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Resource Allocation Strategy for Multi-user Cognitive Radio Systems: Location-Aware Spectrum Access

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***Abstract*—This paper considers a new power strategy and channel allocation optimization for secondary users (SUs) in an OFDM based cognitive radio network where the coverage area of the secondary network is divided into an Overlay Region and a Hybrid Region. SUs in the Overlay Region can adopt the overlay spectrum access method while SUs in the Hybrid Region may adopt underlay or sensing free spectrum access. We first present a general resource allocation framework that optimizes the power and channel allocation to secondary users who adopt these different spectrum access methods depending on their locations. In order to enable sensing free spectrum access, we then propose a new algorithm that incorporates an interference violation test to decide the parameters in the general framework. The proposed scheme intelligently utilizes frequency and space opportunities, avoids unnecessary spectrum sensing and minimizes the overall power consumption while maintaining the quality of service of a primary system. Simulation results validate the effectiveness of the proposed method in terms of energy efficiency and show that enhanced performance can be obtained by utilizing spatial opportunities.**

***Index Terms*—Cognitive radio, energy efficiency, resource allocation, location-aware strategy, OFDM.**

I. Introduction

By allowing secondary users (SUs) to opportunistically access or share the underused spectrum of primary licensed networks, cognitive radio (CR) has been distinguished as a promising technology to improve the spectrum utilization efficiency and meet the stringent requirements in future wireless networks [1], [2]. Depending on the spectrum policies laid by a primary system, the dynamic spectrum access mechanism can be generally classified as overlay spectrum access and underlay spectrum access. In an overlay-based system, SUs access the spectrum only when it is not being used by the primary system [3] while in an underlay-based system, SUs coexist with the primary system and transmit with power constraints to avoid unacceptable interference and guarantee the quality of service (QoS) of the primary system [4], [5].

Recently, power and channel allocation in orthogonal frequency-division multiplexing (OFDM)-based CR systems have received a great deal of attention [6]–[13]. Different spectrum access methods require distinct resource allocation strategies. For the overlay-based systems, hard-decision resource allocation (HDRA) and probabilistic resource allocation (PRA) taking into account spectrum sensing errors are studied in [14] and references therein. For the underlay-based system, interference management among SUs and primary users (PUs) play a key role in the resource allocation. In order to protect the primary system, most literature constrains the interference caused by SUs below a threshold in either average (long term) or instantaneous (short term) sense, e.g., [4], [15] and [7]. Unlike the previous literature that takes into account the amount of interference to the primary system as the protection criterion, the authors of [11] reconsider the protection to the primary system and SUs through different levels of protection in signal to interference-and-noise ratio (SINR). Besides, many researchers consider resource allocation with joint overlay and underlay spectrum access. For instance, subcarrier-and-power-allocation schemes for a joint overlay and underlay spectrum access mechanism are proposed in [8] for a downlink transmission scenario in a centralized multi-user CR network, where both unused and underused spectrum resources are utilized and the interference introduced to the PU is kept below given thresholds with a certain probability. In [12], the authors employ a hybrid overlay/underlay spectrum sharing scheme for a distributed CR network, allowing an SU to adapt its way of accessing the licensed spectrum according to the status of the channel. If the selected channel is detected to be unoccupied, the SU works in an overlay mode, otherwise it works in spectrum underlay. An auction-based power allocation scheme is proposed to solve power competition of multiple SUs. These aforementioned works are based on the maximum data rate design subject to an overall power constraint. On the other hand, energy-efficient design attracts more attention from researchers recently. The energy-efficient power allocation problem of OFDM-based CR systems is studied in [13], where energy efficiency defined as the ratio of data rate to power is taken as the objective function in the optimization for the purpose of holding the promise of advancing green communications.

In all these aforementioned work, every SU uses the same type of spectrum access methods, be it overlay, underlay or hybrid. In reality, it is natural for SUs at different locations to use different spectrum access methods. For example, SUs

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close to or inside the primary system cannot share the channels with PUs and hence should use overlay spectrum access, while SUs located far from the PU system may use underlay spectrum access in addition to overlay, or even sensing free spectrum access proposed in [16]. In fact, space opportunity, which can enhance the spectrum and energy efficiency, was not considered in most of the existing work. In our previous work [14], a novel location-aware power allocation framework that intelligently utilizes frequency and space opportunities of the spectrum was proposed. However, in that work, we only considered the power allocation for the single SU case. Resource allocation strategies for a secondary network consisting of SUs with location dependent heterogeneous spectrum access have not been studied in the literature. The first contribution of this paper is to extend [14] to consider multiple SUs spread out in a secondary network and devises a general problem formulation that incorporates all the spectrum access methods and allows different modes for distinctly located SUs by setting the parameters in this formulation. Unlike the single user case, channel allocation as well as power allocation should be included in this formulation. Meanwhile, to achieve an energy-efficient design, we minimize the total power consumption with a given date rate requirement in this problem formulation. Our resource allocation incorporates the hard-decision based approach for overlay spectrum access, the spectrum sharing based approach for underlay spectrum access, and the sensing-free based approach. The performance of these approaches highly depends on the network topology, and in particular, the distance between the SU transmitter and the PU receiver. In general, it is not straightforward to decide whether spectrum sensing for each channel is required or not even if the location information is known. Therefore, the second contribution of this paper is to propose a novel interference violation test to find out the channels that do not need to be sensed and further avoid unnecessary spectrum sensing to improve energy efficiency. Based on the interference violation test result, the proposed location-aware design then incorporates location information to access the spectrum adaptively and achieves improved energy efficiency (cf. Algorithm 1).

The remainder of the paper is organized as follows. In Section II, system model and problem formulation are described and Section III describes the location-aware multi-user resource allocation. In Section IV, an interference violation test for each sub-channel is discussed and the algorithm for overall resource allocation is given. In Section V, several numerical examples are provided to illustrate the performance enhancement of the proposed scheme over traditional resource allocation schemes. Finally, conclusions are drawn in Section VI.

II. System Model and Problem Formulation

This paper considers a scenario that one CR system co-exists with one primary system, where K mobile SUs are communicating with a cognitive base station (CBS) in the uplink and PUs are receiving signals from a primary base station (PBS) in the downlink, as depicted in Fig. 1. In Fig. 1, the circle to the left represents the service range of the primary system and the shaded circle to the right represents that of the CR system. The intersection of the two circles constructs what we call the Overlay Region. The remaining part of the CR service region is called the Hybrid Region. To ensure the efficacy of the scheme proposed in this paper, we assume that for each SU in the Hybrid Region, there is a corresponding worst case PU location (located at the intersection of the PBS service region boundary and the line between the PBS and the SU itself), which is the closest to this SU. We believe that if the worst case PU (regardless whether this PU is actually present or not) is protected, all the PUs within the coverage area of the primary system are also protected from the transmission of the corresponding SU in long term. The problem formulation and analysis thereafter apply similarly to the secondary downlink scenario and hence this paper focuses on the secondary uplink. We assume that the primary system and CR system are OFDM-based systems, with the licensed spectrum being divided into N sub-channels of the same bandwidth with each sub-channel experiencing flat fading. It is also assumed that there is no spectrum sensing error, and hence the case of imperfect sensing is out of the scope of this paper. As we shall show, depending on the location of SUs, resource allocation design should exhibit an adaptive structure, allowing diverse spectrum access methods when the SUs fall into different service regions[1]. In order to avoid mutual interference among SUs, we assume that each sub-channel can be at most allocated to one SU and each SU may be allocated more than one sub-channel. In addition, it is assumed that $N \geq K$ and the number of unoccupied channels is larger than the number of SUs located in the Overlay Region. Finally we assume that the CBS coordinates channel and power allocation and spectrum sensing (if necessary) in a centralized manner.

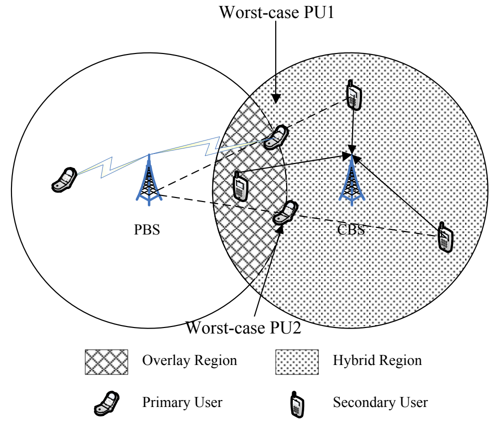

Fig. 1: A CR system coexisting with a primary system (uplink scenario for the CR system). Two regions are highlighted for the CR system to operate different spectrum access methods.

Transmit power control plays an important role in energy efficient communication to prolong the lifetime of the network and achieve the goal of green communication. Therefore, instead of maximizing the system data rate over limited power

[1]The location information of the network can be obtained using, e.g., the cognitive positioning system [17].

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TABLE I: Parameter Definitions in Problem $\mathbf{P1}$

	Overlay	Underlay	SFRA
$\mathcal{A}$	the set of detected unoccupied sub-channels		N/A $(=\emptyset)$
$\mathcal{N}$	the set of detected occupied sub-channels		$\{1, 2, ..., N\}$
$P_{i,k}$	transmit power allocated on the ith sub-channel for the kth SU		
P_p	transmit power of the PBS		
R^{min}	minimum rate requirement of the SUs		
${P_k}^{\text{max}}$	power budget of the kth SU		
I_i^{max}	QoS threshold of the ith sub-channel for the primary system		
h_i^{PS}	instantaneous channel gain on the ith sub-channel from PBS to CBS (path loss, shadowing, and small scale fading)		
$h_{i,k}^{SS}$	instantaneous channel gain on the ith sub-channel from the kth SU to CBS (path loss, shadowing, and small scale fading)		
$L_{i,k}^{SP}$	average channel gain on the ith sub-channel from the kth SU to the worst-case PU (path loss and shadowing)		
σ^2	noise power of each sub-channel at the CBS		
$\alpha^{(k)}$	spectrum sharing indicator of the kth SU ($\alpha^{(k)} = 0$ for Overlay Region user and $\alpha^{(k)} = 1$ otherwise)		
$\rho_{i,k}$	channel allocation indicator ($\rho_{i,k}$=1 represents allocating the ith sub-channel to the kth SU)		

resource [18] as most of the relevant works do, we formulate here a complementary QoS problem [19] with the objective of minimizing the overall power consumption subject to a minimum data rate requirement. The cognitive resource allocation problem permitting different spectrum access methods for SUs can be formulated by a general framework as

$$(\mathbf{P1}) \quad \min_{P_{i,k}, \rho_{i,k} \forall i,k} \ \sum_{k=1}^{K} \sum_{i \in \mathcal{A} \bigcup \mathcal{N}} \rho_{i,k} P_{i,k}$$

$$\text{s.t.} \quad R_k = \sum_{i \in \mathcal{A}} \rho_{i,k} \mathcal{C}\left(\frac{P_{i,k} h_{i,k}^{SS}}{\sigma^2}\right)$$

$$+\alpha^{(k)} \sum_{i \in \mathcal{N}} \rho_{i,k} \mathcal{C}\left(\frac{P_{i,k} h_{i,k}^{SS}}{\sigma^2 + P_p h_i^{PS}}\right) \geq R^{\text{min}}, \forall k \tag{1}$$

$$\sum_{i \in \mathcal{A} \bigcup \mathcal{N}} \rho_{i,k} P_{i,k} \leq {P_k}^{\text{max}}, \forall k \tag{2}$$

$$\alpha^{(k)} \rho_{i,k} P_{i,k} L_{i,k}^{SP} \leq I_i^{\text{max}}, \qquad \forall i \in \mathcal{N}, \forall k, \tag{3}$$

$$\sum_{k=1}^{K} \rho_{i,k} \leq 1, \rho_{i,k} \in \{0, 1\}, \forall k, i, \tag{4}$$

where the parameters are explained in Table I, the function $\mathcal{C}(x) = \log_2(1 + x)$ denotes the Shannon rate, the bandwidth of each sub-channel is assumed to be unitary, the minimum data requirements for all the users are assumed to be identical and P_p is assumed to be known. The average channel gains from system A to system B, L^{AB}, are obtained based on path loss attenuation model d^{-r} for a distance d with exponent r, i.e., $L^{AB} = d_{AB}^{-r}$, where d_{AB} denotes the distance between the transmitter in system A to the receiver in system B.

The overlay-based approaches utilize only unoccupied sub-channels based on sensing results and thus the spectrum sharing indicator $\alpha^{(k)} = 0$ for an SU in the Overlay Region. The underlay-based approaches allow spectrum sharing and thus we have $\alpha^{(k)} = 1$ for an SU in the Hybrid Region. Unlike traditional overlay systems, underlay-based systems further utilize those occupied sub-channels with additional protection to the PUs. Note that for underlay-based systems, the interference constraint (3) in $\mathbf{P1}$ guarantees protection to the primary system on an average sense and hence supports primary system QoS. Another resource allocation scheme termed sensing-free resource allocation (SFRA), is based on sensing free spectrum access, which lets SUs operate on all the sub-channels without spectrum sensing while incorporating the interference constraint (3). When the problem $\mathbf{P1}$ is used to represent SFRA, the spectrum sharing indicator $\alpha^{(k)} = 1$ and the other parameters are set according to Table I with $\mathcal{A} = \emptyset$, and $\mathcal{N} = \{1, 2, ..., N\}$.

The resource allocation problem $\mathbf{P1}$ needs the sub-channel availability information, i.e., the sets $\mathcal{A}$ and $\mathcal{N}$, which can be obtained by spectrum sensing. For a given network topology, CBS calculates each SU's distance to PBS and determines which region the SU falls into. An SU in the Overlay Region only accesses sub-channels in $\mathcal{A}$ while an SU in the Hybrid Region can be assigned sub-channels in both $\mathcal{A}$ and $\mathcal{N}$.

III. Location-Aware Multi-User Resource Allocation

With the location information of the SUs, the key part of the proposed resource allocation scheme in this paper is determining the appropriate parameters for $\mathbf{P1}$, e.g., $\mathcal{A}$, $\mathcal{N}$ and $\alpha^{(k)}$, and solving it. In this section, we focus on solving $\mathbf{P1}$ with the assumption that all the parameters have been determined.

Problem $\mathbf{P1}$ can be infeasible due to the presence of the total power constraint (2) and interference constraint (3). This occurs when the total power budget ${P_k}^{\text{max}}$ or interference capped power cannot support the target minimum rate R^{min} for a given set of channel realizations. We can add a slack variable in (2) or (3) to find the minimum P^{max} or I_i^{max} that makes $\mathbf{P1}$ feasible [20]. When $\mathbf{P1}$ is feasible, it can not be solved directly since it is a non-convex problem. To solve $\mathbf{P1}$, we utilize the dual decomposition approach [21] and the dual problem of $\mathbf{P1}$ can be given as

$$(\mathbf{P2}) \qquad \underset{\mu}{\text{maximize}} \quad \min_{P_{i,k}, \rho_{i,k} \forall i,k} \mathcal{L}$$
$$\text{s.t.} \qquad \mu_{\mathbf{k}} \succeq 0, \tag{5}$$

where $\mu_{\mathbf{k}}$ is a vector of non-negative Lagrangian multipliers for user k and $\mathcal{L}$ is the Lagrangian.

Since $\mathbf{P1}$ is not convex, the dual problem $\mathbf{P2}$ provides a solution, which is an upper bound to the solution of $\mathbf{P1}$. The upper bound is not always tight, and the difference between the upper bound and the true optimum is called the "duality gap." When the duality gap is zero, they have identical solutions. To show the duality gap between $\mathbf{P1}$ and $\mathbf{P2}$ is zero, we first introduce the definition of *time-sharing* condition [21].

Definition 1.[2] Let $P1_{i,k}^*$ and $P2_{i,k}^*$ be optimal solutions to the optimization problem $\mathbf{P1}$ with $R^{\text{min}} = {R_1}^{\text{min}}$ and $R^{\text{min}} = {R_2}^{\text{min}}$, respectively (for $\forall i, k$). The corresponding channel allocation results are $\rho_{1i,k}$ and $\rho_{2i,k}$, respectively. An optimization problem of the form $\mathbf{P1}$ is said to satisfy the

[2] In Definition 1, constraints (2) and (3) are not considered since $\mathbf{P1}$ is assumed to be feasible with satisfied QoS, and interference control is discussed in the next section.

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time-sharing condition if for any ${R_1}^{\min}$, ${R_2}^{\min}$ and for any $0 \leq v \leq 1$, there always exists a feasible solution $P_{i,k}^*$ and channel allocation $\rho_{i,k}$ such that for $\forall k$, $R_k(P_{i,k}^*, \rho_{i,k}) \geq v{R_1}^{\min} + (1-v){R_2}^{\min}$, and $\sum_{k=1}^{K}\sum_i \rho_{i,k}P_{i,k}^* \leq v\sum_{k=1}^{K}\sum_i \rho_{1i,k}P1_{i,k}^* + (1-v)\sum_{k=1}^{K}\sum_i \rho_{2i,k}P2_{i,k}^*$.

Then we have the lemma as shown below:

Lemma 1. *The optimization problem* $\mathbf{P1}$ *satisfies the time-sharing property when the data rate requirements for all the users are identical, and it has a zero duality gap, i.e., the primal problem* $\mathbf{P1}$ *and the dual problem* $\mathbf{P2}$ *have the same optimal value.*

Proof: When the data rate requirements for all the users are identical, the channel allocation results $\rho_{i,k}$ keep constant as $R^{\min}$ varies. For each $R^{\min}$, R_k is a summation of some logarithmic functions of the allocated power. Thus, it is straightforward that for the optimal power solution, R_k is a concave function of the optimal overall power consumption of user k with any channel allocation result. For $\mathbf{P1}$, with the optimal power allocation, the achieved data rate is actually equal to the minimum data rate requirement. Therefore, for any $0 \leq v \leq 1$, $R_k(P_{i,k}^*) \geq v{R_1}^{\min} + (1-v){R_2}^{\min}$ when $\sum_i \rho_{i,k}P_{i,k}^* = \sum_i \rho_{1i,k}vP1_{i,k}^* + \sum_i \rho_{2i,k}(1-v)P2_{i,k}^*$.
This implies that $\mathbf{P1}$ satisfies the time-sharing property. From [21], if the optimization problem satisfies the time-sharing property, then it has a zero duality gap which completes the proof[3]. ■

Problem $\mathbf{P2}$ then can be solved by the algorithm and the subgradient method introduced in Section IV of [21].

IV. Adaptive Resource Allocation with Interference Violation Test

Instead of determining $\mathcal{A}$ and $\mathcal{N}$ before solving $\mathbf{P1}$, we can also consider using SFRA to avoid unnecessary spectrum sensing. The idea is based on the fact that if the primary system QoS can be maintained (constraint (3) in $\mathbf{P1}$ holds) no matter whether the according channels being occupied or not, it is not necessary to perform spectrum sensing.

To be more specific, CBS calculates the resource allocation solution by solving $\mathbf{P1}$ with modified interference constraints shown below.

$$\rho_{i,k}P_{i,k}L_{i,k}^{SP} \leq I_i^{\max}, \qquad \forall i \in \mathcal{V}, k \in \text{Hybrid Region} \tag{6}$$

$$\rho_{i,k}P_{i,k} \leq 0, \qquad \forall i \in \mathcal{V}, k \in \text{Overlay Region} \tag{7}$$

where $\mathcal{V}$ is a channel set representing those sub-channels that can not support primary system QoS. At the beginning of the iterative optimization procedure, $\mathcal{V}$ is initialized to $\emptyset$ which is equivalent to assuming all sub-channels can be used without sensing. It is worth noting that $I_i^{\max}$ for the sub-channels allocated to the SUs located in the Overlay Region should be set to 0, and thus the according sub-channels have to be sensed. With the obtained power and channel allocation results, the generated interference to PUs for those sub-channels in $\mathcal{N}$ will be checked to find out whether the primary system QoS in (6) and (7) is maintained. This is called the interference violation test. Those sub-channels that can not support the primary system QoS will be added into the channel set $\mathcal{V}$. SFRA is not applicable for those sub-channels belonging to $\mathcal{V}$. As a result, spectrum sensing is required. According to the spectrum sensing results, $\mathcal{A}$ and $\mathcal{N}$ are updated. Also if a sub-channel in $\mathcal{V}$ is sensed to be unoccupied by PUs, it can be removed from $\mathcal{V}$. Then next iteration of optimization is required with interference constraints (6) and (7) so that the new optimization solution satisfies the primary systems QoS in previously violated sub-channels. The subsequent interference violation test will update $\mathcal{V}$ if new unsensed sub-channels are found to violate the interference constraints, followed by spectrum sensing for the new members of the set $\mathcal{V}$ and the update on $\mathcal{A}$ and $\mathcal{N}$ according to the sensing result. This iterative optimization procedure stops when there is no sub-channel being added into $\mathcal{V}$ after the interference violation test. Then the optimal solution for resource allocation can be obtained. The algorithm for the proposed adaptive resource allocation scheme is given in Algorithm 1 as shown below. When Algorithm 1 converges, the obtained solution satisfies all the constraints in $\mathbf{P1}$. Therefore, this solution is at least a suboptimal solution (the optimal solution is obtained by solving $\mathbf{P1}/\mathbf{P2}$ with all the sub-channels sensed). The proposed algorithm avoids unnecessary spectrum sensing and hence reduce the energy consumption, at the price of more optimization computation. This provides a tradeoff between sensing energy consumption and signal processing power consumption. When the number of channels is large, it is believed that the proposed algorithm is more promising.

[3]Even if the QoS requirement is not identical for all users, this problem can still be solved since the duality gap between the primal and dual problems tends to be 0 with a large number of sub-channels (the time-sharing condition can be satisfied as the number of sub-channels goes to infinity [6] [21]).

V. Numerical Examples

In this section, we present simulation results to demonstrate the performance of the proposed resource allocation strategy and algorithms. We consider a scenario shown in Fig. 1, where the secondary links attempt to access the spectrum of the primary system. Both the service radius of the primary system, R_1, and that of the CR system, R_2, are set to be 1000 m. The coordinates of CBS and PBS are $(0, 0)$ and $(-1500, 0)$, respectively. There are 5 SUs existing in this area with different coordinates, and they have identical *y* coordinate of -200. We assume that the bandwidth of the primary system is 1.5 MHz, which are divided into 12 sub-channels, each having a bandwidth of 125 kHz. The total path-loss of each transceiver pair is assumed to be affected by both small-scale Rayleigh fading and large-scale path-loss, where the path-loss exponent r is 3. The probability of each sub-channel being unoccupied is 50%, the maximum transmission power of the SU $P^{\max}$ is 20 W, and the transmission power of the PBS P_p is 50 W. Unless stated otherwise, the minimum data rate requirement for each user is identical and ${R_k}^{\min}$ is 0.2 Mb/s, the noise power at CBS σ^2 and the QoS threshold of the primary system $I_i^{\max}$ are set to be -20 dBmW and -25 dBmW, respectively.

The SUs locate in different regions as shown in Fig. 1 and the distance between SUs locating in the Hybrid Region to

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Algorithm 1 Proposed resource allocation algorithm

Initialize:

$\mathcal{A}=\emptyset$, $\mathcal{N}=\{1,2,...,N\}$, $\alpha^{(k)}=1$ for all the users, iteration-counter $l=0$;

${P_k}^{\max}$, $R^{\min}$, ${I_i}^{\max}$, violated channel set is initialized as $\mathcal{V}^l=\mathcal{V}^0=\emptyset$;

Initially assume all channels are occupied by the primary network and no channels violate the interference criterion.

Repeat:

1. $l=l+1$. For the l-th iteration, solve **P1** with modified interference constraints (6) and (7) for those channels belonging to $\mathcal{V}^{(l-1)}$ to get the corresponding power allocation $\mathbf{P}^l$ and channel allocation result $\rho^l_{i,k}$.
2. Check the interference generated to the worst-case PU for each allocated channel in $\mathcal{N}$. Those channels that can not support the primary system QoS in (6) and (7) will be added into the channel set $\mathcal{V}$ and we get $\mathcal{V}^l$.
3. If $\mathcal{V}^l=\mathcal{V}^{(l-1)}$, $\mathbf{P}^*=\mathbf{P}^l$ and $\rho^*_{i,k}=\rho^l_{i,k}$; If $\mathcal{V}^l\neq\mathcal{V}^{(l-1)}$, spectrum sensing should be performed for those channels added into $\mathcal{V}$ in this iteration. Update $\mathcal{A}$ and $\mathcal{N}$. Remove the channels in $\mathcal{A}$ from $\mathcal{V}^l$.

Until

$\mathcal{V}^l=\mathcal{V}^{(l-1)}$, $\mathbf{P}^l=\mathbf{P}^{(l-1)}$, $\rho^l_{i,k}=\rho^{(l-1)}_{i,k}$.

Output:

Optimal solution $\mathbf{P}^*$ and $\rho^*_{i,k}$;

TABLE II: Channel allocation results

	SU 1	SU 2	SU 3	SU 4	SU 5	violate
channel 1	0	0	0	0	1	NO
channel 2	0	1	0	0	0	YES
channel 3	0	0	0	1	0	NO
channel 4	0	1	0	0	0	YES
channel 5	0	0	0	0	1	NO
channel 6	0	0	1	0	0	YES
channel 7	1	0	0	0	0	YES
channel 8	0	0	0	1	0	NO
channel 9	1	0	0	0	0	YES
channel 10	0	0	0	1	0	NO
channel 11	0	0	0	0	1	NO
channel 12	0	0	1	0	0	NO

the cell-edge PU can be calculated by $d^{(k)}_{SP}=D_k-R_1$, where D_k denotes the distance between the kth SU to the PBS. The results in the simulation are obtained by using a same set of random channel realizations for each value of $d^{(k)}_{SP}$. Fig. 2 shows the power consumption of SUs versus user ID with different resource allocation strategies when ${R_k}^{\min}=0.2$ Mb/s. With the overlay-based scheme, only the channels being sensed idle are utilized. We do not give the results with the underlay-based scheme since the resource allocation results using the underlay-based and the proposed scheme are identical for users in the Hybrid Region, which is the case in Fig. 3. The only difference lies in the power spent on spectrum sensing. The x coordinates of these SUs are set to increase from -300 to 900 with the distance of the adjacent SUs being 300 m as shown in Fig. 3. From the coordinates of the SUs, we know that all the SUs locate in the Hybrid

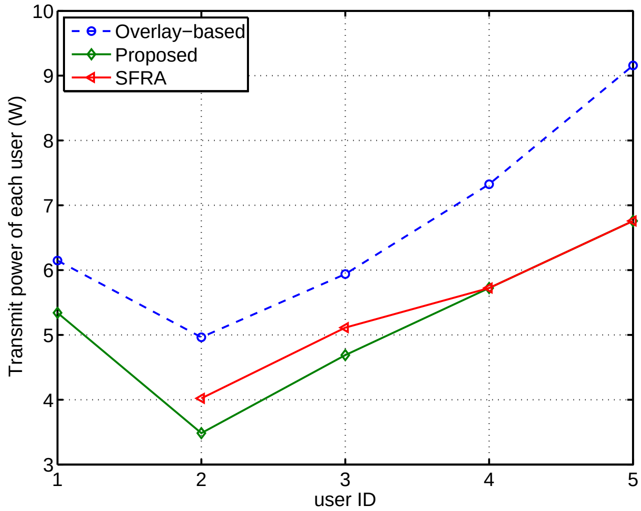

Fig. 2: The transmit power of SUs versus user ID with different resource allocation strategies (x coordinates increase from -300 to 900).

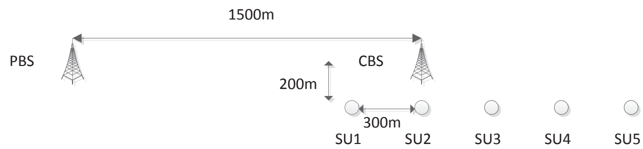

Fig. 3: The location information for simulation.

Region. The corresponding channel allocation results with the proposed scheme using Algorithm 1 are shown in Table II. In this table we can see that SU 4 and SU 5 are assigned one more channel since they are relatively far away from the CBS compared to other SUs which leads to less channel gain due to the large scale fading. The number of iterations for executing Algorithm 1 is 3, and the interference violation test results are shown in Table II. "YES" represents that the channel has ever been in the violated channel set $\mathcal{V}$. It can be seen that spectrum sensing was performed for only 5 channels which means we saved 58% energy for spectrum sensing.

For the SUs being close to the worst-case PU ($d^{(k)}_{SP}=217$ m), the interference constraints translate into very stringent transmit power constraints, so that SFRA provides no solution to guarantee the minimum data requirement as shown in Fig. 2. For the SU that is closest to the CBS ($d^{(k)}_{SP}=513$ m), the consumed power curves for both the proposed scheme and overlay-based scheme decrease rapidly as a result of less path loss, attaining the minimum value around 3.5 W and 5 W, respectively. For the SUs located far away from the worst-case PU, the consumed power curves for all the schemes increase and we observe that the proposed approach is strictly superior to the overlay-based approach in terms of power consumption, and coincides with SFRA for the SUs which are sufficiently far from the worst-case PU.

Fig. 4 shows the energy efficiency of SUs versus user ID with different resource allocation strategies when ${R_k}^{\min}=0.2$ Mb/s. We define energy efficiency for user k as $E^{(k)}=\frac{R^{(k)}_{act}}{\sum_{i\in\mathcal{A}^{(k)}\bigcup\mathcal{N}^{(k)}}P_{i,k}}$, where $R^{(k)}_{act}$ is the actual data rate based

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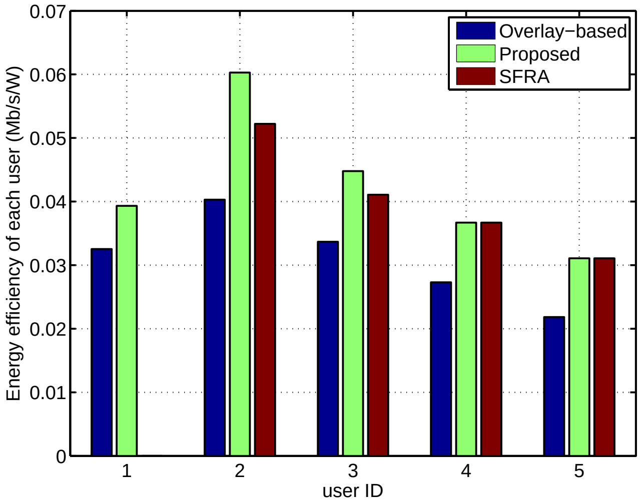

Fig. 4: The energy efficiency of SUs versus user ID with different resource allocation strategies.

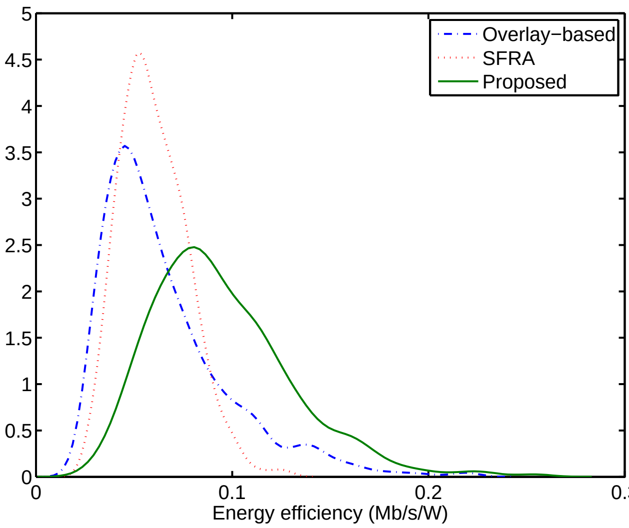

Fig. 5: The probability density functions of energy efficiency with different resource allocation strategies.

on a feasible power allocation solution. The equivalent metric for energy efficiency can be found in some publications, e.g., [14], [22], [23]. From this figure, we can see that the proposed scheme outperforms the overlay-based scheme since more channel resources are utilized. When the SU is close to the CBS ($d_{SP}^{(k)} = 513$ m), the energy efficiency of the proposed scheme is better than SFPA since the interference constraints of some channels are relaxed according to potential spectrum sensing results.

To demonstrate the impact of geographical locations on energy efficiency, all the simulation results above are obtained by using a same set of random channel realizations for different users. We now consider instantaneous random channels for each SU to provide some detailed statistical insight into the simulations. Fig. 5 shows the probability density functions of energy efficiency for SU4 in Fig. 3 obtained by simulation of 1000 sets of channel realizations with different resource allocation schemes. The used simulation parameters are the same as those mentioned at the beginning of this section except the channel information. Here we only give the result of SU4 since all the SUs have similar probability density functions and hence we take SU4 as an example. From this figure, we can see that the mean value of energy efficiency with proposed scheme is around 0.07 Mbps/W while it is only about 0.03 for overlay and 0.05 for SFRA, respectively. Therefore, we can conclude that the SUs achieve the best performance by applying the proposed scheme. In summary, the proposed scheme is able to adapt to different resource allocation strategies for SUs located at different locations and achieves the maximal energy efficiency or minimal power consumptions in all scenarios.

VI. Conclusions

This paper has elaborated the role of adaptive resource allocation in CR networks in terms of energy efficiency since energy-efficiency oriented design is more and more important for wireless communications. Based on the existing research on resource allocation for OFDM-based CR networks, this paper proposes an adaptive hybrid resource allocation strategy to enhance the energy efficiency by utilizing spectrum and spatial opportunities. A novel adaptive power and channel allocation algorithm has been proposed to fulfill the proposed resource allocation strategy based on the interference violation test. In comparison between the existing schemes that do not consider SUs' locations and the proposed resource allocation scheme, we have found that resource allocation by considering spatial information enhances the energy efficiency and avoids unnecessary spectrum sensing.

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