Collusion-Resistant Dynamic Spectrum Allocation for Wireless Networks via Pricing

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***Abstract*— Dynamic spectrum allocation becomes a promising approach to increase the spectrum efficiency for wireless networks. However, the collusion among selfish network users may seriously deteriorate the efficiency of dynamic spectrum sharing. In this paper, we propose a collusion-resistant dynamic pricing approach to optimize overall spectrum efficiency in the scenarios of user collusion. The simulation results show that our proposed scheme achieves high efficiency of spectrum usage even with the presence of severe user collusion.**

I. INTRODUCTION

In order to fully utilize the scarce spectrum resources, with the development of cognitive radio technologies, dynamic spectrum access becomes a promising approach to increase the efficiency of spectrum usage, which allows unlicensed wireless users to dynamically access the licensed bands from legacy spectrum holders based on leasing agreements.

The FCC began to consider more flexible and comprehensive use of available spectrum in [1]. The NeXt Generation program of DARPA also aims to dynamically redistribute allocated spectrum based on cognitive radio technologies [2]. From economical point of view, the deregulation of spectrum use further encourages market mechanisms for implementing efficient spectrum allocation. Researchers have already started to study dynamic spectrum access via pricing and auction mechanisms [3]–[7].

Although the existing dynamic spectrum access schemes have achieved some success on enhancing the spectrum efficiency through distributive design and market mechanisms, in order to have robust dynamic spectrum sharing systems, some basic challenges still remain unanswered. First, existing economical approaches only exploited a limited scope of genuine market designs for spectrum sharing, which requires further study from the perspective of driving economic force and mechanisms. Second, with the emerging applications of mobile ad hoc networks envisioned in civilian usage, the selfish users' cheating behaviors need to be well handled. Although the non-collusive cheating behaviors have been studied in our previous work [3] using belief-assisted pricing mechanisms, the collusive behaviors of selfish users [8], [9], one prevalent threat to efficient dynamic spectrum allocation, have been generally overlooked and needs to be extensively studied. Therefore, novel spectrum allocation approaches need to be developed considering efficient market designs for spectrum allocation and countermeasures to the users' collusive behaviors.

Considering a general network scenario in which multiple primary users (legacy spectrum holders) and secondary users (unlicensed users) coexist, primary users attempt to sell unused spectrum resources to secondary users for monetary gains while secondary users try to acquire spectrum usage permissions from primary users to achieve certain communication goals, which generally introduces reward payoffs for them. In this paper, we propose an efficient collusion-resistant dynamic pricing approach to optimize the overall spectrum efficiency, meanwhile, combating the collusion among selfish users and keeping the participating incentives of the users based on double-auction rules.

The reminder of this paper is organized as follows: The system model of dynamic spectrum allocation is described in Section II. In Section III, a collusion-resistant dynamic pricing approach is proposed to achieve efficient spectrum allocation while combating user collusion. The simulation studies are provided in Section IV. Finally, Section V concludes this paper.

II. SYSTEM MODEL

In our system model, we assume all users are selfish and rational, that is, their objectives are to maximize their own utilities, not to cause damage to other users. However, users are allowed to cheat whenever they believe cheating behaviors can help them to increase their utilities. Note that not only the cheating behaviors from a single selfish user is possible, but also the collusive cheating behaviors among several selfish users will pose threats to efficient spectrum allocation. Generally speaking, in order to acquire the spectrum licenses from regulatory bodies such as FCC, the primary users have certain operating costs. In order to have the rewards of achieving certain communication goals, the secondary users want to utilize more spectrum resources. The selfishness of both primary and secondary users will prevent them from revealing their private information, or even result in user collusion to suppress competition for possible gains.

Specifically, we consider the collection of the available spectrums from all primary users as a spectrum pool, which totally consists of N non-overlapping channels. Assume there are J primary users and K secondary users, indicated by the set $\mathbf{P} = \{p_1, p_2, ..., p_J\}$ and $\mathbf{S} = \{s_1, s_2, ..., s_K\}$, respectively. We represent the channels authorized to primary user p_i using a vector $\mathbf{A}_i = \{a_i^j\}_{j\in\{1,2,...,n_i\}}$, where a_i^j represents the channel index in the spectrum pool and n_i is the total number of channels belonging to user p_i. Define $\mathbf{A}$ as the set of all the channels in the spectrum pool. Moreover, denote the acquisition costs of user p_i's channels as the vector $\mathbf{C}_i = \{c_i^{a_i^j}\}_{j\in\{1,2,...,n_i\}}$, where the jth element represents the acquisition cost of the jth channel in $\mathbf{A}_i$. For simplicity, we write $c_i^{a_i^j}$ as c_i^j. Denote $\mathbf{C}$ as the set of the costs of all spectrum

1-4244-0663-3/07/$20.00 ©2007 IEEE

channels. As for secondary user s_i, we define her/his payoff vector as $\mathbf{V}_i = \{v_i^j\}_{j\in\{1,2,...,N\}}$, where the jth element is the reward payoff if this user successfully leases the jth channel in the spectrum pool.

Based on the above, the utility function of primary user p_i can be written as follows.

$$U_{p_i} = \sum_{j=1}^{n_i} (\phi_{a_i^j} - c_i^j)\alpha_i^{a_i^j}, \tag{1}$$

where $\phi_{a_i^j}$ is the payment that user p_i obtains from the secondary user by leasing the a_i^jth channel in the spectrum pool. Note that $\alpha_i^{a_i^j} \in \{0, 1\}$ indicates if the jth channel of user p_i has been allocated to a secondary user or not. For simplicity, we denote $\alpha_i^{a_i^j}$ as α_i^j. Similarly, the utility function of secondary user s_i can be represented as follows.

$$U_{s_i} = \sum_{j=1}^{N} (v_i^j - \phi_j)\beta_i^j, \tag{2}$$

where $\beta_i^j \in \{0, 1\}$ illustrates if secondary user s_i successfully leases the jth channel in the spectrum pool or not.

III. Efficient Collusion-Resistant Dynamic Spectrum Allocation via Pricing

In this section, we first discuss the impact of user collusion on auction-based dynamic spectrum allocation approaches. Then, we study collusion-resistant dynamic spectrum allocation for three scenarios: multiple secondary users and one primary user (MSOP); one secondary user and multiple primary users (OSMP); multiple primary users and multiple secondary users (MSMP).

A. User Collusion in Auction-Based Spectrum Allocation

Although incentive-compatibility can be assured in most auction-based dynamic spectrum allocation approaches such as the optimal auction [9], [10] or VCG-like auction [9], which indicates that no selfish user will cheat on the auction mechanism unilaterally, one prevalent cheating behavior, the bidding collusion among users, has been generally overlooked. To be specific, the bidders (or sellers) act collusively and engage in bid rigging with a view to obtaining lower prices (or higher prices). The resulting arrangement is called the bidding ring. In the scenarios of auction-based spectrum allocation, the bidding ring among the primary users (or secondary users) will result in increasing their utilities by collusively leasing the spectrum channels at a higher price (or at a lower price). Hence, traditional auction-based spectrum allocation mechanisms become vulnerable and unstable with the presence of collusive behaviors.

In the scenarios of traditional open ascending price, i.e., English auction (or reverse English auction) [9], there is one seller and multiple buyers (or one buyer and multiple sellers). In order to combat the bidding ring, the seller (or buyer) can enhance their utilities by setting proper reserve prices as in [9] based on the size of the bidding ring, i.e, the number of collusive users, and the statistics of each user's true value. However, in our scenarios of dynamic spectrum allocation with multiple primary and secondary users having only local information, double auction mechanism is considered. Further, the number of collusive users are not available and the determination of reserve price becomes very complicated given limited imperfect information. Therefore, how to design efficient collusion-resistant dynamic spectrum allocation mechanisms becomes an imminent and crucial task.

B. Collusion-Resistant Dynamic Spectrum Allocation

Considering there are one primary user and multiple secondary users first, the standard ascending price open auction is chosen for the secondary users to compete for the spectrum resources. Here, the presence of user collusion among secondary users may generate extra utilities for the collusive users by suppressing competition for spectrum resources. Due to the network dynamics and imperfect available information, neither the primary user can make a credible assumption about the presence of user collusion or the number of collusive users, nor there exist trust-worthy anti-cartel authorities in the network. Therefore, the only instrument giving the primary user possible leverage against collusion is to set an optimal reserve price.

Specifically, we assume that K secondary users are divided into K_r bidding rings and the size of the kth bidding ring is m_k. Note that $\sum_{k=1}^{K_r} m_k = K, m_k \geq 1$. Basically, the collusion among the secondary users within each bidding ring does not affect the strategies of users out of the bidding ring. Further, the bidding ring can be represented by the collusive secondary user with the highest reward payoff [9]. The other collusive users only submit non-serious bids at or below reserve price. Thus, there are only K_r effective users instead of K effective competing secondary users. Assume the equivalent reward payoff of the kth bidding ring is $\nu_{m_k}^{a_i^j}$, the highest reward payoff among m_k collusive users for the a_i^jth channel in the spectrum pool. Thus, the payoff vector for effective users can be represented as $\{\nu_{m_1}^{a_i^j}, \nu_{m_2}^{a_i^j}, \nu_{m_3}^{a_i^j}, ..., \nu_{m_{K_r}}^{a_i^j}\}$. Note that we omit the superscript a_i^j in the following parts for simplicity if the spectrum assignment is only considered for one specific channel. Further, let the highest and second highest reward payoff among all effective secondary users to be $v_{(1)}$ and $v_{(2)}$, respectively.

Considering the theoretical equivalence of open ascending price auction and second-price auction, we then study the optimal reserve price for second-price auction setting in our spectrum allocation game. Let the optimal reserve price to be ϕ_{r,p_i}. Then, the spectrum channel can be leased by p_i if and only if $v_{(1)} > \phi_{r,p_i}$. Moreover, if $v_{(2)} > \phi_{r,p_i}$, the spectrum channel is leased for $v_{(2)}$; otherwise, it is leased at the reserve price ϕ_{r,p_i}. Let $F_{v_{(1)}}(x)$ and $F_{v_{(2)}}(x)$ denote the cumulative density functions (CDF) of $v_{(1)}$ and $v_{(2)}$, respectively. Let $f_{v_{(1)}}(x)$ and $f_{v_{(2)}}(x)$ denote the probability density functions (PDF) of $v_{(1)}$ and $v_{(2)}$, respectively. Considering the dynamic game model as in [3] and the second-price auction mechanism [9], the expected utility gain of the primary user with reserve price ϕ_{r,p_i} by leasing her/his jth channel can be written as

$$\underset{\mathbf{V}_i, c_i^{a_i^j}}{E}[U_{p_i}(a_i^j, \phi_{r,pi})] = (\phi_{r,p_i} - E[c_i^{a_i^j}])(F_{v_{(2)}}(\phi_{r,p_i})$$

$$- F_{v_{(1)}}(\phi_{r,p_i})) + \int_{\phi_{r,p_i}}^{M} (z - E[c_i^{a_i^j}]) f_{v_{(2)}}(z) dz, \quad (3)$$

Where M represents the largest possible v_i^j. Note that the first term on the right hand side (RHS) of (3) represents the utility when the spectrum channel is leased at the reserve price. This happens if $v_{(1)} > \phi_{r,p_i}$ but $v_{(2)} < \phi_{r,p_i}$. The second term on the RHS of (3) represents the utility when $v_{(2)} \geq \phi_{r,p_i}$.

Assuming that an interior maximum exists for (3), the optimal reserve price ϕ_{r,p_i}^* satisfies the following first-order condition of (3).

$$F_{v_{(2)}}(\phi_{r,p_i}^*) - F_{v_{(1)}}(\phi_{r,p_i}^*) - (\phi_{r,p_i}^* - E[c_i^{a_i^j}]) f_{v_{(1)}}(\phi_{r,p_i}^*) = 0. \quad (4)$$

Thus the optimal reserve price can be determined by the above (4) if the statistical descriptions for $v_{(1)}$ and $v_{(2)}$ are available.

Similarly, in the scenarios of OSMP, if we let the lowest and second lowest acquisition costs among all effective primary users be $c_{(1)}$ and $c_{(2)}$, respectively, the first-order condition of maximizing the expected utility gain of the secondary user s_i with reserve price ϕ_{r,s_i} can be written as

$$F_{c_{(2)}}(\phi_{r,s_i}^*) - F_{c_{(1)}}(\phi_{r,s_i}^*) + (E[v_i^j] - \phi_{r,s_i}^*) f_{c_{(1)}}(\phi_{r,s_i}^*) = 0. \quad (5)$$

In order to obtain the optimal reserve prices ϕ_{r,s_i}^* and ϕ_{r,s_i}^* from (4) and (5), the statistics of $v_{(1)}$, $c_{(1)}$, $v_{(2)}$, and $c_{(2)}$ need to be obtained. However, in general scenarios of spectrum allocation, each user operates only based on her/his local information and there may be no anti-cartel authorities. Thus, the number of collusive users and the number of bidding rings are unknown to each user. Consequently, even though the statistics of each user's reward payoff is available or can be estimated under homogeneous settings, the order statistics [11] of $v_{(2)}$ and $c_{(2)}$ cannot be derived without the information of the number of collusive users. Thus, the users need to estimate the statistics of $v_{(2)}$ and $c_{(2)}$ in collusive spectrum allocation scenarios based their history of local observed information. Note that the belief definition in [3] can be applied here to obtain the above statistics.

Further, since the total number of active secondary user and the statistics of the reward payoff for each user are generally available, the PDF of $v_{(1)}$ in the scenarios of MSOP can be easily obtained using the order statistics in [11] as follows.

$$F_{v_{(1)}}(x) = \prod_{i \in \{1,2,\ldots,K\}} F_{v_i}(x). \quad (6)$$

Also, the PDF of $c_{(1)}$ in the scenarios of OSMP can be similarly obtained as follows [11].

$$F_{c_{(1)}}(y) = 1 - \prod_{i \in \{1,2,\ldots,J\}} (1 - F_{c_i}(y)). \quad (7)$$

In the general scenarios of MSMP, the user collusion may happen not only within the primary users but also within the secondary users. Also, the dynamic nature of spectrum resources requires that the countermeasures to the user collusion are able to easily adapt to the spectrum dynamics by using only limited resources such as bandwidth of control channels or implementation complexity.

TABLE I: Collusion-resistant dynamic spectrum allocation

1. Initialize the users' beliefs and bids/asks ◇ The primary users initialize their asks as large values close to M and their beliefs as small positive values less than 1; ◇ The secondary users initialize their bids as small values close to 0 and their beliefs as small positive values less than 1.
2. Belief update based on local information: Update primary and secondary users' beliefs $\bar{r}_p$ and $\bar{r}_s$.
3. Optimal reserve price for primary and secondary users: Update primary users' optimal reserve prices ϕ_{r,p_i}^* using (4) and (6); Update secondary users' optimal reserve prices ϕ_{r,s_i}^* using (5) and (7).
4. Optimal bid/ask update: ◇ Obtain the optimal ask for each primary user by solving (8) given ϕ_{r,p_i}^*; ◇ Obtain the optimal bid for each secondary user by solving (9) given ϕ_{r,s_i}^*.
5. Update leasing agreement and spectrum pool: ◇ If the outstanding bid is greater than or equal to the outstanding ask, the leasing agreement will be signed between the corresponding users; ◇ Update the spectrum pool by removing the assigned channel.
6. Iteration: If the spectrum pool is not empty, go back to Step 2.

Consider an important property of the bidding ring in our game settings that the collusive behaviors within an bidding ring won't affect the strategies of the users who are not in the bidding ring. It means that, for instance, a primary user's optimal reserve price is only determined by the spectrum demand statistics and won't be affected by the collusive behaviors of other primary users. Similar arguments can be applied to the secondary users. Therefore, an efficient collusion-resistant dynamic spectrum allocation approach in MSMP scenarios can be similarly derived based on the results of the above discussion on the scenarios of OSMP and MSOP.

In order to develop a collusion-resistant dynamic spectrum allocation algorithm, the belief functions are defined for primary and secondary users, which help them to make decision distributively with local information. Specifically, as in [3], a primary user's belief $\bar{r}_p(x)$ is defined as the ratio of asks from primary users at x that have been accepted; a secondary user's belief $\bar{r}_s(y)$ is similarly defined as the ratio of bids from secondary users at y that have been accepted. Note that practical belief functions [3] can be further derived based on the above definitions.

By using the belief function $\bar{r}_p(x)$, the payoff maximization of selling the ith primary user's jth channel can be written as

$$\max_{x > \phi_{r,p_i}^*} E[U_{p_i}(x, j)], \quad (8)$$

where $U_{p_i}(x, j)$ represents the payoff introduced by allocating the jth channel when the ask is x, and then $E[U_{p_i}(x, j)] = (x - c_i^j) \cdot \bar{r}_p(x)$. Similarly, as for the secondary user s_i, the payoff maximization of leasing the jth channel in the spectrum pool can be written as

$$\max_{y < \phi_{r,s_i}^*} E[U_{s_i}(y, j)], \quad (9)$$

where $U_{s_i}(y, j)$ represents the payoff introduced by leasing the jth channel in the spectrum pool when the bid is y, and then $E[U_{s_i}(y, j)] = (v_i^j - y) \cdot \bar{r}_s(y)$. Therefore, by solving the optimization problem for each effective primary and secondary user using (8) and (9), respectively, the optimal decisions of spectrum allocation at every stage can be made conditional on dynamic spectrum demand and supply. Note that when a leasing agreement for one specific spectrum channel is achieved for a pair of primary and secondary users, the order statistics of $v_{(1)}$, $c_{(1)}$, $v_{(2)}$ and $c_{(2)}$ need to be updated as well as the optimal reserve prices ϕ_{r,p_i}^* and ϕ_{r,s_i}^* using (4) and (5). In brief, the proposed algorithm is illustrated in Table I.

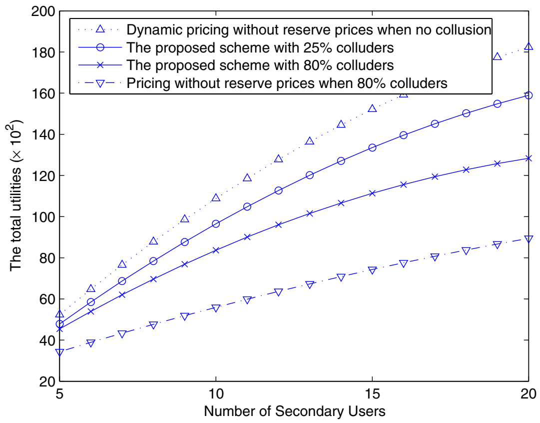

Fig. 1: Comparison of the total utilities of our dynamic pricing scheme with reserve prices and without reserve prices for different user collusion.

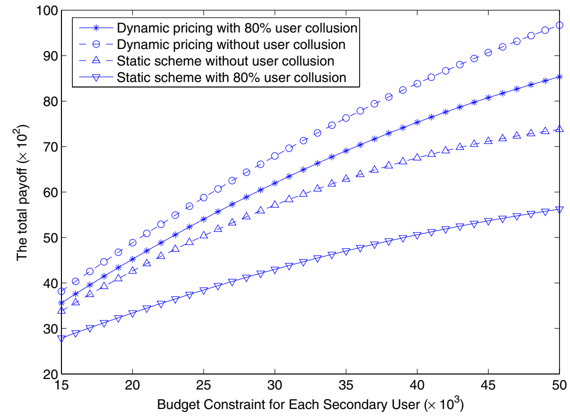

Fig. 2: Comparison of the total utilities of the proposed scheme with those of the static scheme.

IV. Simulation Results

Considering a wireless network covering 100×100 area, we simulate J primary users by randomly placing them in the network. Here we assume the primary users' locations are fixed and their unused channels are available to the secondary users within the distance of 50. Then, we randomly deploy K secondary users in the network, which are assumed to be mobile devices. The mobility of the secondary users is modeled using a simplified random waypoint model as in [3]. Without loss of generality, let the cost of an available channel in the spectrum pool be uniformly distributed in $[10, 30]$, the reward payoff of leasing one channel be uniformly distributed in $[20, 40]$. Note that $J = 5$ and 10^3 spectrum sharing stages have been simulated. Assume each primary user has four unused spectrum channels.

In Figure 1, we compare the total utilities of our dynamic pricing scheme with reserve prices and without reserve prices under various situations of user collusion. This figure shows that the proposed scheme with reserves prices achieves much higher total utilities than those of the scheme without reserve prices when there is user collusion. Note that the total utilities increase when the number of secondary users increases. It is because that the competition among more secondary users helps to increase the spectrum efficiency. However, under the scenarios of user collusion, the performance gap between the proposed scheme with reserve price and the CE becomes greater when the number of secondary users increases. The reason is that the proposed scheme with reserve prices needs to set more strict reserve prices to combat severe user collusion when there are more secondary users.

Then, we study the effect of user collusion for dynamic spectrum allocation when each secondary user is constrained by his/her monetary budget [3]. For comparison, we define a static scheme in which the secondary users make their spectrum-leasing decisions without considering their budget limits. By applying our proposed scheme with reserve prices to the dynamic programming approach in [3] considering budget constraints, we are able to similarly obtain the performance of the proposed collusion-resistant scheme when optimal spectrum allocation needs to be dynamically considered over time. In Figure 2, we compare the total utilities of our proposed scheme with those of the static scheme for different budget constraints when the user collusion is present. It can be seen from the figure that with the presence of user collusion, our proposed scheme with reserve prices achieves significant performance gains over the static scheme when the budget constraints are taken into consideration. That's because the performance loss due to the setting of reserve prices can be partly offset by exploiting the time diversity of spectrum resources.

V. Conclusions

Dynamic spectrum allocation is promising for enhancing the spectrum efficiency for wireless networks. However, user collusion among selfish users severely deteriorates the efficiency of spectrum sharing. In this paper, we propose a collusion-resistant dynamic pricing approach to maximize the users' utilities while combating their collusive behaviors using the derived optimal reserve prices. Simulation results show that the proposed scheme can achieve high spectrum efficiency under various situations of user collusion.

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