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Research Article

Collaborative Cognitive Wireless Network Optimization Model and Network Parameter Optimization Algorithm

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In recent years, the combination of cognitive radio and collaborative communication has been widely studied and applied because of its ability to increase user throughput and improve spectrum utilization in a flat-fading wireless channel environment. Such cognitive radio networks that use user collaboration to improve channel capacity and spectrum utilization are called collaborative cognitive radio networks. A Nash equilibrium game-based relay node selection algorithm is investigated, which aims to maximize the utility function of primary and cognitive users. Secondly, a Stackelberg game is introduced, which aims to select the better set of nodes to achieve spectrum sharing. Simulation results show that the algorithm proposed in the study maximizes the utility functions of both primary and cognitive users and enables the selection of a better set of nodes for spectrum sharing. Specifically, the Nash equilibrium game-based relay node selection algorithm at $c = 0.3 * 10^{-6}$ results in better utility values for both PU and CU, and the algorithm enables more CU to access the spectrum so that users can get longer access time. The relay node selection algorithm based on the Stackelberg game demonstrates high feasibility. Under the condition of parameter $\alpha = \alpha^*$, the algorithm can achieve high-quality cooperation, and CU in better positions can be used as relay cooperation nodes. The algorithm can improve the main user utility function by 20%–35%.

1. Introduction

With the advent of the information society, information and communication technology has been widely used in all aspects of people's lives, and wireless communication technology is changing day by day [1]. With the growing demand for the development of wireless communication services, a variety of new wireless communication systems will be even more scarce [2, 3]. However, the imbalance between the supply and demand of radio spectrum resources has become the main factor restricting the development of wireless communication [4]. According to the spectrum management allocation, the vast majority of radio spectrum is licensed to military, commercial, and other wireless communication systems, which significantly limits the development and commissioning of new radio systems [5]. According to a survey by the Federal Communications Commission, the current spectrum utilization allocated to authorized users is basically between 15% and 85%, which means that there is a growing conflict between the shortage of spectrum sources and the underutilization [6].

Cognitive radio technology is an emerging technology proposed to solve the problem of scarcity of wireless spectrum resources and improve the utilization of spectrum through optimal allocation of resources [7]. The incorporation of collaborative communication technology makes cognitive wireless networks more academically significant and valuable. In a collaborative cognitive radio network (CCRN), authorized and unauthorized users are able to share the same frequency band, i.e., unauthorized users gain access and use spectrum by assisting authorized users to achieve spectrum sharing during forwarding data [8]. For collaborative relay user selection, it is an important issue to choose the appropriate relay node to collaborate with authorized users because of the differences in geographic location and channel fading parameters of each relay node and data transmission capabilities [9]. Since each user can be seen as a rational and selfish individual that will compete with each other for spectrum, game theory can effectively analyze and solve problems such as spectrum allocation and sharing in cognitive wireless networks owing to its ability to effectively solve the adversarial and selection problems of decision-makers [10]. To this end, the study aims to investigate and analyze the relay node selection problem in the collaborative cognitive wireless network environment for the amplify and forward (AF) collaboration model.

The article can be divided into 4 parts. Chapter 1 provides an overview of the current research on collaborative cognitive wireless networks and the direction of relay node selection for their key technologies. Chapter 2 investigates the collaborative relay node selection strategy in collaborative cognitive wireless networks based on the Nash equilibrium game and the Stackelberg game. Chapter 3 presents simulations of the model and discusses the results. Chapter 4 is the conclusion, which describes the overall work of the study.

2. Related Work

Collaborative cognitive radio networks combine the advantages of collaborative communication and cognitive radio technology, so it is of nonnegligible importance in the future development. Vimal et al. proposed a new scheme based on a combined auction. The aim is to allocate the spectrum to subusers. Neighborhood monitoring is used in the scheme to mitigate SSDH attacks and achieve free allocation via improving the secrecy rate of the spectrum [11]. Yao and Jia studied the antijamming defense problem in the context of multiuser scenarios. In the model, the Markov game framework is used to address the antijamming defense problem, and on this basis, they proposed a new algorithm to achieve the optimal antijamming efficiency. The research results show that the algorithm can solve the external malicious interference and the interference between users at the same time [12]. Niaz et al. proposed a new algorithm that utilizes high-quality channels for channel binding to maximize discrete communication in WBAN. Compared with other methods, the algorithm has better performance in terms of latency, performance, and average throughput [13]. Deng et al. proposed a new channel selection method and established an algorithm model based on the Lyapunov optimization theoretical framework to manage and allocate resources. The results show that the method has high accuracy [14]. Xu and Li proposed an effective algorithm to improve the security performance of the PU, and the results show that the algorithm not only allowed the secondary user to get the transmission opportunity but also improved the security of the PU [15].

Based on the MAC protocol framework, Dudhedia and Ravinder optimized the performance of cognitive radio wireless networks under different traffic conditions. Moreover, game theory in the MAC layer was introduced to avoid collisions, with the overall network throughput increased by 57%, and the energy consumption and delay in the process reduced by 54% [16]. Tangsen et al. used a node evaluation and scheduling algorithm to evaluate the reliability of sensing nodes and used a blockchain-based secure spectrum sensing algorithm to obtain the node's trust value. The new algorithm improved detection probability by 5% while using less energy [17]. Cao and Pan optimized the cooperative spectrum sensing strategy based on particle swarm-optimized cognitive wireless sensor networks. The results show that their proposed method improved the throughput of the system [18]. Lyu et al. formed a novel hybrid mode with postharvest transmission as the primary communication and backscatter communication as the secondary communication system. The results prove that the hybrid mode had excellent performance in system throughput [19]. Wang et al. proposed cognitive agents in the context of 5G to enable users to cache and execute tasks ahead of time on mobile edge computing. The experimental results show that the efficiency of the communication network was improved [20].

In summary, the research related to collaborative cognitive wireless networks mainly focuses on the optimization of algorithms and channel allocation, while the study of relay selection strategies based on Nash equilibrium and Stackelberg games has been less reported, so more in-depth, researches will be conducted from these two directions.

3. Game Theory-Based Relay Selection Strategy for Collaborative Cognitive Wireless Networks

3.1. Relay Selection Strategy Based on Nash Equilibrium. The introduction of game theory into cognitive wireless networks can effectively analyze and solve problems such as spectrum allocation and sharing. The collaboration method used in the study is the amplification and forwarding protocol. The hypothetical system model is shown in Figure 1.

$$y_{0i} = \sqrt{P_0}|h_{0i}|x_p + n_0, \tag{1}$$

where h_{0i} is the channel fading coefficient between PU to CU_i, n_0 is the power spectral density of CU_i, the transmit power of the PU PU is P_0, and the transmitted signal is x_p, and then, the signal received by the relay node CU_i in the first period isy_{0i}.

In the second-period relay node CU_i, the signal after amplification is y_{AF}, which is calculated by the following equation:

$$y_{AF} = \beta_1 y_{0i}, \tag{2}$$

where the amplification factor $\beta_1 = \sqrt{P_i/P_0|h_{0i}|^2 + N_0}$. PR receives all the signals from the selected relay $CU_{i\in S}$ for merging to get y_0', where P_i is the power of the data sent by the CU, and then, y_0' is calculated by the following equation:

$$y_0' = \sum_{i\in S} \frac{P_i P_0 |h_{0i}||h_{i0}|}{\sqrt{P_0|h_{0i}|^2 + N_0}} x_p + \left(\sum_{i\in S} \frac{P_i|h_{i0}|}{\sqrt{P_0|h_{0i}|^2 + N_0}} + 1 \right) n_0, \tag{3}$$

where h_{i0} is the channel coefficient transmitted from CU_i to PR, and the signal received by PR from PU is y_0, which is calculated by the following equation:

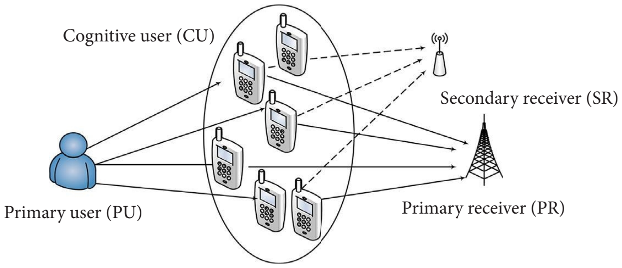


Figure 1: Collaborative cognitive wireless network.

$$y_0 = \sqrt{P_0}\left|h_0\right|x_p + n_0, \tag{4}$$

where h_0 is the channel coefficient of CU_i to SR, and the SNR (SNR) of PR received to the direct link γ_1 can be expressed by the following equation:

$$\gamma_1 = \frac{P_0\left|h_0\right|^2}{N_0}. \tag{5}$$

Merges the received direct signal y_0 from the source node PU and the signal y_0' from the relay node CU in the maximum merge ratio scheme to obtain the transmitted signal y, which is calculated by the following equation:

$$y = a_1 y_0 + a_2 y_0', \tag{6}$$

where a_1, a_2 are the weighting factor of the signals received by the destination node from the source and the relay, respectively. Assuming that the transmit power of CU_i is P_s and the transmit signal is x_i, then the signal y_i at its receiver SR is expressed by the following equation:

$$y_i = \sqrt{P_s}\left|h_i\right|x_i + n_0. \tag{7}$$

Thus, the transfer rate of the collaborative CU in the process when transmitting their own data R_i can be obtained, as shown in the following equation:

$$R_i = \log_2\left(1 + \frac{\left|h_i\right|^2 P_s}{N_0}\right). \tag{8}$$

PR The SNR γ_s from all collaborative relays is obtained at the receiving end, as shown in the following equation:

$$\gamma_s = \left(\frac{P_0^2}{N_0}\right)\left(\frac{\left(\sum_{i=1}^{k}\sqrt{P_i}\left|h_{0i}h_{i0}\right|/\sqrt{P_0\left|h_{0i}\right|^2 + N_0}\right)^2}{\sum_{i=1}^{k}\left(\sqrt{P_i}\left|h_{i0}\right|/\sqrt{P_0\left|h_{0i}\right|^2 + N_0}\right)^2 + 1}\right)\cdot\sqrt{b^2 - 4ac}. \tag{9}$$

In order to simplify the expression of the SNR, define the parameters $\Phi_i = \sqrt{P_i}\left|h_{i0}\right|/\sqrt{P_0\left|h_{0i}\right|^2 + N_0}$, which will be substituted Φ_i into the formula (9) to obtain the following formula:

$$\gamma_s = \left(\frac{P_0^2}{N_0}\right)\left(\frac{\left(\sum_{i=1}^{k}\Phi_i\left|h_{i0}\right|\right)^2}{\sum_{i=1}^{k}\left(\Phi_i\right)^2 + 1}\right). \tag{10}$$

The transmission rate obtained during collaborative transmission is obtained R_0 as shown in the following equation:

$$R_0 = \log_2\left(1 + \frac{\left|h_0\right|^2 P_0}{N_0} + \frac{P_0^2}{N_0}\frac{\sum_{i=1}^{k}\Phi_i\left|h_{0i}\right|^2}{\sum_{i=1}^{k}\left(\Phi_i\right)^2 + 1}\right). \tag{11}$$

For a CU chosen as a collaborative relay $CU_{i\in S}$, the relationship between its access time and collaborative power can be defined as shown in the following equation:

$$ct_i = P_i\left|h_{i0}\right|^2\left|h_{0i}\right|^2 \; i \in S, \tag{12}$$

where c is the price paid per unit of access time jointly determined by the PU and CU, and t_i is the access time received by the CU for transmitting their own data, and the utility function for the i-th CU is shown in the following equation:

$$U_i = w_1 R_i t_i - w_2 P_i\left(\frac{1}{2}\alpha\right), \tag{13}$$

where w_1 is the equivalent amount of revenue per unit of transmission rate, and w_2 is the equivalent amount of expenditure per unit of power consumption. As for the PU, its objective is to maximize its transmission rate, so its utility function is defined as shown in the following equation:

$$U_0 = w_p R_0\left(1 - \frac{1}{2}\alpha\right), \tag{14}$$

where w_p is the equivalent amount of revenue per unit of transmission rate received by the PU.

According to the previously defined utility function, an optimized collaboration power must be chosen to maximize the utility of CU and PU [21]. Since the sum of the node transmission times of all selected relays is equal to the allocation time, then (15) can be obtained.

$$U_i \max_{P_i} = \frac{\left(w_1 R_i - w_2 P\right)\left|h_{i0}\right|^2\left|h_{0i}\right|^2 - w_2\sum_{j\in S, j\neq i}\left|h_{j0}\right|^2\left|h_{0j}\right|^2 P_j}{c}. \tag{15}$$

U_i the second-order derivative of P_i yields

$$\frac{\partial^2 U_i}{\partial P_i^2} = -\frac{2w_2\left|h_{i0}\right|^2\left|h_{0i}\right|^2}{c} < 0. \tag{16}$$

According to the conditions of Nash equilibrium, it is known that there is a Nash equilibrium in the collaborative power of each CU involved in the collaboration in this noncollaborative game G [22]. According to the above equation, the best response function of the utility function can be obtained, and the solution can be obtained, as expressed by the following equation:

$$P_i^* = \left(\frac{w_1 R_i}{2w_2}\right) - \left(\frac{\sum_{j\in S, j\neq i}\left|h_{j0}\right|^2\left|h_{0j}\right|^2 P_j}{2\left|h_{i0}\right|^2\left|h_{0i}\right|^2}\right), \tag{17}$$

where P_i^* is the optimal power response of CU_i and this function is a standard function, and there exists a unique Nash equilibrium point for this noncollaborative power

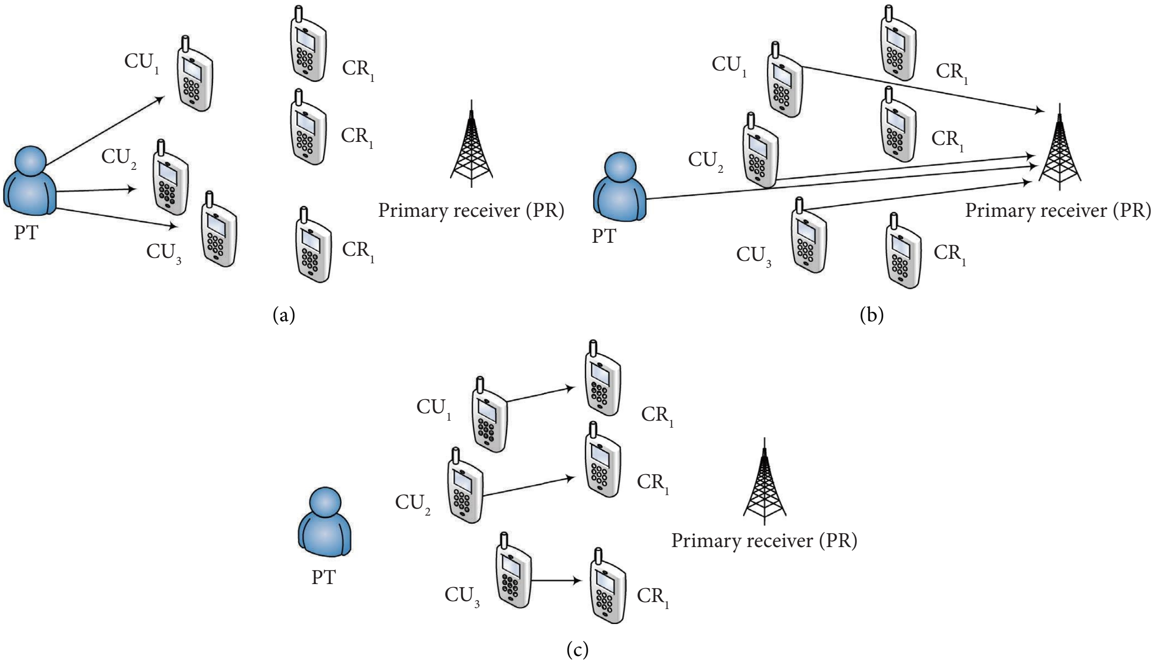


FIGURE 2: The system transmission model. (a) Primary user transmission. (b) Assisted forwarding by cognitive relay nodes. (c) Access to cognitive users.

equilibrium game. The unique equilibrium value of this game G can be derived from the following equation:

$$P_i^* = \frac{2(1+k)\Delta_i - 2\sum_{i\in S}\Delta_i}{(1+k)\left|h_{i0}\right|^2\left|h_{0i}\right|^2}, \tag{18}$$

where $\Delta_i = (w_1 R_i/2w_2)|h_{i0}|^2|h_{0i}|^2$, and it is calculated that if a set of relays is identified, then there exists a unique Nash equilibrium for the participants in that set, such that the utility of each relay is optimized. Based on the relationship between collaboration power and access time, the optimized access time t_i^* can be obtained, as shown in the following equation:

$$t_i^* = \frac{2(1+k)\Delta_i - 2\sum_{i\in S}\Delta_i}{c(1+k)}. \tag{19}$$

As soon as the value of the parameter c is determined, the allocation of the entire time slot can be determined, and in turn, the access time of the selected relay can be obtained. Instead, the PU needs to find a set of nodes that maximize its utility function, which is calculated as shown in the following equation:

$$\max_{\{c>0\}} U_o = \max\left\{ w_p R_0 \left(1 - \frac{2\sum_{i\in S}\Delta_i}{c(1+k)}\right)\right\}. \tag{20}$$

When the i relay node collaborates with the PU to transmit data, the SNR γ_i of each node at i obtained at its *PR* receiving end is shown in the following equation:

$$\gamma_i = \frac{P_0 P_i \left|h_{i0}\right|^2\left|h_{0i}\right|^2}{\left(P_i\left|h_{i0}\right|^2 + P_0\left|h_{0i}\right|^2 + N_0\right)N_0}. \tag{21}$$

The study maximizes the SNR at the receiver end of the system by removing or updating the relay nodes during the iterative process; hence, the study introduces a tuning and averaging factor H_i. This summation factor modifies the previous calculation of the summation average, which is determined by channel information by introducing the transmit power of the PU and CU, as defined in the following equation:

$$H\left(h_{0i}, h_{i0}, P_i^*\right) = \frac{P_0 P_i^* \left|h_{i0}\right|^2\left|h_{0i}\right|^2}{P_i^*\left|h_{i0}\right|^2 + P_0\left|h_{0i}\right|^2}. \tag{22}$$

In order to select more than one relay collaboration node among multiple CU, the study introduces timers in each relay T_i to achieve an increase in the SNR at the receiver end of the entire system by removing the cognitive relays with poor channel links.

3.2. Node Selection Strategy Based on Stackelberg's Game.

Combined with the duopoly game model of PU and CU, this paper proposes a selection algorithm based on the Stackelberg game, which aims to select the optimal node set to achieve spectrum sharing. The system transmission model of the algorithm is shown in Figure 2.

In this model, a time slot is divided into two parts: the first part α is used for the transmission of the PU, and the remaining part $1-\alpha$ is used for the access of the CU. In the first part, 0.5 α time is used for the PU's transmission, and the remaining 0.5 α is used for the assisted forwarding process of the cognitive relay node. The access time of the i -th CU is proportional to the collaborative power of the PU in forwarding data, and the relationship is shown in the following equation:

$$t_i = (1-\alpha)\left(\frac{P_i G_{i,p} G_{p,i}}{\sum_{j\in S}\left(P_i G_{i,p} G_{p,i}\right)}\right), \tag{23}$$

where t_i is the access time, P_i is the transmission power of the CU collaborating with the PU, $G_{i,p}$ is the channel gain between the CU and the PU's receiver, and $G_{p,i}$ is the channel gain between the PU and the CU. In the study, the collaboration protocol of AF is adopted to realize the collaboration between the PU and CU. First, the received SNR $\Gamma_{di\ r}$ transmitted directly by the PU to the PR end is calculated by the following equation:

$$\Gamma_{\text{dir}} = \frac{P_0 G_P}{\sigma^2}, \tag{24}$$

where P_0 is the transmitted power of the PU, G_P is the channel gain from the PU to the receiving end of PR, and σ^2 is the additive Gaussian white noise power. Considering the transmission process, it is assumed that X_i is the transmitted signal of the PU, Y_i is the signal received by the CU, and Z_i is the signal transmitted collaboratively by the CU to the receiving end of the PU, and the relationship between the three is shown in the following equation:

$$\begin{cases} Y_i = \sqrt{P_0 G_{p,i}}\, X_i + \eta_{p,i}, \\ Z_i = \sqrt{P_i G_{i,p}}\, \dfrac{Y}{|Y|} + \eta_{i,p}, \end{cases} \tag{25}$$

where $\eta_{p,i}, \eta_{i,p} \sim N(0, \sigma^2)$, and the received SNR obtained by the i-th CU is shown in the following equation:

$$\Gamma_i = \frac{P_0 P_i G_{i,p} G_{p,i}}{\sigma^2\left(P_i G_{i,p} + P_0 G_{p,i} + \sigma^2\right)}. \tag{26}$$

Let the network under study be energy-constrained, then the SNR obtained by the PU with the transmission of collaborative relaying is shown in the following equation:

$$\Gamma_p = \frac{P_0 G_P}{\sigma^2} + \sum_{i\in S} \frac{P_0 P_i G_{i,p} G_{p,i}}{\sigma^2\left(P_i G_{i,p} + P_0 G_{p,i} + \sigma^2\right)}. \tag{27}$$

The transmission rate obtained by the i-th CU transmitting his own data is shown in the following equation:

$$R_i = W \log_2\left(1 + \frac{P_s G_i}{\sigma^2}\right), i \in S. \tag{28}$$

The study defines the utility functions of the PU and CU, respectively, which are the basis for conducting the game analysis. The PU's objective is to maximize its transmission rate, and therefore, its utility function is defined as shown in the following equation:

$$U_p = w_p \alpha \Gamma_p(\alpha), \tag{29}$$

where w_p is the equivalent amount of revenue obtained by the PU per unit of transmission rate, α is the time slot in which the PU transmits its own data, and the optimization problem for the PU can be expressed as shown in the following equation:

$$\max Up = w_p \Gamma_p(\alpha), 0 \le \alpha \le 1, \tag{30}$$

and the utility function of the i-th CU can be defined as the obtained transmission rate minus the energy consumption to assist the PU in transmission, as shown in the following equation:

$$U_i = (1-\alpha)\left(\frac{P_i G_{i,p} G_{p,i}}{\sum_{j\in S}\left(P_j G_{j,p} G_{p,j}\right)}\right)\left(w_i R_i - w_s P_s\right) - \frac{1}{2} w_s \alpha P_i, \tag{31}$$

where w_i is the equivalent benefit per unit transmission rate contributed to the overall benefit by the i-th CU, and w_s is the equivalent amount of expenditure per unit of power consumed. The strategy of the CU is to choose the appropriate collaborative power P_i, so the optimization problem for the i-th CU will be formulated, as shown in the following equation:

$$\max U_i = \max\left\{(1-\alpha)\left(\frac{P_i G_{i,p} G_{p,i}}{\sum_{j\in S}\left(P_j G_{j,p} G_{p,j}\right)}\right)\left(w_i R_i - w_s P_s\right) - \frac{1}{2} w_s \alpha P_i\right\}, \{P_i\} \ge 0, i \in S. \tag{32}$$

The optimization problem of the game is studied and analyzed based on the previously defined utility function. The second-order derivative of U_i for P_i can be expressed by the following equation:

$$\frac{\partial^2 U_i}{\partial P_i^2} = -2(1-\alpha)\frac{G_{i,p} G_{p,i} \sum_{j\in S, j\ne i}\left(P_j G_{j,p} G_{p,j}\right)}{\left(\sum_{j\in S}\left(P_j G_{j,p} G_{p,j}\right)\right)^2}\left(w_i R_i - w_s P_s\right) < 0. \tag{33}$$

According to the conditions of Nash equilibrium, it is known that there is a Nash equilibrium on the collaborative power of CU in this noncooperative game G [23]. When the first-order derivative is equal to zero, and the best response function of the utility function can be obtained, the unique Nash equilibrium solution of this noncooperative power selection game can be obtained by solving all CU in the set S, as shown in the following equation:

$$P_i^* = \frac{2(1-\alpha)(N_0-1)}{\alpha G_{i,p} G_{p,i}} \frac{\left(B - w_s N_0 - 1/G_{i,p} G_{p,i}\left(w_i R_i - w_s P_s\right)\right)}{B^2}, \tag{34}$$

where $B > w_s\left(N_0 - 1/G_{i,p} G_{p,i}\left(w_i R_i - w_s P_s\right)\right)$, and N_0 is the total number of selected CU. Based on the above analysis, the optimization strategy for the main users is shown in the following equation:

$$U_p = w_p \alpha \left(\frac{P_0 G_p}{\sigma^2} + \sum_{i \in S} \frac{P_0 P_i G_{i,p} G_{p,i}}{\sigma^2\left(P_i G_{i,p} + P_0 G_{p,i} + \sigma^2\right)} \right). \tag{35}$$

The PU aims to maximize the utility function of the PU by choosing the optimization parameter α^*, which is calculated by the following equation:

$$\alpha^* = \alpha^*\left(\sigma^2, \{w_i\}, \{G_i\}, \left\{G_{p,i}\right\}, \left\{G_{i,p}\right\}\right), i \in S. \tag{36}$$

The final optimized parameter α^* and the corresponding optimized collaborative power P_i^* can be obtained, while it can be proved that P_i and α are a Stackelberg equilibrium in this model. Regarding the selection of relay nodes, the primary user selects a suitable set of cognitive users as its collaborative partner for data transmission, and then, the optimal time slot parameter α^* is calculated. $\alpha = 1$ is assumed to be set by the primary user before starting data transmission, and the value will gradually decrease when U_p reaches its maximum value, at which point α reaches its optimal value. Then, the primary user will broadcast $\sum_{i \in S} w_s / G_{i,p} G_{p,i}\left(w_i R_i - w_s P_s\right)$ to each cognitive user such that the cognitive user can calculate the optimized collaborative power corresponding to the value α.

Finally, there is the optimization algorithm for the main users. Suppose $\alpha = 1$, after one loop, the utility function of the primary user is calculated based on the current value of α , and the value of this function is recorded. Then, the utility of the primary user is compared with the previously recorded value. If the utility value of the primary user keeps increasing, it means that the optimized α^* has not been obtained yet, so α becomes smaller by subtracting a smaller value δ; if the utility of the primary user does not continue to grow, it implies that the optimized α^* value has been obtained in the last loop, and the loop stops and the α value is updated. Eventually, it will be possible to obtain a value between $(\alpha^* - \delta, \alpha^* + \delta)$, and when δ is sufficiently small, the obtained optimized α^* can be approximately obtained.

4. Analysis of Results

The study simulates the game-based iterative relay node selection algorithm through experiments and investigates the performance of the algorithm in comparison. The section first discusses how the price c affects the primary and CU utility values and how the value of the price c is determined. Figure 3 shows the effect of the price c of the spectrum on the utility functions of the PU and CU.

As can be seen from the above graph, the utility of the PU increases from 182 to 198 as c increases from 0 to 2.5 * 10, while the utility of the CU-6 CU_{10} decreases from 260 to 20. As the price continues to increase to $3.0 * 10^{-6}$, the utility value will then gradually level off. Since the price c is jointly determined by the PU and CU, $c = 0.3 * 10^{-6}$ is chosen for both the PU and CU. Table 1 shows the variation relationship between the state information of the channel Δ_i and the reconciliation factor, which also reflects the process of relay selection.

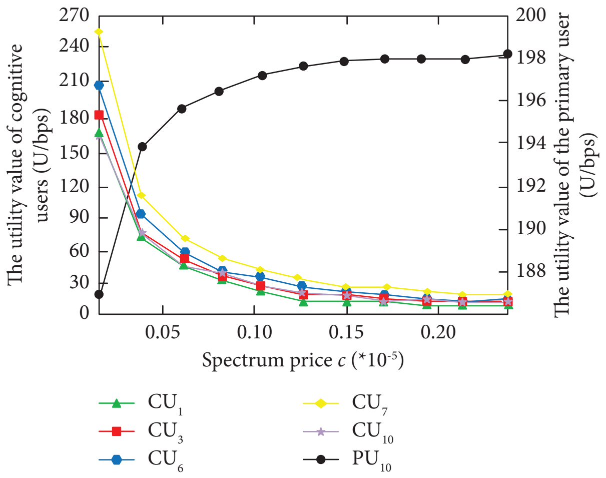


Figure 3: Determination of price c.

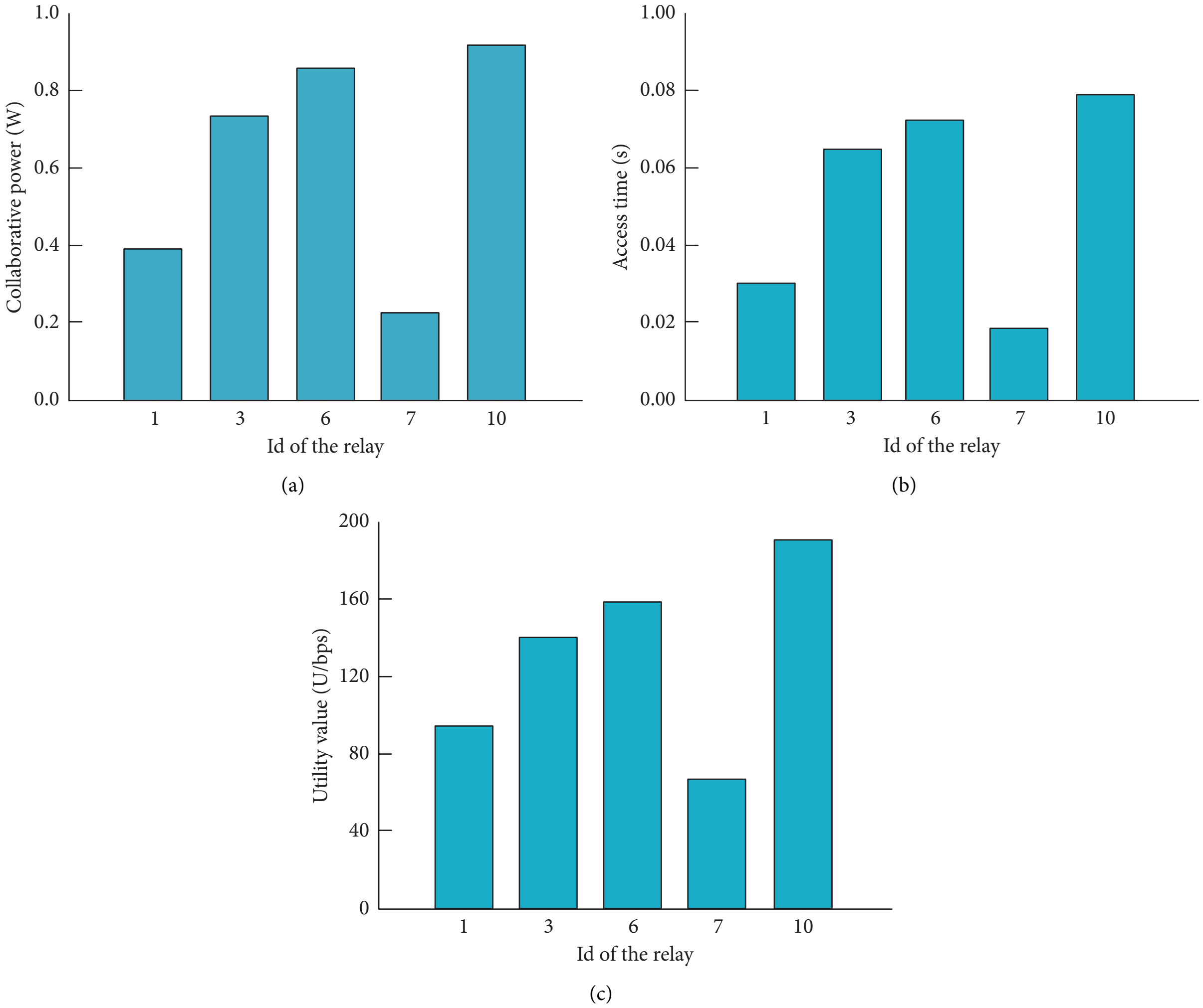
The table lists the final harmonic factor values after CUs noncooperative game and relay selection. Among them, the state information and reconciliation factor values of relays 2, 4, 5, 8, and 9 are small values, which means that the channel status of these relay nodes is poor, and these relay nodes will eventually be deleted, leaving only some nodes with better channel state to perform cooperative relaying. The utility value of the PU can be optimized based on the participation of the relay set. Figure 4 shows the relationship between cooperative power, access time, and utility value in a noncooperative game in a set of CU.

It can be noticed from the figure that the relay nodes with better channel state information and larger modulation factor use larger collaborative power to assist the PU in transmission and obtain longer channel access time, resulting in higher gains for the CU. Relay nodes with higher modulation factor are able to use larger collaborative power to assist the PU in transmission and increase the signal-to-noise ratio of the PU at the destination. Figure 5 shows the relationship between CU access time and utility function for both GTMRS and SGRS algorithms with the same participating relay nodes.

Figure 5(a) shows that the access time obtained by GTMRS is longer than that obtained by SGRS, the number of relay nodes selected by GTMRS is more than that selected by SGRS, and the number of relay nodes selected by GTMRS is at least the same as that obtained by the SGRS algorithm. For each selected CU in the proposed GTMRS algorithm, the utility value will be less than that obtained by SGRS. From Figure 5(b), it can be seen that when the number of selected relay nodes is the same for both schemes, the utility value obtained by the GTMRS scheme is larger than that obtained by GSRS, which is mainly because the GTMRS algorithm

Table 1: The relationship between state information and harmonic factor.

ID	1	2	3	4	5	6	7	8	9	10
Δ_i ($* 10^{-7}$)	0.7836	0.6595	0.8810	0.6492	0.6463	0.9201	0.7041	0.6389	0.6483	0.9007
Initial H_i ($* 10^{-3}$)	0.0769	0.0317	0.0774	0.0223	−0.0119	0.0815	0.0710	−0.4009	−0.0209	0.0903
Final H_i ($* 10^{-3}$)	0.0786	0	0.1289	0	0	0.1437	0.0187	0	0	0.1744



(a) (b) (c)

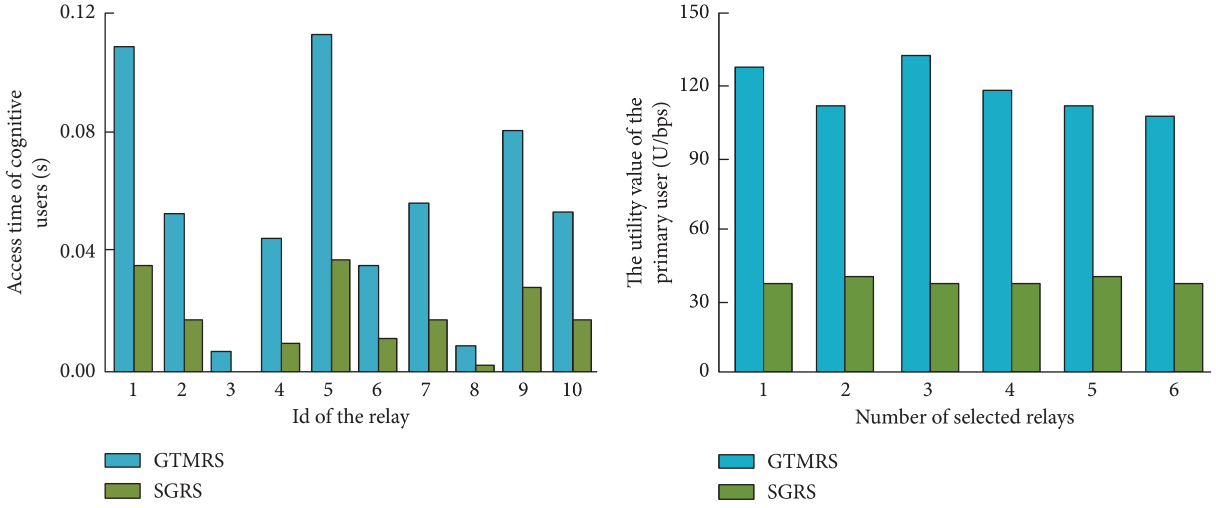
Figure 4: CU collaboration power, access time, and utility value. (a) Optimized collaborative power. (b) Optimized access time. (c) Utility.

optimizes the collaborative power in the selected set and looks for the set that maximizes the SNR of the PU based on the selected set, so as to maximize the utility value of the PU. Figure 6 shows the number of selected relay nodes in GTMRS and SGRS.

It can be seen from the figure that GTMRS enables more relay nodes to participate in collaboration, which satisfies the need for collaborative cognitive radio networks to enable more CU to access the licensed spectrum of the PU and improves the utilization of scarce spectrum.

The primary user PU is located at coordinate (0, 0), the primary user receiver PR is located at coordinate (1, 0), and the secondary users are randomly distributed in a square with center (0.5, 0) and side length 1. The cognitive users' receivers are randomly distributed in the unit square of their corresponding secondary users. The propagation loss factor is set to 2. Assuming 10 cognitive users are present in the network, w_i is set to 10, additive Gaussian white noise is set to $\sigma^2 = 10^{-4}$, and the update step is $\delta = 10^{-5}$. Figure 7 shows the topology of the network.

In Figure 7, the green squares indicate SRs, blue circles indicate STs, and the corresponding STs and SRs are connected with green lines. STs selected as trunks are shown with solid circles, and other STs that are not selected are shown with hollow circles. Secondary users are labeled in the order of $w_1 G_{1,p} G_{p,1} R_1 \geq w_2 G_{2,p} G_{p,2} R_2 \geq \cdots \geq w_{10} G_{10,p} G_{p,10} R_{10}$. In Figure 7, seven cognitive users are selected by the primary users as their collaborative relay partner nodes. There are two factors influencing the selection of relay, including the location of ST and the



(a)

(b)

Figure 5: Comparison of GTMRS and SGRS algorithms in access time and utility. (a) Access time. (b) Utility.

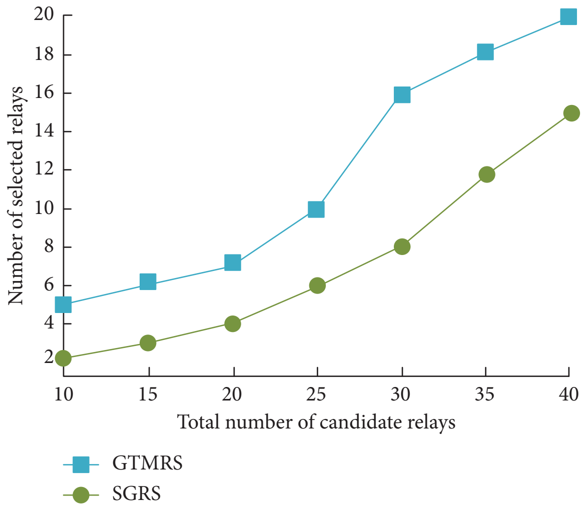


Figure 6: The number of relay nodes selected by GTMRS and SGRS algorithms.

distance between ST and SR. The location of STi influences the distance between STi and PU. The location of STi affects the channel gain between STi and PU, i.e., the values of $G_{i,p}$ and $G_{p,i}$. When the cognitive user has a larger $G_{i,p}$, $G_{p,i}$ will have a greater chance of being selected as the collaborative relay for the primary user. Similarly, the distance between STi and SRi also affects the value of G_i. A cognitive user with a larger G_i will gain more from the collaboration when using the same collaboration power, and such secondary users are more motivated to participate in the collaboration, which is beneficial for the primary users. In Figure 7, we can see that all the selected relay nodes are in a better position. The study performs an experimental simulation of the game model analyzed above. Figure 8 shows the variation of the utility values of the main users, the optimized power, and the utility of the CU when α keeps increasing.

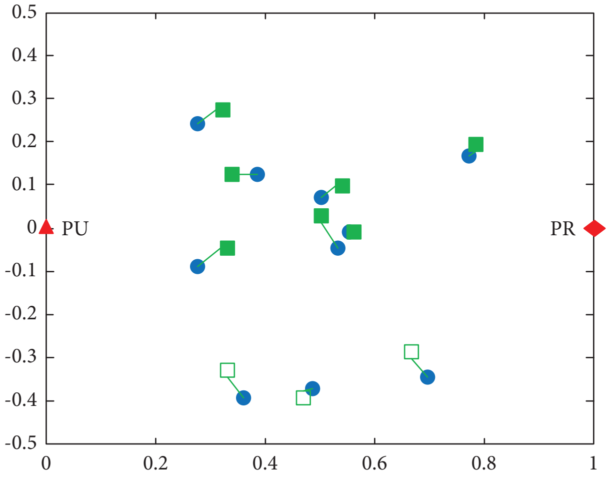
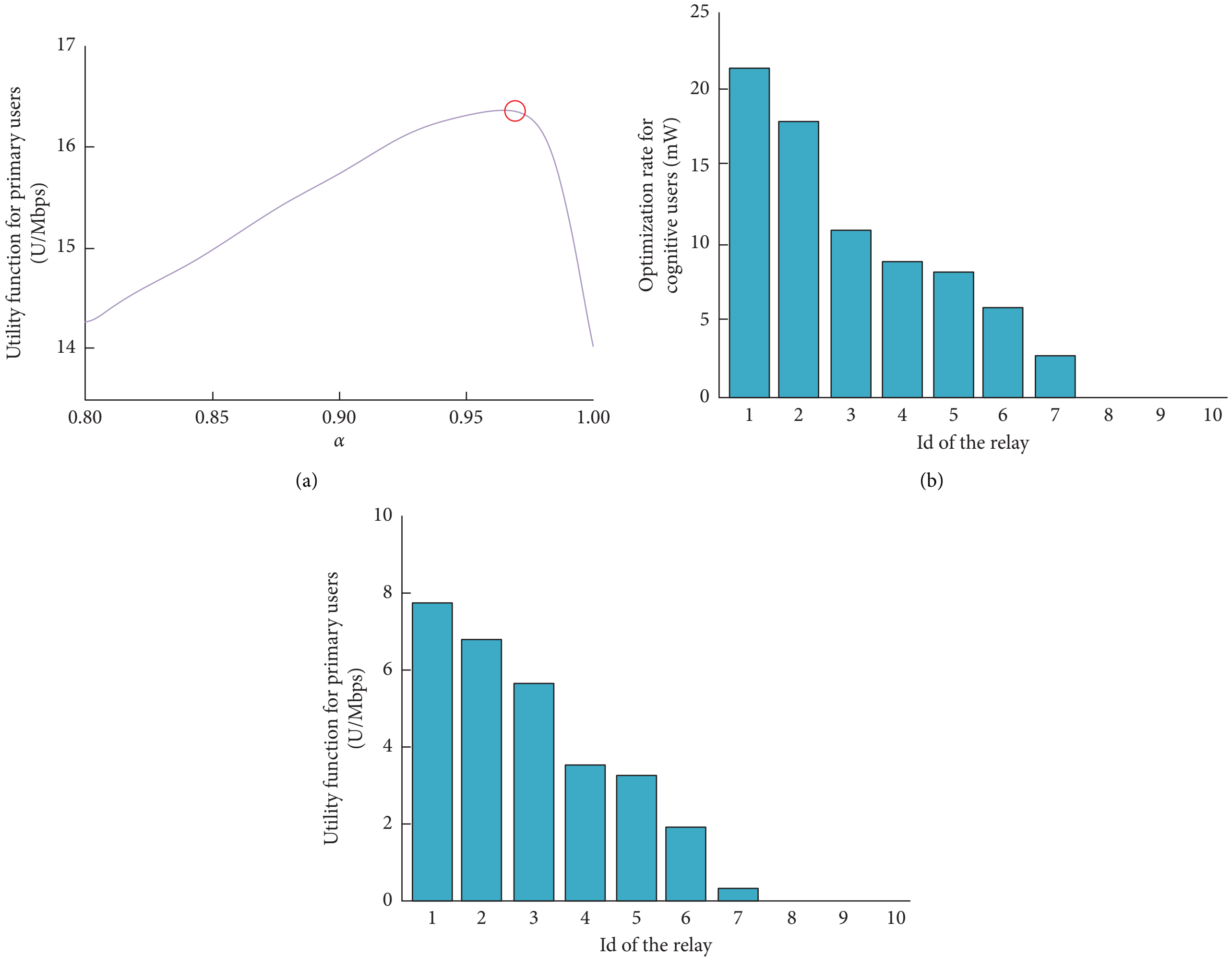


Figure 7: System simulation model.

From the figure, it can be seen that $\alpha^* = 0.96$ is optimal, when the utility value $U_p(\alpha^*) = 16.43$, $U_p(1) = 13.2879$, $\alpha = 1$, $U_p(1) < U_p(\alpha^*)$ as the CU is not motivated to participate in the collaboration. According to the simulation results, the utility function of the PU is improved by 20–35%. Therefore, collaboration is achieved when $\alpha = \alpha^*$. The figure shows that the CU with higher channel gain gets more collaboration power. The CU with better channel conditions is more likely to gain more in collaboration under the condition of consuming the same power and is more likely to be selected by the PU to collaborate. Conversely, CU with larger collaboration power and better channel conditions will also gain more. In contrast, users who are not involved in the collaboration have no collaboration power, and then, their utility value is naturally 0. According to the relay node selection algorithm, the number of relay nodes that satisfy the selection criteria in this simulation is 7. Figure 9 shows the utility values of the optimized PU and optimized α under the different number of relays.



(a)

(b)

(c)

Figure 8: PU utility value, optimized power, and utility for CU. (a) Optimization α for primary users. (b) Cognitive user power. (c) Cognitive user utility.

The figure shows that as the number of relay nodes grows, the utility value of the PU increases, the optimized α^* decreases, the competition among the CU becomes more intense, and the CU will use higher collaboration power to facilitate the transmission of the PU. It is observed from the figure that the optimized $\alpha^* = 1$ when the number of nodes in the relay is 1. In the network when only one relay node is involved in collaboration, the relay will not be motivated to boost the collaboration power because the CU does not need to compete to access the channel. Figure 10 shows how the utility of the PU varies with the location of the *PR* receiver under the different number of collaboration nodes.

It can be seen that with the increase of the x-coordinate position, the utility value of the main user gradually decreases, which is mainly because the channel conditions between the user's transmitter and receiver gradually deteriorate, and when the number of cooperative relays remains unchanged, a decrease in utility value will be resulted. When the x-coordinate value is 2 and the number of nodes is increased to 6, the utility value is 7 U/Mbps, which is 3.6 U/Mbps higher than that when the number of nodes is 0. In order to increase the PU's utility value, the number of cooperative relay nodes needs to be increased. Figure 11 shows the utility values obtained by various mechanisms.

In the figure, U_non-collaborative denotes the utility value obtained by the PU in no relay collaboration mode, U_non-game denotes the utility value obtained without the game model, U_nash denotes the transmission rate obtained under the Nash equilibrium game, and U_stackelberg is the algorithm proposed in the study. It can be seen that the transmission rate obtained with the collaborative model is much larger than that of the noncollaborative model, and the transmission rate of the PU increases as the number of relay nodes increases. In contrast, the transmission rate of the PU obtained with the game model is larger than that obtained with the nongame model. The transmission rates obtained by the Nash equilibrium and Stackelberg models are basically similar, reaching 16.9/Mbps and 17.6/Mbps, respectively, which is because they both use the collaboration

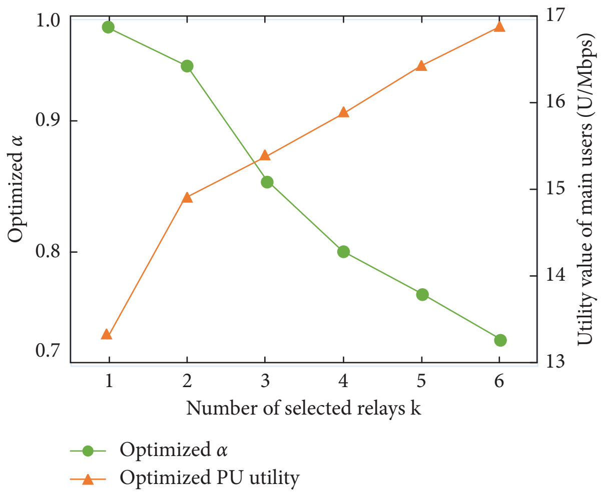


Figure 9: The utility value of the main user and the optimized α in the case of the different number of relays.

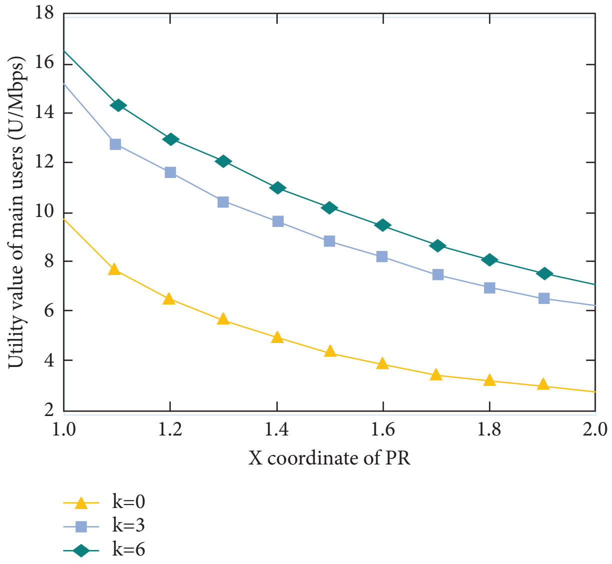


Figure 10: The variation of the utility of the main user with the *PR* under the different number of relays.

strategy that maximizes the utility function of the PU, but the collaboration optimization power used by the CU is different.

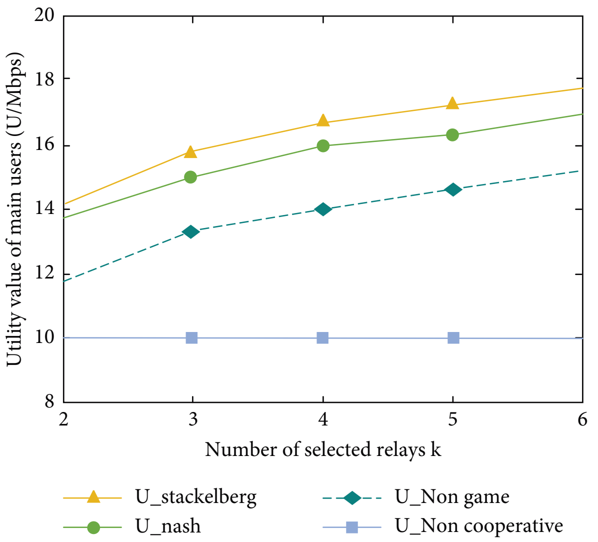


Figure 11: Comparison of the utility values obtained by the number of selected relays under different mechanisms.

5. Conclusion

With the rapid growth of the mobile communications industry, the scarcity of spectrum becomes an increasingly serious problem for the entire industry. One of the feasible solutions is to utilize the potential of the available spectrum to improve the utilization of the spectrum. The research studied relay selection and sharing based on the following two game strategies, including the Nash equilibrium game-based relay node selection algorithm and Stackelberg game-based relay node selection algorithm. The simulation results by the Nash equilibrium game-based relay node selection algorithm show that choosing $c = 0.3 * 10^{-6}$ leads to better utility values for both PU and CU, more CU access to the spectrum, and longer access times. The relay node selection algorithm based on the Stackelberg game is to further optimize the relay node selection algorithm based on the Nash equilibrium game. Simulation results also show that this strategy is feasible, the collaboration is achieved when the parameter $\alpha = \alpha^*$, and the PU selects the CU in a better position as the relay collaboration node so as to obtain a higher utility value. However, it should be noted that this study only considers the existence of one PU. However, in the actual complex network, there may often be more than one PU, and emphasis should be given to not only the game relationship between the PU and the CU or just between the CU but also the cooperative competition between the PU. To this end, studies on the design and construction of multiple PU and multiple CU matching are needed to achieve a spectrum-sharing strategy.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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