Security Spectrum Auction Framework for Cognitive Radio Networks

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Abstract—**Spectrum auction is an effective way to improve spectrum efficiency in cognitive networks. All traditional auction framework such as VCG price auction framework and second price auction framework face security risks. Collusion is the most important risk in multi-user cognitive networks. In this paper, we propose a security mechanism for the multi-user cognitive spectrum auction networks. This security auction framework is based on position information. We use this security spectrum auction framework to increase the total system revenue and prevent collusion. The simulation results show that the security spectrum auction framework can greatly improve spectrum efficiency. Besides, the auction process will be safer and fairer. In particular, when users are uniformly distributed, the proposed auction framework will obtain more seller revenue.**

Index Terms—**cognitive radio, spectrum auction, security framework, multi-user**

I. Introduction

Cognitive radio (CR) is considered to be a technology solving the problem of spectrum resource shortage. Sometimes licensed bands are unused by primary users (PUs) in a mobile cognitive network. Therefore, the allocation strategy of spectrum resource will become more and more important. Spectrum resource should be allocated efficiently and securely among secondary users (SUs) [1]. Dynamic spectrum allocation, with the aid of cognitive radio technology has become a promising approach to utilize the spectrum efficiently. Spectrum auction has been recognized as an effective way to achieve dynamic spectrum access. There are two main spectrum access methods in this research area. One is opportunistic access to the licensed band; the other is sharing the unlicensed band openly [2]. We suppose that PUs in a cognitive network can sell their idle licensed bands to SUs to gain some revenue. In addition, SUs will occupy these idle bands competitively according to certain auction frameworks [3-6]. There are some previous studies on the single-frequency band and single-winner auction framework: for instance, the sealed secondary pricing strategy and the Vickery-Clarke-Groves (VCG) auction strategy [7]. One licensed band can be only awarded to one SU in the above-mentioned auction strategies. Sharing the same band among multiple SUs becomes an important issue.

Nevertheless, radio interference is conceived to be the most important issue in the spectrum auction process. Spectrum auction is an essential problem of interference-constrained resource allocation. It allows multiple winners (SUs) to obtain a single-frequency band below a certain interference threshold. Auction framework is a complex optimization problem by finding a system utility function based on different interference models [8-9]. The authors in [10] proposed a primary prioritized Markov dynamic spectrum access scheme. However, considering auction framework, they have the same effect. Hence, we study auction framework based on binary interference model. Reference [11] has grouped secondary users with negligible interference together as virtual bidders, and then applied the sealed secondary pricing strategy. The problem is that the second-price auction and the Vickery-Clarke-Groves (VCG) auction framework cannot guarantee full efficiency or high revenue [12]. However, the traditional multi-band multi-winner spectrum auction framework faces security threats, because there are more and more secondary users in the mobile or ad hoc cognitive networks. These users may be selfish and merely seek to maximize their own interests. They may cheat in the spectrum auction, which will lead to security problems. Some selfish secondary users will obtain more idle frequency bands and the entire system revenue will be low. So we need to propose a new security spectrum auction framework for the cognitive radio networks.

In this paper, we put forward a security frequency auction framework, in which the proposed strategies not only increase the total system revenue, but also resist possible cheating of secondary users.

The remaining of the paper is organized as follows:

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Section II describes the system model of the cognitive network. Section III outlines the traditional auction framework. Section IV proposes the security auction framework. Simulation results are presented in Section V. Section VI concludes the paper.

II. System Model

We consider a cognitive radio network consisting of a set of primary users (Pus) and a set of secondary transmitter-receiver pairs (SUs).

We suppose that $Z = [z_1, z_2, \cdots z_M]$ is the set of PUs and $R = [r_1, r_2, \cdots r_N]$ is the set of SUs.

This cognitive network can be a Femtocell network, i.e. SU's transmitter is a mobile phone and SU's receiver is a family base station, or a WIFI network, i.e. SU's transmitter is a WiFi-enabled mobile phone and SU's receiver is a wireless router [13-16], as shown in Fig. 1.

We use S_i and Q_i to represent the transmitter and the receiver of SUs（$i \in N$）.

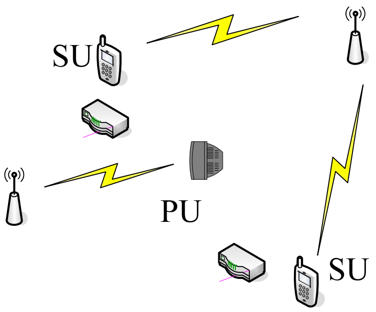

Figure. 1. Cognitive network model

PUs sell their idle spectrum bands to SUs to make a profit when they do not occupy the licensed spectrum they own. Based on the traditional auction framework, PUs are the sellers and SUs are the bidders. The spectrum management base station is an auctioneer who manages the auction process. The auctioneer tries to maximize total system revenue by certain spectrum auction framework.

Supposing that all SUs' valuations are $\mathbf{V} = [v_1, v_2, \cdots v_N]$, when SUs access one idle frequency band successfully, they become winners. Their payment for obtaining the idle frequency band will be $\mathbf{P} = [p_1, p_2, \cdots p_N]$. The SU i's valuation of the frequency band is defined by a utility function $v_i(\gamma_i)$, where γ_i is the received signal-to-interference-plus-noise ratio (SINR) at the SU i's receiver Q_i.

$$\gamma_i = \frac{g_i h_{ii}}{Z_i + \sum_{j \neq i} g_j h_{ji}} \tag{1}$$

Where g_i denotes the SU i's transmit power; h_{ji} denotes the channel gain between the SU j's transmitter S_j and the SU i's receiver Q_i; Z_i denotes the white Gaussian noise at the receiver Q_i. When the signal-to-interference-plus-noise ratio (SINR) exceeds some threshold Γ, it is considered as a successful transmission, i.e. $g_i h_{ii} / (Z_i + \sum_{j \neq i} g_j h_{ji}) \geq \Gamma$. Since the proposed auction framework is not affected by SUs' valuations, so we assume the valuation v_i is generated randomly in the following studies.

III. Traditional Spectrum Auction

In this section we review traditional auction framework such as VCG price auction framework and second price auction framework at first.

Since the cognitive network is an interference-constrained wireless network, previous studies on the spectrum auction framework focus on the interference relationship between the SUs and the auctioneers. This interference relationship is based on the distance in multi-winner spectrum auction framework. The interference relationship is reported by SUs. In such a network environment, the auctioneers collect reports and express the interference relations through the interference matrix [17-18]

$$\mathbf{C} = \begin{pmatrix} c_{11} & \cdots & c_{1N} \\ \vdots & \ddots & \vdots \\ c_{N1} & \cdots & c_{NN} \end{pmatrix}_{N \times N}.$$

According to the above interference matrix, we define $c_{ij} = 1$ when user i and user j are adjacent. When user i and user j are not adjacent, we define $c_{ij} = 0$. When two users are adjacent, they must have mutual interference. So they cannot occupy the same band simultaneously. When user i wins a band, we define $r_i = 1$, otherwise $r_i = 0$. According to the different frameworks, there are different optimization objective functions, such as the second-price auction and the VCG auction strategy which maximizes the social welfare U (the system spectrum efficiency).

A. Second-price Auction

In the cognitive network interference, when we use the second-price auction, the winner bids the highest price. Besides, its payment is equal to the second highest bid. So we are aware that all SUs will submit their bids equivalent to their true valuations, because the above strategy is optimal. For example, there are four secondary users whose valuations are v_1=15, v_2=14, v_3=13, and v_4=2 respectively. If only one idle spectrum band is available for bidding, according to the second-price auction, user 1 r_1 will get the spectrum by paying p_1=14. We all know that p_1=14 equals the second highest bid made by r_3. When the cognitive wireless networks only allow single-winner to obtain single idle spectrum band, this auction framework is an ideal scheme. Nevertheless, the second-price auction is not so efficient in a multi-winner auction.

We suppose that those 4 second users have the interference relationship as shown in Fig. 2, where an edge between two users indicates that the two users are adjacent, i.e., they cannot share the band owing to interference.

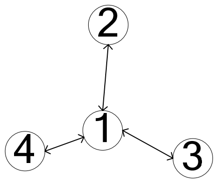

Figure. 2. False interference relationship

When this case allows multiple winners to share one spectrum band, the winners will be $r_2 = r_3 = r_4 = 1$. Afterwards, we will certainly obtain a higher system utility ($v_2 + v_3 + v_4 = 29$) than the second price auction result ($v_1 = 14$). This implies the second price auction may not be efficient in the multi-winner auction [9].

B. VCG price Auction

The VCG auction employs the efficient allocation which is determined by the following binary integer programming problem [10]

$$\max_r U_v(r) = \sum_{i=1}^{N} v_i r_i, \tag{2}$$
$$s.t.\ r_i + r_j \le 1, \forall i, j \text{ if } c_{ij} = 1,$$
$$r_i = 0 \text{ or } 1, i = 1, 2, \cdots N$$

Assume the solution to the optimization problem (2) is r_i^*, and the maximum system utility is U_v^*. We consider $\mathbf{V}_{-i} = [v_1, v_2, \cdots v_N]$ as a new system with all users except for user i. When user i is absent from the system, the maximum system utility would be U_{v-1}^*. If user i obtains the opportunity to access the idle band, the VCG price will be [10]

$$p_i = \mathrm{v}_i + U_{v-1}^* - U_v^* \tag{3}$$

IV. SECURITY SPECTRUM AUCTION

Auction framework based on the interference matrix requires auctioneer to update the real-time matrix elements, according to the interference relationship reported by SUs. There are two defects: 1. if one SU moves to another position, all SUs need to report their mutual interference relationship by exchanging instant messages. Auctioneers also need to update the real-time elements of interference matrix. SUs re-calculate the distance between each other. This increases the computational burden of mobile terminal and leads to low efficiency. 2. Interference matrix, which is the interference relationship between SUs, is reported to auctioneers by SUs themselves, which provides an opportunity to network attacks. SUs' intentional false reports of interference relationship can reach a variety of purposes. For example, collusion between SUs causes winners to become losers and the system total revenue to decline; SUs with mutual interference are attacked by imitated signal through falsely reporting their mutual interference relationship. So some winners will obtain idle spectrum band with lower prices. To take the interference relationship shown in Fig. 3 as an example, there are 5 SUs in this cognitive network.

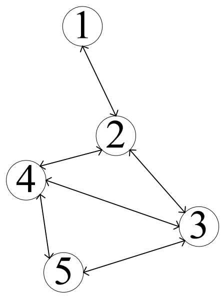

Figure. 3. Original interference relationship

The corresponding interference matrix is shown in Table 1, which shows the auction results when we adopt the VCG strategy first, and then adopt the sealed secondary pricing strategy.

TABLE. 1.

ORIGINAL AUCTION RESULT

r_i	v_i	winner
1	15	1
2	14	0
3	13	1
4	2	0
5	6	0

According to the sealed secondary pricing strategy, SU 1 and SU 3 are winners. The total payment collected by primary users is $v_2 + v_5 = 14 + 6 = 20$. Fig. 4 shows a false report submitted by SU 1, indicating that SU 1 and SU 3 have mutual interference. Then, the auction results are shown in Table 2.

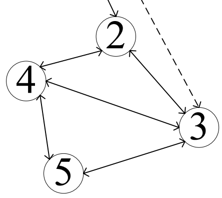

Figure. 4. False interference relationship

TABLE. 2.

FALSE AUCTION RESULT

r_i	v_i	winner
1	15	1
2	14	0
3	13	0
4	2	0
5	6	1

According to the sealed secondary pricing strategy, SU 1 and SU 5 are winners. The total payment collected by the primary user is $v_2 = 14$. Obviously, false report is a defect of auction framework which is based on the interference matrix. Therefore, we propose an anti-false report auction framework on the basis of the position information.

When there are M idle frequency bands in a system, we need to design a multi-band multi-winner auction framework. We extend the classic VGC strategy which maximizes social benefit to multi-band case and obtains a new multi-band optimization objective function.

$$\begin{aligned} &\max_{r^1,r^2,\cdots r^M} U_v(r^1,r^2,\cdots r^M) = \sum_{m=1}^{M}\sum_{i=1}^{N} v_i r_i^m, \\ &s.t.\ r_i^m + r_j^m \le 1, \forall i, j, m \text{ if } c_{ij} = 1, \\ &\sum_{m=1}^{M} r_i^m \le 1, \forall i, \\ &r_i^m = 0 \text{ or } 1, i = 1,2,\cdots N; m = 1,2,\cdots M \end{aligned} \tag{4}$$

According to this multi-band auction framework, the optimization objective function is very computation-consuming. This problem has $M \times N$ variables and its optimization process is complex. So this framework is not suitable to be applied in the real-time mobile cognitive network. Reference [11] has proposed a greedy algorithm to reach an approximate efficiency by solving the following function M times with N variables.

$$\begin{aligned} &\max_{r} U_v(r) = \sum_{i=1}^{N} v_i r_i, \\ &s.t.\ r_i + r_j \le 1, \forall i, j \text{ if } c_{ij} = 1, \\ &r_i = 0, \text{if } i \in \mathbf{W}^m, \\ &r_i = 0 \text{ or } 1, \text{if } i \notin \mathbf{W}^m \end{aligned} \tag{5}$$

Where, $\mathbf{W}^m$ represents those SUs who obtain frequency band m simultaneously. If the base station detects the total M idle frequency bands, the optimization process of (5) will be operated M times. If the base station detects idle frequency band unending, the optimization process of (5) will be ongoing.

The application of (5) can indeed reduce the system burden and response time, but there are some shortcomings of this approximate algorithm. First, resource allocation is unfair. A number of SUs in high-demand share the same frequency band, while some low-demand SUs would be able to occupy a frequency band alone. Second, (5) is considered as the SUs' distribution. The distribution of SUs has an impact on the efficiency of auction framework directly. Third, this is not the only approximate optimization auction framework to maximize system revenue. Application of the proposed spectrum auction framework which is based on position information can address the above issues. The strategy is described as follows.

V. SIMULATION AND PERFORMANCE EVALUATION

We assume that the valuations of different SUs $\{v_1, v_2, \cdots, v_N\}$ to be randomly distributed in (20, 30). When the position of SUs is fixed, we study how the valuation changes can affect spectrum efficiency. We assume there are 8 SUs. Their positions are shown in Fig. 5.

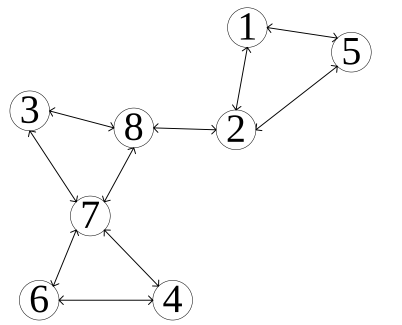

Figure. 5. Interference relationship of 8 SUs

The valuation of each SU changes 50 times randomly. We have simulated the total system revenue as shown in Fig. 6 and the number of idle frequency bands occupied by winners is shown in Fig. 7.

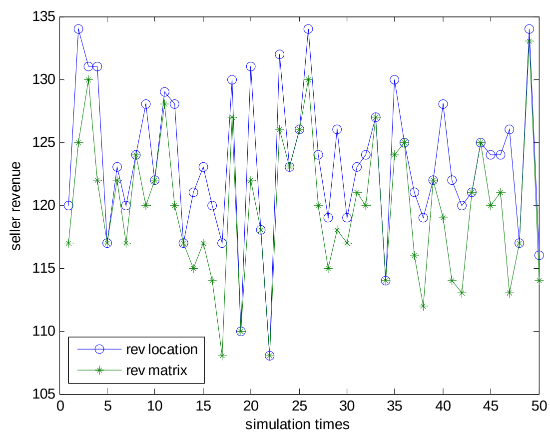

Figure. 6. Total system revenue

The circle symbol indicates the proposed auction framework based on the position information; the asterisk indicates the traditional framework based on the interference matrix.

We assume the position of SUs is fixed and valuations of SUs change randomly every time. Fig. 6 shows that the total system revenue obtained from the proposed auction framework is no less than the traditional framework's, when the number of frequency bands occupied by SUs in the proposed framework is no larger than the traditional framework's. For specific positions, the proposed framework has higher total system revenue. We consider both are effective and fair.

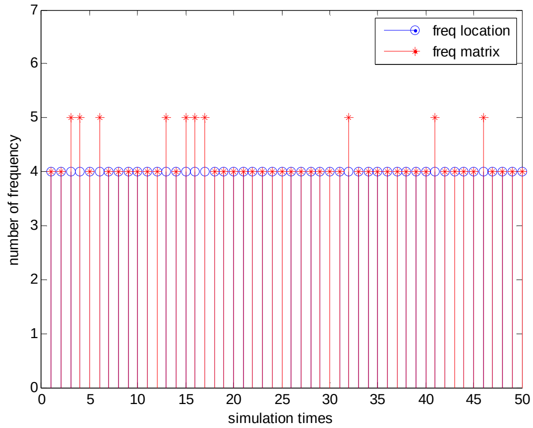

Figure. 7. Number of occupied idle frequency bands

We also simulate the performance of seller revenue, which is different between the second price auction, the VCG price auction and the proposed security spectrum auction. Fig.8 to Fig 11 are the distributions of 8 users, 12 users, 16 users and 20 users respectively. Fig.12 is the seller revenue between the different numbers of users.

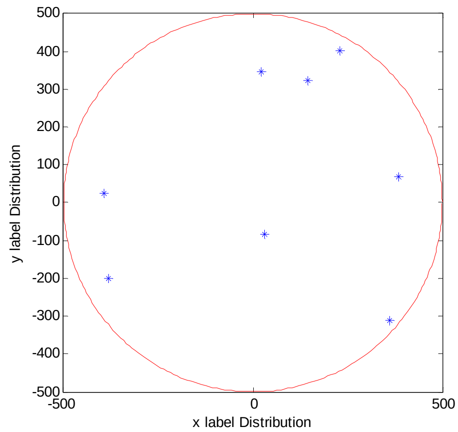

Figure. 8. Distribution of 8 users

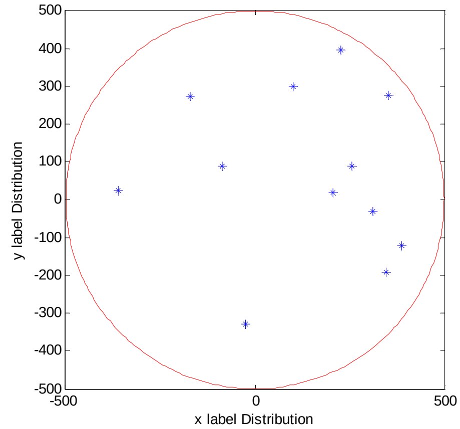

Figure. 9. Distribution of 12 users

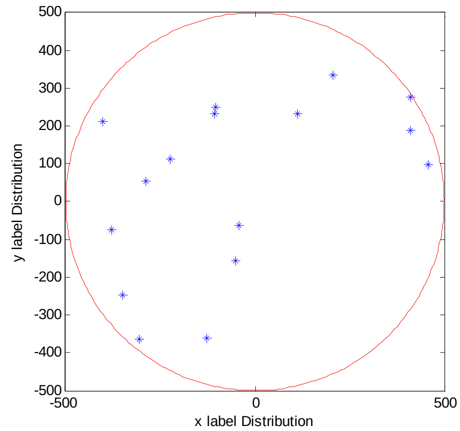

Figure. 10. Distribution of 16 users

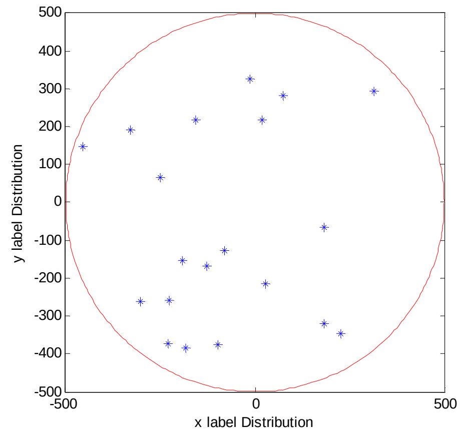

Figure. 11. Distribution of 20 users

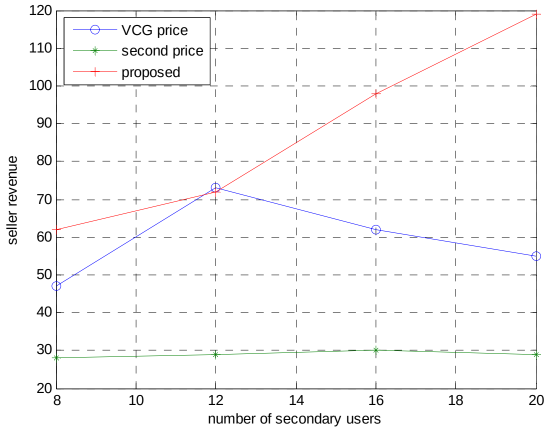

Figure. 12. Seller revenue by different number of users

We can see from Fig. 12 that the proposed auction framework has higher seller revenue than the VCG price and the second price. We simulate different positions of 8 users, 12 users, 16 users and 20 users. The second price auction framework is more simple and easy to implement but it has the lowest seller revenue. Along with the increase of users' number, the proposed auction framework will be more effective than the traditional auction framework. That is because with the increase of users' number, their positions tend to be uniform distributed. We have already proved that when users tend to be uniform distributed, the proposed framework can achieve its best performance [12].

VI. Conclusions

In this paper, we investigate the problem of multi-band multi-winner spectrum auction in the cognitive radio network and propose a security spectrum auction framework with full efficiency and fairness. We simulate the seller revenue by different positions and different numbers of users. When the valuations of SUs change randomly, while, their positions are fixed, then the simulation results will show that the proposed framework has higher total system revenue than the VCG price and the second price. Besides, along with increasing the numbers of SUs, we got the conclusion that our proposed security spectrum auction framework can obtain much more seller revenue than traditional auction frameworks. While, how the distributions of users will impact on the total system revenue? To solve this problem we need to analysis a large deal of information on SUs' position status. In the future work we will focus on this issue.

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