Auction Based Joint Resource Allocation with Flexible User Request in Cognitive Radio Networks

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Abstract. Cognitive Radio (CR) has emerged as a promising technology to address the spectrum scarcity through encouraging the open access of licensed spectrum to unlicensed users. The incentives for licensed users and the resource allocation among unlicensed users are two main critical issues in practical implementation. Recently, auction has been introduced as an efficient tool to solve both incentive and allocation issues in cognitive radio networks. However, existing studies on auction are focusing on either channel allocation or power allocation. Few of them considers the channel and power allocation jointly. In addition, various transmission demands of unlicensed users push the need for flexible user request on spectrum resource. In this paper, we propose an auction scheme to study the joint resource allocation problem among unlicensed users and allow them to submit either range request or strict request according to their demands. To the best of our knowledge, we are the first to focus on this kind of problem. In the final, Theoretical analysis and numerical evaluations verify the truthfulness and efficiency of our scheme.

Keywords: Cognitive radio networks · Joint resource allocation · Auction theory

1 Introduction

Nowadays, the dramatic development of wireless devices and applications puts a growing demand on spectrum resource. The ever-increasing spectrum demand has posed a great challenge on current static spectrum allocation policy, in which the spectrum is allocated to licensed holders in long-term. Cognitive Radio (CR) [1], which utilizes the idle spectrum via opportunistic access, has emerged as a promising technology to alleviate the spectrum scarcity. There are two crucial issues in the adoption of cognitive radio technology: (1) Incentive problem: how to promote licensed holders to open the access of licensed spectrum; and (2) Allocation problem: how to allocate the spectrum resource among unlicensed users (i.e., Secondary Users, SUs).

Many economic tools have been introduced into cognitive radio networks to concurrently solve the incentive and allocation problem [2–4]. Among them,

M. Weichold et al. (Eds.): CROWNCOM 2015, LNICST 156, pp. 43–53, 2015.
DOI: 10.1007/978-3-319-24540-9_4

auction is preeminent due to its efficiency and fairness. However, prior works on auction have the following limitations: First, most of the studies only concentrate on the allocation of either spectrum channels [5–11] or transmitting power [12–14]. Joint channel and power allocation is rarely to see in existing studies. When adopting spectrum reuse in joint resource allocation, we need to consider not only which channel an SU is transmitting on, but also how much power the SU is transmitting with. Second, in existing auction schemes, user requests on spectrum resource are always assumed to be strict (i.e., an SU requests for a given amount of resource and accepts either all of the request or nothing) [5–7]. This assumption restricts the flexibility of user request and may compromise the efficiency of resource usage. The works in [10,11] introduce the concept of range request in the auction, in which an SU requests a given amount of spectrum resource and accepts any possible allocations, but they only consider range request on spectrum channels. Moreover, none of previous studies support both two types of user request in the auction.

In this paper, we allow SUs to bid for spectrum channel and transmitting power simultaneously. We model this joint resource allocation problem as an auction process. Moreover, we offer the SUs the flexibility on request format via allowing them to submit with either strict request or range request in the auction. The proposed auction scheme consists of two sequential sub-schemes, a multi-round auction for range request SUs and a greedy algorithm based auction for strict request SUs. Furthermore, a primary property of an auction scheme is truthfulness, since it makes the auction scheme invulnerable and keeps it from market manipulation. In the end of the paper, we theoretically analyze the truthfulness property of our auction scheme and conduct a numerical evaluation to verify the performance.

The rest of the paper is organized as follows. The network model, design goals and preliminary knowledge on auction are described in Section 2. Our proposed auction scheme and corresponding theoretical analysis are detailed in Section 3. The numerical evaluation is presented in Section 4 and the paper is concluded in Section 5.

2 Network Model and Preliminaries

2.1 Network Model

We consider a network model containing multiple SUs randomly distributed within a certain area. The set of SUs is denoted by $\mathcal{M}$ ($SU_i \in \mathcal{M}$). These SUs request spectrum channels and transmitting power on required channels to fulfill their transmission demands. There also exists a spectrum broker in the network who possesses a number of orthogonal channels and wants to lease out for additional profits. The set of channels is denoted by $\mathcal{C}$. A channel can be leased to multiple SUs as long as they are conflict-free, i.e., they are located out of the interference range from each other. Due to the power differentiation, the interference ranges of SUs are different. In this paper, we employ a conflict graph to reflect the interference relations among SUs. In the conflict graph, a vertex represents an SU and an edge exists between two vertices if they are conflict. We assume these channels are identical to SUs, which means SUs only care about the number of assigned channels and do not distinguish which channel.

We model the joint allocation problem as an auction process, wherein the spectrum broker is the seller and the SUs are buyers. Each SU submits a bid to the spectrum broker at the beginning of the auction. The bid of SU_i is denoted by $\mathcal{B}_i(x_i, n_i, P_i, \lambda_i)$, where x_i represents the type of user request, n_i represents the number of required channels, P_i represents the demand of transmitting power and λ_i represents the unit valuation (i.e., the valuation per channel per unit power). In this paper, we focus on two types of user request, strict request ($x_i = 1$) and range request ($x_i = 0$). In strict request, an SU only accepts the allocation of either transmitting on all n_i channels with power P_i or getting nothing. In range request, an SU is willing to accept any number of channels between 0 and n_i with any value of transmitting power less than P_i. The objective of the joint allocation problem can be formally written as

$$\begin{aligned} \max_{q_i, p_i, \mathcal{C}_i} \quad & \sum_{SU_i \in \mathcal{M}} \lambda_i \cdot q_i \cdot p_i \\ s.t. \quad & \mathcal{C}_i \subseteq \mathcal{C},\ |\mathcal{C}_i| = q_i, \\ & \mathcal{C}_i \cap \mathcal{C}_j = \emptyset,\ \forall SU_j \in N_i,\ SU_i \in \mathcal{M} \\ & q_i \in [0, n_i],\ 0 < p_i \leq P_i,\ \forall SU_i \in \mathcal{M},\ x_i = 0 \\ & q_i \in \{0, n_i\},\ p_i \in \{0, P_i\},\ \forall SU_i \in \mathcal{M},\ x_i = 1. \end{aligned} \tag{1}$$

q_i and p_i denote the number of allocated channels and the amount of allocated power, respectively. $\mathcal{C}_i$ represents the set of channels allocated to SU_i. N_i represents the set of conflicting neighbors of SU_i, i.e., they have common edges with SU_i in conflict graph. The second condition restricts that a channel cannot be reused among two conflicting SUs. The objective of the allocation is to maximize the social welfare, i.e., the sum of all winning SUs' valuations.

2.2 Truthfulness

In the auction, an SU's utility is determined by its valuation, final charge and the amount of obtained resource, which can be denoted as

$$u_i(\mathbf{B}) = \lambda_i \cdot q_i \cdot p_i - g_i, \tag{2}$$

where $\mathbf{B} = \{\mathcal{B}_i\}, \forall SU_i \in \mathcal{M}$. The information of unit valuation is private, which means an SU may or may not report its true valuation in submitted bid. g_i is the price SU_i needs to pay for assigned resource. If an SU obtains nothing, its utility equals 0. Note that we assume the SUs only have incentives to lie about their unit valuations.

The performance of an auction design heavily depends on an economic property called truthfulness. The property requires that no SU_i can obtain a higher utility by submitting a false unit valuation $\tilde{\lambda}_i \neq \lambda_i$ in bid. In other words, revealing the true valuation is the dominant strategy for each SU in a truthful auction.

Let $\mathcal{B}_{-i}$ denote the bids submitted by all SUs other than SU_i, the truthfulness property can be formally written as

$$u_i(\mathcal{B}_i(\lambda_i), \mathcal{B}_{-i}) \geq \tilde{u}_i(\mathcal{B}_i(\tilde{\lambda}_i), \mathcal{B}_{-i}). \quad (3)$$

Guaranteeing the truthfulness keeps the auction scheme invulnerable and avoids market manipulation from SUs.

In general, the goal of this paper is to design an auction scheme to achieve the objective in (1) while satisfying the truthfulness property.

3 Auction Design Under Flexible Request

There are two challenges lying in the design of the auction scheme. First, how to charge the SUs with range requests. Due to the allocation is unfixed, it is difficult to directly apply the traditional pricing solution method which through finding the corresponding critical bids. Second, variable power requests may cause non-identical interference relations among SUs. The neighborhood of each SU varies with the allocated transmitting power. If we update the power allocation, we need to make sure whether preassigned channels are still available. With numerous SUs and continuous power region, the problem is more complicated.

3.1 Auction Design

We divide SUs into two sets $\mathcal{S}$ and $\mathcal{R}$, representing the set of strict request SUs and the set of range request SUs, respectively. We first conduct an auction among the SUs in $\mathcal{R}$. Taking account of the variability of SUs' resource requests, we design a multi-round auction scheme where all the channels are sequentially allocated. In each round, a single channel is allocated to a set of conflict-free SUs with relative higher raise on bid price. The power allocation of winning SUs is gradually updated with the interval δ to guarantee the free of conflicts.[1] Then, we propose a greedy algorithm based auction scheme among winning SUs in $\mathcal{R}$ and SUs in $\mathcal{S}$. The auction greedily assigns the channels and transmitting power to SUs in decreasing order of their bids as long as the allocation in feasible.

Multi-round Auction for SUs in $\mathcal{R}$: We start the auction with randomly distributing every SU_i into n_i different rounds. This ensures that each SU has no knowledge about other competitors, which is essential to keep the auction truthful. In each round, we use Φ_1 to denote the set of SUs that have not been assigned channels and Φ_2 to denote the left SUs. The details of the auction are shown in Algorithm 1.

Lines 1-5 describe the allocation among SUs in Φ_1. Specifically, we sort the SUs in decreasing order of their unit valuations and sacrifice the lowest-rank SU to determine other SUs' payments. In line 4, we gradually raise the power for

[1] δ is a small constant such that the assigned power is multiple times of δ.

Algorithm 1. Multi-round Auction for SUs in $\mathcal{R}$

for *each round* l **do**
  Input: Φ_1, Φ_2, $\{\mathcal{B}_i\}_{SU_i \in \Phi_1 \cup \Phi_2}$, $\mathcal{C}$, δ
1 $L = \{\lambda_i | SU_i \in \Phi_1\}$, $\phi_1 = \emptyset$;
2 Sort L in decreasing order and remove the last SU;
  for *each remaining* SU_i *in* L **do**
3    $\phi \leftarrow \{SU_i\}$;
4   Gradually raise the p_i with a step size of δ until it exceeds P_i or conflicts with others;
5    $q_i = 1$, $g_i^{q_i} = \lambda_{\underline{i}} \cdot p_i$; // $\lambda_{\underline{i}}$ *denotes the unit valuation of the removed SU*;
  end
6 $I = \{I_i = p_i \cdot \lambda_i | SU_i \in \Phi_2\}$, $\phi_2 = \emptyset$;
  while $I \neq \emptyset$ **do**
7    $SU_i = \arg\max\{I_i | I_i \in I\}$; $flag = 1$;
    for *each* $SU_j \in \phi_2$ **do**
8   **if** $SU_j \in N_i^{\Phi_2}$ **then**
9        $g_j^{q_j} = \max(g_j^{q_j}, I_i)$; $flag = 0$;
10   break *for*;
      end
    end
11   **if** $flag == 1$ **then**
12   **if** $\sum_{SU_j \in N_i^{\phi_1}} p_j \cdot \lambda_j < I_i$ **then**
13        $\phi_2 \leftarrow \{SU_i\}$, $q_i = q_i + 1$;
14        $g_i^{q_i} = \sum_{SU_j \in N_i^{\phi_1}} p_j \cdot \lambda_j$;
15        $q_j = 0, \ \forall SU_j \in N_i^{\phi_1}$; $\phi_1 = \phi_1 - N_i^{\phi_1}$;
      end
    end
16    $I = I - \{I_i\}$;
  end
end
Output: $\{p_i, q_i, g_i^{q_i}, \mathcal{C}_i\}_{SU_i \in \mathcal{R}}$

each $SU_i \in \phi_1$ at a step size of δ until it conflicts with others or reaches the upper bound of power request. Once the power allocation of an SU is fixed, it would not change in following auction process. We could notice that, the power allocation only relates to SUs' locations and thus is independent of SUs' bid prices.

Lines 6-16 describe the final allocation among SUs in ϕ_1 and Φ_2. I_i denotes the increment on bid price for $SU_i \in \Phi_2$ if obtaining this channel. $N_i^{\phi_1}$ and $N_i^{\Phi_2}$ denote the set of conflicting SUs of SU_i in ϕ_1 and Φ_2, respectively. From lines 7 to 16, we check each element of I in decreasing order to see whether $SU_i \in \Phi_2$ satisfies the two conditions that enable the allocation: 1) do not conflict with granted SUs in ϕ_2 (lines 8-11); 2) able to cover the loss of social welfare caused by conflict (line 12). If so, SU_i obtains the channel and the conflicting SUs in ϕ_1

Algorithm 2. Auction for Winning SUs in $\mathcal{R}$ and SUs in $\mathcal{S}$

Input: $\{\mathcal{B}_i\}_{SU_i \in \mathcal{S}}$, $\{p_i, q_i, g_i^{q_i}, \mathcal{C}_i\}_{SU_i \in \mathcal{R}}$
1 $\mathcal{H} = \{H_i = n_i \cdot P_i \cdot \lambda_i | SU_i \in \mathcal{S}\}$; $\psi = \emptyset$;
while $\mathcal{H} \neq \emptyset$ **do**
2 $SU_i = \arg\max\{H_i | H_i \in \mathcal{H}\}$; $flag = 1$;
3 **for** *each* $SU_j \in \psi$ **do**
4 **if** $SU_j \in N_i^{\mathcal{S}}$ **then**
5 $g_i = \max(g_i, H_i)$; $flag = 0$;
6 break *for*;
end
end
7 **if** $flag == 1$ **then**
8 $\mathcal{C}_d = \bigcup_{SU_j \in N_i^R} \mathcal{C}_j$;
9 **if** $|\mathcal{C}| - |\mathcal{C}_d| \geq n_i$ **then**
10 $\psi \leftarrow \{SU_i\}$;
else
11 $q_i = n_i - (|\mathcal{C}| - |\mathcal{C}_d|)$;
12 $\mathcal{T} = \{\sum_{ch_k \in \mathcal{C}_j, SU_j \in N_i^R} p_j \cdot \lambda_j | ch_k \in \mathcal{C}_d\}$;
13 Sort $\mathcal{T}$ in increasing order;
14 **if** $\sum_{k=1}^{q_i} T_k < H_i$ **then**
15 $\psi \leftarrow \{SU_i\}$; $g_i = \sum_{k=1}^{q_i} T_k$;
16 $g_j^{q_j} = 0$, $q_j = q_j - 1$, $\mathcal{C}_j = \mathcal{C}_j - \{ch_k\}$, $\forall SU_j \in N_i^{\mathcal{R}}$, $ch_k \in \mathcal{C}_j$, $k = 1, 2, \cdots, q_i$;
end
end
end
17 $\mathcal{H} = \mathcal{H} - \{H_i\}$;
end
Output: ψ, $\{\mathcal{C}_i, g_i\}_{SU_i \in \psi}$, $\{p_i, q_i, g_i^{q_i}, \mathcal{C}_i\}_{SU_i \in \mathcal{R}}$

need to be eliminated (Line 15). Finally, the SUs in ϕ_1 and ϕ_2 win the channel in this round.

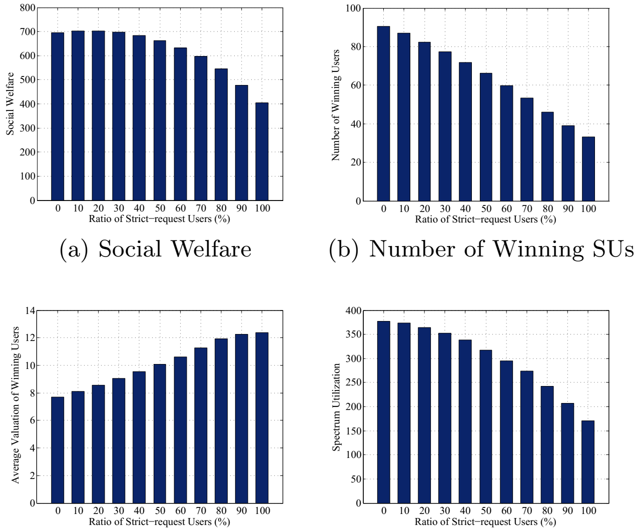
Auction for Winning SUs in $\mathcal{R}$ and SUs in $\mathcal{S}$: The proposed auction scheme is based on a greedy algorithm, the details of which are shown in Algorithm 2. We sort the SUs in $\mathcal{S}$ with decreasing order of their total valuations and examine each SU sequentially (lines 1-2). The allocation is feasible for $SU_i \in \mathcal{S}$ if and only if: 1) SU_i does not conflict with granted SUs in ψ (lines 3-6); 2) the available channels within its interference range can afford its demand (lines 8-10) or its valuation can cover the minimum loss on social welfare caused by its exclusive usage of channels within its interference range (lines 11-16). The minimum loss on social welfare is calculated by ranking the cumulative valuations of winning SUs in $\mathcal{R}$ on competitive channels in increasing order (lines 12-13) and selecting the q_i highest-rank channels (line 14).

Payment Calculation: The total payment of winning SUs in $\mathcal{R}$ is the sum of the payment on each assigned channel,

$$g_i = \sum_{k=1}^{q_i} g_i^k, \ \forall SU_i \in \mathcal{R}. \tag{4}$$

The payment on each assigned channel is obtained through finding out the critical user on this channel. On the first assigned channel, the critical user is the SU with minimum unit valuation, and thus we set the payment as $g_i^{q_i} = \lambda_{\underline{i}} \cdot p_i$. The critical user(s) on other assigned channels is either the set of conflicting SUs in ϕ_1 or the first SU in Φ_2 whose loss of the auction is caused by SU_i. Therefore, we set the payment equal to whichever is larger (line 9 in Algorithm 1).

The payment calculation for winning SU_i in $\mathcal{S}$ inherits the critical user based method. The critical user(s) of SU_i is either the set of conflicting winning SUs in $\mathcal{R}$ on competitive channels or the first SU whose loss of the auction is caused by SU_i. We set the payment in similar way as the last paragraph (line 5 in Algorithm 2).



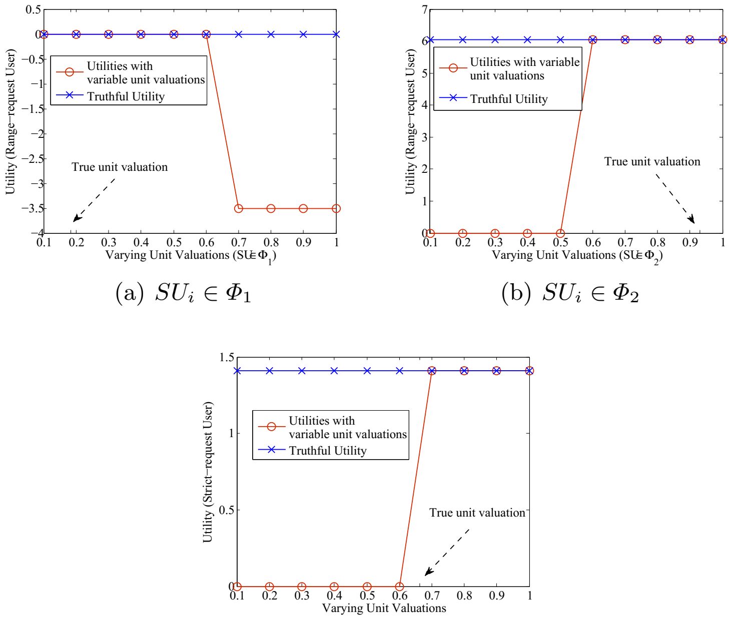
(a) Social Welfare (b) Number of Winning SUs

(c) Average Valuation of Winning SUs (d) Spectrum Utilization

Fig. 1. Impact of Request Type

3.2 Truthfulness Check

We analyze the truthfulness of SUs in $\mathcal{R}$ and $\mathcal{S}$ separately. We first consider the SUs in $\mathcal{R}$. In the auction, we randomly distribute the SUs into different rounds



(a) $SU_i \in \Phi_1$

(b) $SU_i \in \Phi_2$

(c) $SU_i \in \mathcal{S}$

Fig. 2. Truthfulness Check

and allocate only a single channel in each round, thus the whole auction process can be viewed as multiple independent sub-processes. We prove the truthfulness of each sub-process and thus the truthfulness of the auction scheme could be proven.

We focus on a particular round l and assume the participant SU_i lies on its unit valuation. The true and false unit valuation are denoted by λ_i and $\tilde{\lambda}_i$, respectively. In order to prove the truthfulness, we need to show SU_i cannot obtain a higher utility by bidding $\tilde{\lambda}_i \neq \lambda_i$.

– If $SU_i \in \Phi_1$, it would participate the allocation in lines 1-5 of Algorithm 1. The selection of sacrificed SU only relates to submitted unit valuations. If SU_i does not rank last, raising or reducing its unit valuation would not change the selection result and its payment[2]. If SU_i ranks last, rasing unit valuation to avoid being sacrificed only brings him a negative utility since $\lambda_i \cdot p_i < g_i^1 < \tilde{\lambda}_i \cdot p_i$, g_i^1 is SU_i's payment when it lies.
– If $SU_i \in \Phi_2$, it only participates the allocation in lines 6-16. The allocation proceeds in a greedy fashion and the payment of each winning SU is set to an independent critical value below which the SU is unable to win the auction. If SU_i wins when bidding truthfully, raising or reducing the unit

[2] We have claimed above that the power allocation only depends on SUs' physical locations and is independent from SUs' unit valuations.

valuation cannot change the result and the payment. If SU_i loses when bidding truthfully, rasing the unit valuation to win the auction definitely generates a negative utility.

The proof of SUs in $\mathcal{R}$ ends. The proof of SUs in $\mathcal{S}$ is similar to that of SUs in Φ_2, so we omit it here.

4 Numerical Evaluation

In this section, we provide simulation results to evaluate the performance of our auction scheme. We stimulate a wireless cognitive radio networks in an area of $150 \times 150\ m^2$, where a number of SUs are uniformly and randomly distributed. The relation between interference range and transmitting power is formulated as $Ir_i = \alpha \cdot \sqrt{p_i}$, based on free space propagation model. α is a systematic coefficient to match the parameter values[3]. The number of available channels is fixed to 10. The channel requests of SUs are randomly chosen from [1:1:5], the power requests are from $(0, 15]$ dBm and the unit valuations are from $(0, 1]$. The power interval δ is set to 0.2dBm. All simulation results are averaged over 200 runs to reduce randomness.

4.1 Impact of Request Type

To investigate the impact of request type, we fix the total number of SUs to 100 and vary the ratio of strict request SUs from 0 to 1 with a step size of 0.1. In Figure 1, we examine the performance of auction scheme in terms of four metrics: (1) **Social Welfare**, the sum of all winners' valuations; (2) **Number of Winning SUs**; (3) **Average Valuation of Winning SUs**; (4) **Spectrum Utilization**, is calculated based on Shannon's Theory:

$$StrUti = \sum_{SU_i \in \mathcal{R} \cup \mathcal{S}} q_i \cdot \log(1 + p_i). \tag{5}$$

This metric can roughly quantify the achievable data throughput of secondary network.

Figure 1(a) depicts the result on social welfare. We see that, the social welfare declines as the number of strict request SUs increases. The strictness on request restricts the full allocation of network resource and thus discounts the social welfare. Range request SUs can provide adequate flexibility in resource distribution through accepting any possible allocations, which contributes to the increment on social welfare. The restriction of strict request could also be demonstrated in Figure 1(b) and Figure 1(d). Figure 1(b) shows that the number of winning SUs decreases as the ratio of strict request SUs grows. Figure 1(d) shows the result on spectrum utilization which verifies that range request can benefit the efficient usage of network resource.

[3] In practical implementation, the value of α can be set according to antenna gain, channel gain and SNR threshold.

In Figure 1(c), we present the result on average valuation of winning SUs. We can see that, the average valuation increases with the increment on ratio of strict request SUs. As illustrated before, range request can make the resource allocation more flexible by allowing more SUs to share the network resource. Although this could benefit the social welfare, there is a limitation that, a small number of range request SUs can obtain a relative large amount of resource, leading to a low individual valuation among SUs. On the contrary, strict request SUs selected from Algorithm 2 always own a higher individual valuation due to the strictness on request and greedy selection.

4.2 Truthfulness Check

Figure 2 examines the truthfulness of our auction scheme. We randomly select two SUs from $\mathcal{R}$ and $\mathcal{S}$ respectively, and check how their utilities change with variable unit valuation. The unit valuation varies from 0.1 to 1 at a step size of 0.1.

For the case when SU in $\mathcal{R}$, we further divide it into two subcases, SU in Φ_1 and SU in Φ_2. The results are shown in Figure 2(a) and 2(b). Figure 2(c) shows the result for the case when SU in $\mathcal{S}$. We can note that, no matter which type of request the SU bids, it cannot improve its utility by bidding untruthfully on its unit valuation.

5 Conclusion

In this work, we study the problem of joint channel and power allocation among multiple SUs in cognitive radio networks. We consider a mixed form of resource request, wherein the SUs can bid with either strict request or range request. To solve the problem, we propose an auction scheme consisting of two sequential subschemes, a multi-round auction for range request SUs and a greedy algorithm based auction for strict request SUs. The calculation of winners' payments is based on the corresponding critical value. We theoretical analyze the truthfulness of our auction scheme for both range request SUs and strict request SUs. The simulation results also evince the efficient performance of our auction scheme.

In our future work, we will investigate the power budget for SUs in power allocation which caused by PUs' interference constraints. Moreover, the heterogeneities among available channels and the truthfulness on other attributes in the demand are also worth exploiting.

Acknowledgments. The authors would like to thank the support from the National Natural Science Foundation of China (Grant No.61172074,61272505 and 61471028) and the Specialized Research Fund for the Doctoral Program of Higher Education (Grant No.20130009110015).

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