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LYRIC: Local Recall-Based Dynamic Double Spectrum Auction Mechanism With Heterogeneous-Demand Secondary Users

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ABSTRACT In this paper, we investigate the problem of recall mechanism in a dynamic spectrum auction system. The licensed spectrum holders (SHs) can auction their idle channels to the secondary wireless service providers (SWSPs) for economic incentive. However, the primary user (PU) of an SH has higher priority than the SWSPs for the spectrum access. To deal with a sudden increase in PUs' spectrum demands after auction and guarantee their quality of services (QoS), we propose a Local recall-based dYnamic double spectRum auctIon meChanism (LYRIC) for SHs' spectrum auction operation. Different from the most existing approaches about spectrum recall-based spectrum auction, the proposed spectrum auction method for heterogeneous spectrum transaction takes account of the joint effect of *heterogeneous demand*, *spectrum spatial reusability*, and *the economic efficiency*. Simulation results show that the proposed LYRIC algorithm can improve the auction process of SHs, the channels utilization efficiency and the average buyers' satisfactory level with guarantees on the QoS of PUs.

INDEX TERMS Double auction, truthfulness, spectrum reusability, individual rationality, heterogeneous demand, heterogeneous spectrum, local recall.

I. INTRODUCTION

With the dramatically increasing demand of wireless data traffic, 5G, as the next generation cellular network, has been put forward to meet a higher demand of spectrum allocation [1]. Meanwhile, the rapid development of wireless networks has been impeded by the inefficiently static spectrum allocation policy. Dynamic spectrum allocation has been regarded as an effective method to solve artificial shortage of spectrum [2]–[4].

By spectrum providing from idle channels, such as TV white spectrum, the freeing-up spectrum can satisfy the demands of different unlicensed users in the temporal and spatial dimensions, improving spectrum utilization. Specifically, besides serving their own primary users (PUs), the licensed spectrum holders (SHs) have the capability to release idle channels or dynamically share their idle channels with secondary wireless service providers (SWSPs). Moreover, SWSPs have strong spectrum demands to access dynamically in certain time frame and location. However, cost-free access to the idle channels of SHs is not appropriate, which may reduce SHs' incentives. From the perspective of spectrum owners' profit, SHs are easily inclined to pursuit rewards for sharing spectrum to SWSPs. Auction, as one of competitive market models, is applied widely to deal with resource allocation issues in the field of communication networks [5]. Thereinto, spectrum auction is an effective dynamic spectrum allocation solution, which has attracted increasing attention in recent years [6]. Different from the generic product auctions, spectrum auction cover the factors of the spectrum reusability, the dynamic features of spectrum supply and demands for different types of SHs (sellers) and SWSPs (buyers). Considering various transmission characteristics of different frequency bandsthere is potential diversity in the relative interference relationship, when users select frequency bands to transmit. Therefore, the spectrum spatial reusability and complex interference relationship make the spectrum auction significantly different from the traditional goods auctions such as paint.

In addition to spatial and frequency heterogeneity, it is also practical to consider the diverse demands and preferences of SWSPs. Most existing works only consider the single demand situation in which each user transmits only at one frequency band [7]–[9]. However, users usually cannot be satisfied their demands with single channel, such as transmission rates. To solve this problem, an intuitive method is to allow the users access to multiple channels simultaneously. In practice, wireless data transmission on multiple channels simultaneously is a popular topic [10]. For example, The Radio Spectrum Policy Group (RSPG) of the European Commission (EC) has proposed a new concept of sharing-based licensed shared access (LSA), which offers more opportunities of frequency band access for different types of wireless communication systems. Moreover, SWSPs may have different preferences for the available different frequency bands based on their individual characteristics. For example, in the future wireless network with a mixture of macro cells, small cells, microcells and femtocells, SWSPs with different cell coverage may have disparate spectrum frequency preferences and heterogeneous demands [11]. In this paper, the SWSPs could request for multiple channels based on their demands.

Challenges of spectrum auction always appears, accompanying with imposed constraints of spectrum usages. Based on [12], [13], and [16], incomplete common characters on designing auction mechanism are discussed, such as the truthfulness, spectrum reusability, and the heterogeneity of different frequencies. Furthermore, in [14], taking the buyers' heterogeneous demands into account, Zheng *et al.* discussed a strategy-proof combinatorial auction for heterogeneous channel allocation, which comprehensively considered channel spatial reusability and social welfare. Moreover, these works only assumed that the winning SWSPs will exclusively occupy and use these channels until the next auction period when the channels were sold. Under such circumstance, the SHs may result in the degradation of PUs' QoS because of the lack of adequate channels for a sudden increase of demands from PUs.

In this paper, we focus on ensuring the PUs' spectrum usage because the PUs in SHs ought to have higher priority than SWSPs for practical applications, particularly as it relates to priority content such as the public services. On the one hand, SHs want to get more auction revenue through renting idle spectrums; On the other hand, SHs are not likely to lower the quality of services (QoS) target of SHs' PU due to the auction of spectrum, which makes it a thorny problem. To solve such a problem, we design a Local recall-based dYnamic double spectRum auctIon meChanism (LYRIC) method to maximize SHs' auction profit on the basis of guaranteeing PUs' QoS. Different from existing recall-based spectrum auctions [17]–[19], we jointly consider the heterogeneous demands, spectrum heterogeneous characters and spectrum reusability in the design of our scheme. The two most important technical challenges to design a local recall scheme for double spectrum auction are as follows:

- How to make the spectrum auction satisfy the economic properties with considering the channel recall, especially truthfulness and individual rationality.
- How to search for the optimal recall method for maximizing the benefits of SHs.

Our method utilizes geographical position information of PU to reduce the influence of spectrum recall for SWSPs by the way of local-recall, thus achieving a relatively high economic efficiency result and the reusability of spectrum. To the best of authors' knowledge, this is the first work to combine the local recall-based dynamic double spectrum auction, jointly considering heterogeneous spectrum, spectrum reusability and diverse spectrum demand. For clarity, the main contributions of this paper are summarized as follows:

- A recall-based multi-seller-multi-buyer double spectrum auction method is developed by jointly considering spectrum heterogeneity, spectrum reusability and heterogeneous buyers.
- A new regional channel recall scheme is proposed in multiple winner spectrum auctions, which can obtain better economic efficiency by exploiting the full potential of the information of PUs and SWSPs.
- Theoretical analysis and simulation results are provided to prove that the proposed algorithm satisfies the economic properties in terms of truthfulness, individual rationality and economic efficiency.

The rest of this paper is organized as follows. In Section II, the related works are introduced. In Section III, the system model and the problem formulation are presented. In Section IV, the main process and detail description of LYRIC are presented. In Section V, the economic properties of the proposed LYRIC is analyzed. In Section VI, simulation results are given. Finally, the conclusion is drawn in Section VII.

II. RELATED WORK

For dynamic spectrum allocation, auction-based methods have attracted much attention. Zhou *et al.* firstly proposed a truthful dynamic single-demand spectrum auction mechanism with interference conflict graph by considering spectrum reusability and allocation efficiency [9]. In [21], Wang *et al.* developed the TRUMP mechanism to guarantee the QoS performance through spatial spectrum reuse. Furthermore, in [8], Feng *et al.* proposed a truthful double auction based on heterogeneous interference relationship, named as TAHES, by taking the spatial heterogeneity, frequency heterogeneity into account, where the authors assume that each buyer only needs one channel. In practice, the concern about the spectrum heterogeneity and buyers' multi-demand is very important. It is common for SWSPs to request multiple heterogeneous items (or channels), particularly in

TABLE 1. Comparison with main related auction mechanisms.

Existing works	SMALL [23]	TAHES [8]	TAMES [24]	RBDSA [17]	TAGS [18]	RMSA [19]	LYRIC
Double auction	×	√	√	×	×	×	√
Truthfulness	√	√	√	√	√	×	√
Spectrum Reusability	×	√	√	×	×	×	√
Individual Rationality	√	√	√	√	√	√	√
Heterogeneous Demand	×	×	√	×	√	√	√
Heterogeneous Spectrum	×	√	×	×	√	×	√
Spectrum Recall	×	×	×	√	√	√	√
Local Channel Recall	×	×	×	×	×	×	√

wireless communications, because different types of application service and network load of SWSPs will lead to various spectrum demands for different SWSPs. However, many classical auction mechanisms, such as VCG-style auctions, cannot guarantee truthfulness due to the spectrum reusability [22]; meanwhile, combinatorial spectrum auction mechanisms must be redesigned. In [13], Rami *et al.* considered the combinatorial auction for a cognitive radio networks by using the English auction model. However, the authors only consider a relatively simple case, in which each channel can be allocated to one user at most. In [23], Wu and Vaidya designed a truthful spectrum auction, named as SMALL, in which the channels are available to all buyers under the assumption that all buyers have the same interference graph. In [15], to avoid both valuations and channel demands cheating behaviors, Zheng *et al.* proposed AEGIS, which is a combinatorial auction model for the problem of heterogeneous spectrum redistribution.

Above mentioned auctions are single-sided auctions, only buyers' preferences are considered. However, in our model, spectrum providers' preferences also need to be considered. Therefore, the double auction model is more practical. The authors in [7] proposed a general framework for multi-winner double spectrum auctions, which jointly considered the truthfulness and spectrum reusability. The coalition double auction was proposed in [16], SUs are partitioned into several coalitions as the spectrum reusability. One SU can try to join different spectrum coalitions to obtain the better economic goals. However, the authors consider only single-demand situation and ignore the heterogeneous interference relationship in different spectrum. In [24], Chen *et al.* proposed a truthful double auction named as TAMES, for multi-demand heterogeneous spectrum, taking into consideration of various spectrum factors, in which TAMES employs a relatively simple user selecting way for buyers and ignores the total social welfare of the final outcome. Sun *et al.* extended their work to a novel overlapping coalition based double action scheme for the better economic efficiency [20].

Furthermore, recall situation as a novel topic has been explored by establishing recall-based spectrum auction to achieve new arrival PUs' requirements for both spectrum demands and system stability. To solve such issues, researchers apply various approaches. For example, Wu *et al.* firstly proposed the recall-based dynamic spectrum auction [17], where PUs are granted a higher channel access priority, and if necessary, the corresponding SHs can recall auctioned channels. However, the work only considered a simple framework of single winner and ignored the buyers' heterogeneous spectrum demand. Furthermore, Yi and Cai proposed a two-stage spectrum allocation scheme consisting of auction and recall-based Stackelberg game in [18]. The work processed separately the second price sealed auction and the recall-based Stackelberg game to deal with a sudden increase in its own demand. Further, Yi and Cai present an alternate recall-based multiple-winner spectrum auction (RMSA) algorithm using combinatorial VCG model in [19]. The disadvantage of this research is to ignore both spectrum reuse and heterogeneity, while, truthfulness and individual irrationality are not guaranteed effectively. From the above, in this paper, we propose a dynamic local recall mechanism according to the actual spectrum usage of the PUs in SHs to obtain the better profit for SHs. The two significant improvements between the proposed scheme and existing recall-based auction schemes [17]–[19] result in: (i) Considering spectrum heterogeneity and spectrum reusability into the system model for more general and practical. (ii) Formulating recall-based dynamic spectrum auction to minimize profit loss caused by recall.

In order to clearly present the differences between the proposed LYRIC and the main related works, the comparison results in terms of multiple performance metrics of the mentioned schemes are shown in Table 1. If a scheme considers the corresponding metric, it is marked with "√"; otherwise, with "×".

III. SYSTEM MODEL AND PROBLEM FORMULATION

As shown in Fig. 1, we outline the framework of recall-based dynamic heterogeneous spectrum auction in an orthogonal licensed communication system, consisting of N licensed SHs, M SWSPs and one spectrum broker. Let $\mathbf{S} = \{s_1, s_2, \ldots, s_N\}$ denote the set of SHs and $\mathbf{B} = \{b_1, b_2, \ldots, b_M\}$ represent the set of SWSPs. The total number of SHs and SWSPs are defined as $N = |\mathbf{S}|$ and $M = |\mathbf{B}|$, respectively, where $|\bullet|$ is the cardinality of the set. Each SH owns different amounts of heterogeneous spectrum resource to serve its own subscribed PUs. We assume that the channel demands of PUs in the same SH, i.e. SH j, are identical, which is denoted by d^j_{PU}, but may be varying for different SHs. The PUs get spectrum service according to the first-come-first-served (FCFS) rule. Without loss of generality,

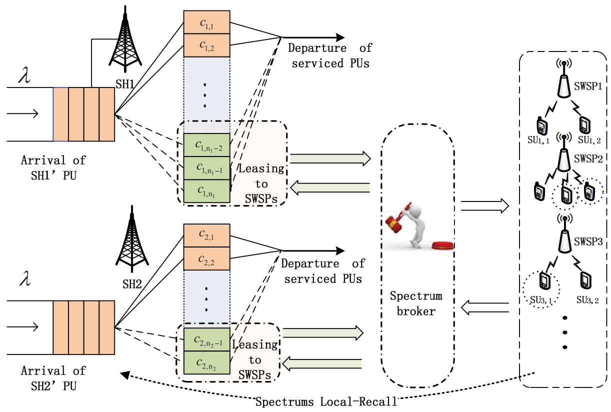


FIGURE 1. System model.

TABLE 2. Key variables used in this paper.

Variables	Explanation
S	SHs (sellers)' set
B	SWSPs (buyers)' set
N	Number of SHs
M	Number of SWSPs
n_j	Number of channels provided by SH j
K	Total available channels of sellers
$\mathbf{a}_j$	The SH j' ask set for the available channel set
λ_j	The arrival rate of the PU at each SH j
$v_{i,k}$	The preference utility value of SWSP i for the channel k
$b_{i,k}$	The SWSP i's bidding price for the channel k
d_i	The SWSP i's demand
$p_{i,j}^{SWSP}$	The SWSP i's payment for channel j
$w_{i,j}^{auction}$	The SWSP i's winning result for channel j
g_j	The j-th winner group (coalition)
Φ_j	The winning group bid of channel j

the arrival interval of the PU in SH j follows Poisson distribution with the arrival rate of λ_j and the distribution of the channel service time is exponential with expectation $1/\mu_j$. Therefore, the inter-arrival time and channel occupancy time of PU are independent and identically distributed random variables. Furthermore, the spectrum service of PUs in SH j can be formulated as a M/M/c queuing system, where c is the number of available channel SH j when $d_{PU}^j = 1$. As the arrival time of PU is random, it is costly to reserve a large number of channels for PUs. Therefore, SHs can lease their unused channels temporally to gain revenue from the auction operation by spectrum broker. Spectrum broker is auctioneer, who needs to collect sellers and buyers' context information to create and complete the auction. If the idle channels of SHs have been sold at auction for profit, SHs may not have enough channels to handle the peak demand of PUs. To solve this conflict, we allow spectrum local recall for SHs by spectrum broker, i.e., each SH can recall some auctioned channels from the winning SWSPs in order to satisfy its own PUs' demands if necessary. Moreover, we assume that recalled channel will not be returned to SWSPs until the next auction period. Certainly, the SWSPs affected by the recall will receive the corresponding compensation through bid price cuts.

The available channel set of SH j is denoted by $\mathbf{f}_j = \{f_{j,1}, f_{j,2}, \ldots, f_{j,n_j}\}$ and its corresponding ask is $\mathbf{a}_j = \{a_{j,1}, a_{j,2}, \ldots, a_{j,n_j}\}$, implying the minimum acceptable payment for leasing spectrum. Here j is the index of SH, n_j is available channel index of SH j'. In this paper, we assume that the number of available channels is diverse for different SHs, and the spectrum transmission character of each channel is diverse. For an entire network in certain time period, the total available channel number is denoted by $K = \sum_{j=1}^{N} n_j$. Note that not all channels are available for each SWSPs due to the limited coverage of certain channel.

Each SH can make profit by leasing idle channels to SWSPs within this area under the condition of the QoS guarantee for its PUs. In this paper, we define the mean waiting time M_{PU} in the queue as the measurement of QoS for PUs [25]. If there are no available idle channels for certain SH, new arriver PUs must wait in the queue. The SH must guarantee the QoS of its PUs due to their higher spectrum access priority. To be specific, the mean waiting time for new arriver PUs in SH j, M_{PU}^j must be less than a certain threshold γ_j. Specially, the maximum number of recalled channels can be obtained by

$$M_{PU} = \frac{Q(c,\psi)}{\mu(c-\psi)} \le \gamma;$$
$$Q(c,\psi) = \frac{\psi^c/c!}{[(c-\psi)/c]\sum_{r=0}^{c-1}(c^r/r!) + \psi^c/c!} \tag{1}$$

where M_{PU} represents the mean waiting time of PUs, $\psi = \lambda/\mu$ and $Q(c,\psi)$ is the queuing probability, which can be obtained from the queuing theory [26]. The certain SH has $C \ge c$ licensed channels, the number of recalling channels is not only affected by the number of new arrival PUs, but also by the requirement of its mean waiting time. By calculation, we can seek the least required number of the PUs c at a given the minimum waiting time γ. When the auction begins, each SH first notifies the actual number of auction spectrums C_a and the maximum channel number of possible recalled C_r (obviously $C_a \ge C_r$). So C_r should satisfy $c \le C - C_a + C_r$ or $C_r \ge c - (C - C_a)$. Furthermore, because reserving c channels can guarantee the QoS of PUs, the SH only needs to recall $C_r = c - (C - C_a)$ channels.

SWSPs are secondary base stations with different types, which have various preferences for available heterogeneous spectrums. For example, small cells seem to prefer lower-frequency spectrum with long transmission range while femtocells seem to prefer higher-frequency spectrum for reducing interference at close range. We denote $\mathbf{V} = \{v_{i,1}, v_{i,2}, .., v_{i,k}, .., v_{i,K}\}$ as the preference values profile for spectrum accessing for SWSPs, where the $v_{i,k}$ reflects the preference utility value of SWSP i for the channel k, such as the channel capacity, frequency character. In order to reflect the effect of channel recalls for SWSPs, the SWSP i's bidding price can be defined as

$$b_{i,k} = (1 - \frac{C_r}{C_a}(1-\theta_i) - \rho_i\frac{R - r_i}{R})v_{i,k} \tag{2}$$

In (2), we introduce a risk factor θ_i to reflect various impacts from SWSPs to the potential channel recall. C_r/C_a represents the maximum channel recall ratio. Similarly, denote $\mathbf{b}_i = \{b_{i,1}, b_{i,2}, .., b_{i,k}, .., b_{i,K}\}$ as buyer i's payment profile. In this paper, we use a local region recall method based on the auction revenue and the position information of SWSPs. R is spectrum service radium for SH, r_i is the distance between the SH and SWSP i. Thus, a smaller distance r_i corresponds to a greater probability to be recalled. $(R - r_i)/R$ reflects the potential probability of be recalled. The parameter $\rho_{\rm i}$ is the discount factor, which reflects location influences. Note that θ and r are constant, which are related to the traffic type and location respectively.

The SWSPs have heterogeneous demands for available channels. In [18], the authors adopted strict request of bundled demand, in which the buyer could obtain either all demand channels or nothing. In the proposed model, the auction results of the achieved number of its requirements are relatively flexible. For example, the demand of one SWSP are 3 channels, the achieved number of the auction channels can be 3 or less, which is more relaxed than the strict request of bundled demand. Let d_i denote the spectrum demands of SWSP i, $1 \le d_i \le K$, implying each SWSP can access more than one channel. At the end, the buyer will obtain x channels, $x \in [0, d_i]$. In this paper, the spectrum can be spatially reused by finding independent sets in the same spectrum interference graph, that is to say, non-conflict SWSPs can synchronously transmit their signals at the same channel to improve spectrum utilization. For the result of allocation, denote $W_i = \{w_{i,1}, w_{i,2}, .., w_{i,k}, .., w_{i,K}\}$ as the channel available profile. If the channel k is not available for SWSP i, $w_{i,k} = 0$ and the corresponding valuation $v_{i,k} = 0$. In this paper, the profit of SWSP i involved in our auction model is presented in the following:

$$u_i^{auction} = \sum_{j=1}^{a_i} w_{i,j}^{auction} \times (v_{i,j} - p_{i,j}^{SWSP}) \tag{3}$$

where a_i is the actual number of access channels for SWSP i, $a_i \le d_i$. $p_{i,j}^{SWSP}$ is the payment of SWSP i for channel j. The whole practical auction-recall utility of the SWSP i consists of three terms, i.e., the profit of auction, loss of recall and the compensation of recall, and is expressed as

$$u_i^{all} = u_i^{auction} - \sum_{k=recall} b_{i,k} + \sum_{k=recall} \overline{p}_{i,k}^{SWSP} \tag{4}$$

where $\overline{p}_{i,k}^{SWSP}$ is the recall compensation of SWSP i for channel k. In this paper, we assume the payment $p_{i,k}^{SWSP}$ is equal to the compensation $\overline{p}_{i,k}^{SWSP}$ for easy analysis.

In an auction process, the utility of SH j also consists of three terms, i.e., profit from its PUs, revenues from spectrum leasing, and the compensation caused by its spectrum recall. Thus, we can define the utility function of each virtual SH j channel as

$$u_j^{VS} = \sigma_j \sum_{pu} num_{pu} + \sum_{j=1}^{n_j} \Phi_j - \sum_{k=recall} \overline{p}_{k,j}^{SWSP} \tag{5}$$

where σ_j denotes the unit payment of PUs for a SH j's channel; $\sum_{pu} num_{pu}$ is the number of PUs for SH j; Φ_j is the winning group bid of channel j, i.e., rental profit for the channel j. We assume that the value of PU's access exceeds the leasing revenues of single channel for SWSPs, to reflect the priority of PU. In other words, each SH should preferentially ensure the access of a PU, and then lease these channel to SWSPs. Therefore, each SH will minimize its recall compensation to maximize its own utility. Since the SWSPs have already considered the effect of channel recall in the offer stage (in form of discount in Eq.(2)), without loss of generality, we assume that the SH's compensation for channel recall equals the winning SWSP's payment for channel lease. Therefore, the optimal auction is to sell all idle channels at the beginning of each frame.

The spectrum broker, who hosts the double auction with recall, plays a intermediary role. Similar to [8] and [20], the buyers with pricing in the same channel was termed as coalition. In our work, every SWSP acts as a buyer and can simultaneously joint multiple coalitions based on his actual demand. The broker can assign multi-SWSPs to one channel through frequency reuse scheme. The spectrum broker needs to determine the groups of winning buyers according to the maximum independent set and implements the spectrum allocation, and the subsequent recall scheme, containing the corresponding payment and local recall for winning buyers and so on. The notations that will be used in the rest of this paper are summarized in TABLE II.

IV. LOCAL RECALL-BASED DYNAMIC SPECTRUM DOUBLE AUCTION

In this part, we will present the details of the proposed LYRIC.

A. CHALLENGES AND MAIN PROCESS IN AUCTION DESIGN

Multi-demand heterogeneous spectrum brings new challenges for recall-based multiple winner spectrum auction. Owing to the frequency-selective characteristic for signal propagation, higher-frequency has a shorter transmission ranges with better spatial reusability. In contrast, lower-frequency can provide better coverage and penetration. In practice, we should consider the heterogeneity of spectrum. Moreover, spectrum reuse is an effective way to improve the spectrum efficiency. To solve the problem of spectrum reusability in spectrum auction, we have to pick the multiple non-conflicting buyers to one channel. Therefore, to appropriately address heterogeneous spectrum reusability is a big challenge to the spectrum auction. To this end, we employ the heterogeneous conflict graph referring to [8], which is defined as $G_j = \{\Pi_j, E_j\}, j \in [1, 2, \ldots, K]$, where G_j denotes the interference graph of channel j, Π_j represents all available buyers in channel j, and E_j denotes all the interference relations on channel j. Due to the difference of transmission range for heterogeneous spectrum, the interference graphs G are obviously different for the same group of buyers in different channels. If the buyers (SWSPs) use different transmission powers, the interference relationship among the buyers will be asymmetric. For simplicity, it is assumed that the interference relationship is symmetric in this paper, considering the fact that differences of interference graph criterion have no impact on the following auction model.

To solve multiple spectrum demands of the SWSPs while avoiding the collusion and bid manipulation, one intuitive solution is to replace the original SWSP by multiple single-demand virtual SWSPs, which is inspired by [20]. In this paper, the required channel number of each SWSP is a random integer. We can create a corresponding number of single-demand virtual SWSPs based on the demands of each original SWSP. The single-demand virtual SWSPs will inherit the original SWSP' characteristic, such as the bid profit values for different spectrum bands. Note that any two virtual SWSPs belonging to the same original SWSP cannot propose to the same spectrum. The auction is carried out periodically and follows a T cycle. The process of the proposed recall-based auction is divided into four main stages, as follows:

1) INITIALIZATION

To begin with, the spectrum broker collects the essential information from SHs and releases them to SWSPs, such as the maximum available channels, maximum quantity of channel that may be recalled, sellers' and buyers' location, buyers' bids $\mathbf{B} = \{\mathbf{b}_1, \mathbf{b}_2, \ldots, \mathbf{b}_M\}$, sellers' ask $\mathbf{A} = \{\mathbf{a}_1, \mathbf{a}_2, \ldots, \mathbf{a}_N\}$. Every SWSP creates a corresponding number of single-demand virtual buyers according to its own channel demand. Every virtual buyer will inherit characters of the original SWSP, i.e. the bidding profile and the interference relationship. It should be noted that any two virtual brokers cannot be put into the same channel.

2) SPECTRUM AUCTION AND ALLOCATION

We term the buyers who apply for the same channel as a coalition. Thus, the maximum number of coalitions is K, including possible empty coalition. Multiple virtual buyers belonging to the original SWSP must exist on the different coalitions. Specially, virtual buyers belonging to the same original SWSP will send applications of channel lease to the spectrum broker based on the spectrum valuation profile $\mathbf{V}$ of the SWSP (i.e. the top-ranked channel). The spectrum broker picks up no interference members from available maximum independent sets (MISs)[1] in every coalition based on the conflict graph among virtual buyers. Then, based on the bids of the virtual buyers, the broker selects the MIS with the maximal coalition bid as the winner group. If there are several MISs with equal maximum group bid, one of them is chosen randomly. The broker announces the final winning buyers from the winning group based on the "Lowliest bid elimination" mechanism of channel bid.

[1] We do not focus on the construction of the maximum independent set and only pay attention to design a truthful double spectrum auction for a given independent set model. The auctioneer can choose different independent set selection policies for different purposes. In this paper, we adopt MIS to obtain maximize group bid, which can increase spectrum reusability.

3) RECALL

As PUs in every SH have the higher service priority, we permit channel recall from the winning SWSP(s) when a SH tries to satisfy the new coming PUs' demands. Due to the randomness of arrival PU, the heterogeneity of spectrum and difference of channel recall compensation, we take the minimum compensation cost as the object of recall under the conditions of meeting PU's spectrum demands, so as to maximize the benefits of SHs.

4) PRICING

At the end of each frame, the spectrum broker charges each SWSP $p_{i,j}^{SWSP}$ according to three different cases:

Case 1: If SWSP i loses or it wins but no other channels bid (i.e., $b_{-i} = 0$), then its payment is 0;

Case 2: For these winners with no-recalled, the group bid Φ_j is divided by the member in the group except for the one with the lowest bid, their payment is $p_{i,j}^{SWSP} = \sum_{j=1}^{a_i} w_{i,j}^{auction} \Phi_j / (|g_j| - 1)$;

Case 3: For these winners with recalled, these SWSPs only pay the corresponding payment for practical unrecalled channel.

B. DETAILED LYRIC MECHANISM

1) THE AUCTION STAGE

Without loss of generality, we assume the demand d_i of buyers i is no more than the total number of channels K. The details of auction stage are presented in Algorithm 1.

For ex-post budget balanced in three parties, if the group g_j can win in the auction period, it must satisfy $(1 - \varepsilon) \times \Phi_j \geq a_j, j \in [1, 2, \ldots, K]$. The payment of the group is Φ_j as the auction revenue of channel j for the master SH. a_j is the corresponding seller's ask for channel j. $\varepsilon \times \Phi_j$ is the fee paid to the broker, where ε is the commission rate for the spectrum broker to host auction. In this paper, we assume the spectrum broker is non-profit organization such as government bodies, so $\varepsilon = 0$. In each channel, the buyers in MIS with highest coalition bid can get the channel access rights except the lowest bid one. This regulation can guarantee each buyer truthfully submits his bid. If there are multiple virtual buyers with the same lowest bid, the spectrum broker randomly picks one of them as the "loser". Therefore, the payment of virtual buyer i in group g_j can be obtained as

$$p_{i,j}^{SWSP} = \begin{cases} \dfrac{\Phi_j}{|g_j| - 1} = \min\limits_{i \in g_j} b_{i,j} & iisnotloser \\ 0, \quad iisloser, \end{cases} \tag{6}$$

2) THE LOCAL RECALL STAGE

After the auction, the winning SWSPs can access the corresponding idle channels of SHs. However, the SHs can recall channels to meet their own spectrum demands for sudden arrival PUs with the aid of the spectrum broker. Since the position and time of arrival PU are random, the spectrum broker can only recall the spectrum permission of local SWSPs to

Algorithm 1 Implement Process of Spectrum Auction ($t \in [0, \Delta T]$)

1. The spectrum broker collects and broadcasts the auction information of every SH, such as C_a and C_r.
2.The original buyers submit their bidding information to the broker, including the wanted channel number, bidding price set $\mathbf{b}_i$, and the corresponding location information.
3.The broker generates a corresponding number of virtual buyers for every original SWSPs based on their demands if $d_i > 1$. Delete the original buyer and insert the virtual buyers, then distribute them to the top-ranked channels based on the bid vector set $\mathbf{b}_i$.
4.**For** all channel j, $j = 1, 2,.., K$, the spectrum broker executes auction at the same time, similar to the second sealed bid auction.
5. The spectrum broker generates the potential conflict graph for coalition Π_j in channel j. Π_j is the buyer set of apply channel j.
6. Find MIS $\mathbf{g}_j$ and $g_j = \max \min\limits_{i \in g_j, g_j \in \mathbf{g}_j} b_{i,j} \times (|g_j| - 1)$ match the buyers in group g_j to channel j.
7. The group bid of g_j is $\Phi_j = \min\limits_{i \in g_j} b_{i,j} \times (|g_j| - 1)$, where $|g_j|$ is the number of winning SWSPs in the group Π_j in spectrum j. Π_j is the buyer set of apply channel j.
8. If $\Phi_j \geq a_j$, the auction of channel j succeeds. Otherwise, failure, channel j is for use of its master SH only.
9.**End**

meet the QoS of PUs. Due to the heterogeneity of spectrum, the appeared location of PU will decide which channel is available, i.e., when the distance between an appeared PU and its SH is long, the relatively low-frequency channel will be selected. This time, the whole SWSPs on the channel may be deported. However, if the arrival PU appears in the range near its SH, the broker will prefer to select some channels of relatively higher frequency. What is more, the SH may only need to recall the tenancies of the local SWSPs within a small radius between a PU and the relative SH, and the rest of SWSPs can continue renting their channel, so as to reduce the losses due to recalls. Because of the difference of winning group bid and winning SWSPs' location in each channel, the costs of channels recall are diverse. Therefore, it is unreasonable to sell all channels with equal recall probability. This motivates us to use local channel recall scheme to mitigate the problem. Intuitively, the SH should pick up the unused channels in the first place, and then consider recalling partial channels from the winning SWSPs with low payments to reduce losses. We assume that all channels are homogeneous for the PUs belonging to the same SH. Due to independent arrival of PU, each SH can run its spectrum recall strategy independently based on arrival situation of its PU.

Take the certain SH j as an example, we assume the SH j have $\bar{C}_j$ idle channels. After the auction during $t \in [\Delta T, T]$, C_a^j channels are sold to the C_a^j buyer groups successfully. Denote $\mathbf{\Omega}_1, \mathbf{\Omega}_2, \ldots, \mathbf{\Omega}_{c_a^j}$ as the buyer group in these C_a^j channels. As the arrival of PU is random, SH j can recall channels one by one to meet the sudden spectrum demand of PUs. Since the spectrum broker knows the payment and positional information of each SWSP, it can figure out the recall cost of each channel based on the arrival information of PU. Thus, the broker would choose the unused channels in the first step, and then recall the channel with lower price based on each SH's demands of arrival PUs. For each winning SWSPs, their location and payment will affect the probability of the channel recall occurrence. The spectrum broker operates each SH spectrum recall independently. The dynamic local spectrum recall procedure is shown in Algorithm 2.

Algorithm 2 Implement Process of Dynamic Local Spectrum Recall

Initialization (Take one PU in SH j as an example)
1.The spectrum broker knows the payments and usage in each channel.
2.The SH j report the information of PU arrival timely, including the corresponding location $O_j = (o_j^x, o_j^y)$ and demand d_{PU}^j.
Local recall
If $\bar{C}_j - C_a^j \geq d_{PU}^j$
3. SH j directly assigns idle channels to PU, $\bar{C}_j = \bar{C}_j - d_{PU}^j$.

else
4. Channels allocations are divided into two parts, i.e., idle channel $\bar{C}_j - C_a^j$ can be directly allocated and the number of recall channels is $d_{PU}^j - (\bar{C}_j - C_a^j)$, $\bar{C}_j = \bar{C}_j - d_{PU}^j$.
5. *For* all C_a^j channels sold and $\mathbf{\Omega}_1, \mathbf{\Omega}_2, \ldots, \mathbf{\Omega}_{c_j}$.
6. Calculate $radiu_{PU} = \sqrt{(l_j^x - o_j^x)^2 + (l_j^y - o_j^y)^2}$, where $l_j = (l_j^x, l_j^y)$ represents the location of SH j.
7. Find the winning SWSPs within the range of $radiu_{PU}$ in the available channel groups, record the sum payment of these members $p_j^{SWSP_{recall}}$.
8. *End*
9. Sort $\mathbf{p} = \{p_1^{SWSP_{recall}}, p_2^{SWSP_{recall}}, \ldots, p_{c_j}^{SWSP_{recall}}\}$ from small to large; Find the first $d_{PU}^j - (\bar{C}_j - C_a^j)$ corresponding channels to recall for meeting the need of the arrival PU.
10.**End a recall**

The LYRIC mechanism makes a full cycle in auction and recall over a period of T time. At the end of T, these SWSPs pay the appropriate spectrum fee to certain SHs. Specifically, the spectrum broker charges winning SWSP i with $p_{i,j}^{SWSP} \times (C_a^i - C_r^i)$, where C_r^i denotes the number of channels that are actually recalled from SWSP i. Note that C_r^i is different for each winning SWSP. Finally, every SH reports the auction information for next auction base on channel use.

V. ECONOMIC PROPERTIES AND PERFORMANCE EVALUATION

In this section, we prove that the proposed LYRIC individually rational, ex-post budget balanced, truthful.

Proposition 1: The proposed auction mechanism is individually rational.

Proof: For any buyer (SWSP), the buyer i's bidding price for channel k is $b_{i,k}$ as shown in Eq.(2)in which $v_{i,k}$ denote the spectrum true value. Apparently, $v_{i,k}^{SWSP} > b_{i,k}^{SWSP}$. In addition, as the payment of virtual buyer i is the lowest bid in the certain coalition, the winning buyers will pay less than their bids, i.e., $b_{i,k}^{SWSP} > p_{i,k}^{SWSP}$, thus $v_{i,k}^{SWSP} - p_{i,k}^{SWSP} > 0$. If recall happens, the winning buyers do not charge. The final benefit of buyer in the auction must be nonnegative.

For all sellers (SHs), each winning seller obtains paid more than its ask. Therefore, all SHs and SWSPs would be guaranteed with nonnegative utilities.

Proposition 2: The proposed auction is truthful.

1. SWSP's bidding for one channel has no impact on the winning result of another channel.

Proof: The auction process shows that whether the SWSPs within the same coalition can be matched to a specific channel is random and uncertain. Any SWSP has no ability to control over the group process in certain spectrum. In addition, the coalition bid is only about the lowest bid of buyers in the specific spectrum, and is independent of their bids for other spectrums.

2. Buyer's untruthful bidding for one channel cannot increase its utility gained from that channel.

Proof: Take buyer (SWSP) iąŕs bid $b_{i,j}$ as an instance. We assume the result of allocation is $w_{i,j}$ and the profit is $u_{i,j}$ when buyer i bids truly; When he misreport the bidding price, the result of allocation is $w_{i,j}^{\bullet}$ and the profit is $u_{i,j}^{\bullet}$. We discuss four cases if $b_{i,j} \neq v_{i,j}$ in the following:

Case 1: $w_{i,j} = w_{i,j}^{\bullet} = 0$. Apparently, $u_{i,j} = u_{i,j}^{\bullet} = 0$.

Case 2: $w_{i,j} = w_{i,j}^{\bullet} = 1$. $u_{i,j} = u_{i,j}^{\bullet} = v_{i,j} - p_{i,j}$, in which $p_{i,j}$ is the actual payment of virtual buyer i in spectrum j, which is independent of $b_{i,j}$.

Case 3: $w_{i,j} = 1, w_{i,j}^{\bullet} = 0$. $u_{i,j} = v_{i,j} - p_{i,j} \geq 0$ and $u_{i,j}^{\bullet} = 0$.

Case 4: $w_{i,j} = 0$, $w_{i,j}^{\bullet} = 1$. In this case, if the buyer of untruthful bid wants to win the channel, it must bid higher than the truthful bid $v_{i,j}$, i.e., $p_{i,j}^{\bullet} > v_{i,j}$ and $u_{i,j}^{\bullet} = v_{i,j} - p_{i,j}^{\bullet} < 0 = u_{i,j}$.

Therefor, to report the true valuation is the (*weakly*) dominant strategy for buyers, i.e. a buyer cannot misreport the bidding price for a channel to increase its utility gain. Moreover, since compensation mechanism makes SHs take no risk in balancing the amount of spectrum for leasing and reservation, SHs should auction all idle channels. For each SH, the auction revenue u_j^{VS} is obviously a non-decreasing function. In other words, the auction mechanism is incentive compatible. Hence, the proposed auction is truthful.

Proposition 3: LYRIC is ex-post budget balanced.

Proof: From the auction process and Proposition 1, three parties (SHs, SWSPs and the spectrum broker) involved in auction can obtain non-negative utility, so the proposed LYRIC is ex-post budget balanced.

A. ADDITIONAL REMARKS

Channel recall can protect the PUs' service. If no such recalled situation, the practical bid should equal to the real value of each channel for every SWSPs. In this paper, the bid of each SWSP is influenced by the maximum channel recall ratio, stability factors and own location. The stability factor θ is a definite value depending on SUs' traffic types and transmission requirements. Larger θ indicates that SWSP i has more robustness for the potential channel recall. $\rho_i(R - r)/R$ denotes the possibility of recall. Therefore, the farther away SWSP is from the SH, the lower the possibility of recall.

VI. PERFORMANCE EVALUATION

A. SIMULATION SCENARIO

We consider a heterogeneous network with 5 SHs and 20 SWSPs, and assume that the SHs and the SWSPs randomly distributed within 1×1 area, which is similar to [8] and [20]. On the private networks of SHs, PUs' arrival rate $\lambda_j = 2$, and channel service rate $\mu_j = 0.1$. Threshold γ_j is set to be $6.25 \times 10^{-}4$s. The length of each frame T = 6 s; hence, an expected value of PUs arriving is 20 per min and the average service time of each PU is 60 s. The number of contributed channels of each SH follows uniform distribution on the range [1, 5]; the demand of each SWSP follows uniform distribution on the range [1, 3]. Furthermore, each buyer's bid for an available channel and seller's ask follow uniform distribution over [0, 1]. The channels belonged to one SH are available for a SWSP if their distance is less than 0.5 unit. To manifest the heterogeneous interference relationship, we assume the interference distance of K channels is from 0.1 to 0.3, so the interference distance of the k channel can be calculated by $0.1 + (k - 1) \times 0.2/(K - 1)$. These parameters are fixed unless expressly stated.

Fig. 2 shows the state information of SHs' auction channel at each frame. For each frame, the number of active PUs is generated automatically given the queuing system condition. Because each SH will auction all the idle channels, the number of auctioned channels and the number of maximum

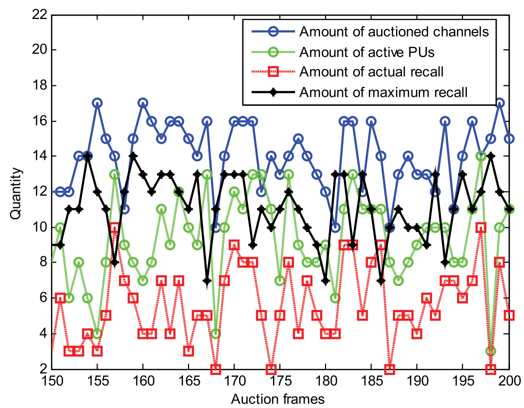


FIGURE 2. State information of the PBS in different auction frames.

recall channels have the similar variation trends. In addition, the number of auctioned channels decreases when the number of active PUs increases. The performance comparisons of Fig. 3, 4, 5 are based on the state information shown in this figure.

B. PERFORMANCE OF THE LYRIC ALGORITHM

We present the performance comparison in terms of the following 3 kinds of metrics:

Social Welfare reflects the revenues of SHs, which is defined in Eq. (4).

Average Buyers' Satisfaction (ABS) reflects the users' satisfaction of spectrum services (channel assignment), which is defined as the ratio of winning virtual SWSPs to the total demands, in Eq. (7), where $serve_{PU}/demand_{PU}$ denotes the discount factor and reflects the degree of priority for PU.

$$ABS = \frac{\sum_{j=1}^{K}\sum_{i=1}^{N} w_{i,j}}{\sum_{i=1}^{N} d_i} * \frac{serve_{PU}}{demand_{PU}} \quad (7)$$

Spectrum Reusability Degree (SRD) reflects spectrum efficiency, which is defined, in Eq. (8),as the ratio winning virtual buyers to the total channels.

$$SRD = \frac{\sum_{j=1}^{K}\sum_{i=1}^{N} w_{i,j}}{K} \quad (8)$$

In Fig. 3, we present the comparison of the social welfare in the form of a cumulative sum of all SHs' utility. As is shown, the SHs have higher revenue based auction with recall than auction without recall, and the proposed LYRIC algorithm has the highest revenue among the four mechanisms. This is mainly because the auction with local recall fully utilizes the information of SWSPs, so as to minimize the decrease of auction revenue due to the channel recall for servicing arrival PUs.

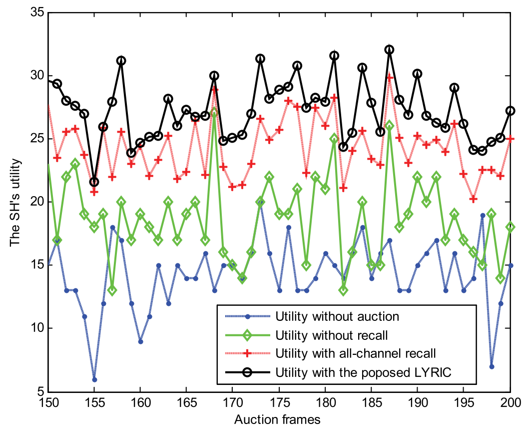


FIGURE 3. Cumulative sum of SHs' utility.

In Fig. 4 and Fig. 5, we present the comparison of the average buyers' satisfactory level and spectrum utilization,

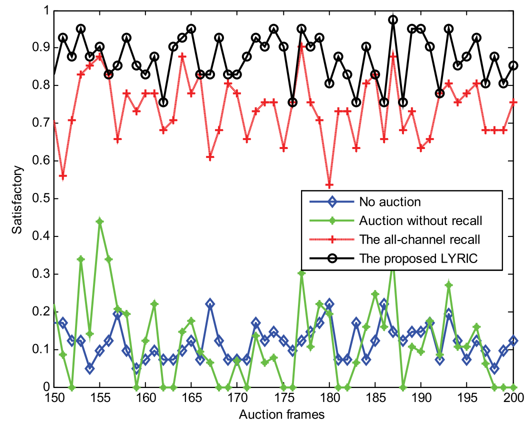


FIGURE 4. The comparison of average buyer's satisfactory level.

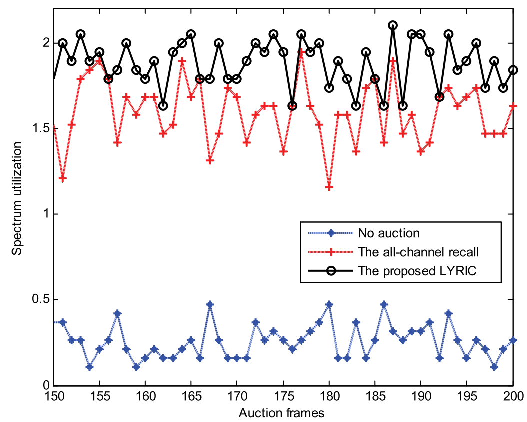


FIGURE 5. The comparison of the spectrum utilization degree.

respectively. Under the premise of guarantee PUs' QoS, the proposed LYRIC algorithm yields the best performance. It can be observed that no auction will not satisfy the demands of SWSPs and waste lots of idle the spectrum, which results in the lowest buyers' satisfaction and spectrum utilization. Auction without recall will not guarantee PUs' QoS to dramatically lower the discount factor ($serve_{PU}/demand_{PU}$). The method of all-channel recall does not take full advantage of spectrum heterogeneity and spectrum reusability to reduce the influence of the recall to SWSPs. Compared to other prior all-channel recall methods, the proposed LYRIC considers the heterogeneous spectrum reusing between PUs and SWSPs, fully utilize channel resource, and it can provide more access of SWSPs as much as possible and generate higher benefits.

In Fig. 6, we vary the PUs' arrival rate to compare the performance of social welfare. It can be seen that the SHs' utility with no auction and the auction with all-channel recall towards equality. The reason is that the larger PUs' arrival rate will reduce the number of idle channels that can be auction. Because of the punishment associated with unrealized PUs' QoS, the SHs' utility of auction without recall continuously reduces with the increase of the PUs' arrival rate.

In Fig. 7, we present the comparison of social welfare with the increase of the number of SWSPs. Fig. 7 shows that the

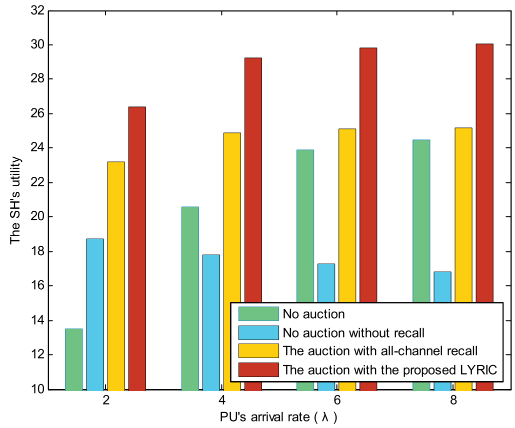


FIGURE 6. Cumulative sum of SHs' utility versus the different PUs' arrival rate.

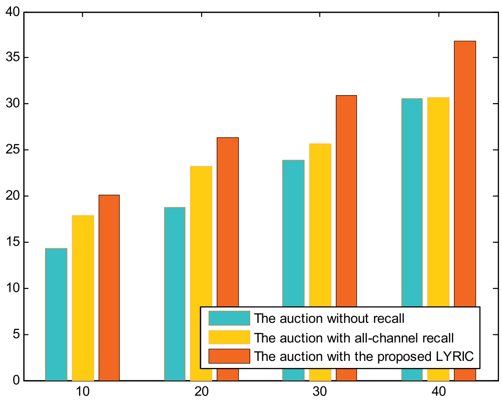


FIGURE 7. Cumulative sum of SHs' utility versus the number of SWSPs.

SHs' utility of the auction without recall and the auction with all-channel recall tends to be same with the increase of the number of buyers. The reason is that the increasing number of SWSPs will lead to the increase of the number of recalled SWSPs, which mean the auction method with all-channel recall will not be able to obtain the desired recall profit in dense networks. From the Fig. 6 and Fig. 7, it is demonstrated that the proposed LYRIC outperforms other auction methods, with the better utility and ABS and SRD performance.

VII. CONCLUSION

In this paper, heterogeneous spectrum sharing among multiple heterogeneous SHs and SWSPs are discussed. To better balance the conflict of interest and to meet the bilateral demands, we proposed a Local recall-based dYnamic double spectRum auctIon meChanism (Lyric) method to maximize SH's auction profit on the basis of guarantying PUs' QoS. LYRIC jointly considered the spectrum reusability, the heterogeneous buyers' demand and heterogeneous interference relationship. Furthermore, we proved that LYRIC satisfies good economic properties of individual rationality and truthfulness. Simulation results show that our proposed spectrum LYRIC can improve the auction utility of the SH, buyers' satisfaction and spectrum reusability degree.

REFERENCES

[1] J. G. Andrews *et al.*, "What will 5G be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[2] Y. Xu, J. Wang, Q. Wu, A. Anpalagan, and Y.-D. Yao, "Opportunistic spectrum access in cognitive radio networks: Global optimization using local interaction games," *IEEE J. Sel. Topics Signal Process.*, vol. 6, no. 2, pp. 180–194, Apr. 2012.

[3] H. Shao, Y. Sun, H. Zhao, W. Zhong, and Y. Xu, "Locally cooperative traffic-offloading in multi-mode small cell networks via potential games," *Trans. Emerg. Telecommun. Technol.*, vol. 27, no. 7, pp. 968–981, Mar. 2016.

[4] Y. Sun, H. Shao, X. Liu, J. Zhang, J. Qiu, and Y. Xu, "Traffic offloading in two-tier multimode small cell networks over unlicensed bands: A hierarchical learning framework," *KSII Trans. Internet Inf. Syst.*, vol. 9, no. 11, pp. 4291–4310, Nov. 2015.

[5] Y. Zhang, D. Niyato, P. Wang, and E. Hossain, "Auction-based resource allocation in cognitive radio systems," *IEEE Commun. Mag.*, vol. 50, no. 11, pp. 108–120, Nov. 2012, doi: 10.1109/MCOM.2012.6353690.

[6] Z. Han, D. Niyato, W. Saad, T. Başar, and A. Hjørungnes, *Game Theory in Wireless and Communication Networks*. Cambridge, U.K.: Cambridge Univ. Press, 2012.

[7] X. Zhou and H. Zheng, "Trust: A general framework for truthful double spectrum auctions," in *Proc. IEEE INFOCOM*, Rio de Janeiro, Brazil, Apr. 2009, pp. 999–1007.

[8] X. Feng, Y. Chen, J. Zhang, Q. Zhang, and B. Li, "TAHES: A truthful double auction mechanism for heterogeneous spectrums," *IEEE Trans. Wireless Commun.*, vol. 11, no. 11, pp. 4038–4047, Nov. 2012.

[9] X. Zhou, S. Gandhi, S. Suri, and H. Zheng, "eBay in the sky: Strategyproof wireless spectrum auctions," in *Proc. ACM Mobicom*, San Francisco, CA, USA, Sep. 2008, pp. 1–12.

[10] M. Mustonen, T. Chen, H. Saarnisaari, M. Matinmikko, S. Yrjola, and M. Palola, "Cellular architecture enhancement for supporting the European licensed shared access concept," *IEEE Wireless Commun.*, vol. 21, no. 3, pp. 37–43, Jun. 2014.

[11] J. G. Andrews, H. Claussen, M. Dohler, S. Rangan, and M. C. Reed, "Femtocells: Past, present, and future," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, pp. 497–508, Apr. 2012.

[12] Y. Wu, B. Wang, K. J. R. Liu, and T. C. Clancy, "A scalable collusion-resistant multi-winner cognitive spectrum auction game," *IEEE Trans. Commun.*, vol. 57, no. 12, pp. 3805–3816, Dec. 2009.

[13] R. Mochaourab, B. Holfeld, and T. Wirth, "Distributed channel assignment in cognitive radio networks: Stable matching and Walrasian equilibrium," *IEEE Trans. Wireless Commun.*, vol. 14, no. 7, pp. 3924–3936, Jul. 2015.

[14] Z. Zheng, F. Wu, and G. Chen, "A strategy-proof combinatorial heterogeneous channel auction framework in noncooperative wireless networks," *IEEE Trans. Mobile Compt.*, vol. 14, no. 6, pp. 1123–1137, Jun. 2015.

[15] Z. Zheng, F. Wu, S. Tang, and G. Chen, "Unknown combinatorial auction mechanisms for heterogeneous spectrum redistribution," in *Proc. MobiHoc*, Philadelphia, PA, USA, Aug. 2014, pp. 3–12.

[16] G. Sun *et al.*, "Coalitional double auction for spatial spectrum allocation in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 6, pp. 3196–3206, Jun. 2014.

[17] G. Wu, P. Ren, and Q. Du, "Recall-based dynamic spectrum auction with the protection of primary users," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 10, pp. 2070–2081, Nov. 2012.

[18] C. Yi and J. Cai, "Two-stage spectrum sharing with combinatorial auction and stackelberg game in recall-based cognitive radio networks," *IEEE Trans. Commun.*, vol. 62, no. 11, pp. 3740–3752, Nov. 2014.

[19] C. Yi and J. Cai, "Multi-item spectrum auction for recall-based cognitive radio networks with multiple heterogeneous secondary users," *IEEE Trans. Veh. Technol.*, vol. 64, no. 2, pp. 781–792, Feb. 2015.

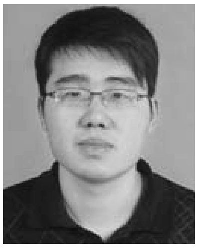
[20] Y. Sun, Q. Wu, J. Wang, and A. Anpalagan, "VERACITY: Overlapping coalition formation-based double auction for heterogeneous demand and spectrum reusability," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 10, pp. 2690–2705, Oct. 2016.

[21] Q. Wang, B. Ye, S. Lu, and S. Guo, "A truthful QoS-aware spectrum auction with spatial reuse for large-scale networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 25, no. 10, pp. 2499–2508, Oct. 2014.

[22] T. Sandholm, "Algorithm for optimal winner determination in combinatorial auctions," *Artif. Intell.*, vol. 135, nos. 1–2, pp. 1–54, May 2002.

[23] F. Wu and N. Vaidya, "A strategy-proof radio spectrum auction mechanism in noncooperative wireless networks," *IEEE Trans. Mobile Comput.*, vol. 12, no. 5, pp. 885–894, May 2013.

[24] Y. Chen, J. Zhang, K. Wu, and Q. Zhang, "TAMES: A truthful double auction for multi-demand heterogeneous spectrums," *IEEE Trans. Parallel Distrib. Syst.*, vol. 25, no. 11, Nov. 2014.
[25] K.-H. Liu, X. Ling, X. Shen, and J. W. Mark, "Performance analysis of prioritized MAC in UWB WPAN with bursty multimedia traffic," *IEEE Trans. Veh. Technol.*, vol. 57, no. 4, pp. 2462–2473, Jul. 2008.
[26] N. Benvenuto and M. Zorzi, *Principles of Communications Networks and Systems*. New York, NY, USA: Wiley, 2011.



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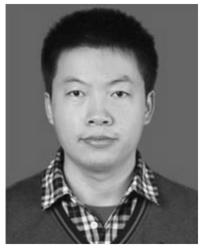

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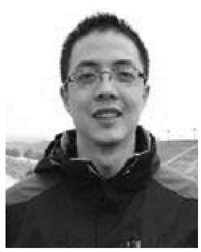

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