Database-Assisted Dynamic Spectrum Access with QoS Guarantees: A Double-Phase Auction Approach

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Abstract: Since FCC's opening for white space (WS) utilization, database-assisted dynamic spectrum access (DSA) has become the de facto solution for the realization of dynamic spectrum sharing (DSS), due to its simplicity and compatibility with commercial off-the-shelf (COTS) devices. It is envisioned that such technology will strongly support the prosperous wireless multimedia networking (WMN) applications with satisfying QoS guarantees in the future. However, how to counter the time-frequency variant property when exploiting the WS spectrum for the provision of these services to secondary users (SUs) still remains a great challenge. In such context, a dynamic secondary access scheme for database-assisted spectrum sharing networks is proposed in this paper. In the beginning, the spectrum requirements of SUs for diverse services are modeled by considering the minimum required service data-rate and spectrum access duration. Afterwards, the spectrum demand evaluation and bidding policy are formulated based on the service classes of SUs. Furthermore, a double-phase (DP) spectrum allocation scheme, which consists of the initial resource allocation phase and resource allocation adjustment phase, is carefully designed for DSA. Finally, extensive simulations are conducted and the results demonstrate that our scheme can increase the spectrum trading revenue and adapt to varying service requirements.

Keywords: dynamic spectrum allocation; quality of service; white-space spectrum; secondary access networks;

I. INTRODUCTION

It has been pinpointed that the bottleneck for improving the wireless spectrum utilization efficiency is the static spectrum allocation strategy. Such problem is aggravated with the increasing demand on multimedia contents. Fortunately, database-assisted dynamic spectrum access (DSA) in the under-utilized TV bands has emerged and has the capability to alleviate the situation [1][2]. It enables unlicensed users in secondary access networks to opportunistically share the available white-space (WS) spectrum without the need of spectrum sensing of unlicensed users, which are customarily referred to as secondary users (SUs).

The efficient coordination for the dynamic access of secondary spectrums of a huge number of SUs is still under discussion in a database-assisted DSA network. In [3], X. Chen et al., discussed a database-assisted distributed spectrum sharing approach by using

This paper proposes a dynamic secondary access scheme for database-assisted spectrum sharing networks.

the cooperative and non-cooperative game, respectively. In [4], M. Fitch et al., investigated how to apply the cognitive radio technique to provide the wireless services in TV space. However, most of the existing works focus on the general single/multiple channel(s) resource allocation issue [5][6], where the temporal, spectral and spatial characteristics of resource are considered. In fact, how to meet the specific requirements of SUs is also critical in designing spectrum allocation scheme for database-assisted spectrum sharing networks, e.g., the delay sensitive requirement and the multiple service classes, etc. To provide sufficient quality of service (QoS) guarantee for SUs, Alshamrani et al., in [7] proposed a spectrum allocation framework for heterogeneous secondary real-time and non-real time users, respectively. In [8], Shiang et al., considered diverse rate requirements and delay deadlines in the proposed dynamic channel selection solution. In addition, Torabi et al., in [9] proposed a rank-optimal channel selection strategy which helps QoS provisioning in terms of the average throughput. Jha et al., in [10] proposed a novel priority based channel reservation scheme for delay sensitive applications. In [11], S. Gunawardena et al., investigated the service response time of elastic data traffic in cognitive radio networks.

The database-assisted spectrum trading technique for TV white space is another widely investigated issue and is convinced as an efficient DSA service provisioning approach [12][13]. In [14], Xin et al., proposed a demand spectrum access as a service approach to achieve DSA. With the booming of DSA service provision by the way of secondary bandwidths trading market [8], the goal of this paper is to focus on the practical bidding scheme design for database-assisted DSA, which considers different service priorities and SUs' QoS requirements, i.e., the minimum required service data-rate and minimal required spectrum access duration. In this work, we firstly model spectrum application requirements of SUs based on the multimedia service features. What is more, an evaluation function of secondary bandwidths for the bidding decision making is defined, in which the strategy of SUs can be formulated based on the different service classes. Moreover, we propose a double-phase (DP) spectrum allocation scheme to support the DSA for diverse service applications. It is a bidding based spectrum allocation method, which is composed of the initial resource allocation phase and resource allocation adjustment phase. With two main features, the proposed DP scheme can adapt to the variation of diverse service requirements: 1) in the bidding strategy, the users with different priorities can claim different prices for their required secondary bandwidths; 2) by introducing a practical and flexible preemption rule, in which an energy cost metric is considered in the preemption process, and by setting different preemption ratios for energy consumption compensation to the preempted users, the auctioneer is able to control the number of preempted bidding winners in different application scenarios, e.g., the energy constrained multimedia applications. The main contribution of our work is two-fold:

- We characterize the services with distinct secondary spectrum requirements and formulate the resource bidding behaviors of SUs based on their corresponding service classes. Such model can shed light on the design of practical bidding strategy for SUs in the database-assisted WS spectrum trading market.
- We propose a double-phase dynamic spectrum allocation scheme to support prioritized services such as real-time multimedia applications. In this way, better service can be provided to the users with higher priority while achieving significant improvement of revenue.

The reminder of this paper is organized as follows. The network model is presented in Section II. In Section III, the modeling of service requirements and problem formulation are provided. In Section IV, we present the double-phase dynamic spectrum allocation scheme. The evaluation results and discussions are given in Section V. At last, we close the paper with conclusions.

II. NETWORK MODEL

We consider a spectrum database-assisted DSA scenario for self-organized wireless multimedia applications in secondary spectrum access networks, as shown in Fig. 1, which consists of a spectrum allocation coordinator and multiple SUs to opportunistically access to the unused WS spectrum. Here, we define that SUs only need to report their locations and spectrum resource requirements to the coordinator, and the coordinator can dynamically allocate the available spectrum to SUs with a bidding approach. The set of SUs is denoted by $N = \{n_1, n_2, n_3, ..., n_K\}$. Considering the time and frequency variance of obtained WS spectrum, let $a_m^t (m = 1, 2, ..., M)$ denotes the availability of channel m at time-slot t, where M is the total spectrum channel number, $a_m^t = 1$ represents channel m is available for SUs, otherwise, it is busy. The total available channels at the time-slot t can be represented as $\sum_{m=1}^{M} a_m^t = \Gamma^t$.

III. SERVICE REQUIREMENTS MODELING AND PROBLEM FORMULATION

Typically, for wireless multimedia services, different applications will have their own requirement features. Here, we consider two main parameters for different multimedia services: the minimum required service data-rate $v_{n_i}^{min}$ and minimum required spectrum access duration $l_{n_i}^{min}$, which are elaborated in the following,

Definition 1 ($v_{n_i}^{min}$) Given that the SU n_i with data transmission task can estimate the achievable data rate of one unit of channel, i.e., Θ_{n_i}. The minimum required service data-rate $v_{n_i}^{min}$ can be guaranteed by applying minimum number of required channels $k_{n_i}^{min}$, which satisfies the relationship that $v_{n_i}^{min} = k_{n_i}^{min} \cdot \Theta_{n_i}$.

The achievable data rate of one unit channel Θ_{n_i} can be calculated based on Shannon-Hartley theorem, and is expressed as follows,

$$\Theta_{n_i} = \omega \cdot \log_2(1 + \frac{\varrho_{n_i} \cdot |g_{n_i}|^2}{(\sigma_{n_i})^2}), \forall n_i \in N \quad (1)$$

Where ω denotes the spectrum bandwidth of one standard channel, ϱ_{n_i} denotes the power allocation, g_{n_i} denotes the channel gain and $(\sigma_{n_i})^2$ denotes the channel noise level.

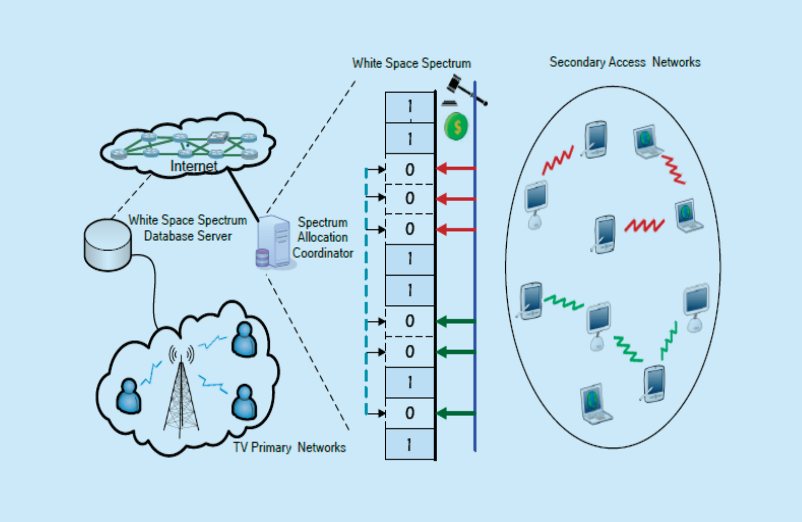

Fig.1 *A spectrum database-assisted dynamic spectrum access scenario*

Definition 2 ($l_{n_i}^{min}$) Given that SU n_i has Φ_{n_i}-bit burst multimedia data to transmit, the minimum required spectrum access duration $l_{n_i}^{min}$ has to meet the maximal one-hop communication delay requirement $c_{n_i}^{max}$, i.e., $l_{n_i}^{min} = c_{n_i}^{max}$.

To calculate the minimum required spectrum access duration, the maximal one-hop communication delay of SU n_i for Φ_{n_i}-bit burst data transmission can be estimated by $c_{n_i}^{\max} = \frac{\Phi_{n_i}}{v_{n_i}^{\min}}, \forall n_i \in N$.

Lemma 1 For SU n_i, to reach the minimum required service data-rate $v_{n_i}^{min}$, the relationship between the minimum number of required channels $k_{n_i}^{min}$ and the minimum required spectrum access duration $l_{n_i}^{min}$ can be expressed as:

$$k_{n_i}^{min} = \frac{\Phi_{n_i}}{l_{n_i}^{min} \cdot \Theta_{n_i}}, \forall n_i \in N \quad (2)$$

Proof According to the transformation of

(2), and combining the equation $k_{n_i}^{min} = v_{n_i}^{\min}/\Theta_{n_i}$, we can get the proof.

To allocate varied available channels among SUs with different application requirements, we utilize the bidding approach for allocating spectrum. At each time slot, any SU who plans to start a service can submit a triplet $(\beta_{c,n_i}, k_{n_i}^{req}, l_{n_i}^{req})$ to the auctioneer (i.e., the coordinator for the secondary access networks), which is defined as a spectrum request set.

Definition 3 (Spectrum request set) We define a triplet $(\beta_{c,n_i}, k_{n_i}^{req}, l_{n_i}^{req})$ as the spectrum request set of SU n_i, where β_{c,n_i} denotes the bid of user, $k_{n_i}^{req}$ denotes the number of required channels, $l_{n_i}^{req}$ denotes the applied spectrum access duration, and we define that $l_{n_i}^{req} = l_{n_i}^{min}$.

Before claiming the spectrum request set to the auctioneer, SUs will evaluate and set current resource request parameters for competing and obtain the dynamic spectrum access opportunity. For any n_i, the utility function of unit channel can be given by

$$U_i \triangleq \beta_{d,n_i} \cdot \Theta_{n_i} - \beta_{p,n_i} \cdot \varrho_{n_i} - \beta_{c,n_i} \tag{3}$$

Where β_{d,n_i} is the data-rate evaluation value in unit of $\$/(bits)$ and β_{p,n_i} is the power consumption cost value in unit of $\$/(W \cdot s)$.

Generally, the SUs in the licensed networks are selfish, they try to maximize their utility U_i which makes an incentive for the spectrum application. However, the factual application demand regulates their spectrum claims, i.e., the spectrum usage should reach the minimum required service data-rate $v_{n_i}^{min}$, minimum required spectrum access duration $l_{n_i}^{min}$, and the power constraint $\varrho_{\mu_i,\rho_j} \in [0, \rho_{\max}]$. From the perspective of SUs' benefit, we formulate the revenue evaluation function under the factual application requirement as follows,

$$\begin{array}{lll} & \underset{n_i \in U}{\text{Maximize}} & U_i \cdot l_{n_i} \cdot \kappa_{n_i} \\ s.t. & (a) & U_i \geq 0, \\ & (b) & \varrho_{n_i} \in [0, \rho_{\max}] \\ & (c) & \Theta_{n_i} \cdot \kappa_{n_i} \geq v_{n_i}^{min} \end{array} \tag{4}$$

Since the utility of user n_i is not only related to the bid price but also other parameters such as data-rate evaluation value and power consumption cost value. In specific, the data-rate evaluation value is based on factual service class. The more urgent service requirement, the higher data-rate evaluation value that the SUs will be given. Correspondingly, user n_i will bid probably higher price in the dynamic access competition. Because the bid price is also related to the power consumption cost according to the Eq. (3) in the utility function, SU n_i has to decide the optimal transmission power.

Lemma 2 The optimal power transmission for SU n_i is denoted by $\varrho_{n_i}^* = \dfrac{\beta_{d,n_i}}{\ln 2 \cdot \beta_{p,n_i}} - \dfrac{\sigma_{n_i}^2}{|g_{n_i}|^2}$, and β_{p,n_i} is a constant in the range of $\left[\dfrac{|g_{n_i}|^2 \cdot \beta_{d,n_i}}{(\sigma_{n_i}^2 + \rho_{\max} \cdot |g_{n_i}|^2) \cdot \ln 2}, \dfrac{|g_{n_i}|^2 \cdot \beta_{d,n_i}}{\sigma_{n_i}^2 \cdot \ln 2}\right]$.

Proof For any SU n_i, due to the power consumption cost, it can maximize the resource benefit in the dynamic spectrum access via power control. The resource benefit can reach the maximum value when $\Omega_i = \dfrac{\partial U_i(\varrho_{n_i})}{\varrho_{n_i}} = 0$,

$$\begin{aligned} \Omega_i &= \frac{\partial U_i(\varrho_{n_i})}{\varrho_{n_i}} \\ &= \frac{\beta_{d,n_i}}{\left(\frac{\sigma_{n_i}^2}{|g_{n_i}|^2} + \varrho_{n_i}\right) \ln 2} - \beta_{d,n_i} = 0 \end{aligned} \tag{5}$$

under the constraint of β_{p,n_i} and when $\varrho_{n_i} \in [0, \rho_{\max}]$, it can be easily found that, $\Omega_i \geq 0$ if $\varrho_{n_i} \leq \dfrac{\beta_{d,n_i}}{\ln 2 \cdot \beta_{p,n_i}} - \dfrac{\sigma_{n_i}^2}{|g_{n_i}|^2}$, which indicates Ω_i is monotonically increasing; and $\Omega_i > 0$ if $\varrho_{n_i} > \dfrac{\beta_{d,n_i}}{\ln 2 \cdot \beta_{p,n_i}} - \dfrac{\sigma_{n_i}^2}{|g_{n_i}|^2}$, which indicates Ω_i is monotonically decreasing. Hence, $\dfrac{\beta_{d,n_i}}{\ln 2 \cdot \beta_{p,n_i}} - \dfrac{\sigma_{n_i}^2}{|g_{n_i}|^2}$ is the optimal transmission power.

Combined with (1) and the optimal transmission power $\varrho_{n_i}^*$, $k_{n_i}^{req}$ can be given as,

$$k_{n_i}^{req} = \frac{v_{n_i}^{min}}{\omega \cdot \log_2\left(1 + \frac{\varrho_{n_i}^* \cdot |g_{n_i}|^2}{(\sigma_{n_i})^2}\right)} \tag{6}$$

Lemma 3 The upper bound of bid price that SU n_i could bid for the channel is

$$\beta_{c,n_i}^{up} = \beta_{d,n_i} \cdot \log_2\left(\frac{\beta_{d,n_i}}{\Lambda \cdot \ln 2}\right) - \frac{\beta_{d,n_i}}{\ln 2} + \Lambda \quad (7)$$

Where $\Lambda = \sigma_{n_i}^2 \cdot \beta_{p,n_i} \big/ \left|g_{n_i}\right|^2$.

Proof For all users in the spectrum applicants, they can only be incentive to bid the spectrum *iif* the whole evaluated value U_i should be more than 0, i.e., $\beta_{d,n_i} \cdot \Theta_{n_i} - \beta_{p,n_i} \cdot \varrho_{n_i} - \beta_{c,n_i} \geq 0$. Combining with the optimal power consumption $\varrho_{n_i}^*$, we can easily get the proof.

Lemma 4 The upper bound of bidding price β_{c,n_i}^{up} is a monotonically increasing with respect to data rate evaluation factor β_{d,n_i}.

Proof Take the first order derivative with respect to β_{d,n_i} in (6), we have

$$\frac{\partial \beta_{c,n_i}^{up}}{\beta_{d,n_i}} = \log_2\left(\frac{\beta_{d,n_i}}{\Lambda \cdot \ln 2}\right) \quad (8)$$

When $\beta_{d,n_i} = \Lambda \cdot \ln 2$, we can get that $\frac{\partial \beta_{c,n_i}^{up}(\beta_{d,n_i})}{\beta_{d,n_i}} = 0$. Hence, to prove $\beta_{c,n_i}^{up}(\beta_{d,n_i})$ is always monotonically increasing, we should prove that $\beta_{d,n_i} \geq \Lambda \cdot \ln 2$. For $0 \leq \theta \leq 1$,

$$\beta_{p,n_i} = \frac{\theta \cdot \left|g_{n_i}\right|^2 \cdot \beta_{d,n_i}}{\sigma_{n_i}^2 \cdot \ln 2} + \frac{(1-\theta) \cdot \left|g_{n_i}\right|^2 \cdot \beta_{d,n_i}}{(\sigma_{n_i}^2 + \rho_{\max} \cdot \left|g_{n_i}\right|^2) \cdot \ln 2} \quad (9)$$

Combining $\Lambda = \frac{\sigma_{n_i}^2 \cdot \beta_{p,n_i}}{\left|g_{n_i}\right|^2}$ with (9), we can have

$$\begin{aligned} \beta_{d,n_i} &\geq \frac{\sigma_{n_i}^2 \cdot \beta_{p,n_i}}{\left|g_{n_i}\right|^2} \cdot \ln 2 \\ &= \theta \cdot \beta_{d,n_i} + \frac{(1-\theta) \cdot \sigma_{n_i}^2}{(\sigma_{n_i}^2 + \rho_{\max} \cdot \left|g_{n_i}\right|^2)} \cdot \beta_{d,n_i} \quad (10) \\ &\overset{\text{simplify}}{\Rightarrow} \quad 1 \geq \frac{\sigma_{n_i}^2 + \rho_{\max} \cdot \left|g_{n_i}\right|^2 \cdot \theta}{\sigma_{n_i}^2 + \rho_{\max} \cdot \left|g_{n_i}\right|^2} \end{aligned}$$

Obviously, from (10), we can get that for any β_{d,n_i} $\beta_{d,n_i} \geq \Lambda \cdot \ln 2 > 0$. Hence, the proof is completed.

Remark 1 In many widely applied wireless networks, the varied spectrum evaluation prices β_{d,n_i} indicates different spectrum access priorities, e.g, for the time-sensitive services and some critical transmission services, the SU prefers to set a higher spectrum evaluation price.

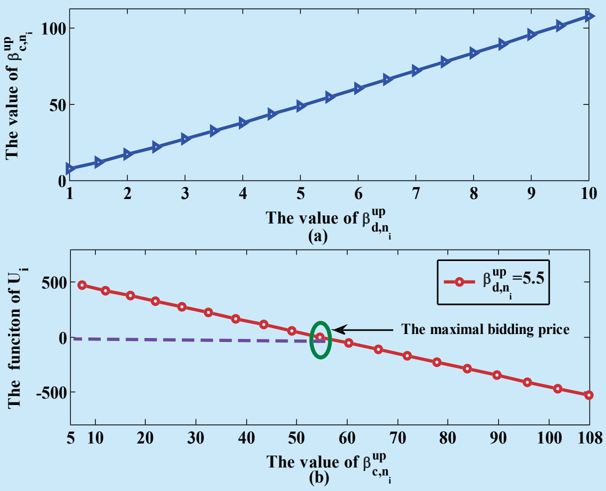

Fig.2 *The relationship between the bid price* β_{c,n_i} *and* β_{d,n_i}

The evaluation setting β_{d,n_i} is critical in factual application. For example, for some time-sensitive services, SUs prefer to get the spectrum usage right rapidly. Hence, the evaluation price of the service rate could be higher than other services. In addition, for the same spectrum applications, one SUs' priority level is higher than others, e.g., in VIP spectrum applicants, the evaluation price for the service rate could be higher. Fig. 2(a) shows the relation between the bid price β_{c,n_i} and the data rate evaluation factor. From this monotonically increasing relationship, we can see that the diverse services can be achieved by setting different values of β_{d,n_i}. Therefore, β_{d,n_i} is very critical for differentiated services. Fig. 2(b) shows the relationship between the utility U_i and the bid price β_{c,n_i} given a data-rate evaluation value β_{d,n_i}. Note that with the increase of bid price β_{c,n_i}, the achieved utility decreases since the user needs to pay more to the auctioneer when it wins the bidding. The upper bound of bid price, shown as circled point in Fig. 2(b), is the bid with the utility of zero since the rational users cannot bid a price higher than this value, which will lead to a negative utility.

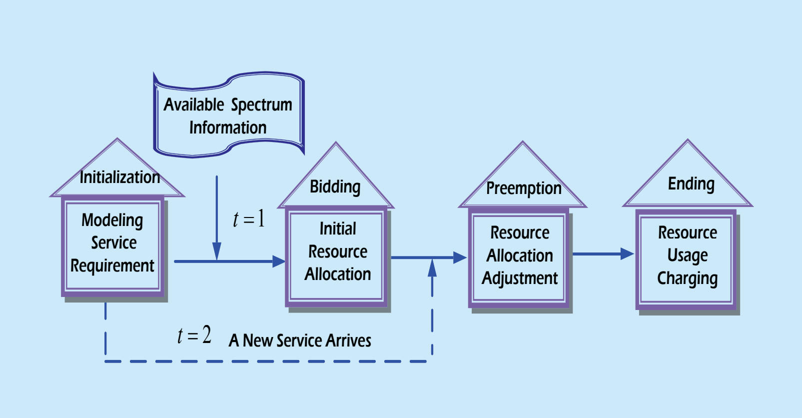

Fig.3 *A double-phase spectrum allocation process by bidding for diverse secondary access services*

IV. DOUBLE-PHASE DYNAMIC SPECTRUM ALLOCATION SCHEME

In factual wireless communication applications, different applications have their own service requirements and priorities. We propose a double-phase dynamic spectrum allocation scheme, namely DP, to achieve the diverse QoS provisions such that the wireless communication applications with higher priority such as real-time multimedia can be favored. As shown in Fig. 3, the proposed scheme includes preliminary allocation phase and resource allocation adjustment phase, which are elaborated in the following section.

For ease of presentation, we divide SUs into three categories: idle users, busy users and start users. The idle users do not involve any data transmission. Busy users are the SUs whose services have started already, but do not finish yet at this time slot. Start users just want to initiate a service/transmission at this time slot. Let N_t^d, N_t^b, N_t^s represent the sets of idle users, busy users and start users at time slot *t*, respectively. The spectrum allocation process is performed slot by slot. At any time slot t, SUs in N_t^s submit their spectrum request triplet $(\beta_{c,n_i}, k_{n_i}^{req}, l_{n_i}^{req})$ to the coordinator. To reduce the information exchange overhead, the users in N_t^b do not need to submit their spectrum request set again since they have submitted before and their services don't end.

Phase 1: *Initial Resource Allocation.* We denote that the spectrum allocation at instant time *t*=1 is the initial resource allocation phase. We consider that all start users submit their bid prices β_{c,n_i} in a sealed-bid way, and β_{c,n_i} is among $[0, \beta_{c,n_i}^{up}]$. At instant time point *t*=1, the start user set is denoted by N_1^s. Based on the bid prices of SUs, the initial spectrum allocation is to maximize the following objective:

$$\Pi_p^1 \overset{\Delta}{=} \operatorname{argmax}_{N_1^s} \sum_{n_i \in N_1^s} \beta_{c,n_i} \tag{11}$$

$$s.t. \qquad \sum\nolimits_{n_i \in N_1^s} k_{n_i}^{req} \le \Gamma^t, \qquad t = 1 \tag{12}$$

Where Π_p^1 is the set of winners (successful SUs) after the phase 1 at time slot *t*=1, with the initial value $\Pi_p^0 = 0$.

Phase 2: *The Resource Allocation Adjustment.* The resource allocation in phase 1 is based on the bid price. In order to further consider the service continuity, we introduce the resource allocation adjustment phase. We adopt a practical preemption strategy to control the allocation adjustment process, where the power consumption compensation for the preempted SUs is considered. Shown in Fig. 4, the preemption is triggered when any of the following cases occurs: 1) available spectrum resource changes (e.g., the change in the number or position of available channels); 2) some new service requests with high priority are submitted to the coordinator.

$$\Im_p^t = \Im_{p1}^t - \Im_{p2}^t - \Im_{p3}^t \tag{13}$$

$$\Im_{nop}^t = \underbrace{\sum\nolimits_{n_i \in \Pi_p^{t-1}} b_{n_i} \cdot l_{n_i} \cdot k_{n_i}^{\min}}_{\Im_{nop1}^t} + \underbrace{\sum\nolimits_{n_i \in \Pi_r^t} b_{n_i} \cdot l_{n_i} \cdot k_{n_i}^{\min}}_{\Im_{nop2}^t} \tag{14}$$

Let Π_p^{t-1} be the set of SUs who win the resource at time slot *t*=1. Comparing Π_p^t with Π_p^{t-1}, we define the set of preempted SUs as the set of SUs who win the resource at the time slot *t*=1, but don't get the resource at the time slot *t* although they don't finish their services, which is denoted as $\Pi_{pd}^t = \{n_i | n_i \in \Pi_p^{t-1}, n_i \in N_t^b, n_i \notin \Pi_p^t\}$. Since the preempted SUs don't finish their services, the stop of their services will lead to the waste of resource consumed in previous slots. Therefore, in phase 2, the coordinator will do the resource allocation adjustment by taking the possible power waste and resource waste into account. We adopt a practical strategy to control the allocation adjustment process in phase 2, where the power consumption compensation for the preempted SUs is considered. Specifically, the coordinator will calculate the potential revenue with preemption $\mathfrak{I}^t_p$ and without preemption $\mathfrak{I}^t_{nop}$, respectively, and then make comparison to get the potential benefit $\varepsilon^t = \mathfrak{I}^t_p - \mathfrak{I}^t_{nop}$. According to the comparison results, the coordinator will make resource allocation decision including the following two types of cases:

- $(\boldsymbol{\mathfrak{I}^t_p - \mathfrak{I}^t_{nop}}) > \mathbf{0}$. The coordinator will preempt the potentially preempted SUs in Π^t_{pd} for the larger total trading revenue.
- $(\boldsymbol{\mathfrak{I}^t_p - \mathfrak{I}^t_{nop}}) \leq \mathbf{0}$. The coordinator will not preempt any potentially preempted SUs and let the existing winners and the replacing winners be the final winners.

In (13) and (14), $\mathfrak{I}^t_{p_1}$ is the bid payment from potential winners, and can be expressed by $\mathfrak{I}^t_{p1} = \sum_{n_i \in \Pi^t_{p1}} b_{n_i} \cdot l_{n_i} \cdot k^{\min}_{n_i}$; $\mathfrak{I}^t_{p_2}$ is the expected loss from the potentially preempted SUs, and can be expressed by $\mathfrak{I}^t_{p2} = \sum_{n_j \in \Pi^t_{pd}} b_{n_j} \cdot (t - t^0_{n_j}) \cdot k^{\min}_{n_j}$; $\mathfrak{I}^t_{p_3}$ is the compensation cost to the potential preempted SUs for the wasted power, and can be expressed by $\mathfrak{I}^t_{p3} = \sum_{n_j \in \Pi^t_{pd}} \eta \cdot (t - t^0_{n_j}) \cdot k^{\min}_{n_j} \cdot \varrho^*_{n_j}$; Π^t_r is the set of new winning SUs without considering the preemption of SUs, $t^0_{n_i}$ is the time point that one winner SU starts the transmission, and η is the compensation ratio. Obviously, η and $t - t^0_{n_i}$ can both control the preemption ratio, the larger compensation ratio and the SUs with longer time staying in the winner set are hard to be replaced. The coordinator will make different decisions according to different values of ε^t, and the coordinator will target to maximize the trading revenue for each slot by adjusting the allocations, shown as

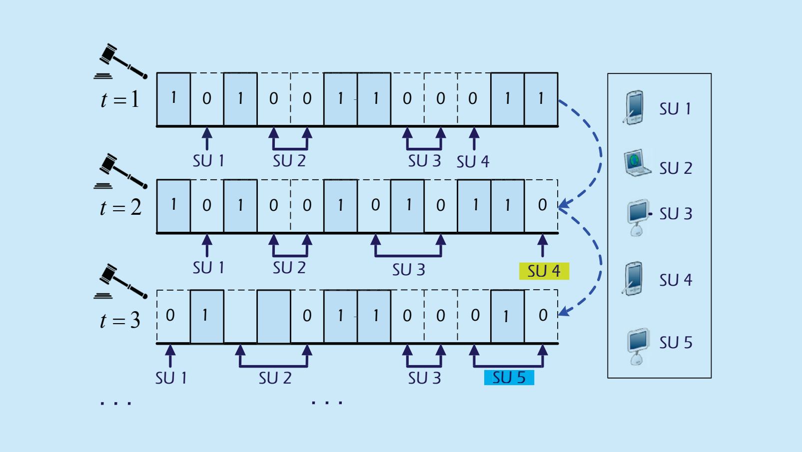

Fig.4 *The illustration of spectrum allocation process with bidding*

$$\Pi^t_p \overset{\Delta}{=} \arg\max_{N^b_t \cup N^s_t} \mathfrak{I}^t_p - \mathfrak{I}^t_{nop}, t \geq 2 \tag{15}$$

$$s.t. \qquad \sum_{n_i \in N^b_t \cup N^s_t} k^{req}_{n_i} \leq \Gamma^t \tag{16}$$

Resource Usage Charging: The coordinator (i.e., auctioneer) charges each SU when it finishes the service. Based on the second-price sealed bid strategy [16], the total payment of the SU is the sum of the payment it needs to pay for the whole service period, and the payment corresponding to each of these time-slots is the highest bid price of the losing SUs at that time-slot. Notice that the coordinator cannot collect any payment from the SUs that are preempted in the middle of their services. Let $\mathcal{S}^t_f$ and Π^t_L be the set of SUs that finish their services at time t and the set of losing SUs (i.e., SUs without obtaining the resource) at the time-slot t, respectively. Hence, the revenue of coordinator at time-slot t is given as follows:

$$\Psi_t = \sum_{n_i \in \mathcal{S}^t_f} \sum_{q = t^0_{n_i}}^{t^0_{n_i} + l_{n_i}} \max_{n_j \in \Pi^q_L} \left\{ b_{n_j} \right\} \cdot l_{n_i} \cdot k^{min}_{n_i} \tag{17}$$

Theorem 1: The truthful bidding $b_{n_i} = \beta^{up}_{n_i}$, $\forall n_i \in (\mathcal{S}^t_u \cup \mathcal{S}^t_s)$ is a dominant strategy in the proposed DP scheme, where $\beta^{up}_{n_i}$ is the maximum payment the SU n_i could pay and given in (7).

Proof We assume an SU n_i with the truthful bidding $\beta^{up}_{n_i}$ is one of the winners obtaining the spectrum resource at the time-slot t, and the

Algorithm 1: Double-Phase Dynamic Spectrum Allocation

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Input: $\Gamma^t, \omega, \varrho_{n_i}, g_{n_i}, \sigma_{n_i}, b_{n_i}, l_{n_i}, k_{n_i}^{\min}, K, \eta$
Output: The channels allocation set at time $t, \Pi_p^t$
$\Pi_p^0 = \Pi_{pd}^0 = \Pi_r^0 = \emptyset$
Sort $n_i$ in $\Pi_p^t$ with $\downarrow^{b_{n_i}}$
For $t$=1, do
    While $\sum_{n_i \in N_i^t} k_{n_i}^{min} \le \Gamma^t$
        $\Pi_p^1 \cup n_i \rightarrow \Pi_p^1$ and record $t_{n_i}^0$.
End for
For $t = 2$, $i$ ++, do
    While new applicants arrived, do
        If $n_i \in \Pi_p^t$, do
            Calculate $(t - t_{n_i}^0) \cdot k_{n_i}^{\min} \cdot (b_{n_i} + \eta \cdot \varrho_{n_i}^*) \rightarrow b_{n_i}$
        Else $n_j \notin \Pi_p^t$ do
            Calculate $b_{n_j} \cdot l_{n_j} \cdot k_{n_j}^{\min} \rightarrow b_{n_j}$
            While $b_{n_j} > b_{n_i}, n_i \in \Pi_p^t$, then
                $n_i \cup \Pi_r^t \rightarrow \Pi_r^t$ and $n_j \cup \Pi_p^t \rightarrow \Pi_p^t$
        End if
    Return $\Pi_p^t$
End for
```

Table I *Parameters used in the simulations*

Parameters	Value
Size of channel ω	$2W$
Preemption value η	100
Simulation times T	100
Number of SUs	200
Channel gain $\lvert g_{n_i}\rvert^2/\sigma_{n_i}^2$	10^3
Bidding price of SUs β_{c,n_i}	[1,20]
Number of spectrum channel Γ^t at t	[8,15]
Number of required time-slot $l_{n_i}^{\max}$	[1,5]
Number of requimd channels by n_j	[1,3]
Capacity of allocated power by n_j	[1,5]

payment it needs to pay is $\max_{n_j \in \Pi_L^t}\{b_{n_j}\}$. Given that n_i provides another bidding price $b'_{n_i} \ne \beta_{n_i}^{up}$ while other SUs don't change their bidding prices. There exist three cases: (I) $b'_{n_i} > \beta_{n_i}^{up}$ and n_i is still one of winners; (II) $b'_{n_i} < \beta_{n_i}^{up}$ and n_i is still one of winners; (III) $b'_{n_i} < \beta_{n_i}^{up}$ and n_i is one of losers; In Cases I and II, the payment of n_i is the same as the case of the bidding price $\beta_{n_i}^{up}$ since the highest bidding price of the losing SUs is the same in these cases. In the case III, n_i doesn't obtain any resource. Therefore, it get zero utility, which is worse than the case of the bidding price $\beta_{n_i}^{up}$. Therefore, truthful bidding is the best response of the SU n_i. It has no incentive to unilaterally deviate from this bidding strategy. We can get the proof.

Theorem 2 DP spectrum allocation scheme is benefit-undamaged for SUs.

Proof SUs can be divided into three parts: 1) the SUs who finish their service without being preempted, 2) the SUs who don't finish their service because of being preempted and 3) the SUs who never win an auction and become a winner in Π_p^1. For 1), due to the SU's rationality, it won't transmit data without utility, so its benefit won't be damage. For 2), the AP won't charge the preempted SU n_i, and will compensate it for its wasted power, so n_i will gain the extra compensation $\Im_{p3}^t = \sum_{n_j \in \Pi_{pd}^t} \eta \cdot (t - t_{n_j}^0) \cdot k_{n_j}^{\min} \cdot \varrho_{n_j}^*$. For $\eta > 0$, n_i's benefit won't be damaged. For 3), n_i don't transmit at all, so its benefit won't be damaged. We can get the proof.

Due to the attractive feature of truthful bidding and the monotonically increasing relationship between the truthful bidding price (i.e.,$\beta_{n_i}^{up}$) and the data rate evaluation factor (i.e., β_{d,n_i}) (See Fig. 2 in Section III), the designed DP scheme can provide the diverse services by setting different values of β_{d,n_i}. For instance, time-sensitive multimedia service can set a larger data rate evaluation factor β_{d,n_i} such that it can have a larger truthful bidding price, which results in a higher probability to win the bidding and obtain the required channels. The bidding process starts from the time point t=1. Firstly, the coordinator ranks the SUs in a non-increasing order according to their bidding price, and then the coordinator let X SUs with maximal bid prices to form a new winner candidate set Π_p^t. Finally, the coordinator will allocate the Γ^t channels to X SUs. The detailed double-phase dynamic spectrum allocation algorithm is given as follows.

V. PERFORMANCE EVALUATION

We evaluate the performance of the DP scheme by using Matlab, and the simulation parameters are in Table 1.

We first give the matlab simulation results about the preemption result illustration, shown as in Fig. 5. Seen from Fig. 5, we can see that during the preemption process, the chances of some reservation winners will be canceled and some SUs are preempted, which will increase the total revenue without doubt.

We then give the spectrum trading revenues comparison by applying different schemes. Fig. 6 shows the achieved spectrum trading revenue by the proposed DP scheme and the dynamic spectrum scheme without preemption. It can be seen that the revenue achieved by DP scheme is 16.9% higher than that by the dynamic spectrum scheme without preemption, which means the spectrum trading revenue can be improved by providing different spectrum resource allocation priorities. Specifically, under different charging policies, the proposed DP scheme charged with the second-price can only achieve 86.6% of the spectrum trading revenue by the proposed DP scheme charged with the faucal bidding price.

To analyze the preemption ratio η on the total trading revenue of our proposed dynamic spectrum allocation scheme, Fig. 7 shows the related simulation results. We can see that the total trading revenue reduces with the increase of preemption ratio (η=1,4,15). The main reason is the reduced preempted number of SUs. For more details, Fig. 8 shows the spectrum trading revenue statistic with different preemption parameters. For instance, with the increase of preemption ratio, i.e., from η=1 to η=15, the whole spectrum trading revenue during the 120-slot spectrum access has reduced to 102%.

Furthermore, Fig. 9 shows the winner number distribution for two prioritized services. From the spectrum access time-slot point 1 to 120, the service with higher priority can have more chance to access the spectrum holes, which indicates that the scheme can satisfy

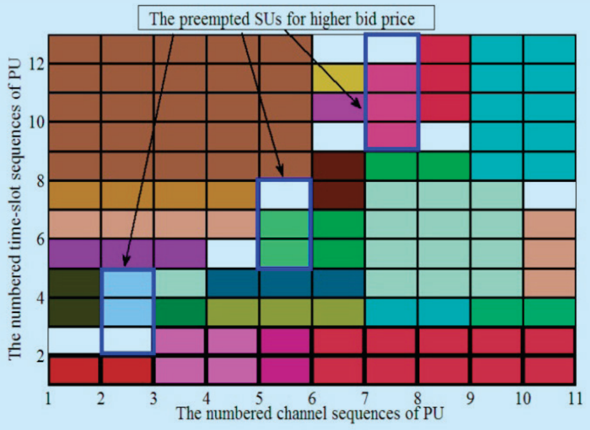

Fig.5 *The preemption result illustration*

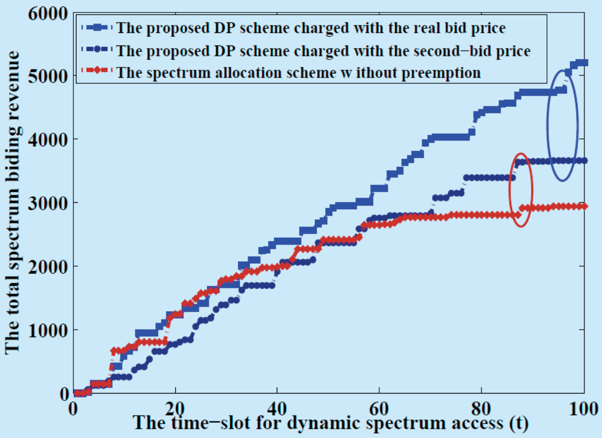

Fig.6 *The tracking of spectrum trading revenue of different spectrum allocation schemes*

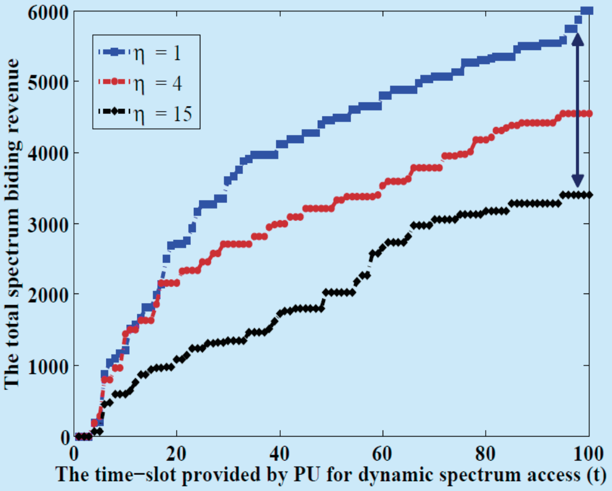

Fig.7 *The tracking of spectrum trading revenue with different η*

different service requirements. Fig. 10 shows the preempted ratio statistic of SUs with different preemption parameters. With the increase of preemption ratio (η=1,4,15), the preempted ratios of SUs are 30.91%, 21.2%, 15.19%, respectively.

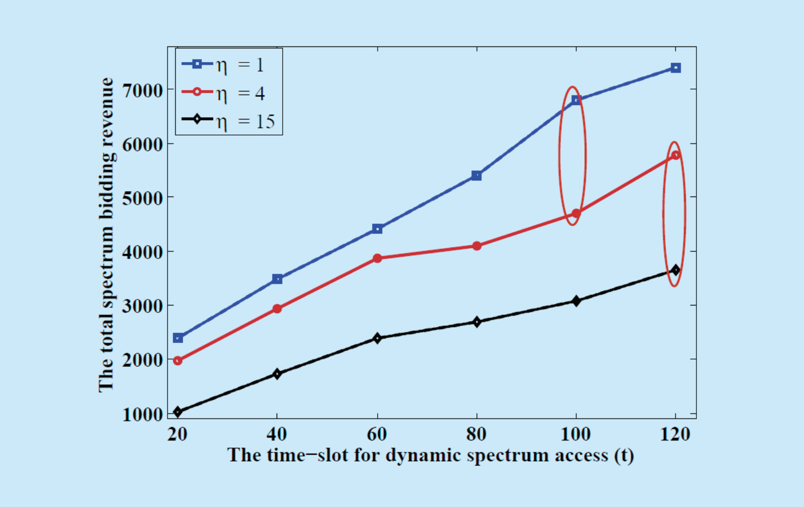

Fig.8 *The spectrum trading revenue statistic with different η*

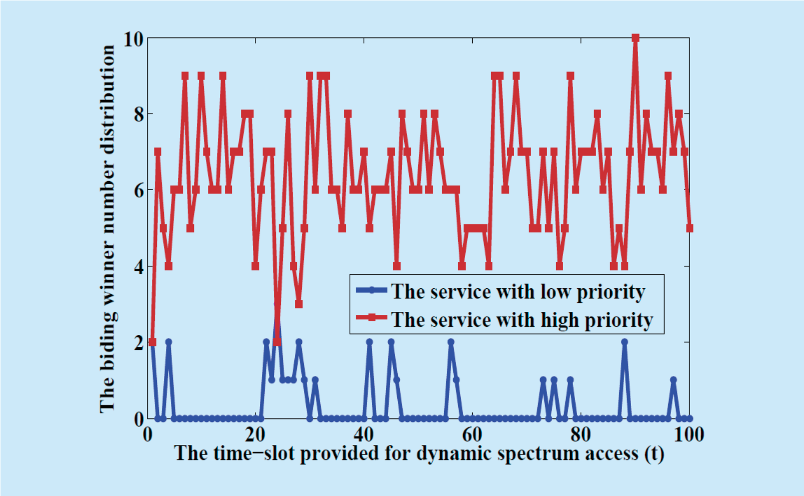

Fig.9 *The winner number distribution for two prioritized services*

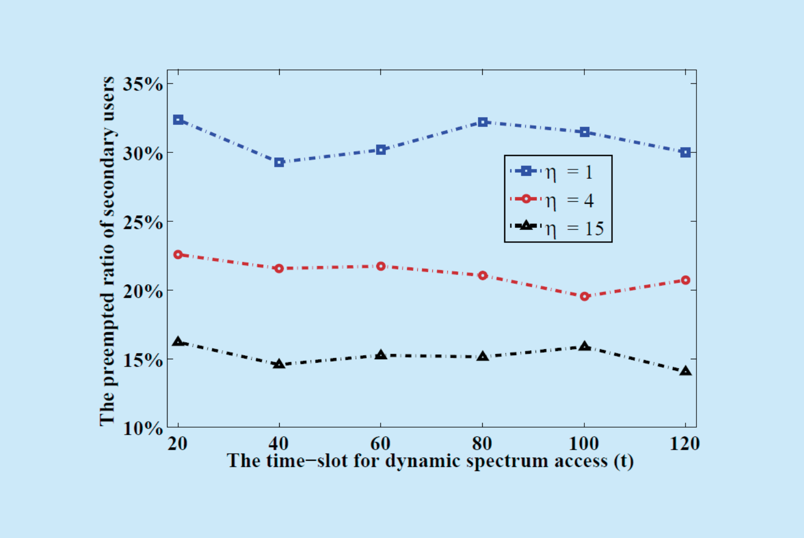

Fig.10 *The preempted ratio statistic of SUs with different η*

VI. CONLCUSTIONS

A database-assisted dynamic spectrum sharing scenario for wireless multimedia networks is studied in this paper. A double-phase spectrum allocation scheme is proposed to deal with the distinct characteristics of the multimedia services such that the diverse QoS requirements of secondary users are met. First, different service types are modeled accordingly. Then, by taking into account the diverse services priorities, the auction is elaborately formulated, which incorporates the resource evaluation, bid price making and power control for SUs. Finally, a practical and efficient dynamic spectrum allocation scheme is developed, in which the preemption operation is adopted for improving the whole resource revenue. Our future work may include further improvement on the spectrum revenue in WS spectrum trading market by designing an incentive-compatible charging policy for dynamic secondary user access.

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References

[1] T. Baykas, M. Kasslin, M. Cummings, Kang Hyunduk, J. Kwak, R. Paine, A. Reznik, R. Saeed, and S.J. Shellhammer, Developing a standard for TV white space coexistence: technical challenges and solution approaches, IEEE Wireless Communications[J], 2012, 19(1):10-22.

[2] M. Nekovee, T.; KarlsIrnich, J. son, Worldwide trends in regulation of secondary access to white spaces using cognitive radio, IEEE Wireless Communications [J], 2012, 19(4):32-40.

[3] X. Chen, and J. Huang, Database-assisted distributed spectrum sharing, IEEE Journal on Selected Areas in Communications[J], 2013, 31(11) :2349-2361.

[4] M. Fitch, M. Nekovee, S. Kawade, K. Briggs, R. MacKenzie, Wireless service provision in TV white space with cognitive radio technology: A telecom operator's perspective and experience, IEEE Communications Magazine [J], 2011, 49(3): 64-73.

[5] N. Zhang, H. Liang, N. Cheng, Y. Tang, Jon W. Mark, and X. Shen, Dynamic spectrum access in multi-channel cognitive radio networks , IEEE Journal on Selected Areas in Communications[J], to appear.

[6] E. Tragos, S. Zeadally, A. Fragkiadakis, V. Siris, Spectrum assignment in cognitive radio networks: a comprehensive survey, IEEE Communications Surveys & Tutorials [J], 2013, 15(3): 1108-1135.

[7] A. Alshamrani, X. Shen, and L.-L. Xie, QoS provisioning for heterogeneous services in cooperative cognitive radio networks, IEEE Journal on Selected Areas in Communications [J], 2011, 29(4): 819-830.

[8] H.-P. Shiang, M. Van der Schaar, Queuing-based dynamic channel selection for heterogeneous multimedia applications over cognitive radio networks [J], IEEE Transactions on Multimedia, 2008, 10(5):896-909.

[9] N. Torabi, K. Rostamzadeh, and V.C.M. Leung, Rank-optimal channel selection strategy in cognitive networks, in Proceeding of IEEE GLOBECOM, 2012, 410-415.

[10] S.-C. Jha, U. Phuyal, M.M. Rashid, and V.K. Bhargava, Design of omcmac: an opportunistic multi-channel MAC with QoS provisioning for distributed cognitive radio networks, IEEE Transactions on Wireless Communications[J], 2011, 10(10): 3414-3425.

[11] S. Gunawardena, and W. Zhuang, Service response time of elastic data traffic in cognitive radio networks, IEEE Journal on Selected Areas in Communications[J], 2013, 31(3): 559-570.

[12] H.Bogucka, M.Parzy, P.Marques, J.W. Mwangoka, T.Forde, Secondary spectrum trading in TV white spaces, IEEE Communications Magazine [J], 2012, 50(11):121-129.

[13] Y. Luo, L. Gao, J. Huang, Price and inventory Competition in Oligopoly TV White Space Markets, IEEE Journal on Selected Areas in Communications [J], to appear.

[14] C. Xin, M. Song, Dynamic spectrum access as a service, In Proceeding of IEEE INFOCOM, 2012, 666-674.

[15] M.-J. Osborne, An introduction to game theory, Oxford University Press[M], 2011.

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