# Towards Cheat-Proof Cooperative Relay for Cognitive Radio Networks

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**Abstract**—In cognitive radio networks, cooperative relay is a new technology that can significantly improve spectrum efficiency. While the existing protocols for cooperative relay are very interesting and useful, there is a crucial problem that has not been investigated: Selfish users may *cheat* in cooperative relay, in order to benefit themselves. Here by cheating we mean the behavior of reporting misleading channel and payment information to the primary user and other secondary users. Such cheating behavior may harm other users and thus lead to poor system throughput. Given the threat of selfish users' cheating, our objective in this paper is to suppress the cheating behavior of selfish users in cooperative relay. Hence, we design the *first* cheat-proof scheme for cooperative relay in cognitive radio networks, and rigorously prove that under our scheme, selfish users have no incentive to cheat. Our design and analysis start in the model of strategic game for interactions among secondary users; then they are extended to the entire cooperative relay process, which is modeled as an extensive game. To make our schemes more practical, we also consider two aspects: fairness and system security. Results of extensive simulations demonstrate that our scheme suppresses cheating behavior and thus improves the system throughput in face of selfish users.

**Index Terms**—Cognitive radio networks, cooperative relay, cheat-proof, fairness

## 1 INTRODUCTION

FREQUENCY spectrum is a scarce resource in wireless communications. Hence, a major challenge for wireless networks is to use the limited available frequency bands to achieve better communications. To address this challenge, cognitive radio has been proposed in recent years. With cognitive radio devices, secondary users can access frequency bands when they are not being accessed by primary users. In recognition of the importance of cognitive radio, there have been a lot of studies [6], [9], [13], [15], [8], [17] of cognitive radio networks.

In cognitive radio networks, cooperative relay [28], [21], [27], [7] is a new technology that can significantly improve the system throughput. For example, Zhang and Zhang [27] propose a protocol for cognitive radio networks in which secondary users relay packets for their primary user as rewards (in addition to paying the primary user) for allowing them to use the primary user's licensed frequency band. To analyze their protocol, they assume involved users are *selfish*, and model the interactions among secondary users as a strategic game, which is a part of an extensive game (more precisely, a Stackelberg game) that represents the entire process of cooperative relay. They elegantly show that the primary user can maximize its own utility while all secondary users reach the unique Nash Equilibrium (NE) in their strategic game.

While the existing protocols for cooperative relay are very interesting and useful, there is a crucial problem that has not been investigated: in reality, selfish users may *cheat* in cooperative relay, for example, reporting false transmission rates about their relay channels, in order to benefit themselves. Such cheating behavior may harm other users and thus lead to poor system throughput. For example, in the Zhang-Zhang protocol [27], when secondary users are in the NE, each secondary user's equilibrium strategy depends on other users' secondary links' transmission rates. Consequently, if a selfish secondary user cheats by reporting a wrong transmission rate of its own secondary link, then other users may be misled to choose strategies that benefit the cheater and harm themselves. In Sections 3 and 6, we present a detailed study of such cheating behavior, demonstrating how a user's cheating behavior can benefit himself and harm other users. We also illustrate how cheating behaviors affect the system throughput negatively.

Given the threat of selfish users' cheating, our objective in this paper is to suppress the cheating behavior of selfish users in cooperative relay, so that all these users have incentives to follow the protocol. We achieve this objective through two steps. In our first step, we focus on the interactions among secondary users, and design a basic scheme that gives selfish users incentives to follow the protocol faithfully, i.e., not to cheat. Our basic scheme guarantees that if a secondary user cheats in these interactions, the cheating behavior never benefits himself. Hence, under the basic scheme we design, secondary users have no incentive to cheat. In our second step, we use simple security techniques to extend our scheme to the entire process of cooperative relay, which involves not only the secondary users but also the primary

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user. The extended scheme suppresses cheating behavior throughout the entire process of cooperative relay, so that selfish users have incentives to follow the protocol faithfully all the way through the entire process.

Our contributions can be summarized as follows:

- We design a basic scheme for interactions among secondary users, which is the *first* cheat-proof scheme for cooperative relay in cognitive radio networks. In the model of strategic game, we rigorously prove that under our scheme, it is a dominant strategy for secondary users to faithfully follow the protocol. In other words, cheating is never beneficial under our basic scheme.
- We also extend our scheme to the entire cooperative relay process. In an extensive game model that involves all users, we prove that it is a Subgame Perfect Nash Equilibrium (SPNE) for both primary user and secondary users to follow our extended scheme.
- We consider fairness and propose an approach to reduce starvation of secondary users while maintaining good throughput.
- We perform extensive simulations. Results demonstrate that, without our schemes, a secondary user can cheat to benefit himself while harming other users. In contrast, with our schemes, a user's cheating is never beneficial to himself. By suppressing cheating behavior, our schemes improve the system throughput in face of selfish users.

The remainder of this paper is organized as follows. Section 2 presents the necessary technical preliminaries, including the system model, the notations we use, and the involved game theoretic concepts. We design our basic scheme in Section 3, and extend our scheme to the entire process of cooperative relay in Section 4. Fairness is discussed in Section 5. Simulation results are presented in Section 6, while related work is discussed in Section 7. We conclude in Section 8. In addition, game theoretic definitions, proofs, part of evaluation results and some discussions are presented in supplementary material, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2013.151, due to limited space.

## 2 Technical Preliminaries

Before we design and analyze our cheat-proof scheme, we first describe our system model for cooperative relay in a cognitive radio network, and give a brief review of some definitions from game theory. We use a system model similar to that of [27] and keep our notations consistent, because in Section 3 we will show how cheating behaviors affect their protocol, and also in Section 6 we will compare our schemes with theirs in relation to secondary users' utilities in the face of selfish users.

### 2.1 Cooperative Relay in Cognitive Radio Networks

We consider a cognitive radio network, in which there are a primary sender $PS$ and a primary receiver $PR$. The ordered pair $(PS, PR)$ is called *the primary user*. A set of $N$ secondary transmission pairs $SU$ are working in the same spectrum band. This set $SU = \{(SS_i, SR_i) \mid i = 1, \ldots, N\}$, where each secondary sender $SS_i$ always seeks opportunities to transmit data to its paired receiver $SR_i$. For simplicity, suppose that each pair $(SS_i, SR_i)$ in $SU$ represents a distinct secondary user $i$. Cooperative relay is introduced in this network in order to increase the system throughput as follows: $PS$ distributes its data to (a subset of) secondary users, which relay the data to $PR$. In return, these secondary users who provide relay service can access channels under the primary user's permission. We assume all data relays involve only secondary senders, not secondary receivers. Hence, when we talk about data relays, we refer to "secondary users" and "secondary senders" interchangeably.

The channels are modeled as independent Gaussian random variables; all of them are assumed to be slow fading channels. (Note that slow fading channels generally require frequent exchanges of packets. We discuss why this assumption makes sense in Section IV-E of the supplementary file, available online.)

We consider data transmissions in time slots; the channel variables vary over all slots but are assumed to be constants within each slot [21]. Let $P_0$ be the power level used by the primary user, and $P_i$ be the power level used by secondary user $i$. Denote by $h_0$ the complex channel gain between $PS$ and $PR$, by $h_{0i}$ the channel gain between $PS$ and $SS_i$, by $h_{i0}$ the channel gain between $SS_i$ and $PR$, and by $h_i$ the channel gain between $SS_i$ and $SR_i$.

For cooperative relay, the primary user chooses a subset $S$ of secondary users based on the values of $|h_{i0}|$ and $|h_{0i}|$ (but *independent* from the values of $|h_i|$). The primary user also determines two parameters $\alpha$ and $\beta$ $(0 \le \alpha \le 1, 0 \le \beta \le 1)$. Accordingly, each time slot is divided into three phases: the first phase occupies $\alpha\beta$ of the slot, and is used for data distribution from $PS$ to secondary users in the set $S$; the second phase occupies $\alpha(1-\beta)$ of the slot, and is used for $PR$ to receive data from $PS$ and those selected secondary users; the third phase is the remaining $(1-\alpha)$ of the slot. The secondary users in $S$ can use the third phase for their own data transmissions.

In addition to providing relay service, each secondary user $i \in S$ also needs to make a payment $c_i$ to the primary user for its use of the band, where $c_i$ is determined by secondary user $i$ to obtain its optimal utility (see Section 2.2 for definition of utility). The access time in the third phase is assigned to these secondary users based on the amounts of their payments. The method of this assignment depends on the protocol used. In particular, the scheme we design uses a method different from any other existing work—detailed explanations are given in Section 3.

Regardless of which protocol is used, the transmission rates in the system can be calculated as follows [27]:

$$\begin{cases} R_{PS}(S) = \log_2\left(1 + \dfrac{\min_{i\in S}|h_{0i}|^2 P_0}{N_0}\right), \\ R_{SP}(S) = \log_2\left(1 + \dfrac{|h_0|^2 P_0}{N_0} + \displaystyle\sum_{i\in S} \dfrac{|h_{i0}|^2 P_i}{N_0}\right), \\ R_i = \log_2\left(1 + \dfrac{|h_i|^2 P_i}{N_0}\right), \end{cases} \tag{1}$$

where $R_{PS}$ is the transmission rate from the primary user to the secondary users in the first phase, $R_{SP}$ is the transmission rate from the secondary users to the primary user in the second phase, and $R_i$ is the transmission rate of secondary user $(SS_i, SR_i)$ in the third phase. In the first equation of (1), $\frac{\min_{i\in S}|h_{0i}|^2 P_0}{N_0}$ represents the lowest received SNR from $PS$ to all $SUs$. In the second equation of (1), $\frac{|h_0|^2 P_0}{N_0}$ represents the received SNR from $PS$ to $PR$, and $\frac{|h_{i0}|^2 P_i}{N_0}$ represents the received SNR from secondary user $i$ to $PR$. In the third equation of (1), $\frac{|h_i|^2 P_i}{N_0}$ represents the received SNR from the sender of $i$ to the receiver of $i$. The transmission rate from $PS$ to $PR$ via cooperative relay is

$$R_P(\alpha, \beta, S) = \min\{\alpha\beta R_{PS}(S), \alpha(1-\beta)R_{SP}(S)\}. \quad (2)$$

Intuitively, $\alpha\beta R_{PS}(S)$ is the rate from $PS$ to the relay nodes, and $\alpha(1-\beta)R_{SP}(S)$ is the rate from the relay nodes to $PR$. Hence, the smaller of these two rates is the effective rate from $PS$ of $PR$.

One can easily see that, in the model we described above, the primary user can communicate with the secondary users. This implicit assumption is actually inherited from the existing literature, for example, [27]. One may wonder why this implicit assumption makes sense. Detailed discussions can be found in Section IV-D in the supplementary file available online.

## 2.2 Game Theoretic Concepts

We first model the interactions among secondary users as a pure strategic game to analyze secondary users' actions when set $S$ is determined. Then we consider the entire process of cooperative relay, and extend the above model of strategic game to a model of extensive game in which all users (primary user and secondary users) participate.

### 2.2.1 Basic Game among Secondary Users

In the strategic game among secondary users, the set of players is $S$. Since we can easily detect the cheating behavior if a secondary user pays an amount not identical to what it claims, we assume the secondary users are smart enough that they always pay amounts identical to what they claim. For each $i \in S$, the action defined in our game is to report a payment $c_i$ to the primary user. Based on the profile of all players' actions, player $i$ gets utility

$$u_i = w(1-\alpha)R_i t_i - c_i, \quad (3)$$

where $w$ is the amount of equivalent payment for each unit of data transmission rate, and $t_i$ is ratio of the assigned access time to the duration of the third phase. Intuitively, this utility is equal to the benefit of accessing the free channel minus the payment to the primary user.

A strategy profile $s$ is a set of strategies which specifies actions of all players in a game. Denote by $s_i$ the strategy player $i$ chooses in strategy profile $s$, and by $s_{-i}$ the strategies in profile $s$ chosen by all players other than player $i$.[1]

1. It is a convention in game theory that subscript $-i$ represents all players other than $i$. We adopt this convention throughout this paper.

$u_i(s_i, s_{-i})$ denotes the utility of user $i$ while all users choose actions in strategy profile $s$. Moreover, we define two important solution concepts: Nash Equilibrium and dominant strategy equilibrium (DSE) (which can be found in the supplementary material available online).

### 2.2.2 Extensive Game among All Users

We model the interactions among all users, including the primary user and the secondary users, in each slot as a two-stage extensive strategic game with perfect information. The definition of the two-stage extensive game with perfect information can be found in the supplementary material available online, together with two more concepts: subgame of extensive game with perfect information and Subgame Perfect Nash Equilibrium. Specifically, the utility function of the primary user is equal to the value of the overall throughput through cooperative relay plus the sum of the payments collected from selected secondary relay users:

$$u_0 = wR_P + \sum_{i\in S} c_i. \quad (4)$$

The utility function of a secondary user is given above in Equation (3).

Although in practice there might be multiple primary users, we would like to first present our model in the case where only one primary user is present. The reason is that if there are multiple primary users, not only the secondary users, but also the primary users have to bid for their demanding resources from a game theory point of view. As a result, the game will become a double auction instead of our current extensive game model. We found it very challenging if we integrate the model of multiple primary users into current one, and would like to study this new model in the future.

# 3 Basic Scheme to Suppress Cheating

Given the model, we can now build a cheat-proof scheme for cooperative relay. To illustrate the need for cheating suppression, we analyze the cheating behavior that may bring increased utility to the secondary user in the supplementary material available online. Our cheat-proof scheme is presented in details below followed by a game theoretic analysis result.

## 3.1 Design of Basic Scheme

In order to suppress cheating in cooperative relay, the main idea underlying our design of a cheat-proof scheme is that we should make sure a user's utility is *never* affected by any other user's reported transmission rate.

To achieve this objective, we examine the definition of utility, Equation (3). For a secondary user $i$, the payment $c_i$ and the access time $t_i$ calculated in existing protocols can be affected by other users' reported transmission rates. Hence, we design a new method of payment determination and time assignment such that $c_i$ and $t_i$ are not affected by any other user's reported transmission rate. And each secondary user does not have to report its own transmission rate to the primary user and other secondary users.

Of course, to make the scheme practical, there are additional requirements on the time assignment method. For example, the assignment of access time should be fair to all secondary users in $S$. Furthermore, when a secondary user increases (decreases, resp.) its payment to the primary user, its assigned amount of time should increase (decrease, resp.) accordingly.

A summary of our basic cheat-proof scheme is given as Algorithm 1. We choose to use a simple method of access time assignment that satisfies all the above requirements. Our method first divides the total amount of time for secondary access evenly among all the secondary users in $S$. Then, it reduces the amount of time assigned to user $i$ based on user $i$'s payment. More precisely, the amount of time assigned to user $i$ is multiplied by $1 - \frac{c}{c_i}$, where $c$ is a constant determined by the primary user.

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**Algorithm 1** Basic Scheme for Cheating Suppression

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**Input:** $S$—selected secondary user set; $\alpha$—time slot parameter; $R_i$—transmission rate; $c$—constant selected by primary user; $w$—payment equivalent to one unit of transmission rate.

**Before each time slot, secondary user $i \in S$ does the follows:**

1. Calculate (and make) the payment to the primary user

$$c_i = \sqrt{\frac{w(1-\alpha)R_i c}{k}}, \tag{5}$$

where $k = |S|$.

2. In the third phase of the time slot, use the following ratio $t_i$ to compute the allocated time for own access:

$$t_i = \frac{1}{k}\left(1 - \frac{c}{c_i}\right). \tag{6}$$

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The above method of access time assignment normally produces some leftover of the access time. Given Equations (5) and (6), we get the leftover time ratio in each time slot

$$T_{left} = 1 - \sum_{i=1}^{k} t_i = 1 - \frac{1}{k}\sum_{i=1}^{k}\left(1 - \frac{\sqrt{kc}}{\sqrt{w(1-\alpha)R_i}}\right). \tag{7}$$

Using this equation which connects $T_{left}$ to $c$, we can easily obtain that $\lim_{c\to 0} T_{left}(c) = 0$, which means the leftover can be negligible if the system parameter $c$ is sufficiently small. We will evaluate how $c$ can affect the leftover and each secondary user's utility in a numerical example in Section 6. We can show that although $c$ may be very small, secondary users can still have positive utilities which ensures that our scheme is feasible.

Following this algorithm, we guarantee that user $i$'s assigned time is not affected by other users' reported transmission rates. Moreover, the allocated access time of each secondary user increases if they pay more to the primary user. Note that although the primary user does not need to know each secondary user's own data transmission rate $R_i$, $R_i$ does affect the secondary user's payment thus further influencing the primary user's utility.

**Theorem 1.** *In our scheme, it is a dominant strategy equilibrium (DSE) that all players $i \in S$ follow the protocol faithfully.*

The proof is presented in the supplementary material available online, due to limited space.

## 4 Extended Scheme

The previous section presents a basic scheme to suppress cheating in the interactions among secondary users. In this section, we extend the scheme to suppress cheating throughout the entire process of cooperative relay, which involves both the primary user and the secondary users. In other words, we need to take into consideration the primary user's selection of relay users, and also aim to suppress possible cheating during this selection. The prerequisite of our extended scheme is that channel reciprocity holds for a reasonably long period of time and that we need to achieve a high level of accuracy in channel measurements. In some practical scenarios, the assumption of channel reciprocity is not reasonable. We will discuss the approaches that could measure relay channel information without the assumption of channel reciprocity at the end of this section. We assume that there are some fixed sending power levels $(PW_1, PW_2, \ldots, PW_n)$ secondary users may choose from, and such power levels are already known by the primary user. In practice, this means secondary users use types of devices known by the primary user. The channel gain amplitudes are assumed to be the same for different sending power levels.

We first analyze the cheating behaviors of secondary users in Section 4.1, then present our extended scheme for the primary user in Section 4.2.

### 4.1 Cheating Behavior

As we have mentioned in Section 2, in the first phase of cooperative relay, the primary sender $PS$ distributes data to secondary users in $S$, and in the second phase, the secondary users in $S$ relay data to the primary receiver $PR$. The primary user chooses the set $S$ which provides the largest utility. From Equations (1), (2), (4), we know that the utility of the primary user is affected by the reported channel gain $h_{0i}$ and $h_{i0}$ of each secondary user $i \in SU$.

Suppose there is a secondary user $i$ which has no chance to be selected as a relay user if it truthfully reports its relay related information. However, by cheating in values of $|h_{0i}|$ or $|h_{i0}|$, secondary user $i$ may mislead the primary user to select itself as a relay user. As a result, this user $i$ can benefit from the cheating behavior, while on the other hand the primary user and the system may be harmed.

### 4.2 Design of Extended Scheme

We consider a radio model, in which each involved device can freely determine which power level among $PW_1, PW_2, \ldots, PW_n$ is used to send signals, and each such device can receive signals from others at any receiving power level. Clearly, a major challenge for designing the extended scheme is to correctly measure $|h_{i0}|$ and $|h_{0i}|$ of selfish secondary user $i$ by the primary user, because these selfish users may use power control and cheat when reporting the channel information. To address this challenge, we require secondary users to send test signals to the primary user.[2]

2. Throughout this paper, we assume such test signals must be sent by the secondary senders, *not by the secondary receivers*, because only secondary senders are involved in data relay.

Specifically, we require secondary users to send test signals at their highest and lowest power levels, respectively. $PR$ computes $|h_{i0}|$ using the strengths of the received test signals. Since the test signals are transmitted at two different power levels, there are two results for $|h_{i0}|$, based on the highest transmission power and the lowest transmission power, respectively. If these two results are (roughly) equal to each other, then secondary user $i$ has not cheated. Otherwise, secondary user $i$ has cheated and should be punished (e.g., be excluded from relay permanently). To measure $|h_{0i}|$, we can use channel reciprocity and let $PS$ compute the channel gain using the strengths of received signals of $PS$.[3]

The underlying idea of the above design is very simple: If a secondary user cheats, it can only decrease the power level when it is supposed to transmit at the highest power level, and it can only increase the power level when it is supposed to transmit at the lowest power level. The former definitely decreases the measured $|h_{i0}|$, while the latter definitely increases the measured $|h_{i0}|$. There is no way for a cheating user to keep the two measured values of $|h_{i0}|$ equal to each other.

Consequently, the extended scheme works by first measuring $|h_{0i}|$ and $|h_{i0}|$ correctly as described above. After that, the primary user first excludes the cheating users (if any) from the relay candidates, and then searches[4] for a proper set of relay users that can maximize its utility based on the information of all honest secondary users. Finally, the payment due and the secondary users' access time are computed just as in the basic scheme.

The details of the extended scheme are presented in Algorithm 2.

In our scheme, we compare two measured values of a channel gain using a threshold $\epsilon$. This $\epsilon$ determines whether two values are "equal" to each other. Specifically, when $|x_1 - x_2| < \epsilon$, we say $x_1$ and $x_2$ are equal. To determine the value of $\epsilon$, one possibility is to consider a slow fading model, in which the received power levels have log-normal distributions [11]. Given a signal sent at power level $PW_i$, the probability density function of the received power level is $f_i(x \,|\, PW_i) \sim lnN(\mu_i, \sigma_i)$. If we assume that the expected channel gain amplitudes are the same for different sending signal power levels, then we can compute the system parameter: $\epsilon = |(x_i/PW_1 - e^{\mu_1+\sigma_1^2/2}/PW_1) + (e^{\mu_n+\sigma_n^2/2}/PW_n - x_j/PW_n)| = |x_i/PW_1 - x_j/PW_n|$,where $x_i$ and $x_j$ are receiving power levels of test sending signal $PW_1$ and $PW_n$ respectively.

It is noteworthy that, in this algorithm, the decision on $S$ is computed in a centralized manner. There are a couple of reasons that make it difficult to do the same thing in a fully distributed manner. However, it is still possible to do the same thing in a slightly more distributed manner. Detailed discussions of these issues can be found in Section IV-C of the supplementary material available online.

3. The computed channel gains would be more precise if the primary user could repeat the measurement and take the average of the results.

4. In existing protocols, e.g. [27], exhaustive search is used to enumerate all the possible set $S$. Depending on the application, we can either use the same approach, or pursue a better search strategy. We do not discuss this issue here in more detail, because it is out of the scope of this paper.

**Theorem 2.** *It is a Subgame Perfect Nash Equilibrium that all users truthfully follow our schemes.*

We present the proof of Theorem 2 and a discussion of Algorithm 2 in the supplementary material available online.

**Algorithm 2** Extended Scheme

**Input:**
$PW = \{PW_1, PW_2, \ldots, PW_n\}$ ($PW_1 <, \ldots, < PW_n$); system parameter $\epsilon > 0$; $SU$; $SU' = \phi$; $SU^* = \phi$.

**Cheating Detection:**

1. Secondary user $i \in SU$ sends test signal at power level $PW_n$.
2. $PR$ ($PS$, respectively) receives the signal. Let the strength of the received signal be $Q_{R,n}$ ($Q_{S,n}$).
3. Secondary user $i$ sends test signal at power level $PW_1$.
4. $PR$ ($PS$, respectively) receives the signal. Let the strength of the received signal be $Q_{R,1}$ ($Q_{S,1}$).
5. $PR$ computes $h_{i0,1} = Q_{R,1}/PW_1$ and $h_{i0,n} = Q_{R,n}/PW_n$. If $|h_{i0,n} - h_{i0,1}| < \epsilon$, then $PS$ sends $(h_{i0,n} + h_{i0,1})/2$ as the measured values of $|h_{i0}|$ to $PR$. Otherwise, cheating is detected and $SU' = SU' \cup \{i\}$.
6. $PS$ computes $h_{0i,1} = Q_{S,1}/PW_1$ and $h_{0i,n} = Q_{S,n}/PW_n$. If $|h_{0i,n} - h_{0i,1}| < \epsilon$, then $(h_{0i,n} + h_{0i,1})/2$ is used as the measured values of $|h_{0i}|$. Otherwise, cheating is detected and $SU' = SU' \cup \{i\}$.

**Decision on $S$:**

7. The primary user obtains the set of honest users $SU^* = SU - SU'$, and punishes the secondary users in $SU'$.
8. The primary user searches for the cooperative relay set $S \subseteq SU^*$, that provides the primary user with the maximum utility.
9. Each secondary user $i \in S$ computes $c_i$ and $t_i$ as in the Basic Scheme.
10. $i$ pays $c_i$ to the primary user.

The overhead of the extended scheme is quite small. The most significant might be the the computational overhead of the primary user, which is $O(2^{N-1}N)$. But $2^{N-1}N$ is also quite small, because usually $N$ is a very small constant. Detailed analysis of the overhead can be found in Section IV-A of the supplementary material available online.

## 5 Fairness

In this section, we study the fairness issue of our schemes. In some scenarios under existing cooperative relay protocols, the primary user may always select certain secondary users with higher relay transmission rates as its cooperative relay candidates. Consequently, the primary user's free channel is accessed by only a few users. Other secondary users have no opportunity at all to access the free channel because of their low relay transmission rates. Thus we need to consider how to allocate resources to all possible relay candidates wisely.

One may suggest that a scheme is fair only if all secondary users obtain roughly equal shares of the spectrum. However, we argue that this may not be a good fairness metric for our schemes. Recall in our system model, the secondary users share the primary user's free channel if they are selected as relay nodes. And the achievable throughput of each selected user $i$ is $R_i t_i$, which is determined by the transmission rate $R_i$. From Equations (5) and (6), we know that the two users $i$ and $j$ have the same achievable throughput $R_i t_i = R_j t_j$, if and only if $R_i = R_j$. On the other hand, the secondary users' transmission rates are predetermined and might be different. Therefore, it is not appropriate for the primary user to equally share the spectrum with all secondary users in our system.

*a) Throughput Ratio.* Now let us take a closer look at the throughput ratio between different secondary users and examine how large it could be. Assume that all secondary users follow our schemes (because, as we have shown, they have incentives to do so). Then using Equations (5) and (6), we can easily obtain that the throughput ratio between the two users $i$ and $j$ is

$$\eta_{ij} = \frac{R_i t_i}{R_j t_j} = \frac{R_i(1 - \frac{c}{c_i})}{R_j(1 - \frac{c}{c_j})} = \frac{R_i\left(1 - \frac{\sqrt{ck}}{\sqrt{w(1-\alpha)R_i}}\right)}{R_j\left(1 - \frac{\sqrt{ck}}{\sqrt{w(1-\alpha)R_j}}\right)} = \frac{R_i - \frac{\sqrt{ckR_i}}{\sqrt{w(1-\alpha)}}}{R_j - \frac{\sqrt{ckR_j}}{\sqrt{w(1-\alpha)}}}.$$

If all secondary users' transmission rates are sufficiently high (i.e., if for all $i \in S$, $R_i >> \frac{ck}{w(1-\alpha)}$), then we can easily get that

$$\eta_{ij} \approx \frac{R_i}{R_j} \leq \frac{\max_\ell R_\ell}{\min_\ell R_\ell}.$$

Therefore, $\max_\ell R_\ell / \min_\ell R_\ell$ is an upper bound for $\eta_{ij}$. Nevertheless, if the above condition is not satisfied, then $\eta_{ij}$ might become large. For example, consider the extreme case in which both $R_i$ and $R_j$ are close to $\frac{ck}{w(1-\alpha)}$. In this case, we get that

$$\eta_{ij} \approx \frac{\sqrt{R_i} - \frac{\sqrt{ck}}{\sqrt{w(1-\alpha)}}}{\sqrt{R_j} - \frac{\sqrt{ck}}{\sqrt{w(1-\alpha)}}},$$

which implies that a small difference between the transmission rates $R_i$ and $R_j$ can lead to a large difference between the throughputs achieved by the two secondary users $i$ and $j$. Consequently, in order to have good fairness, the primary user should make sure an appropriate value is chosen for $c$.

*b) Starvation.* Due to limit of space, please see Section IV-F in the supplementary file available online.

Besides the above analysis and discussion, we also empirically study fairness. Specifically, we measure the starvation percentage of our extended scheme and that of the starvation-reduced scheme in the Evaluation section. In addition, although we do not aim to equally share the primary user's free spectrum with secondary users in our system, we measure the Jain's fairness index [10] and make comparisons. The results can be found in Section 6.2.

In summary, we have the following three contributions in terms of fairness analysis: First, we provide a throughput ratio analysis, in which we derive an upper bound for throughput ratio under a condition and also discuss the situation not satisfying this condition. Second, we analyze the starvation of secondary users and propose a starvation-reduced scheme. Third, we empirically study Jain's fairness index, the results of which can be found in Section 6.2.

## 6 Evaluations

We implement our schemes and conduct extensive experiments using GloMoSim[22]. First, we measure and compare the utilities of secondary users when a cheat-proof scheme is absent and present respectively. Second, we measure the system throughput and observe how it is affected by the cheating behaviors. Third, we evaluate the starvation percentage of secondary users when our proposed approach for starvation reduction is used and not used respectively, and we also evaluate the fairness following Jain's fairness index and compare the results. Finally we measure the payments of secondary users in random cases when our algorithms are implemented.

However, due to space limit we present part of evaluation results, including two sets of experiment data of utility measurement and one set of experiment data of throughput measurement, in the supplementary material available online. These results can also be found in the conference version [26].

### 6.1 User Utilities - How Parameter $c$ Affects Leftover Time and User Utilities

In each time slot under our algorithms, the primary user will have some leftover time which is not assigned to any secondary user after resource allocation. We have shown that the leftover time is affected by system parameter $c$. Furthermore, when the value of $c$ approaches zero, the length of the leftover time ratio (the ratio of the leftover time to the duration of third phase in a time slot) approaches zero as well.

In this part, we set up experiments in which we observe how parameter $c$ affects the value of the leftover time ratio in simulation. We assume $|S| = 5$, $w = 2$ and $\alpha = 0.5$. The network topology of these experiments is the same as in the first set of experiment data presented in the supplementary material available online, and all five of the secondary users are honest. The transmission rates of these secondary users are the same as in the first experiment data: $R_1 = 3.7887$, $R_2 = 3.7157$, $R_3 = 1.9611$, $R_4 = 3.2774$, $R_5 = 0.85593$ which are randomly picked before simulation. The secondary users truthfully report their transmission rates to the primary user and the primary user computes the payment $c_i$ and the assigned access time ratio $t_i$ for each secondary user following the Algorithm 1. The value of system parameter $c$ varies from $0$ to $0.01$, with step of $0.001$ during the tests. In each test, we record the leftover time ratio $T_{left} = 1 - \sum_{i=1}^{5} t_i$. Thus we have 11 different results on the leftover time ratio $T_{left}$ which is shown in Fig. 1.

In Fig. 1, we notice that when $c$ is set to be $0$, the leftover time ratio is $0$ as well, which means there is no leftover time after resource allocation. This can be actually be derived from Equation (6) because when $c$ equals $0$, $t_1 = t_2 = \cdots = t_k$, i.e., the available access time is equally allocated to all selected secondary users, making our incentive schemes no longer useful. Hence zero is not an appropriate value of $c$ in practice and we have to keep $c$ positive. We

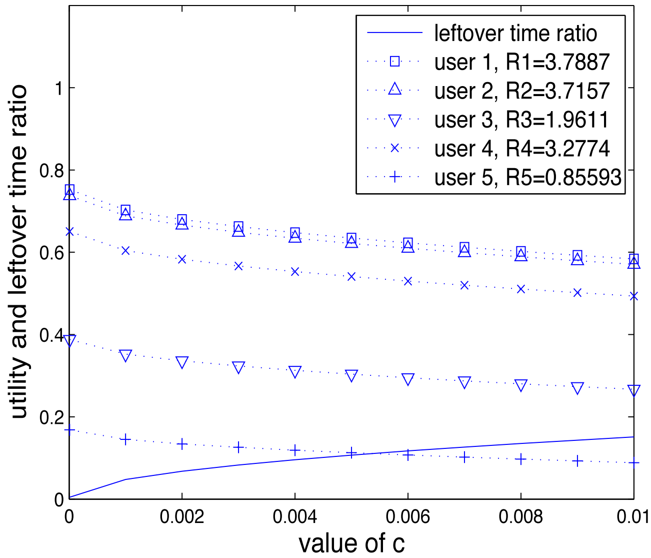


Fig. 1. The leftover time ratio and secondary users' utilities.

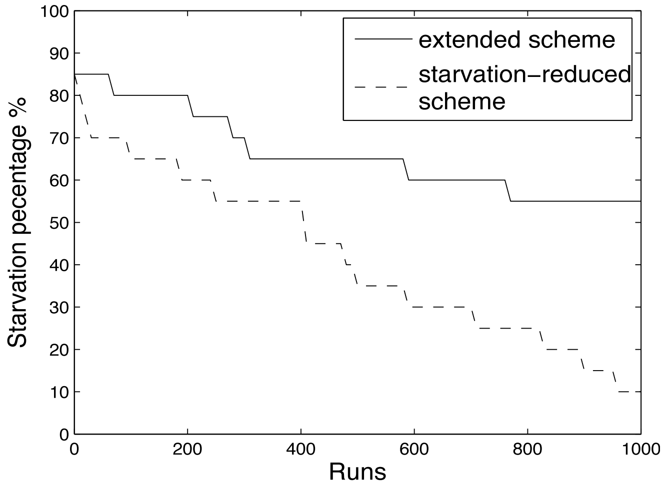


Fig. 2. Starvation percentage in 1,000 runs.

can also observe the fact that $T_{left}$ decreases when $c$ decreases, which can also be theoretically derived from the definition of $T_{left}$ in Section 3.

Other than measuring the value of $T_{left}$ in this part, we also measure the corresponding computed utility of each secondary user. Because the utility of each secondary user is affected by parameter $c$ as well (from Equations (3), (5), (6)). We need to make sure the utilities are positive and the algorithm stays feasible when we change $c$.

To measure the secondary users' utilities, we use exactly the same experiment settings as above. The primary user computes $t_i$ and $c_i$ of each secondary user in a test run and we record the computed utilities of all five secondary users in all 11 runs. The results are shown in Fig. 1. We can see that all utilities decrease but stay positive in all runs, which means our algorithm is still able to function well when parameter $c$ has different values.

Now let us consider two example scenarios. The first example scenario is that $c = 0.01$, and the second is that $c = 0.001$. Below are our experimental results in these two example scenarios:

- In the first example scenario, the leftover time ratio is $0.1512$. The secondary users' utilities are $0.5836$, $0.5707$, $0.2670$, $0.4936$, and $0.0884$, respectively.
- In the second example scenario, the leftover time ratio is $0.0478$. The secondary users' utilities are $0.7027$, $0.6886$, $0.3526$, $0.6043$, and $0.1450$, respectively.

It is easy to see that in the second example scenario, the leftover time ratio is lower, which means less time is wasted. It is also easy to see that in the second example scenario, the secondary users have higher utilities. These benefits are all consequences of having a smaller (but still positive) value of $c$.

### 6.2 Fairness Evaluation

In this section, we evaluate the starvation percentage and the Jain's fairness index within each spectrum allocation.

First, without loss of generality, we measure the starvation percentage in a setting identical to that of the third set of experiment in utility evaluation, where there are $20$ secondary users and one primary user. The starvation percentage of secondary users (i.e., the percentage of secondary users never selected as relay users) is measured in $1{,}000$ runs. We allow each secondary user to change their channel gain magnitudes within a range of $\pm 1\%$ (due to movement) after each run so as to simulate a more dynamic scenario. We compare the results of the original version of our extended scheme with that of our starvation-reduced scheme, in which the system parameter $\tau = 80\%$.

Second, under the same simulation settings, we measure the Jain's fairness indices [10] in our system. The fairness index is computed as

$$J(x_1, x_2, \dots, x_n) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \cdot \sum_{i=1}^{n} x_i^2}. \tag{8}$$

In our evaluation, we measure two types of fairness indices: 1) $x_i = R_i t_i$, the allocated transmission rate of user $i$ in each run. 2) $x_i = \sum_j R_{ij} t_{ij}$, user $i$'s accumulative transmission rate in all runs. Specifically, in case (1), $x_i = 0$ when $i$ is not selected as a secondary relay user in one run, and in case (2), $x_i = 0$ if $i$ has never been selected as relay user during all runs. For each type of fairness index, we test $1{,}000$ runs. In case (1), we evaluate $x_i$ in each run when our starvation-reduced scheme is implemented and when it is not, and after all $1{,}000$ runs we compare the cumulative distribution of $x_i$ for both situations. In case (2), we record $i$'s allocated transmission rate in each run, and compute the fairness index of sum $x_i$ after all $1{,}000$ runs.

In Fig. 2, we can see that with our starvation-reduced scheme, the final starvation percentage after $1{,}000$ runs is 10 percent, which means that 90 percent of the secondary users (18 users) have participated in the cooperative relay service and have benefited from accessing the primary user's free channel. However, if we merely use the extended scheme, only 45 percent of secondary users (9 users) have been selected, while 55 percent users have never been in these $1{,}000$ runs.

Fig. 3 shows that we achieve better Jain's fairness indices when the starvation-reduced scheme is present in case (1). The minimum index for both schemes is $0.05$

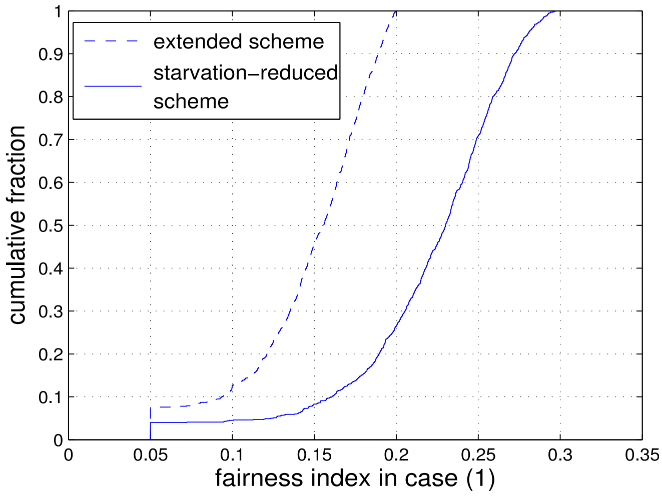


Fig. 3. The cumulative fraction of Jain's fairness index in case (1). The solid line indicates the results when the starvation-reduced scheme is implemented, while the dotted line indicates the results when the starvation-reduced scheme is absent.

when one and only one secondary user is selected as relay user out of 20 users in one run. The maximum index our starvation-reduced scheme can achieve is 0.3. However, when the starvation-reduced scheme is absent, the maximum index drops to 0.2. The two cumulative fractions at the starting point are different, because it is less likely that only one user is selected as relay user in our starvation-reduced scheme. Although the improved fairness indices are no more than 0.3, far less than 1, we emphasize that our objective in fairness is not to equally share the free spectrum among all secondary users. Instead, we aim to provide opportunities of spectrum access for as many capable secondary users as possible.

In case (2), we measure all secondary users' cumulative transmission rates allocated by the primary user in all 1,000 runs. We then compute the Jain's fairness index following Equation (8). The result is shown in Table 1. In our tests, only two users have *never* been selected as relay users when the starvation-reduced scheme is present and up to 12 users fail to become relay candidates when that scheme is absent (as shown in Fig. 2). Compared to the fairness index under our original extended scheme, the new fairness index has been improved by 83.64 percent.

### 6.3 Payment

Payment is another important factor in our system. We observe payments of secondary users in this section. In this set of experiments, we create a random topology ($2 \leq |SU| \leq 20$) for each test and in each test all secondary users have random channel information under constraints $0 < R_i \leq 10, -80dB < |h_{0i}|, |h_{i0}| \leq -50dB$. System parameter $\omega$ is set to be 2 and $c$ is set to be 0.01.

TABLE 1
The Measurement of Jain's Fairness Index In Case (2)

| If the starvation-reduced scheme is present | the value of Jain's fairness index |
|---|---|
| No | 0.3381 |
| Yes | 0.6209 |

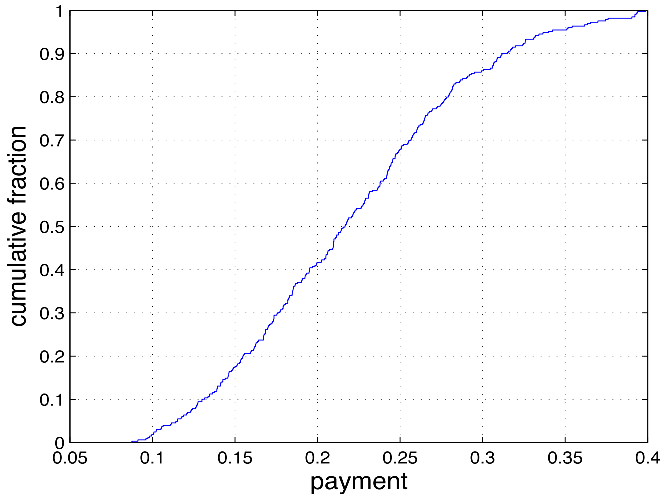


Fig. 4. The cumulative fraction of all payments in 1,000 runs.

We assume all secondary users behave truthfully in each test, because cheating behavior can always be detected under our algorithms and the cheater will never be selected as relay candidate. After the primary user determines the relay candidates, the required payment of each candidate is recorded. We test 1,000 runs and record all payments. The cumulative distribution fraction results are shown in Fig. 4.

In Fig. 4, among all payments, the smallest value is 0.088 and the largest value is 0.396. We can also see the payments are almost uniformly distributed between 0.088 and 0.396. This result is consistent with our settings in which transmission rate $R_i$ and channel gain $h_{0i}, h_{0i}$ all follow uniform distributions and are all independent of each other.

Then we record the payments of the first three secondary users when $|SU|$ is set to be five (and other settings are kept the same as in above experiments). The cumulative fraction results are shown in Fig. 5: 1) For any of the three users, the chance of not being selected as relay candidate is about 27 percent; 2) The minimum payment among all three users is 0.086 which is achieved by user 2; 3) The maximum payment among all

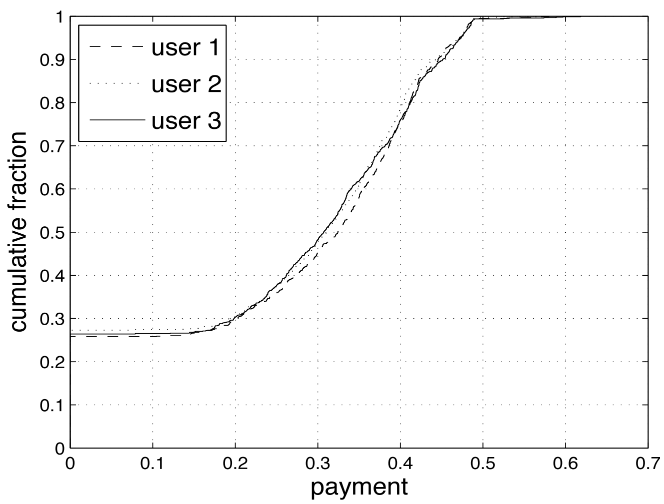


Fig. 5. The cumulative fraction of three secondary users' payments when there are five secondary users in 1,000 runs.

three users is $0.612$ which is achieved by user 3. The reason why the maximum payments are different in Figs. 4 and 5 is that in Fig. 4 it is possible that more than five secondary users ($k > 5$) are selected as relay candidate which makes the payment less. In summary, all these observations are consistent with our expectations.

## 7 Related Work

Cognitive radio networks have been studied extensively [6], [9], [13], [15], [8], [17]. In the literature, there are three pieces of existing work [21], [27], [7] that study roughly the same problem as ours. In this section, we summarize these three pieces of work first, compare them with our work, and then briefly discuss other related work.

The first piece of such work, by Simeone et al. [21], proposes that secondary users can relay data transmission for the primary user and in return the primary user can allocate portions of her spectrum for secondary users. They present a model of Stackelberg game for this problem. In this model, they present a nice proof for the existence of NE. In [27], Zhang and Zhang study the same problem but use a different model. They calculate the utilities of users using the achieved transmission rates and the payments. In their model , they elegantly prove that following their protocol is a unique NE. Yet another model for this problem, a Bayesian potential game model, is proposed by Giupponi and Ibars [7]. They present an interesting analysis of the connection between the system performance and power control and channel allocation. In terms of users' selfish behavior, they mention that the existence of Bayesian Nash Equilibrium (BNE) is an immediate consequence of the NE existence theorem. It is worth noting that our paper uses a different model, which takes cheating into account. And our paper focuses on the study of cheating and cheating suppression.

Besides the above existing work, there are studies of cooperative relay from different perspectives. Their studied problems are related to ours, but completely different. For example, Belmega et al. [2] study the competition for relay in cognitive radio networks. More precisely, they consider two pairs of source and destination nodes who compete with each other for one relay node's relay service. They use game theory to analyze their problem and obtain interesting results. But since their problem is different, their results cannot be directly applied to our problem.

There is an amount of other work on cooperative relay that does not consider selfish behavior or utilities, for example, Jia, et al.'s protocol [14]. We do not discuss such work because we focus on incentives and cheating suppression in this paper.

There is also a lot of work on incentives issues in wireless networks without cognitive radios. For example, a lot of protocols (e.g., [18], [23], [4], [20], [1], [19], [29], [24], among many others) have been developed for packet forwarding and routing in ad hoc networks to deal with selfish behavior. Similar work has been done in multi-hop cellular networks[16], [12], [3], and opportunistic-coding-based wireless networks [25], [5].

## 8 Concluding Remarks

In this paper, we study the cheating behavior of selfish users in cooperative relay and present the first cheat-proof scheme to suppress cheating. Theoretically, in the model of strategic game, we rigorously show that with our basic scheme, all secondary users following the protocol is a DSE. Then we extend our study to the model of the entire cooperative relay process. In the model of an extensive game with perfect information, we show that it is a SPNE for all users to follow our extended scheme. Experimentally, we perform extensive simulations to test the effectiveness of our scheme. The simulation results verify that, without our scheme, selfish users can cheat to harm other users in cooperative relay, but with our scheme, they have incentives to follow the protocol, i.e., not to cheat. Consequently, our schemes improve the system throughput significantly in face of selfish users. In our experiments, it improves the system throughput by up to 69.4 percent. Furthermore, we consider fairness and present a starvation-reduced scheme.

We stress that, while our paper has a lot of theoretical analysis, the problem we study is closely related to some real world scenarios. For instance, consider a scenario in which relay stations are established to support 4G communications between a base station and mobile phones. These relay stations may belong to owners other than the base station operator, and thus may have their own interests that differ from the base station's. So if a relay station can cheat to benefit itself (more precisely, its owner), then it is likely to cheat.

Recall the numerical example presented in the supplementary material available online. User 1 in this numerical example could be a selfish relay station as mentioned above. When user 1 cheats as we showed in this example, user 1 can get more access time, though it also needs to make more payment. When the extra access time outweighs the additional payment, user 1 has incentives to cheat—-this is very likely because the relay stations may have been established by an owner who is in need of a large amount of access time.

Although the scope of this paper is mainly focused on cognitive radio networks, we notice that with minor modification the proposed algorithms can be applicable to many kinds of cooperative relay networks. But we also stress that certain aspects our scheme (in the current form) may be more suitable for cognitive radio networks than for other networks. One reason is that an identifying feature of cognitive radio networks is the fact that both primary user and secondary user coexist in the same spectrum and share resources without interference or conflict. And the main objective of cognitive radio design is to increase the spectrum utilization among different users. Recall in our system, the primary user and the secondary user share the same spectrum. And the cooperative relay is allowed only when the overall throughput of the primary user is improved. Given other network models, like DTN, the relay mechanism designed in our system cannot be perfectly deployed as in cognitive radio networks. We hope our work will be the first step towards cheat-proof cooperative relay.

## Acknowledgments

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