A Cooperative Matching Approach for Resource Management in Dynamic Spectrum Access Networks

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***Abstract*—Dynamic spectrum access (DSA) can be leveraged by introducing external spectrum sensing for secondary users (SUs) to overcome the hidden primary users (PUs) problem and improve spectrum utilization. In this paper, we investigate the DSA networks with external sensors, i.e., external sensing agents, to utilize spectrum access opportunities located in cellular frequency bands. Considering the diversity of SUs' demands and the secondary bandwidths discovered by external sensors, it is critical to manage the detected spectrum resources in an efficient way. To this end, we formulate the resource management problem in the DSA networks as a dynamic resource demand-supply matching problem, and propose a cooperative matching solution. Specifically, spectrum access opportunities are classified into two types by the resource block size: massive sized blocks and small sized blocks. For the former type, SUs are encouraged to share the whole time-frequency block via forming coalitional groups with a "wholesale" sharing approach. For the latter type, the resource "aggregation" sharing approach is proposed to meet the time-frequency demand of individual SUs. To further reduce the delay in the spectrum allocation and compress the matching process, we develop a distributed fast spectrum sharing (DFSS) algorithm, which can deal with both two aforementioned types of resource sharing cases. Simulation results show that the DFSS algorithm can adapt to the dynamic spectrum variations in the DSA networks and the average utilization of detected spectrum access opportunities reaches nearly 90%.**

***Index Terms*—Dynamic spectrum access, cooperation, coalition, matching, utilization maximization.**

I. INTRODUCTION

CURRENT static spectrum allocation policy has resulted in inefficient spectrum utilization in the licensed spectrum bands [1]. To improve the spectrum utilization, the cognitive radios (CR) empowered dynamic spectrum access (DSA) technology allows the secondary users (SUs) to opportunistically exploit the unused spectrum resource that are temporally released by primary users (PUs), which gains growing attentions from both academia and industry [2][3][4].

Currently, most extensive research efforts have been made to exploit the TV "white spectrum" for DSA, and among them, a novel solution of radio environmental maps (REM) is proposed in [5]. However, the recent investigations revealed that the cellular bands have also shown the potential for DSA implementation [6][7], where the SUs can use the temporally unused time-frequency resources in cellular networks in an opportunistic way. As discovered in [6], the cellular DSA applications are promising and attractive in non-peak hours, for example, the period of nights and weekends. Furthermore, based on spectrum data mining technology, such as the frequent pattern mining [7], the long-term spectral and temporal state in cellular bands can be predicted with a prediction accuracy higher than 95%, which motivates the study of DSA technology in cellular bands.

In this paper, we first introduce an external sensor aided dynamic spectrum access model in cellular networks, where the external sensors, i.e., external sensing agents, can perform cooperative spectrum sensing and supply flexible available licensed spectrum resources in cellular networks to SUs with different resource demands. Specifically, as the external sensing agents can cooperatively sense the spectrum usage state and process the collected sensing information in a distributed way in the cellular networks, the realtime spectral-temporal availabilities of spectrum resource in specific local cellular networks can be acquired. Therefore, the SUs can request for those time-frequency resources according to their own needs. Those available time-frequency resources are referred to as time-frequency blocks (TFBs), where one TFB is composed of different number of resource block units in the cellular system [8]. We then propose a set of resource management rules, and model the dynamic spectrum sharing process as a cooperative supply-demand matching problem, to match the dynamical TFBs supplied by external sensing agents and various resource demands of SUs. Considering the time-frequency variation of detected resource blocks, those TFBs can be classified into two types according to the TFBs size: massive sized blocks and small sized blocks; and the "wholesale" sharing and "aggregation" sharing approaches are proposed accord-

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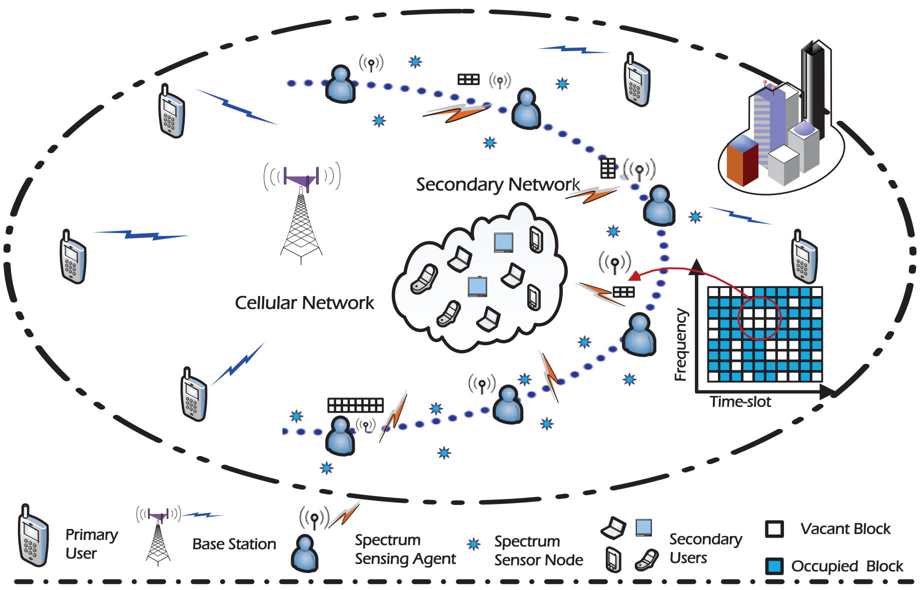


Fig. 1. Coexistence scenario with cellular network and unlicensed network.

ingly. Particularly, in the "wholesale" sharing approach, the cooperation among the SUs is utilized for maximizing the utilization of massive sized blocks, while in "aggregation" sharing approach the external sensing agents cooperate with each other for minimizing the under utilized small sized blocks. Finally, we devise a distributed fast spectrum sharing (DFSS) algorithm to realize both the "wholesale" sharing and "aggregation" sharing approaches based on the heuristic packing method. The main contributions of our work are summarized as follows,

- We propose a scalable DSA model and novel associated resource management rules, which can provide a thread for efficiently utilizing the unused spectrum resources in cellular bands in a distributed and flexible way.
- We introduce a dynamic spectrum supply-demand matching strategy for the dynamic spectrum access networks, which can significantly improve the utilization of cellular bands, while helping to alleviate the spectrum scarcity.
- We develop the DFSS algorithm to reduce the delay in the spectrum allocation for resource management in cellular DSA applications, which can be helpful to accelerate the spectrum access process in the real applications.

The reminder of this paper is organized as follows. Related work is presented in section II. Network model and problem formulation are presented in section III. In section IV, we give the cooperative strategies for two cases in the formulated supply-demand resource matching problems. In section V, we present the performance analysis and simulations of the algorithm. Section VI concludes this paper.

II. RELATED WORK

Spectrum sensing is to detect dynamic access opportunities for SUs [9]. In [10][11], joint spectrum sensing and dynamic access are investigated using coalitional games. However, in cellular networks, the spectrum usage tends to exhibit much more temporal and geographical variations [6], the internal spectrum sensing scheme including some centralized or distributed sensing technology cannot handle it properly. To increase the spectrum vacancy detection probability and accuracy while decreasing the sensing time [12]-[14], external sensing agents aided spectrum sensing schemes become more popular to accurately acquire and predict the available spectrum resources in the cellular bands [15][16]. Under the external-aided spectrum sensing scenarios [17], external sensing agents can act as the sink nodes in the spectrum sensor networks for cooperative sensing and centralized processing.

Another issue of the DSA application in cellular bands is the management of spectrum resources in an effective way. Although the approach based on REM in [5] provides an attractive architecture for the DSA application in TV bands, it is more complicated in the REM approach to perform the functionality of storage and dynamic spectrum resource management for cellular bands. Typically, there are two main challenges: i) different SUs have various resource requirements, in terms of the wireless access duration, bandwidth, etc.; and ii) compared with TV spectrum, the spectrum usage in licensed spectrum tends to exhibit much more temporal and geographical variations, and for different spectrum usage behaviors and service requirements, the pre-allocated spectrum resources for PUs are composed of variant time-frequency blocks (TFBs), especially in existing heterogeneous communication systems. Considering that the explored available TFBs in cellular networks have different number of continuous subchannels with different holding slots [6], the improper resource management and utilization approach will lead to low resource utilization. In [18], H. Mutlu et al. investigated efficient pricing policies for resource providers to price the excess cellular spectrum bandwidths to SUs. In [19], Y. Liu et al. proposed an adaptive resource management framework to improve spectrum utilization efficiency and mitigate the interference to PUs. To quickly and properly match those variant and scattered time-frequency blocks with various demanders in cellular DSA, the problem of dynamic resource supply with various demanders should be well investigated [20]. From the perspective of quality of service for SUs' demands, in [21], Alshamrani et al. proposed a spectrum allocation framework for heterogeneous SUs in real time and non-real time (NRT) applications, respectively. In [22], Sodagari et al. proposed a time-optimized and truthful dynamic spectrum rental mechanism. In [23], H. Zhou et al. introduced a packing approach to fast and optimally allocate the time-frequency blocks. In [24], Yuan et al. discussed a dynamic time-spectrum blocks allocation problem in cognitive radio networks. In [25], C. Singh et al. introduced a provider-customer matching resource allocation strategy based on the coalitional games. In [26], N. Zhang et al. investigated a maximum weight matching problem for the cooperative DSA in multi-channel cognitive radio networks. However, none of these works are specific for cellular networks and consider the aforementioned features of cellular DSA.

III. NETWORK MODEL AND PROBLEM FORMULATION

A. *Dynamic Spectrum Access Service Model*

We consider a dynamic spectrum access scenario which consists of a cellular network as a primary network, a local spectrum sensing network and a secondary network as shown in Fig. 1. In the cellular network, the base station (BS) manages the resource scheduling to serve mobile stations (MSs) that are referred to as PUs. Due to different communication requirements of PUs, the statically pre-assigned time-frequency resource blocks are different. In the meantime, the MSs have different characteristics of spectrum usage behaviors [6][7], such as the frequent variations in time and space domain. Similar to [10], the secondary network is self-organized in the same area. Once a transport link is requested for a realtime bulk data flow transmission between two SUs, e.g., video conference, data forwarding and multi-media service, etc., SUs will apply to external sensing agents for the DSA opportunities with appropriately sized bandwidths and spectrum access durations.

The local spectrum sensing network is composed of the common sensor nodes and sink sensor nodes. The sink sensor nodes can obtain the realtime channel prediction information and provide the dynamic spectrum access opportunities for SUs. Once PU turns on in the free spectrum bands, the realtime spectrum usage update made by sensor nodes will inform SUs to stop transmission tasks to avoid the interference to PUs.

Definition 1: (TFBs Supply) The available TFBs supply set from external sensing agents at time t is defined by $\mathrm{RB}^t = \{f^t_{p_1}, f^t_{p_2}, ..., f^t_{p_n}\}$, where the available TFBs supply function of external sensing agents is $f^t_{p_i}(\kappa^t_{p_i}, \alpha^t_{p_i}, \beta^t_{p_i}, \Delta^t_{p_i}, \rho^{\max,t}_{p_i}, \pi^t_{p_i})$, $\forall i = 1, 2, ..., n$, n is the available time-frequency block number, $\kappa^t_{p_i}$ is channel bandwidth, $\alpha^t_{p_i}$ and $\beta^t_{p_i}$ are the arrival time and ending time, respectively, $\Delta^t_{p_i}$ is the time-slot size, $\Delta^t_{p_i} = \beta^t_{p_i} - \alpha^t_{p_i}$, $\rho^{\max,t}_{p_i}$ is the permitted transmission power, and $\pi^t_{p_i}$ is the required price for the TFBs.

Definition 2: (TFBs Demand) For SUs with TFBs demand, the set of n TFBs demanders is defined by $\Phi = \{\mu_1, \mu_2, ..., \mu_n\}$, and the user demands set is defined by $\mathrm{D}^\dagger = \{\gamma^\dagger_{\mu_1}, \gamma^\dagger_{\mu_2}, ..., \gamma^\dagger_{\mu_j}\}$, where the j-th user $\gamma^\dagger_{\mu_j} = \{\kappa^\dagger_{\mu_j}, \Delta^\dagger_{\mu_j}, \rho^\dagger_{\mu_j}, \pi^\dagger_{\mu_j}\}$, $\kappa^\dagger_{\mu_j}$ is the required channel bandwidth, $\Delta^\dagger_{\mu_j}$ is the applied time-slot, $\rho^\dagger_{\mu_j}$ is the power transmission ability, and $\pi^\dagger_{\mu_j}$ is the acceptable leasing price.

TABLE I
SUMMARY OF IMPORTANT SYMBOLS

Symbol	Definition
p_i	Primary user i
μ_j	Secondary user j
$f^t_{p_i}$	Resource block supply function of p_i at time t
N	Resource block number provided at time t
$\kappa^t_{p_i}$	Channel bandwidth in $f^t_{p_i}$
$\Delta^t_{p_i}$	Time-slot size in $f^t_{p_i}$
$\rho^{\max,t}_{p_i}$	Permitted transmission power in $f^t_{p_i}$
$\pi^t_{p_i}$	Required price in $f^t_{p_i}$
$\gamma^\dagger_{\mu_j}$	Resource block demand function of μ_j at time t
$\kappa^\dagger_{\mu_j}$	Required channel bandwidth of μ_j at time t
$\Delta^\dagger_{\mu_j}$	Applied time-slot of μ_j at time t
$\rho^\dagger_{\mu_j}$	Transmission power ability of μ_j at time t
$\pi^\dagger_{\mu_j}$	Accepted leasing price of μ_j at time t
RB^t	The available time-frequency block supply set at time t
RB^t_p	The massive sized time-frequency block supply set at time t
RB^t_d	The small sized time-frequency block providing set at time t
$\Theta^t_{p_i}$	Evaluated transmitting data capacity
$\phi^\dagger_{\mu_j}$	The real transmitting data of SU μ_j
$\mathcal{N}$	The coalitional player set
v	Spectrum sharing payoff function
$\mathcal{B}$	Realtime coalition structure
$\zeta^{f^t}_{\mu_j}$	Real resource consuming cost of SU μ_j at time t
$\zeta^{c^t}_{\mu_j}$	Under utilized resource cost shared by SU μ_j at time t

In Definition 1, we assume that the sensing function of cooperative agents can guarantee the short detection time of vacant spectrum [17][27], and the release time of spectrum vacancy information t' is no late than the resource available time $\alpha^t_{p_i}$, i.e., $\alpha^t_{p_i} - t' \geq 0$. Hence, the released spectrum information can satisfy both the demands of online dynamic spectrum sharing and offline spectrum reservation. In Definition 2, all the parameters can be calculated according to the factual transmitting data volume, required data rate and power constraint conditions, etc. For the delay-sensitive SUs, they can reserve the realtime TFBs before transmission, to avoid the problems caused by the channel reservation delay.

Generally speaking, all the external sensing agents act like the local sellers in a spectrum market [28]-[30]. At time instant t, each sensing agent will publish TFBs information. There are a random number of supplied TFBs that will be traded among the n independent SUs with different demands. We assume that all the realtime information provided by the agents is available for all the SUs in the restricted area. Meantime, we do not consider the market competition, i.e., the realtime spectrum resource blocks will be tagged with the fixed price $\pi^t_{p_i}$. According to the defined TFB supply and demand function, for $\forall \mu_j$, if the price of TFB can be accepted by the SUs, i.e., $\pi^\dagger_{\mu_j} \geq \pi^t_{p_i}$, all the SUs can join the resource selection procedure.

B. Problem Formulation

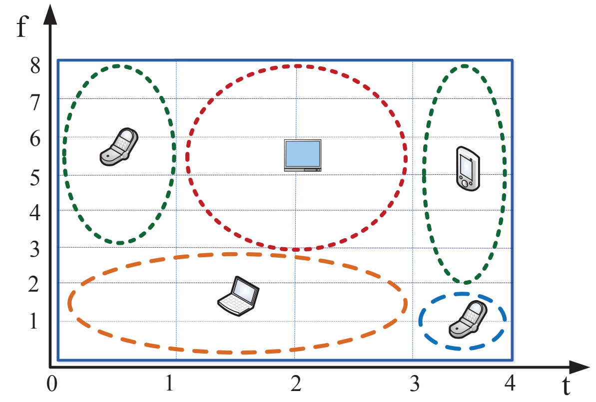
For practical resource sharing in the spectrum market, the application rule of TFB demanders at time t is as follows,

Definition 3: (Spectrum Application Rule, SAR) Given the TFB supply set RB^t, to meet the transmission data rate and service duration requirements of SUs at time t, the spectrum application conditions are as follows, i), $\kappa^t_{p_i} \geq \kappa^\dagger_{\mu_j}$; ii), $\Delta^t_{p_i} \geq \Delta^\dagger_{\mu_j}$, $\forall t = 1, 2, ..T$.

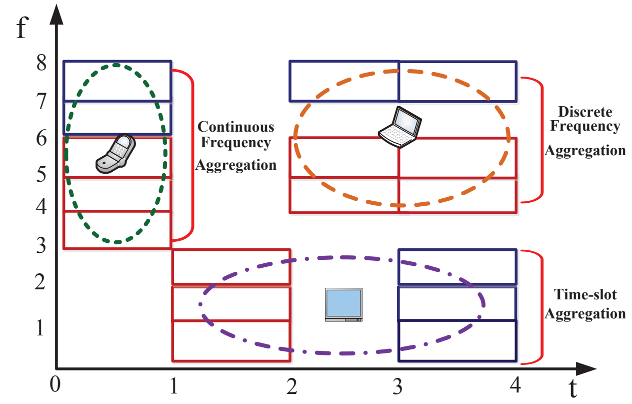
In practice, due to the time-frequency variation of TFBs supply and different demanded TFB sizes, there exists a supply-demand resource matching problem in the spectrum trading market. On one hand, if the sizes of some TFBs are larger than the resource demands of SUs, the improper allocation of TFBs may make the TFBs underutilized. On the other hand, if the sizes of some TFBs are smaller so that they cannot meet the need of any individual SU, those smaller sized TFBs will be wasted. Considering those two cases, the TFB supply function set RB^t can be divided into two subsets, i.e., RB^t_p and RB^t_d. For RB^t_d, $\forall f^t_{p_i} \in RB^t_d$, $\exists \kappa^t_{p_i} < \kappa^\dagger_{\mu_k}$ or $\Delta^t_{p_i} < \Delta^\dagger_{\mu_k}$, $\mu_k \in \Phi$, $\forall t = 1, 2, ..., T$, and $RB^t = RB^t_p \cup RB^t_d$, $RB^t_p \cap RB^t_d = \emptyset$. The TFBs provided by external sensing agents are labeled with the unit of TFBs' number, and the detailed dynamic resource management rule is regulated as follows,

- **Case 1:** If the time-frequency size of one individual TFB is larger than any current applicant's demand, it will be leased as a whole and allowed to be re-divided among multiple applicant SUs for required sub-channels and sub-slots. We name this approach as "wholesale" sharing, where the SUs will be charged for the whole value of applied resource blocks.
- **Case 2:** If the time-frequency size of one individual TFB cannot meet the needs of users, the multiple small sized blocks will be aggregated. We name this approach as "aggregation" sharing. To encourage SUs to apply for small TFBs in B^t_d, the applicants will be only charged for the practical applied block sizes.

Fig.2 demonstrates the examples to effectively share the provided TFBs in the two cases. Case 1 illustrates that one TFB can be shared via the optimal combination of multiple SUs to increase the TFB's utilization. Case 2 shows that if either the bandwidth or time-slot requirement cannot be met by SUs, the multiple TFBs have to be aggregated for the resource usage. The resource aggregation approach requires the SUs to use the spectrum switch technology for resource sharing and the proposed charging policy will be an incentive for them to use the small sized resources.



Case 1: RB is shared by multi-SUs.



Case 2: The aggregation of multi-RB shared by one SU.

Fig. 2. Two cases in the supply-demand resource matching problem.

Based on SUs' transmission rates and data capacity, at time t, SU μ_j can select any of the two resource subsets for the TFB leasing, i.e., RB^t_p or RB^t_d. Before the resource selection, the SU μ_j will evaluate the value of spectrum resource of p_i, according to the specific wireless communication parameters, i.e., the allowed transmission power $\rho^{\max,t}_{p_i}$ on the demanded channel, the available channel bandwidths $\kappa^t_{p_i}$, channel gain $g^t_{p_i}$, and the noise variance $(\sigma^t_{p_i})^2$. We choose the transmitting data capacity $\Theta_{p_i,t}$ as the evaluation function, according to the Shannon-Hartley theorem, which is given as follows,

$$\Theta^t_{p_i} = \underbrace{\kappa^t_{p_i} \cdot \log_2(1 + \frac{\rho^{\max,t}_{p_i} . |g^t_{p_i}|^2}{(\sigma^t_{p_i})^2})}_{\gamma_{p_i}} \cdot \Delta^t_{p_i}, \tag{1}$$

where γ_{p_i} is the maximum achievable data rate if SUs own the spectrum resource of p_i. Here, $\forall j = 1, 2, ..n$ in the SU set, we assume that all SUs can satisfy the transmission power constraint. Also, for all the SUs in the restricted area, we assume that the wireless communication environment at time t is the same, i.e., for $\forall i \neq j$, we have $\rho^{\max,t}_{p_i} = \rho^{\max,t}_{p_j}$, and $g^t_{p_i} = g^t_{p_j}$. Hence, the evaluation function of shared spectrum resource is only related to the bandwidth and time-slot size. For simplification, let $\log_2(1 + \frac{\rho^{\max,t}_{p_i} . |g^t_{p_i}|^2}{(\sigma^t_{p_i})^2}) = \omega^t_{p_i}$, we can rewrite (1) to be

$$\Theta^t_{p_i} = \kappa^t_{p_i} \cdot \omega^t_{p_i} \cdot \Delta^t_{p_i}, \quad \forall i = 1, 2, ..., m. \tag{2}$$

Similar to (2), we assume that SU μ_j leases the vacant spectrum of PU p_i. Considering the spectrum management rule, the practical benefit of SU μ_j is

$$\phi^{\dagger}_{\mu_j} = \kappa^{\dagger}_{\mu_j} \cdot \omega^{\dagger}_{\mu_j} \cdot \Delta^{\dagger}_{\mu_j}, \quad \forall j = 1, 2, ..., n. \tag{3}$$

Lemma 1: For $\forall \mu_j$ in the secondary network, it can apply to the external sensing agents for the resource of p_i iff $\Theta^t_{p_i} \geq \phi^{\dagger}_{\mu_j}$.

Proof: According to SAR, SU μ_j only reserves the spectrum resource of PU p_i, under the conditions that, $\kappa^t_{p_i} \geq \kappa^{\dagger}_{\mu_j}$ and $\Delta^t_{p_i} \geq \Delta^{\dagger}_{\mu_j}$, $\forall t = 1, 2, ..T$. Combining (1) and (3), the lemma is proved. ■

Based on the considered charging policy for the spectrum access opportunities in the two discussed cases, we can calculate the spectrum leasing charge based on bandwidth and the duration of the time-slot, i.e., at time t, the leasing revenue of whole spectrum block p_i is $\Theta^t_{p_i} \cdot \pi^t_{p_i}$. Hence, the TFB with larger bandwidth and longer holding time will have more leasing revenue.

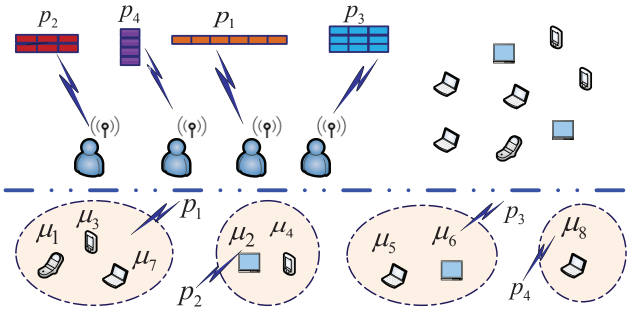


Fig. 3. At time t, the idle spectrum information of PUs are as follows, $\kappa^t_{p_1} = 1, \Delta^t_{p_1} = 6$; $\kappa^t_{p_2} = 2, \Delta^t_{p_2} = 3$; $\kappa^t_{p_3} = 3, \Delta^t_{p_3} = 3$; $\kappa^t_{p_4} = 4, \Delta^t_{p_4} = 1$. The spectrum demand information of SUs are as follows, $\kappa^{\dagger}_{\mu_1} = 1, \Delta^{\dagger}_{\mu_1} = 1$; $\kappa^{\dagger}_{\mu_2} = 2, \Delta^{\dagger}_{\mu_2} = 1$; $\kappa^{\dagger}_{\mu_3} = 1, \Delta^{\dagger}_{\mu_3} = 3$; $\kappa^{\dagger}_{\mu_4} = 2, \Delta^{\dagger}_{\mu_4} = 2$, $\kappa^{\dagger}_{\mu_5} = 3, \Delta^{\dagger}_{\mu_5} = 1$; $\kappa^{\dagger}_{\mu_6} = 3, \Delta^{\dagger}_{\mu_6} = 2$; $\kappa^{\dagger}_{\mu_7} = 1, \Delta^{\dagger}_{\mu_7} = 2$; $\kappa^{\dagger}_{\mu_8} = 4, \Delta^{\dagger}_{\mu_8} = 1$.

IV. THE COOPERATIVE SUPPLY-DEMAND RESOURCE MATCHING APPROACH

To satisfy users' demands in the DSA network and reduce the spectrum sharing cost for SUs to share the time-frequency blocks, we consider two dynamic spectrum sharing cases. For Case 1, when the provided TFB $f^t_{p_i} \in RB^t_p$, the TFB demanders can cooperate to share one time-frequency block and the corresponding cost; For Case 2, i.e., $f^t_{p_i} \in RB^t_d$, the TFB providers can cooperate for the resource aggregation. The following section will show the detailed supply-demand resource matching solutions.

A. Case 1: TFB Demanders' Cooperation for "Wholesale" Sharing

We first consider the case that $f^t_{p_i} \in RB^t_p$, i.e., $\exists \mu_j$, $\kappa^t_{p_i} \geq \kappa^{\dagger}_{\mu_j}$ && $\Delta^t_{p_i} \geq \Delta^{\dagger}_{\mu_j}$. According to the resource management rule, for μ_j, the burden of spectrum sharing cost will be increased if the RB cannot be shared fully both in time and bandwidth domain.

Remark 1: The resource management rule can guarantee a high utilization for the supplied TFBs because it can avoid the unordered demanders to get the unmatched resources. However, the spectrum leasing cost of p_i is far beyond the actual benefit of μ_j, i.e., $\Theta^t_{p_i} \cdot \pi^t_{p_i} \geq \phi^{\dagger}_{\mu_j} \cdot \pi^t_{p_i}$. Hence, the TFB demanders' cooperation is necessary for the spectrum and cost sharing.

In Fig. 3, we show one example of the TFB demander's cooperation case, where μ_1, μ_3, and μ_7 form coalitional group 1 to share the resource of p_1. Accordingly, μ_2, and μ_4 form group 2, μ_5 and μ_6 form group 3, and μ_8 forms group 4, to share the resource of p_2, p_3 and p_4, respectively. Via the cooperation of SUs for the resources application, the supply and demand for TFBs can be perfect matched, so all the cooperative SUs in the four groups can get benefits.

Definition 4: (Coalition structure) The characteristic function of coalition is $\langle \mathcal{N}, v \rangle$ [31], where $\mathcal{N}$ is the cooperative player set and $\mathcal{N} \subseteq \Phi$, v is the utility function. At time t, the number of player set is $\lambda = \left| RB^t_p \right|$. For a realtime coalition structure $\mathcal{B}$, $\mathcal{B} = \{B_1, B_2, ..., B_\lambda\}$, $\forall i \neq j$, $B_i \bigcap B_j = \emptyset$ and $\bigcup_{i=1}^{\lambda} B_i = \mathcal{N}$. For $\forall \mu_j \in \mathcal{N}$, $\forall t = 1, 2, ...T$, when grouped into B_i to lease one resource candidate $f^t_{p_i}$, the utility function $v^t_{\mu_j}$ can be given by

$$v^t_{\mu_j} = |\Theta^t_{f^t_{p_i}} \cdot \pi^t_{p_i} - \underbrace{\Theta^t_{f^t_{p_i}} \cdot \frac{\phi^t_{\mu_j}}{\sum\limits_{\mu_h \in B_i} \phi^t_{\mu_h}} \cdot \pi^t_{p_i}}_{\zeta^t_{\mu_j, B_i}} |, \tag{4}$$

where $v^t_{\mu_j}$ is composed of two parts: the whole sharing cost of TFB $\Theta^t_{f^t_{p_i}} \cdot \pi^t_{p_i}$, and the sharing cost in the formed coalition $\zeta^t_{\mu_j, B_i}$.

Remark 2: From (4), we can see that μ_j can benefit from the decreased cost sharing, and the payoff $C^t_{\mu_j}$ via forming coalitional groups is in the following range:

$$0 \leq C^t_{\mu_j} \leq \left| \Theta^t_{f^t_{p_i}} \cdot \pi^t_{p_i} - \phi^t_{\mu_j} \cdot \pi^t_{p_i} \right|.$$

Remark 2 shows that the spectrum cost for each cooperative player will be decreased, so the cooperation can bring benefits for all cooperative players. Furthermore, $\zeta^t_{\mu_j, B_i}$ in coalition B_i shows a fair cost sharing principle, and $\zeta^t_{\mu_j, B_i}$ includes two parts,

i) the practical resource consuming cost $\zeta^{f^t}_{\mu_j}$, and $\zeta^{f^t}_{\mu_j} = \phi^t_{\mu_j} \cdot \pi^t_{p_i}$;

ii) the common sharing cost $\zeta^{c^t}_{\mu_j}$ for under utilized TFB, which is given by

$$\zeta^{c^t}_{\mu_j} = (\Theta^t_{f^t_{p_i}} - \sum_{\mu_h \in B_i} \phi^t_{\mu_h}) \frac{\phi^t_{\mu_j}}{\sum\limits_{\mu_h \in B_i} \phi^t_{\mu_h}} \cdot \pi^t_{p_i}.$$

From Remark 2, if μ_j cannot join any coalition for cooperation, $\mathcal{C}^t_{\mu_j}$ equals to zero. In addition, for an optimal matching in the coalition [32], any SU μ_j only expects to pay for the practical resource consuming cost, i.e., $\zeta^{c^t}_{\mu_j} = 0$ and $\Theta^t_{f^t_{p_i}} = \sum\limits_{\mu_h \in B_i} \phi_{\mu_h, t}$, which is also the goal for all the coalitions forming.

For $\forall \mu_j$, μ_j can cooperate with different SUs which also satisfy the SAR. To form a coalition B'_{p_i} for sharing the resource of $f^t_{p_i}$, the goal is to minimize the resource sharing cost in coalition candidate B'_{p_i}, and the resource sharing cost

$\zeta^t_{\mu_j,B'_{p_i}}$ can be given as follow

$$\zeta^t_{\mu_j,B'_{p_i}} = \Theta^t_{f^t_{p_i}} \cdot \frac{\phi^t_{\mu_j}}{\sum\limits_{\mu_h \in B'_{p_i}} \phi^t_{\mu_h}} \cdot \pi^t_{p_i}.$$

Equivalently, we can minimize the under utilized time-frequency resource in TFB by cooperation, to achieve the minimal resource sharing cost. Hence, the process of coalition forming B'_{p_i} can be obtained as follow,

$$B'_{p_i} \triangleq \underset{\mu_h \in N' \setminus \mu_j}{\arg\min} \left| \Theta^t_{f^t_{p_i}} - \phi^t_{\mu_j} - \sum_{\mu_h \in \mathcal{N}' \setminus \mu_j} \phi^t_{\mu_h} \right|, \tag{5}$$

where $\mathcal{N}'$ is the SUs set satisfying the SAR to share the resource of $f^t_{p_i}$.

Definition 5: For a rational player (RP) μ_j, the resource preference relation between B'_{p_j} and B'_{p_k} is defined as: if $\zeta^t_{\mu_j,B'_{p_j}} \succeq_{\mu_j} \zeta^t_{\mu_j,B'_{p_k}}$, $B'_{p_j} \succeq_{\mu_j} B'_{p_k}$. The symbol $\succeq$ is expressed as the preference relation.

The preference relation is transitive among all the RPs, i.e., if $\zeta^t_{\mu_j,B'_{p_j}} \succeq_{\mu_j} \zeta^t_{\mu_j,B'_{p_k}}$ and $\zeta^t_{\mu_j,B'_{p_k}} \succeq_{\mu_j} \zeta^t_{\mu_j,B'_{p_w}}$, we can get $\zeta^t_{\mu_j,B'_{p_j}} \succeq_{\mu_j} \zeta^t_{\mu_j,B'_{p_w}}$. Via the optimal matching, μ_j can find the best group that could minimize the spectrum sharing cost of $f^t_{p_i}$. In fact, all the SUs are rational and thus they will have a strong preference to choose the groups with more cooperation benefits. Moreover, we assume that all the group members and the new group applicants are treated equally in any coalition in terms of the contributions to the payoff in the coalition forming process. If B'_{p_k} is the final formed coalition, it means that μ_j can form coalition B'_{p_k} with other SUs, at the minimal spectrum sharing cost $\zeta^t_{\mu_j,B'_{p_k}}$, i.e.,

$$B'_{p_k} \triangleq \underset{B'_{p_i} \in B'}{\arg\min} \{\zeta^t_{\mu_j,B'_{p_i}}\}, \forall k = 1, 2, ..., \left|RB^t_p\right|. \tag{6}$$

For a new rational applicant μ_j who will be compatible with the evolving coalitional player set B_{p_i}, there are two situations:

i) enlarging the cooperative player set iff

$$\sum_{\mu_h \in \mathrm{B}_{p_i} \cup \mu_j} \phi^t_{\mu_h} \leq \Theta^t_{f^t_{p_i}}.$$

.

ii) replacing some existed players in the formed coalition iff

$$\sum_{\mu_h \in \mathrm{B}_{p_i}} \phi^t_{\mu_h} \leq \sum_{\mu_h \in B^*_{p_i}} \phi^t_{\mu_h},$$

where $B^*_{p_i}$ is the renewed coalition after the replacement.

Definition 6: Given the coalition B'_{p_i}, if no rational player prefers to join the coalition or leave the coalition for better utility, then the coalition B'_{p_i} is stable, i.e.,

$$\mathrm{B}'_{p_i} \triangleq \underset{\mu_h \in \mathcal{N}}{\arg\min} \left| \Theta^t_{f^t_{p_i}} - \sum_{\mu_h \in \mathcal{N}} \phi^t_{\mu_h} \right|.$$

.

Theorem 1: If a coalition in the dynamic matching game is stable, the coalition can reach the equilibrium.

Proof: For any rational player μ_j, $\mu_j \in \mathcal{N}$, we assume that they can acquire the dynamic matching information in the process of coalition forming. Hence, the rational player can calculate and compare the payoffs in different B_{p_i}, where $B_{p_i} \subseteq \mathcal{B}$. If they can benefit from B_{p_k}, and $B_{p_k} \neq B_{p_i}$, the player μ_j will choose to cooperate with B_{p_k}. Due to the fixed time-frequency block size, i.e., $\Theta^t_{p_i}$ is fixed, with the repeated matching game[1], Legros and Newman have proved in [33] that a stable coalition will be formed as Definition 6. ■

Dynamic coalitional matching game is a well-known NP-hard problem [33]. To solve the dynamic sharing problem via TFB demanders' cooperation, we design a DFSS algorithm. The DFSS algorithm can solve the two-dimensional packing problem based on the minimal surplus strategy [34]. We first formulate the packing problem with the best first fit (BFF) approach. Specifically, in the two-dimensional BFF packing approach, the packing process takes the channel bandwidth as the first packing condition to satisfy. The packing process runs with round, and denote by $\hbar$ the number of rounds in the process of coalition forming, where B^k_i is the subset of $\mathcal{B}$ each round, and $\bigcup_{k=1}^{\hbar} B^k_i = B_i$. At each time, the most suitable SU μ_j will be selected, i.e., the SU with maximal $\phi^\dagger_{\mu_j}$ to be packed in TFB $f^t_{p_i}$. At each round, the reservation time range is $max\{\Delta^\dagger_{\mu_h}\}_{\mu_h \in B^k_i}$. If the bandwidth of channel in the fixed reservation time range is allocated, the condition that whether there is residual time-slot left will be checked. If the condition holds, the DFSS algorithm will keep allocating the residual time-frequency block in the next round. According to the time complexity analysis in [34], the time complexity of DFSS algorithm is $O(n \log(n))$. The formulation of packing problem is as follows,

$$\min_{\forall f_{p_i} \in RB^t_{\mathrm{p}}, B_i \subseteq B} \quad \{0,\ \Theta^t_{f_{p_j}} - \sum_{k=1}^{\hbar} \sum_{\mu_h \in B^k_i} \phi^\dagger_{\mu_h}\}, \tag{7}$$

$$\text{s.t.} \quad \kappa^{\mathrm{t}}_{f_{p_j}} \geq \sum_{\mu_h \in B^k_i} \kappa^\dagger_{\mu_h}, \forall f_{p_j} \in RB^{\mathrm{t}}_{\mathrm{p}}, \tag{8}$$

$$\Delta^{\mathrm{t}}_{f_{p_j}} \geq \sum_{k=1}^{\hbar} max\{\Delta^\dagger_{\mu_h}\}_{\mu_h \in B^k_i}, \forall f_{p_j} \in RB^{\mathrm{t}}_{\mathrm{p}}. \tag{9}$$

Based on the up-to-date spectrum leasing information from agents and the application requirement of neighboring SUs, each SU decides to request for the needed resources from any possible external agent. To realize the fast matching process in a distributed way, the coalition leaders can be selected to organize the fast dynamic matching game.

Definition 7: (Coalition Leader): Given χ coalition leaders, and $\chi = |RB^t|$, to match the χ different TFBs, the leader selection process is formulated as

$$\{l_1, l_2, ...l_\chi\} \triangleq \underset{\mu_j \in \mathcal{N}, f^t_{p_i} \in RB^t_p}{\mathrm{argmin}} \left| \Theta^t_{f^t_{p_i}} - \phi^\dagger_{\mu_j} \right|.$$

.

Once the χ coalition leaders are selected, the remaining SUs will choose to join one of the χ groups to share the spectrum in a distributed way, according to the packing target and constraints. At time t, the SUs' demand function set applying for the resources in $F^{\mathrm{t}}_{\mathrm{p}}$ is D^{p}. The DFSS algorithm is shown in Algorithm 1.

---

[1] The minimal surplus strategy is adopted in the dynamic matching game.

Algorithm 1 DFSS algorithm for TFB demanders' cooperation.

```
Input: $RB_p^t$ and $\mathrm{D}^{\mathrm{p}}$,
Output: $B' = \{B'_{p_1}, B'_{p_2}, ..., B'_{p_{\|F_p^t\|}}\}$
Initialize: $t$, $\rho_{p_i,t}^{\max}$, $\mathrm{g}_{p_i}$, $B_{j'} = 0$ and $\sigma_{p_i,t}^2$
while $(F_d^t \neq \emptyset$ && $\mathrm{D}^p \neq \emptyset)$ do
    $Sort(F_p^t)$ with $\downarrow^{\Theta_{p_i}^t}$
    $Sort(\mathrm{D}^p)$ with $\downarrow^{\phi_{\mu_j}^\dagger}$
    $Coalition\_leader \leftarrow \{l_1, l_2, ...l_x\}$
    $B^* \leftarrow$ Coalition_leader
    $\hbar \leftarrow 1$
    while $(SAR\_condition(\hbar))$ do
        $Minimize\_surplus\_RB_{supply}(\hbar)$
        $\mathrm{B}^* = [\mathrm{B}^* \ B_\hbar]$
        $\hbar \leftarrow \hbar + 1$
     else while
end while
Return $B' = \{B^*_{p_1}, B^*_{p_2}, ..., B^*_{p_{|RB_p^t|}}\}$
$t \leftarrow t + 1$
```

B. Case 2: TFB Providers' Cooperation for "Aggregation" Sharing

For Case 2, i.e., $\forall f_{p_i}^t \in RB_d^t$, $\exists \kappa_{p_i}^t < \kappa_{\mu_j}^\dagger$ or $\Delta_{p_i}^t < \Delta_{\mu_j}^\dagger$, $\forall t = 1, 2, ..., T$, the provided TFBs cannot satisfy the SAR of any individual SU. Since the spectrum aggregation technology [8] includes the contiguous and non-contiguous resource aggregation approaches, multiple individual TFBs can be aggregated together to widen the carrier bandwidth and prolong the duration of spectrum usage.

We assume that μ_k prefers to apply the TFB resource from the TFBs set RB_d^t. Hence, multiple external sensing agents will schedule and cooperate to supply the resources for μ_k. The TFB aggregation approaches in RB_d^t can be divided into three types: frequency-band aggregation (FBA), time-slot aggregation (TSA), and mixed aggregation (MA). For $\forall k, \mu_k \in \Phi^*$, and Φ^* is the applicants set of SUs, and the spectrum switch technology for the spectrum access will be utilized by those SUs.

- ***FBA:*** $\forall p_i, p_i \in P$, and $f_{p_i}^t \in F_d^t$, if p_i has the required available duration, i.e., $\min\limits_{f_{p_i}^t \in F_d^t} \{\Delta_{p_i}^t\} \geq \Delta_{\mu_k}^\dagger$, to meet the requirement of bandwidth, the FBA condition is $\sum_{f_{p_i}^t \in F_d^t} \kappa_{p_i}^t \geq \kappa_{\mu_k}^\dagger$.
- ***TSA:*** $\forall p_i, p_i \in P$, and $f_{p_i}^t \in RB_d^t$, if p_i has the required available bandwidth, i.e., $\min\limits_{f_{p_i}^t \in RB_d^t} \{\kappa_{p_i}^t\} \geq \kappa_{\mu_k}^\dagger$, to meet the requirement of time-slot, the TSA condition is $\sum_{f_{p_i}^t \in RB_d^t} \Delta_{p_i}^t \geq \Delta_{\mu_k}^\dagger$.
- ***MA:*** $\forall p_i, p_i \in P, f_{p_i}^t \in RB_d^t$, the MA procedure includes two steps: FBA and TSA. Firstly, the provided TFBs are aggregated to form several larger TFBs which can meet the bandwidth requirement of TFB demander μ_k, and the renewed TFBs set is $RB_{d,\mu_k}^t = \{RB_{d_1,\mu_k}^t, RB_{d_2,\mu_k}^t, ..., RB_{d_m,\mu_k}^t\}$. Then, the larger TFBs in RB_{d,μ_k}^t are aggregated to meet the time-slot requirement of TFB demander μ_k. The MA conditions are: i), $\sum_{f_{p_i}^t \in RB_{d_m,\mu_k}^t} \kappa_{p_i}^t \geq \kappa_{\mu_k}^\dagger$, $\forall RB_{d_m,\mu_k}^t \subset RB_{d,\mu_k}^t$; and ii), $\sum_{RB_{d,\mu_k}^t} \min_{f_{p_i}^t \in RB_{d_m,\mu_k}^t} \{\Delta_{p_i}^t\} \geq \Delta_{\mu_k}^\dagger$.

According to the charging policy regulated for TFBs in Case 2, the applicants only pay for the practical values of applied TFBs, i.e., $\phi_{\mu_k}^t \cdot \pi_{\mu_k}^\dagger$. For all rational TFBs providers, they want to lease the TFBs to the demanders via the cooperative combination. Meantime, they prefer to avoid the redundant time-frequency block supply, because more resource supply does not necessarily mean more payoff. Hence, in Case 2, each resource provider will have the preference relation to choose partners for the TFB aggregation. The cooperative matching game can be utilized to select the best combination among different providers to match the demand of one SU.

Remark 3: $\exists f_{p_i}^t \in RB_d^t$, it is incentive for TFBs providers to form coalitions with other providers, satisfying the TFB requirements of applicant μ_k, i.e., $(\Theta_{p_i}^t + \sum_{f_{p_i}^t \in RB_d^t} \Theta_{p_k}^t) \geq \phi_{\mu_k}^\dagger$, and minimizing the waste of redundant time-frequency space in TFB, i.e., $\underset{f_{p_i}^t \in F_d^t}{minimize} \ (\Theta_{p_i}^t + \sum_{f_{p_i}^t \in RB_d^t} \Theta_{p_j}^t) - \phi_{\mu_k}^\dagger$. The payoff of p_i denoted by ψ_{p_i} is as follow,

$$\psi_{p_i} \triangleq \phi_{\mu_k,t} \cdot \pi_{\mu_k,t} \cdot \frac{\Theta_{p_i,t}}{\Theta_{p_i,t} + \sum_{f_{p_k}^t \in RB_p^t} \Theta_{p_k,t}} \ . \tag{10}$$

Theorem 2: For $\forall\ p_i$, to form coalition in the set of RB_d^t, the equilibrium under the constraint of SAR can be reached when maximizing ψ_{p_i}, where $\forall p_i \in RB_{\mathrm{d}}^t$.

Proof: The coalition forming process of TFB providers is similar to that of TFB demanders. For the cooperation among TFB demanders in Case 1, the objective function is linear with the required size of TFB from the demanders and constrained by the packing upperbound, i.e., the capacity of provided TFBs. For any rational player p_i, $p_i \in RB_d^t$, when maximizing ψ_{p_i}, where $\forall p_i \in RB_{\mathrm{d}}^t$, all the players will have no incentive to join a new coalition. Obviously, the optimal formed coalition can approach to the equilibrium state, i.e., $\Theta_{p_i,t} + \sum_{f_{p_j}^t \in RB_p^t} \Theta_{p_j,t} = \phi_{\mu_k,t}$, to aggregate to be a renewed TFB with the demanded size of time-frequency block. Hence, once the minimal waste of redundant time-frequency space in TFB is approached, the maximal payoff of p_i will be achieved, and the coalition forming equilibrium will be reached. ■

The coalition forming process of TFB providers is also a NP-hard problem. Similar to Case 1, we can apply the minimal surplus strategy to form the dynamic groups among the cooperative external sensing agents. Specifically, we formulate the dynamic spectrum sharing as a two-dimensional packing problem. For general formulation, we consider the MA case. Firstly, via the FBA technology, the multiple TFBs are aggregated to meet the demand of bandwidth requirement of the objective μ_k, $\mu_k \in \Phi^*$. After that, the renewed TFBs are aggregated for the longer duration to meet the demand of time-slot of the objective μ_k. The packing process runs in the unit of round, and the round number is assumed to be equal to the number of renewed TFB m. For the fast spectrum sharing, on the basis of time-slot and channel requirements, the TFB with larger available time-slot and bandwidth size, the higher priority the TFB will be packed first. Meantime, the surplus of time-frequency sizes provided for an applied TFB should

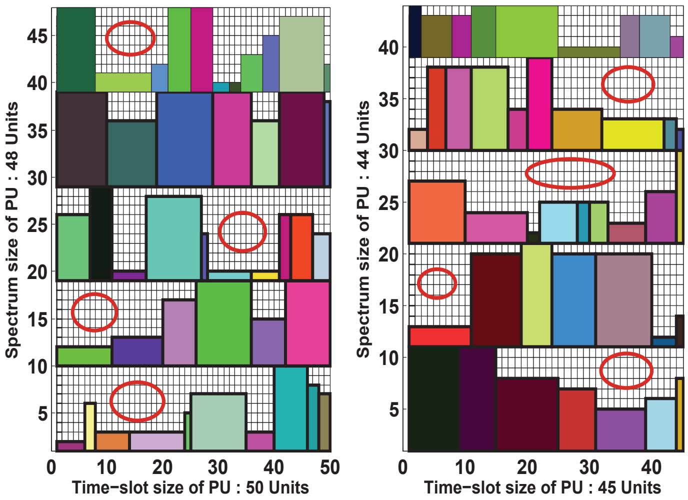


Fig 4. The packing result by random packing strategy.

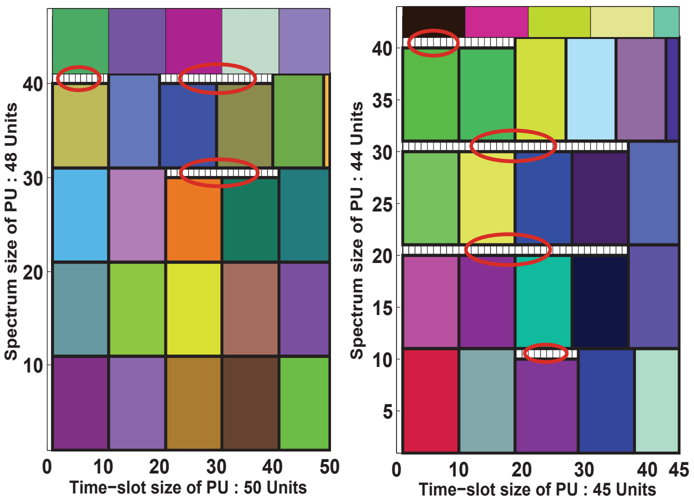


Fig 5. The packing result by DFSS algorithm.

be minimized. The detailed packing formulation is shown as following,

$$\min_{f^t_{p_i}\in RB^t_d} \quad \{(\sum_{h=1}^{m} \sum_{RB^t_{d_{h,\mu_k}}} \Theta^t_{f^t_{p_i}}) - \phi^\dagger_{\mu_k}, 0\} \tag{11}$$

$$\text{s.t.} \quad \sum_{f^t_{p_i}\in RB^t_{d_{m,\mu_k}}} \kappa^t_{p_i} \geq \kappa^\dagger_{\mu_k}, \forall RB^t_{d_{m,\mu_k}} \subset RB^t_{d,\mu_k}, \tag{12}$$

$$\sum_{h=1}^{m} \min_{f^t_{p_i}\in RB^t_{d_{m,\mu_k}}} \{\Delta^t_{p_i}\} \geq \Delta^\dagger_{\mu_k}. \tag{13}$$

Furthermore, we also adapt the BFF strategy to form coalitions. Similarly, we will choose W coalition leaders to be responsible for this coalition forming. Considering that not all the applications of TFB demanders can be accepted due to the factor of supplied resources capacity, $W \leq |\Phi^*|$. The coalition leader selection rule is just like the Definition 7, i.e., $\{l_1, l_2, ...l_W\} \triangleq \arg\min_{\mu_j\in\Phi^*, f^t_{p_i}\in RB^t_d} \left|\phi^\dagger_{\mu_k} - \Theta^t_{f^t_{p_i}}\right|$. The SUs' functions set applying for the TFBs in RB^t_{d} is denoted by D^{d} at time t, and the aggregated TFB providers set is denoted by $B^\Delta = \{B^\Delta_{\mu_1}, B^\Delta_{\mu_2}, ..., B^\Delta_{\mu_W}\}$. The DFSS algorithm for TFB providers' cooperation is shown in Algorithm 2.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of DFSS algorithm using Matlab. To verify the effectiveness of the proposed dynamic resource demand-supply matching approach, the simulation scenario is simplified by setting $\omega^t_{p_i}$ and $\omega^t_{\mu_j}$ to be constant. The detailed simulation parameters are shown in Table 2. To specify the simulation results, Fig. 4 and Fig. 5 show the packed results under random packing strategy and our proposed DFSS algorithm for Case 1. In the two figures, there are two provided RBs for the SUs' sharing. For the random packing, we do not consider the minimal surplus strategy in the packing process. Obviously, the DFSS algorithm can minimize the surplus space in the time-frequency block of RBs. Furthermore, Fig. 6 shows that the achieved utilization ratio by three typical packing approaches. Specifically, by DFSS algorithm, the highest spectrum utilization ratio is about 96.09%, and the lowest utilization ratio can also reach up to 88.48%, which is at least 25.75% higher than the utilization ratio achieved by the random packing. Compared with one typical two-dimensional packing algorithm, i.e., SHELF-BWF algorithm in [35], which considers the strategy that the remaining width of the shelf space is minimized, the DFSS algorithm can achieve nearly the same average packed ratio. However, the time complexity of SHELF-BWF algorithm is $O(n^2)$, hence, the dynamic spectrum matching time of DFSS algorithm can be greatly reduced. More importantly, as a fast convergence algorithm, the DFSS algorithm can quickly find the optimal SUs to form coalitional group for the spectrum sharing. Fig. 7 shows that DFSS algorithm can reach 95% packed ratio with roughly 1/3 of the packing time by random packing.

Algorithm 2 DFSS algorithm for TFB providers' cooperation.

```
Input: $RB^t_d$ and $D^d$,
Output: $B^\Delta = \{B^\Delta_{\mu_1}, B^\Delta_{\mu_2}, ..., B^\Delta_W\}$,
Initialize: $t$, $\rho^{\max}_{p_i,t}$, $g_{p_i}$, $B^\Delta = 0$ and $\sigma^2_{p_i,t}$
while ($RB^t_d \neq \emptyset$ && $D^d \neq \emptyset$) do
    $Sort(RB^t_d)$ with $\downarrow^{\Theta^t_{p_i}}$
    $Sort(D^d)$ with $\downarrow^{\phi^\dagger_{\mu_j}}$
    $Coalition\_leader \leftarrow \{l_1, l_2, ...l_W\}$
    $B^\Delta \leftarrow$ Coalition_leader
    $\hbar \leftarrow 1$
    while (SAR_condition($\hbar$)) do
        $Minimize\_surplus\_RB_{demand}$
        $B^\Delta = [B^\Delta \ \ B_\hbar]$
        $\hbar \leftarrow \hbar + 1$
    else while
end while
Return $B^\Delta = \{B^\Delta_{\mu_1}, B^\Delta_{\mu_2}, ..., B^\Delta_W\}$
$t \leftarrow t + 1$
```

We also present the simulation results on the performance of TFB providers' cooperation case. Via the packing process of

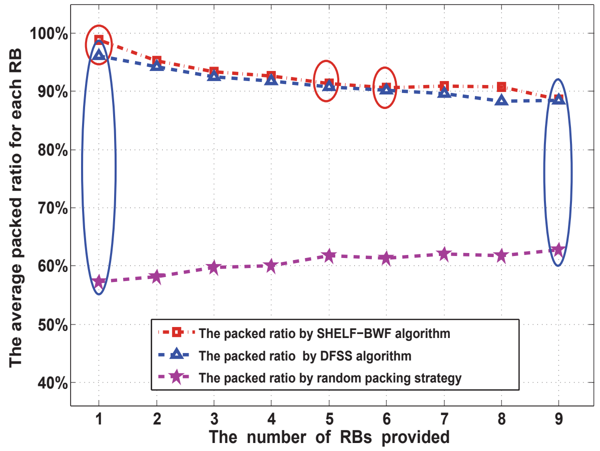


Fig. 6. The comparison of packing results by different algorithms in Case 1.

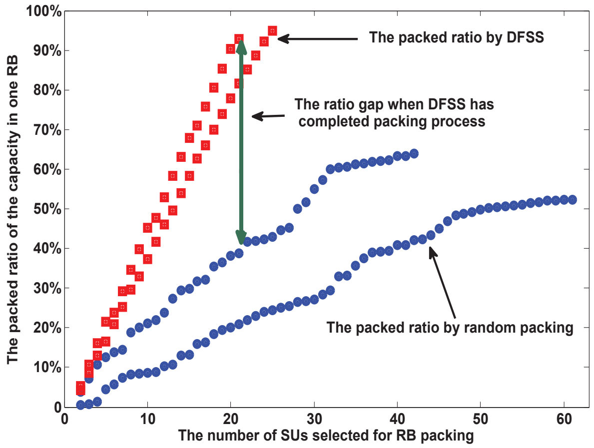


Fig. 7. The tracking process comparison between the DFSS and random packing.

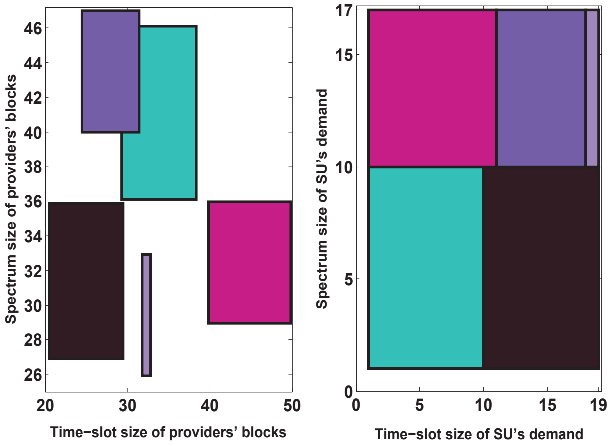


Fig. 8. An illustration of cooperation in Case 2.

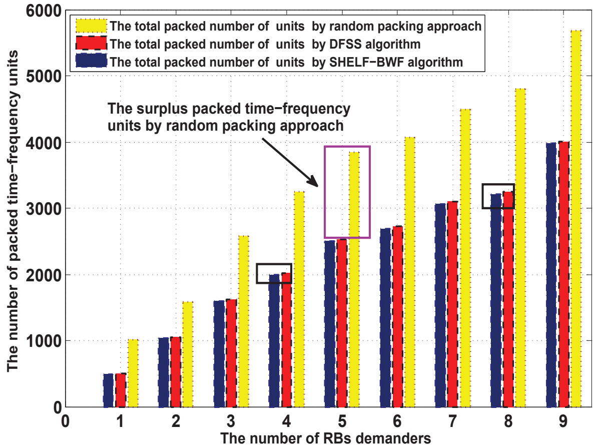


Fig. 9. The comparison of packing results by different algorithms in Case 2.

TABLE II
PARAMETERS USED IN THE SIMULATIONS

Parameters	Value
Number of TFBs in F_p^t at t	[1,10]
Number of SUs in D^p at t	[1,2000]
Number of TFBs in F_d^t at t	[1,500]
Number of SUs in D^d at t	[1,10]
$\kappa_{p_i}^t$ in F_p^t at t	[30,60]
$\Delta_{p_i}^t$ in F_p^t at t	[30,60]
$\kappa_{\mu_j}^\dagger$ in D^p at t	[1,11]
$\Delta_{\mu_j}^\dagger$ in D^p at t	[1,11]
$\kappa_{p_i}^t$ in F_d^t at t	[1,12]
$\Delta_{p_i}^t$ in F_d^t at t	[1,12]
$\kappa_{\mu_j}^\dagger$ in D^d at t	[16,32]
$\Delta_{\mu_j}^\dagger$ in D^d at t	[16,32]
simulation times	100

DFSS algorithm, different scattered small sized TFBs can be aggregated to meet the resource requirement of one specifical individual SU, as shown in Fig. 8. To compare the performance of packing process in Case 2 among the SHELF-BWF algorithm, DFSS algorithm, and random packing strategy, the detailed packed results under different number of TFB demanders are illustrated in Fig. 9. From the physical meaning of packed results for TFBs aggregation in Case 2, the less over-packed TFB space, the higher utilization that the TFBs will have. The data shows that, for the DFSS algorithm, the packed TFB units nearly meet the requirement of the demanded TFB units. Specifically, the maximal surplus ratio of DFSS algorithm is only about 1.76% more than that of the SHELF-BWF algorithm. However, for random packing strategy, at least 43.08% time-frequency TFB capacity is wasted which indicates the significant performance improvement provided by the DFSS algorithm for the two sides matching problem.

VI. CONCLUSION

In this paper, we have investigated the resource management problem for DSA in cellular networks using external sensing agents, and formulated the resource management problem as a dynamic spectrum supply-demand matching problem. The time and frequency domains are jointly considered to improve the utilization of unused spectrum in cellular networks, which has made the dynamic spectrum resource management and sharing approach more rational and effective. Furthermore, we have discussed the massive sized and small sized TFB matching cases, and the "wholesale" sharing approach and resource "aggregation" sharing approach are proposed, respectively.

Finally, we have designed a distributed fast spectrum sharing algorithm which can be applied in the real external sensing agents aided dynamic spectrum access scenarios. For future work, the effects of imperfect sensing on the DSA services will be considered. Furthermore, we will design the marketing competition scheme for DSA in the cellular networks.

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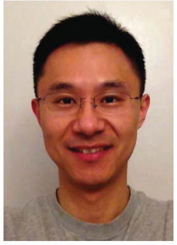

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