Research Article

The User Requirement Based Competitive Price Model for Spectrum Sharing in Cognitive Radio Networks

Fang Ye, Yibing Li, Rui Yang, and Zhiguo Sun

1 College of Information & Communication Engineering, Harbin Engineering University, Harbin 150001, China
2 China Electronics Standardization Institute, Beijing 100176, China

Correspondence should be addressed to Yibing Li; liyibing@hrbeu.edu.cn

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1. Introduction

Cognitive radio is viewed as an effective approach for improving the utilization of the radio spectrum [1]. The cognitive transceivers have flexible spectrum sensing ability and can adjust transmission parameters adaptively according to the ambient environment. The spare spectrum of licensed users (primary user) can be accessed by the cognitive users (secondary user) dynamically without causing harmful interference, and certain economic revenue can be achieved by the primary users [2, 3].

As the behaviors of the primary users and secondary users interact with each other, game theory, which is viewed as an effective tool for the analysis of interactive decision making, is applied in the spectrum sharing problem of cognitive radio networks [4]. The players in game model are primary and secondary users. The strategy space for each user consists of various actions related to spectrum sharing. Specifically, for secondary users, the strategy space includes which licensed channel they will use, what transmission parameters (e.g., transmission power or time duration) to apply, and the price they agree to pay for leasing certain channels from the primary users. For primary users, the strategy space may include which unused channel they will lease to secondary users and how much they will charge secondary users for using their spectrum resources [5, 6]. The competitive price model is applied to analyze the spectrum sharing problem in cognitive radio networks and obtain the Nash equilibrium price strategies that maximize the profits of primary users. As the price strategies of other primary users are usually not available simultaneously, the iterative equilibrium price calculation was further analyzed [7, 8]. The spectrum sharing problem with price strategies offered simultaneously and sequentially is also discussed in [9]. The selection of adjustment factor in the calculation of the equilibrium price is discussed in [10]. The auction mechanism is used to analyze the spectrum sharing of cognitive users to obtain the transmit power that satisfies the interference constraints [11], and the auction mechanism based on the signal to noise ratio and power is proposed; it can be applied to achieve the iterative calculation of the equilibrium price in distributed cognitive radio networks. The spectrum allocation algorithm based on dynamic multiband auction is discussed in [12], and the spectrum auction problem is converted to the 0/1 integer...
knapsack problem. The shared spectrum price is determined according to the supply-demand relationship. The spectrum resource allocation of cognitive radio networks based on auction mechanism is also analyzed in [13]. The cognitive users bid for the spectrum resource, the licensed users as the spectrum broker determine the spectrum sharing strategies without the deterioration of its communication quality, and the iterative calculation of the spectrum bid from secondary users in distributed cognitive radio networks is discussed. With the consideration of the collaboration among cognitive users, the mechanism of monetary compensation and motivation is used to improve utility function of the cognitive users; thus the licensed spectrum can be shared with better fairness performance [14]. The spectrum leasing problem in cognitive radio networks is discussed in [15], which is different from the spectrum leasing model mentioned above; the primary users allow the spectrum sharing with selection of the affordable interference levels. The auction mechanism based spectrum sharing between single primary user and multiple secondary users in cognitive radio networks is discussed in [16], the shared spectrum power strategies of the secondary users are determined by Vickrey auction mechanism to guarantee the interference power levels without causing harmful influence to the communication quality. The auction agent-based spectrum sharing in cognitive radio networks is analyzed in [17]. In addition to the primary users and secondary users, specialized agent is responsible for the spectrum resources allocation. It applies for the spectrum resource from the primary users and reallocates the licensed spectrum resource to the secondary users at certain price strategies. The transmit information between the primary users and secondary users can be reduced by the spectrum sharing mechanism, and effective spectrum sharing strategies can be achieved.

As the competitive price game model is applied in the cognitive radio networks with multiple primary users and single secondary user service, and the auction mechanism spectrum sharing model is applied in the cognitive radio networks with single primary user and multiple secondary users, this paper focused on the spectrum sharing problem with multiple primary users and secondary users. Moreover, on the basis of the competitive price game model, the spectrum resource demand levels of the secondary user are taken into account; the secondary service can adjust the applied spectrum resource according to the spectrum demand of secondary users and the shared spectrum price from the primary users. It is more applicable in the practical cognitive radio networks with the consideration of the spectrum requirements of secondary users, and the spectrum efficiency can be improved.

The rest of this paper is organized as follows. Section 2 describes the system model of spectrum sharing in cognitive radio networks. In Section 3, the spectrum sharing problem based on competitive price game is analyzed. Section 4 presents the simulation results, and Section 5 draws some conclusions.

2. System Model

We consider a wireless system with multiple primary users, the total number of which is denoted by N. For simplicity, assume the communication of secondary users is served by a secondary service. In this case, primary user \( i \) wants to sell portions of its spare spectrum to secondary user at price \( p_i \). The communication requirements of secondary user should be satisfied with assurance of primary users’ communication qualities, and certain economic revenue is obtained by the primary users through spectrum sharing. The demanded spectrum size of secondary user here depends on its transmission efficiency and the shared spectrum price charged by primary users. The transmission efficiency of secondary user is related to the modulation and channel qualities, which can be expressed as follows [18]:

\[
k = \log_2 (1 + K \gamma),
\]

where \( \gamma \) is the SNR at the secondary receiver, \( K = 1.5 / \ln (0.2/\text{BER}^{\text{tar}}) \), and \( \text{BER}^{\text{tar}} \) is the target bit error rate of the secondary user.

We apply Bertrand price model in economics to analyze the spectrum sharing problem in cognitive radio networks. The primary users provide the price strategies of shared spectrum, and the demanded spectrum size of the secondary user is determined from its utility function, which is relevant to the price strategies provided by primary users. The spectrum sharing profits of primary user depend on the economic revenue and the cost due to spectrum sharing. Here, the cost of spectrum sharing is defined as the degradation of the quality of service (QoS). The primary users constantly adjust the price strategies of shared spectrum to achieve the maxima of their own profits.

The demanded spectrum size of secondary user can be calculated through the quadratic utility function that is described as follows [5]:

\[
U(\mathbf{b}) = \sum_{i=1}^{N} b_i k_i^{(s)} - \frac{1}{2} \left( \sum_{i=1}^{N} b_i^2 + 2 \nu \sum_{i \neq j} b_i b_j \right) - \sum_{i=1}^{N} p_i b_i,
\]

where \( \mathbf{b} \) is the set of the shared spectrum size from different primary users, \( \mathbf{b} = [b_1, b_2, \ldots, b_N] \); \( p_i \) is the price strategy of shared spectrum from primary user \( i \), \( \mathbf{p} = [p_1, p_2, \ldots, p_N] \); \( k_i^{(s)} \) is the spectrum efficiency of secondary user that can be achieved by occupying the spectrum resource from primary user \( i \); \( \nu \) is the spectrum substitutability factor, and \( \nu \in [0, 1] \). When \( \nu = 0 \), the spectrum resource of different primary users cannot be substituted, while when \( \nu = 1 \), the spectrum resource of different primary users can be substituted freely. The demanded spectrum size by secondary users can be obtained by

\[
\frac{\partial U(\mathbf{b})}{\partial b_i} = 0.
\]
3. The Competitive Price Gamed Based Spectrum Sharing with User Requirement

On the basis of the spectrum sharing model in cognitive radio networks based on the competitive price game, we take the impact of cognitive users’ spectrum requirement in the spectrum sharing into account and establish an improved spectrum sharing model with the combination of competitive price game and auction mechanism as shown in Figure 1. The secondary service can collect the spectrum bids of the secondary user within the secondary user group, and the demanded spectrum resource level can be determined by the spectrum bids of the secondary users. With the acknowledgement of the shared spectrum price provided by the primary user and the spectrum demand levels of the secondary users, the secondary service determines the optimal shared spectrum size by competitive price game model. After the secondary service obtains the exclusive spectrum access right of certain spectrum resource, the secondary service reallocates the obtained spectrum resource to the secondary users by auction mechanism. Thus, the spare licensed spectrum resource can be shared between multiple primary users and secondary users.

In the spectrum sharing model based on auction mechanism, the secondary users submit the spectrum bids \( \mathbf{b}' = [b'_1, b'_2, \ldots, b'_I] \) to the secondary service according to the communication requirement, where \( I \) is the number of secondary users within the group. The secondary service collects the spectrum bids of different primary users and determines the demanded spectrum price from the primary users \( \mathbf{p} = \{p_1, p_2, \ldots, p_N\} \), where \( N \) is the number of primary users.

At the secondary service terminal, the demanded spectrum resource of the secondary is \( \sum_{i=1}^{I} b'_i \); the quadratic utility function based on the competitive price game model can be described as follows:

\[
U'(\mathbf{b}) = \sum_{i=1}^{N} b_i k_i(s) - \frac{1}{2} \left( \sum_{i=1}^{N} b_i^2 + 2 \sum_{j \neq i} b_ib_j \right) - \sum_{i=1}^{N} p_i b_i - \sigma \left( \sum_{i=1}^{N} b_i - \sum_{k=1}^{I} b'_k \right)^2,
\]

where \( \sigma \) is constant factor. In order to achieve the shared spectrum size that maximizes the utility function of the secondary service, the demanded spectrum size by secondary users can be obtained by

\[
\frac{\partial U'(\mathbf{b})}{\partial b_i} = 0.
\]

From (5), we can get

\[
(1 + 2\sigma)b_i + (v + 2\sigma) \sum_{j \neq i} b_j = k_i(s) - p_i + 2\sigma \sum_{k=1}^{I} b'_k.
\]

The size of shared spectrum can be rewritten as the linear equations according to (6):

\[
(1 + 2\sigma)b_1 + (v + 2\sigma)b_2 + \cdots + (v + 2\sigma)b_N = k_1(s) - p_1 + 2\sigma \sum_{k=1}^{I} b'_k,
\]

\[
(1 + 2\sigma)b_1 + (v + 2\sigma)b_2 + \cdots + (v + 2\sigma)b_N = k_2(s) - p_2 + 2\sigma \sum_{k=1}^{I} b'_k,
\]

\[
\vdots
\]

\[
(1 + 2\sigma)b_1 + (v + 2\sigma)b_2 + \cdots + (1 + 2\sigma)b_N = k_N(s) - p_N + 2\sigma \sum_{k=1}^{I} b'_k.
\]
The size of demanded spectrum can be obtained by
\[
\mathbf{D} = \mathbf{A}^{-1} \mathbf{F},
\]  
where
\[
\mathbf{A} = \begin{bmatrix}
1 + 2\sigma & v + 2\sigma & \cdots & v + 2\sigma \\
v + 2\sigma & 1 + 2\sigma & \cdots & v + 2\sigma \\
\vdots & \vdots & \ddots & \vdots \\
v + 2\sigma & v + 2\sigma & \cdots & 1 + 2\sigma 
\end{bmatrix},
\]  
\[
\mathbf{F} = \begin{bmatrix}
k_i^{(1)} - p_1 + 2\sigma \sum_{k=1}^{l} b_k' \\
k_i^{(2)} - p_2 + 2\sigma \sum_{k=1}^{l} b_k' \\
\vdots \\
k_i^{(N)} - p_N + 2\sigma \sum_{k=1}^{l} b_k'
\end{bmatrix},
\]  
\[
\mathbf{D} = \begin{bmatrix}
b_1 \\
b_2 \\
\vdots \\
b_N
\end{bmatrix},
\]  
\[
\sum_{j \neq i} (k_j^{(i)} - p_j + 2\sigma \sum_{k=1}^{l} b_k') (1 - v) \left(1 + 2\sigma + (N - 1)(v + 2\sigma)\right)^{-1}.
\]  

3.1. Adoption of the Shared Spectrum Price. The cost of spectrum sharing in this paper is defined by the QoS degradation of primary users. The revenue function \( R_i \) and cost function \( C_i \) for the primary user \( i \) that provides certain size of shared spectrum are defined as follows, respectively [7, 8]:
\[
R_i = c_1 M_i,
\]  
\[
C_i (b_i) = c_2 M_i \left( B_i^{(p)} - k_i^{(p)} \frac{W_i - b_i}{M_i} \right),
\]  
where \( c_1, c_2 \) are constants that denote the weights between revenue function and cost function, \( B_i^{(p)} \) is the bandwidth requirement of primary user, \( W_i \) is the total size of available spectrum, \( M_i \) is the number of primary connections, and \( k_i^{(p)} \) is the transmission efficiency of primary users.

In Bertrand price model, the players of the game are the primary users, the strategies of the players are prices of shared spectrum, that is, \( \{ p_i \} \), and the utility function is the achieved profit, that is, \( \{ p_i \} \). If the spectrum demand of cognitive user can be satisfied by the primary users, that is, the available spectrum resource of the primary users is larger than the spectrum demand \( D_i (p) \) of the secondary user, the profit function of primary users \( i \) is given by
\[
P_i (p) = p_i D_i (p)
\]  
\[
+ c_1 M_i - c_2 M_i \left( B_i^{(p)} - k_i^{(p)} \frac{W_i - D_i (p)}{M_i} \right)^2.
\]  

However, in practical spectrum sharing model for cognitive radio networks, the spectrum resources of the primary users are usually restricted. The spectrum demand of the secondary users will not be definitely satisfied by the primary users. Thus, it needs to consider the constraints of the shared spectrum size. \( B_i^{\text{max}} \) is the maximum shared spectrum size of primary user \( i \), and the competitive price game based spectrum sharing model with constraints of shared spectrum for cognitive radio networks can be formulated as (17), that is, determining the price strategy \( p^* \) satisfies
\[
p^* = \arg\max_{p} \left( \sum_{i=1}^{N} P_i (p) \right),
\]  
\[
s.t. \quad D_i (p) > 0, \quad i = 1, 2, \ldots, N,
\]  
\[
D_i (p) < B_i^{\text{max}}, \quad i = 1, 2, \ldots, N,
\]  
\[
\text{where } p^* \text{ is also defined as the Nash equilibrium price of the competitive price game. In order to achieve the } p^* \text{ that satisfies (17):}
\]  
\[
\frac{\partial P_i (p)}{\partial p_i} = 0.
\]  
It can be achieved from (16)–(18) that
\[
D_i (p) + p_i \frac{\partial D_i (p)}{\partial p_i} - 2c_2 k_i^{(p)} \left( B_i^{(p)} - k_i^{(p)} \frac{W_i - D_i (p)}{M_i} \right) \frac{\partial D_i (p)}{\partial p_i} = 0,
\]  
where
\[
\frac{\partial D_i (p)}{\partial p_i} = - \frac{1 + 2\sigma_i + (N - 2)(v + 2\sigma_i)}{(1 - v)(1 + 2\sigma_i + (N - 1)(v + 2\sigma_i))}.
\]
In practical cognitive radio networks, the price strategies of other primary users cannot be achieved simultaneously; the Nash equilibrium price strategy of the competitive price model cannot be achieved through the linear equations formed by (19). Thus, it is needed to further discuss the iterative method without acknowledgment of price strategies from other primary users.

Assume the price strategies of other primary users cannot be achieved simultaneously, but the price strategies of primary users during last cycle are available. The Nash equilibrium price that maximizes the system profits of the primary users during last cycle are available. The Nash equilibrium price cannot be achieved simultaneously, but the price strategies of other primary users cannot be achieved simultaneously; the Nash equilibrium price strategy cannot be achieved through the linear equations.

The linear gradient descent algorithm is one of the effective tools to calculate the maximum and minimum value of continuous target function during the optimization problems. For the primary users, the profit function is convex with the variation of shared spectrum price. At the kth iteration, \( p_i^k \) is the shared spectrum price of primary user \( i \) and \( f_i^k(p) \) is the profit of primary user \( i \). We can establish the improved system profit function \( \phi^k(p) \) using the Lagrange function in the condition of limited spectrum resource [3]. If the available spectrum resource of the primary users is larger than the spectrum demand of the secondary user, the value of the improved system profit function of primary users increases with \( p_i^k \) until the maximum of the improved system profit function is obtained, at which \( \partial \phi(p)/\partial p_i^k \) is positive, and \( p_i \) will increase iteratively until the equilibrium price is achieved or the spectrum constraints of the primary users cannot be satisfied. The value of the improved system profit function will decrease with the increase of the demanded spectrum size of the cognitive users when the price of the shared spectrum is too high for the cognitive user. At this time, \( \partial \phi(p)/\partial p_i^k \) is negative, and the shared spectrum price \( p_i \) decreases until the equilibrium price is achieved. Otherwise, with the increase of \( p_i^k \), the spectrum demand of the secondary user decreases and the profit of the primary user also decreases accordingly, \( \partial \phi(p)/\partial p_i^k \) is negative, and \( p_i^k \) tends to decrease by (21) until the Nash equilibrium price strategy is achieved. When the spectrum demand of the secondary user cannot be satisfied by the available spectrum resource of primary users, that is, the cognitive user tends to apply for more spectrum resource than spectrum constraints, the value of the improved profit function decreases. Thus the equilibrium price of the shared spectrum that maximizes the improved system profit function and satisfies the constraints of spectrum resource can be achieved iteratively:

\[
p_i^{k+1} = p_i^k + a \frac{\partial \phi(p)}{\partial p_i^k}, \tag{21}
\]

where \( a \) is a nonnegative adjustment factor. With appropriate adjustment factor, the shared spectrum price that maximizes the improved system profit function can be achieved iteratively.

### 3.2 Reallocation of Achieved Spectrum Resource

The secondary users submit the spectrum bids \( b_i' \) to the secondary service. Here, we use the demanded spectrum size as spectrum bids of the secondary users, where \( 0 \leq b_i' \leq B_i^{\text{tot}} \) and \( B_i^{\text{tot}} = \sum_{j=1}^{N} b_j \) is the total achieved spectrum resource of the secondary service from the primary users. The secondary service, as the spectrum resource broker, collects the spectrum bids from the secondary users and determines the shared spectrum size to the secondary users \( B = [B_1, B_2, \ldots, B_J] \):

\[
B_k = \frac{b_k^*}{\sum_{k=1}^{J} b_k^* + \beta} B_i^{\text{tot}}, \tag{22}
\]

where \( \beta \) is a positive reserve bid used by the PU to control the remaining portion of the spectrum for its own usage [13], which is set by PU to satisfy

\[
\sum_{k=1}^{J} B_k > \sum_{i=1}^{N} B_i^{\text{req}}. \tag{23}
\]

With the shared spectrum resource \( B_i \), the revenue \( R_i \) of the secondary user \( i \) can be shown as

\[
R_i = r_i k_i B_i, \tag{24}
\]

where \( r_i \) is the revenue of secondary user \( i \) per unit of achievable transmission rate, which relates to the QoS in a real network; that is, the higher the QoS required by the secondary user \( i \) is, the greater the revenue \( r_i \) will be. \( k_i \) is spectral efficiency of transmission, which can be obtained from (1).

The economical cost \( C_i \) of secondary user \( i \) with shared spectrum size \( B_i \) can be shown as

\[
C_i = p_i \theta_i b_i, \tag{25}
\]

where \( \theta_i \) is the priority factor of secondary user. The profit function of secondary user \( i \) that can be achieved through spectrum sharing is defined as follows:

\[
U_i \left( b_i', b_i', p \right) = R_i \left( B_i \left( b_i', b_i' \right) \right) - C_i \left( b_i', p \right)
\]

\[
= r_i k_i \frac{b_i'}{\sum_{j=1}^{J} b_j} B_i^{\text{tot}} - p_i \theta_i b_i', \tag{26}
\]

where \( b_i' = [b_i', b_i', \ldots, b_i', b_i', b_i', \ldots, b_i'] \) is the spectrum bids of secondary users except secondary user \( i \). The secondary user \( i \) adjusts its spectrum bid to achieve the maximal profit function according to the communication parameters. Thus the equilibrium price strategies can be obtained, and the secondary users cannot get higher profit with price strategy variation; the equilibrium price strategy \( (b_i')^* \) must satisfy

\[
(b_i')^* = \arg \max_{0 \leq b_i' \leq B_i^{\text{tot}}} U_i \left( b_i', b_i', p \right), \tag{27}
\]

where \( (b_i')^* = [(b_i')^*, (b_i')^*] \). In order to obtain the price strategies that maximize its spectrum sharing profits, we can get

\[
\frac{\partial U_i \left( b_i', b_i', p \right)}{\partial b_i'} = 0. \tag{28}
\]
4. Simulation Results

We consider a cognitive radio network with two primary users and two secondary users sharing a frequency spectrum of size 20 MHz. The target BER for each secondary user is $\text{BER}_{\text{tar}} = 10^{-4}$. Each secondary user knows its revenue per unit transmission rate $r_i = 10$, and it also knows its spectral efficiency of transmission through channel estimation. The primary user sets the price $p = 10$ per unit bandwidth and reserves bid $\beta_1 = \beta_2 = 0.2$. The speed adjustment parameter is set as $\alpha_1 = \alpha_2 = 0.1$.

Figure 2 shows simulation results of the shared spectrum size of the secondary service under different spectrum requirements from the secondary users, where spectrum requirement $b_{\text{level}} = \sum_{i=1}^{I} b_i'$. It can be concluded from Figure 2 that, with the increasing spectrum requirement of secondary users, the secondary service can demand more spectrum resource from the primary users.

Figure 3 shows the simulation results of the system profit of the primary users by providing spectrum sharing to the secondary users. It can be concluded from Figure 3 that, with the increasing spectrum requirement of the secondary users, more shared spectrum size can be obtained by the secondary users, and the primary users can also achieve more spectrum sharing profits.

Then, we compare the proposed approach with the conventional approach which combines the competitive price game and auction mechanism directly without considering different spectrum requirement levels from the secondary users. Figure 4 shows the simulation results of spectrum bids with different spectrum requirement levels from the secondary users, when applying the proposed spectrum leasing model and the conventional competitive price game model for cognitive radio networks. The factor $\theta$ is reduced to control the cost function in the improved spectrum leasing model. On the contrary, with the increase of factor $\theta$, the spectrum requirements of the secondary users are increased. Where the signal to noise ratio of the secondary receiver 1 is 18 dB and the signal to noise ratio of the secondary receiver 1 is 22 dB. In the conventional spectrum leasing model with the combination of the competitive price game and auction mechanism, $\theta_1 = 1$, and in the improved spectrum leasing model $\theta_2 = 0.8$ to improve the spectrum requirement of the secondary users. It can be concluded from Figure 4 that, with the increase of the spectrum requirement levels from the secondary user, the improved spectrum leasing model can achieve more spectrum resource with higher shared spectrum price.

Figure 5 shows the simulation results of the shared spectrum resource size of the secondary service by the improved spectrum leasing model and the conventional spectrum leasing model with direct combination of the competitive price game and auction mechanism. It can be concluded from Figure 5 that, in the improved spectrum leasing model, the secondary user can increase the spectrum bids to apply for more licensed spectrum resource. It is more suitable for the spectrum leasing problem in cognitive radio networks.

5. Conclusion

In this paper, we analyze the spectrum leasing problem of the cognitive radio networks with multiple primary users and multiple secondary users, and propose an improved spectrum sharing model considering the spectrum requirement of the secondary users. This approach introduces the demanded spectrum resource of the secondary users into the utility function base on the competitive price game model and uses a spectrum requirement level to quantify the communication requirements of the secondary users. Then the secondary service can determine the size of shared spectrum according to the spectrum requirement of the secondary users and the provided spectrum sharing price,
The shared spectrum profit from primary users

\[ b_{\text{level}} = 1 \text{ PU}_1 \]
\[ b_{\text{level}} = 2 \text{ PU}_1 \]
\[ b_{\text{level}} = 1 \text{ PU}_2 \]
\[ b_{\text{level}} = 2 \text{ PU}_2 \]

Figure 3: The profit of primary users by providing spectrum resource under different requirement levels of cognitive users.

The spectrum bid of cognitive users system revenue performance of primary users in the improved spectrum trading model.

- Conventional algorithm CR$_1$ bids
- Conventional algorithm CR$_2$ bids
- Improved algorithm CR$_1$ bids
- Improved algorithm CR$_2$ bids

Figure 4: The spectrum bid of cognitive users system revenue performance of primary users in the improved spectrum trading model.

and the primary users adjust the price of shared spectrum to maximize their spectrum sharing profits. The simulation results show that the achieved spectrum resource of the secondary user can be adjusted flexibly according to its spectrum requirements and the shared spectrum price of the primary user, especially when the demand spectrum size of the secondary users cannot be satisfied by the primary users.

It can also avoid the waste of spectrum resource when the spectrum requirement of the secondary user is low.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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