figure 3. PU's utility at different reimbursement unit price λ vs. parameter α, with cooperation subset size $|\mathcal{S}| = 5$ and normalized distance $d = 0.5$.

Both PU and SUs transmit at a fixed transmitting power P, and the Signal to Noise Ratio (SNR) is $P/N_0 = 10$. The size of the cooperation subset $\mathcal{S}$ is 5, and reimbursement unit price λ is 0.5, unless explicitly stated otherwise.

Fig. 2 depicts the PU's utility under different schemes. Line optimal α^* denotes the proposed scheme, in which PU involves SUs to retransmit cooperatively in optimal time interval α^* and in return, leases time interval $1 - \alpha^*$ for SU's transmission. Line $\alpha = 0$ denotes the scheme that PU allocates the whole retransmission interval to the SUs' transmissions without retransmitting its own data. And line $\alpha = 1$ denotes the scheme that PU utilizes the whole retransmission interval for cooperative retransmission, without leasing any spectrum to SUs. We observe that, by optimally setting the time fraction α, the PU's utility could be maximized. Fig. 3 shows the relationship between PU's utility and parameter α at different reimbursement unit price λ. We can observe that

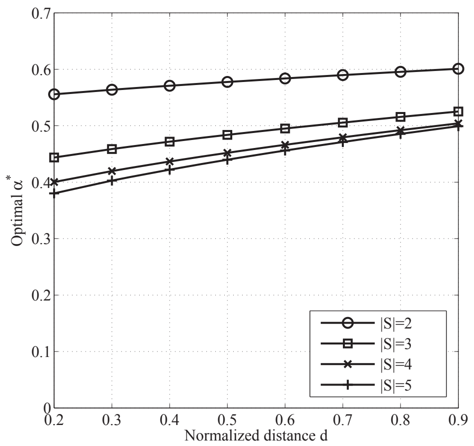


Figure 4. Optimal α^* under different cooperation subset size $|\mathcal{S}|$ vs. normalized distance d, with the reimbursement unit price $\lambda = 0.5$.

optimal α^* decreases as the λ raises. For the case $\lambda = 0$, i.e., no reimbursement is paid, PU is always willing to reserve the whole retransmission time interval to the cooperative retransmission ($\alpha^* = 1$). Actually, this is the reason why we incorporate money-exchange model to foster the cooperation. And for the high reimbursement case with $\lambda = 1$, U_p equals 0 when the whole retransmission time interval is reserved to the cooperative retransmission. It implies that in the high reimbursement case, without leasing time to SUs, PU's gain from cooperative retransmission will be totally offset by the reimbursements it pays to the SUs. Recall the Eqn. (15), setting $0.5 \leq \lambda \leq 1$ is appropriate for all the scenarios.

Fig. 4 shows the optimal α^* versus the normalized distance d at different cooperation subset size $|\mathcal{S}|$. We can observe that optimal α^* raises as the normalized distance d increases. The reason is that small d implies high channel gain and thus, leads to high cooperative retransmission rate. It is reasonable for PU to reduce α to avoid the high reimbursement and mainly rely on the charges received from SUs to maximize its utility. Moreover, the optimal α^* decreases with the size of the cooperation subset $\mathcal{S}$ raises. The reason is that with large number of cooperating SUs, the money-exchange gain from time interval $1 - \alpha$ dominates the resource-exchange gain from time interval α.

Figs. 5 and 6 depict the variation of the utilities and retransmission rates of PU with normalized distance d, respectively. It is straightforward that both U_p and $R_p(\mathcal{S})$ decrease as distance d raises. It is clear that PU tends to involve as many SUs as possible for the sake of larger utility value. Since PU is the leader of the game, it will select the maximal number of SUs to cooperate, as long as the cooperating SU satisfies constraint Eqn. (10). However, the retransmission rate does not increase as

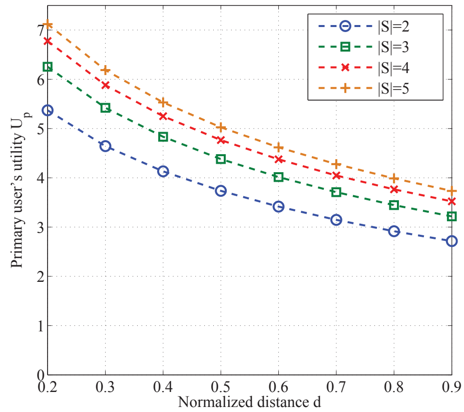


Figure 5. PU's utility at different cooperation subset size $|\mathcal{S}|$ vs. normalized distance d, with the reimbursement unit price $\lambda = 0.5$.

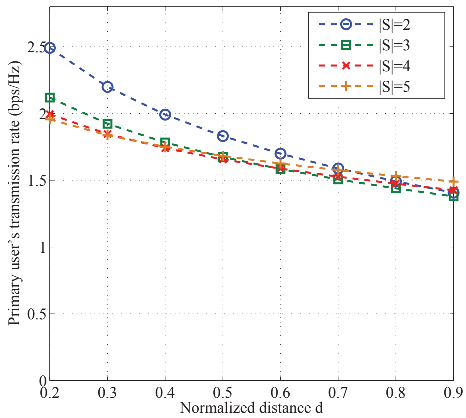


Figure 6. PU's transmission rate at different cooperation subset size $|\mathcal{S}|$ vs. normalized distance d, with the reimbursement unit price $\lambda = 0.5$.

the number of involved SUs raises. This result implies that the achieved large utility value on large $|S|$ case mainly results from the economic income.

Finally, Figs. 7 and 8 depict the utilities and transmission rates of a selected SU vary with the normalized distance d, respectively. We could observe that, in contrast with the results of PU, SU prefers less contenders. This result is straightforward, since more contenders leads to smaller shared access time for each SU. However, as we mentioned, the PU is the leader in the cognitive radio networks, thus SUs have to react to the strategy of the PU.

5. Conclusions

In this paper, we have proposed a novel trading-based spectrum leasing mechanism for cooperative retransmission in cognitive radio networks. We have modeled the considered problem into a Stackelberg game. The unique Nash equilibrium of the proposed

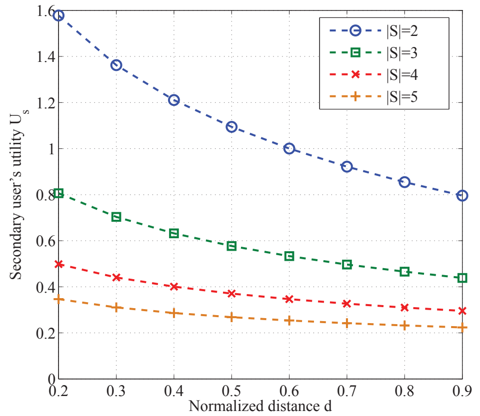


Figure 7. SU's utility at different cooperation subset size $|\mathcal{S}|$ vs. normalized distance d, with the reimbursement unit price $\lambda = 0.5$.

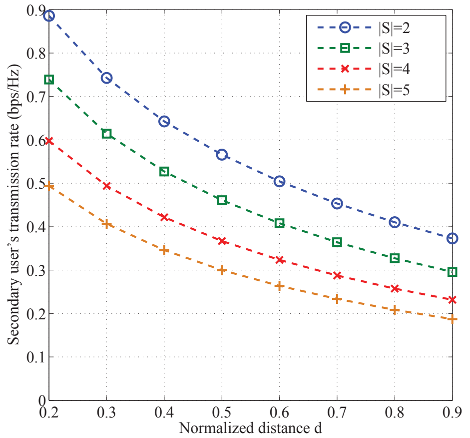


Figure 8. SU's transmission rate at different cooperation subset size $|\mathcal{S}|$ vs. normalized distance d, with the reimbursement unit price $\lambda = 0.5$.

game has been analyzed and, its optimal solutions with corresponding constraints have been derived. The proposed game theoretical framework could be implemented with low communication overhead and lead to a win-win result for both PU and SU. By numerical results, we have demonstrated that the proposed framework can substantially improve the utilities for both PU and SU in terms of data rates and economic profit.

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