A High-Efficiency Resource Allocation Scheme under the Interference Constraints in Cognitive Radio

Hong Du, Zaixue Wei, Yu Wang and Dacheng Yang
Wireless Theories and Technologies Lab (WT&T)
Beijing University of Posts and Telecommunications (BUPT)
Beijing, China
duhong929@gmail.com

***Abstract*—Resource allocation is one of the key issues to improve the efficiency of spectrum utilization in cognitive radio networks. It has been widely investigated with the assumption that the secondary users have a good knowledge of the channel state information of primary system. However, it is not reasonable in practice owing to the imperfect sensing. In this paper, a high-efficiency resource allocation scheme is proposed by considering the imperfect spectrum sensing. Particularly, in order to solve the problem of interference and lower efficiency of spectrum utilization, interference constraints and quality of service requirement are considered to reduce the impact from imperfect spectrum sensing. The goal of the presented scheme is to maximizing the capacity under the interference constraints of primary users. Simulation results indicate that the proposed resource allocation scheme can represent the better performance successfully.**

Keywords-cognitive radio; resource allocation; imperfect spectrum sensing; interference constraints

I. INTRODUCTION

Cognitive radio (CR) [1] is fast becoming one of the most promising transmission technologies for efficient spectrum utilization. Cognitive radio networks (CRNs) open up the under-utilized sectors of the licensed spectrum for secondary usage, and thus the spectrum utilization is improved. Stations are classified into two types based on whether they are licensed users or not. The primary users (PUs) are the licensed users of the spectrum. The cognitive radio users, also called the secondary users (SUs), are the unlicensed users who could use the spectrum opportunistically without influence the operation of the PUs.

Dynamic spectrum allocation is a key mechanism in CRNs. It is a joint channel allocation and power control optimization problem with the objective such as maximizing the total throughput or the number of served users. This problem is especially difficult in multi-channel multi-user CRNs. Solutions to the resource allocation problem have to specify which channels each SU should transmit on, and how much power each SU should allocate on these channels.

Currently, resource allocation scheme is drawing a lot of attentions in much of the literature. In particular, an extensive research has been recently performed for resource allocation in CRNs. The problem of channel and power allocation for multiple SUs is studied in [2]. Specifically, the authors propose a joint resource allocation algorithm under the constraints condition. In [3], the authors study the resource allocation for underlay spectrum sharing technology and propose a power control scheme to guarantee that each SU has a minimum quality of service (QoS) requirement. In addition, the distributed multi-channel power allocation with QoS guarantee is studied in [4].

However, only a few studies such as [5-6] investigate the impact from imperfect spectrum sensing on resource allocation in CRNs. Most previous works neglected the spectrum sensing and assumed that the channel states of PUs are well knowledge of the SUs. Nevertheless, it is not reasonable in practice. Besides, most studies assumed that the SUs have the same requirement without considering the various services for SUs. Only few works consider the heterogeneous services of SUs such as [7-10]. Furthermore, the previous works concentrate on efficiency of the resource allocation approach without considering the fairness the SUs. Only few works jointly consider the fair and efficient such as in [11]. Although the existed resource allocation strategies have successfully enhanced spectrum efficiency, however, these existed researches do not consider the resource allocation problem comprehensively.

In this paper, a resource allocation problem is investigated by joint considering the imperfect spectrum sensing of SUs and interference constraints of PUs. The proposed scheme fully makes use of the spectrum resource based on the spectrum sensing results. It allows the SU to access the frequency band originally allocated to a PU with higher or lower power when the PU is detected to be idle or active. In addition, we classify the SUs by various service requirements. The goal of the presented strategy is to maximizing the average capacity while satisfying the interference constraints of PUs.

The rest of this paper is organized as follows. Section II describes the system model. Section III elaborates the presented resource allocation strategy in detail. Then we address the problem optimization for the resource allocation scheme. Section IV presents and analyzes the simulation results. Finally, the paper is concluded in Section V.

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II. SYSTEM MODEL

The system model is depicted as shown in Fig.1. We consider a CRN consists of a primary system and a cognitive system. In particular, a primary system is composed of a primary transmitter and several primary users, while a cognitive system is composed of a base station (BS) and several SUs with various types of service. We assumed that there is a common control unit (i.e. cognitive BS) to coordinate the resource allocation for SUs. SUs can be classified by higher and lower services requirement respectively. The PUs can be classified as PU-idle and PU-busy, respectively.

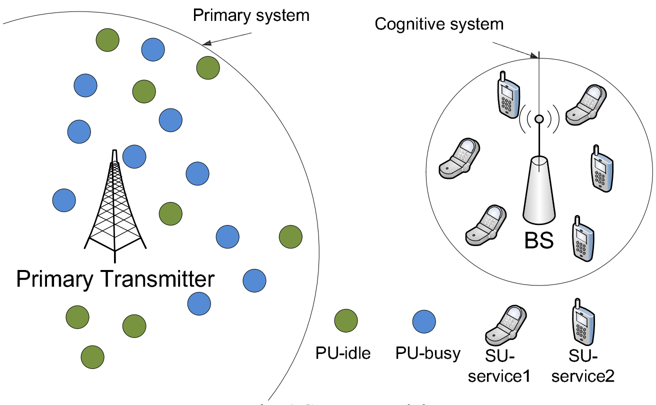

Fig. 1 System Model

In Fig.1, SUs in cognitive system exploit the spectrum sensing to obtain the channel state information of PUs. Then SUs forward the sensing results to the BS in cognitive system. Finally, the BS assigns the resource to SUs according to the channel state of PUs and QoS requirement of SUs.

In our resource allocation scheme, two aspects are considered comprehensively. They are channel usage model of PUs and spectrum sensing model of SUs, respectively. Consequently, the models of two aspects are provided in detail as follows.

1) Channel model of PUs

Usually, a channel could be modeled as an ON-OFF source alternating between ON (busy) and OFF (idle) periods. Since there are only two possible states, the behavior of this process can be analyzed by using the theory of alternating renewal processes. The state transition model of the semi-Markov process captures the time period in which the channel can be utilized by SUs without causing any harmful interference to PUs. For simplicity, $P(H_{0,j})$ and $P(H_{1,j})$ denote the probability that the jth channel is idle and active, respectively. $P(H_{0,j}) + P(H_{1,j}) = 1$.

2) Sensing Model

According to [12], there are typically two kinds of sensing errors when the SUs try to access a channel. An active PU which is using a channel may experience disruption if an arriving SU call searching for a free channel incorrectly determines that this channel is idle. Such sensing errors are referred to as misdetection events, which may incur the service degradation of the PUs. On the other hand, an SU may incorrectly determine that a channel is busy when in fact the channel is idle. This type of errors is named as a false alarm event. A false alarm event does not incur the degradation of PU's performance, but reduces the potential spectrum utilization. Denote the probabilities of misdetection and false alarm by P_m and P_f, respectively.

III. RESOURCE ALLOCATION STRATEGY

In this section, a resource allocation algorithm based on imperfect spectrum sensing is addressed in detail. The presented scheme considers the heterogeneous services of SUs. Besides, the objective of the presented scheme is to maximize the average capacity. Then, we give the problem optimization of the proposed approach.

3.1 Imperfect sensing for each SU

Usually, the previous works on resource allocation focus on the power control without considering the imperfect sensing. In fact, the performance of spectrum sensing affects the performance of resource allocation. When the SU detects the PU correctly, the probability of detection can be expressed by P_d. In addition, there are two metrics for the imperfect sensing [12]. They are the probability of false alarm P_f and the probability of misdetection P_m. The larger false alarm probability leads to the lower spectrum efficiency and the larger misdetection probability brings to the higher interference to the PUs. Therefore, it is not reasonable to take the assumption that the resource allocation strategy based on the accurate channel usage state of PUs.

In our resource allocation scheme, SUs transmit on channels and adapt their transmit power on each band based on the decision made during spectrum sensing. We consider a cognitive radio network that can access a wideband spectrum licensed to a primary network, which is divided into M narrowband channels. In order to access the channels, the SU must first perform spectrum sensing to determine the status (active/idle) of each channel.

3.2 The Proposed Resource Allocation Scheme

For the conventional resource allocation scheme, the SUs only can access to the channels when PUs are idle based on the spectrum sensing. Then the power is allocated for the SUs for the target of maximizing the system capacity of CRNs. And the optimal sensing time and transmitting power are studied.

In our resource allocation scheme, in order to fully make use of frequency bands and enhance the throughput of the cognitive radio network, we study the problem of designing the power allocation strategy. Based on the decision made for all frequency bands, the SU can access j*th* busy or idle channel with lower transmit power $P_{s,j}^0$ and higher transmit power $P_{s,j}^1$, respectively.

Due to the limitations of the spectrum sensing techniques and the nature of wireless communications that include phenomena such as shadowing and fading, the status of a frequency band may be falsely detected. As a result, four different cases for the average throughput can be distinguished regarding the sensing decision (present or absent) and the actual status of the primary users (active or idle) [13]. Therefore, transmission power based on four cases is shown in TABLE I.

TABLE I. TRANSMISSION POWER BASED ON VARIOUS CASES

Sensing Decision and actual status	**probability**	**power**
Decision is present & PU is active	$P(H_1)*P_d$	$P^0_{s,j}$
Decision is absent & PU is idle	$P(H_0)*(1-P_f)$	$P^1_{s,j}$
Decision is absent & PU is active	$P(H_1)*P_m$	$P^1_{s,j}$
Decision is present & PU is idle	$P(H_0)*P_f$	$P^0_{s,j}$

In addition, heterogeneous services requirement of SUs are considered. Specifically, the SU with the higher service requirement is allocated to the higher power $P^1_{s,j}$, the SU with the lower service requirement is allocated to the lower power $P^0_{s,j}$.

3.3 The Problem Optimization of Resource Allocation

In order to obtain the throughput of CRNs, the transmission rate of each SU is considered. The instantaneous transmission rate of the SU on the j*th* channel for the cases of TABLE I are given by

$$\mathrm{r}_{0,0,\mathrm{j}} = \log_2\left[1+\frac{g_{ss,j}P^1_{s,j}}{N_0}\right] \tag{1}$$

$$\mathrm{r}_{1,1,\mathrm{j}} = \log_2\left[1+\frac{g_{ss,j}P^0_{s,j}}{g_{ps,j}P_{p,j}+N_0}\right] \tag{2}$$

$$\mathrm{r}_{1,0,\mathrm{j}} = \log_2\left[1+\frac{g_{ss,j}P^1_{s,j}}{g_{ps,j}P_{p,j}+N_0}\right] \tag{3}$$

$$\mathrm{r}_{0,1,\mathrm{j}} = \log_2\left[1+\frac{g_{ss,j}P^0_{s,j}}{N_0}\right] \tag{4}$$

where $P_{p,j}$ denotes the transmit power of the primary user on the jth channel. The instantaneous channel power gain of the secondary link, the link between the primary transmitter and the secondary receiver, and the link between the secondary transmitter and the primary receiver for the jth channel are denoted by $g_{ss,j}$, $g_{ps,j}$ and $g_{sp,j}$ respectively. The channels are assumed to be flat fading and the channel power gains ergodic, stationary and known at the secondary users. The noise at the SU is assumed to be circularly symmetric complex Gaussian with zero mean and N_0 variance, namely $CN(0,N_0)$.

Therefore, the capacity of the j*th* channel based on the decision and the actual status of the band is given by

$$C_j = P(H_{0,j})(1-P_f)r_{00,j} + P(H_{1,j})P_d r_{11,j} + P(H_{0,j})P_f r_{01,j} + P(H_{1,j})(1-P_d)r_{10,j} \tag{5}$$

Then, the average capacity of the CRN is given by

$$R = \frac{1}{M}\sum_{j=1}^{M}\frac{T-t}{T}C_j \tag{6}$$

where T is the frame duration of cognitive radio. t represents the sensing time of SU [14].

In the following, we consider two constraints for the proposed resource allocation strategy. Firstly, when primary users are active, average interference power constraint P_{inter} is taken into account to provide better protection of the primary network. Consequently, it can be formulated as

$$P_{inter} = \frac{1}{M}\sum_{j=1}^{M}\frac{T-\tau}{T}\left[P(H_{1,j})(1-P_{d,j})P^1{}_{1,j} + P(H_{1,j})P_{d,j}P^0{}_{1,j}\right] \le I_{th} \tag{7}$$

where I_{th} denotes the interference threshold of the primary user.

In addition, sensing performance is considered for the constraint condition. Specifically, a higher detection probability is required to effectively protect the primary users. Here, we choose this probability to be $P_d \ge P_d^*$, where P_d^* denotes the target probability of detection. Similarly, a lower probability of false alarm is required to effectively improve the spectrum efficiency. Here, we choose this probability to be $P_f \le P_f^*$, where P_f^* denotes the target probability of false alarm.

Thus, the optimization problem that maximizes the average channel capacity under interference constraint can be written as follows

$$\begin{aligned} \max_{\{P^0_{s,j},P^1_{s,j}\}} imize\ R &= \frac{1}{M}\sum_{j=1}^{M}\frac{T-t}{T}C_j \\ subject\ to\quad & P^0_{s,j}, P^1_{s,j} \ge 0,\quad 1 \le j \le M \\ & P_{\mathrm{inter}} \le I_{th}, \\ & P_d \ge P_d^*, P_f \le P_f^* \\ & T \ge t \ge 0 \end{aligned} \tag{8}$$

Therefore, the problem is convex optimization problems and by writing their Lagrangian functions

$$L(\lambda,\mu,v,p^0_{s,j},p^1_{s,j}) = \frac{1}{M}\sum_{j=1}^{M}R_j(P_{s,j}) - \lambda(P_{inter}-I_{th}) - \mu(P_d-P_d^*) - v(P_f-P_f^*) \tag{9}$$

where λ,μ,v are the Lagrangian multiplier factors. Substitute the equals (5), (6) and (7) into equal (9), we have

$$
\begin{aligned}
L(p_{S,j}^0, p_{S,j}^1) = & \sum_{j=1}^{M} \frac{T-\tau}{T} P(H_{0,j})(1-P_f) r_{00,j} + P(H_{1,j}) P_d r_{11,j} \\
& + \sum_{j=1}^{M} \frac{T-\tau}{T} P(H_{0,j}) P_f r_{01,j} + P(H_{1,j})(1-P_d) r_{10,j} \\
& - \lambda \left(\sum_{j=1}^{M} \frac{T-\tau}{T} \left[P(H_{1,j})(1-P_d) P_{s,j}^1 + P(H_{1,j}) P_d P_{s,j}^0 \right] - I_{th} \right) \\
& - \mu\left(P_d - P_d^*\right) - \nu\left(P_f - P_f^*\right)
\end{aligned} \quad . \quad (10)
$$

Then we can differentiate equal (10) and get

$$
\begin{aligned}
\frac{\partial L}{\partial p_{S,j}^1} = & \frac{T-t}{T} \cdot P(H_0) \cdot (1-P_f) \cdot \frac{1}{\ln 2} \cdot \frac{1}{N_0 + P_{s,j}^{\ 1}} \\
& + \frac{T-t}{T} \cdot P(H_1) \cdot (1-P_d) \cdot \left[\frac{1}{\ln 2} \cdot \frac{1}{P_{p,j} + N_0 + P_{s,j}^{\ 1}} - \lambda \right]
\end{aligned} \quad (11)
$$

$$
\begin{aligned}
\frac{\partial L}{\partial p_{S,j}^0} = & \frac{T-t}{T} \cdot P(H_0) \cdot P_f \cdot \frac{1}{\ln 2} \cdot \frac{1}{N_0 + P_{s,j}^{\ 0}} \\
& + \frac{T-t}{T} \cdot P(H_1) \cdot P_d \cdot \left[\frac{1}{\ln 2} \cdot \frac{1}{P_{p,j} + N_0 + P_{s,j}^{\ 0}} - \lambda \right]
\end{aligned} \quad (12)
$$

Let the equal (11) and equal (12) are equal to 0, then we can get

$$
\frac{P(H_0) \cdot (1-P_f)}{N_0 + P_{s,j}^{\ 1}} + \frac{P(H_1) \cdot (1-P_d)}{P_{p,j} + N_0 + P_{s,j}^{\ 1}} = P(H_1) \cdot (1-P_d) \cdot \lambda \cdot \ln 2 \quad (13)
$$

$$
\frac{P(H_0) \cdot P_f}{N_0 + P_{s,j}^{\ 0}} + \frac{P(H_1) \cdot P_d}{P_{p,j} + N_0 + P_{s,j}^{\ 0}} = P(H_1) \cdot P_d \cdot \lambda \ln 2 \quad (14)
$$

IV. SIMULATION RESULTS AND DISCUSSION

In this section, the proposed resource allocation mechanism is evaluated under various simulation configurations. The simulation is implemented by using MATLAB. Suppose the PU's bandwidth is equals to SU's. The parameters are set to be T=100 ms, Pp,j = 10dB, N0 = 1. Five narrowband channels are considered here. Assume that the channel are idle for most time, the active probability of each channel is $P(H_{1,j})$ = [0.1 0.15 0.2 0.25 0.3].

Fig.2 compares the average capacity of the SU under the interference power constraint between the proposed and conventional allocation scheme. It is observed that the capacity for the proposed scheme is higher than the conventional scheme. It can be explained that the conventional scheme only allocate the spectrum to the SUs when the sensing decision is idle. It didn't consider the problem of the imperfect spectrum sensing. The presented allocation scheme makes full use of the spectrum resource which may be detected incorrectly by SUs. Therefore, the observation shows the superiority of the proposed scheme over the conventional scheme.

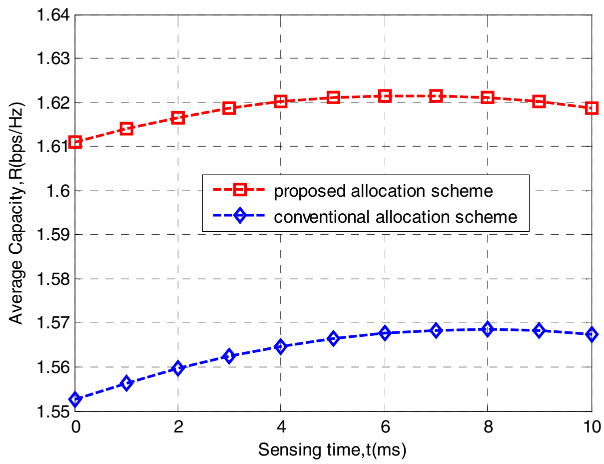

Fig. 2 Comparison of average capacity for different allocation schemes

In the following, we investigate the performance of the proposed allocation scheme in detail. In Fig.3, the impact from the interference threshold to the average capacity is presented. It can be clearly seen that the capacity increases as the interference threshold increases, this is because that the higher interference threshold allows SUs access to the spectrum by using higher power.

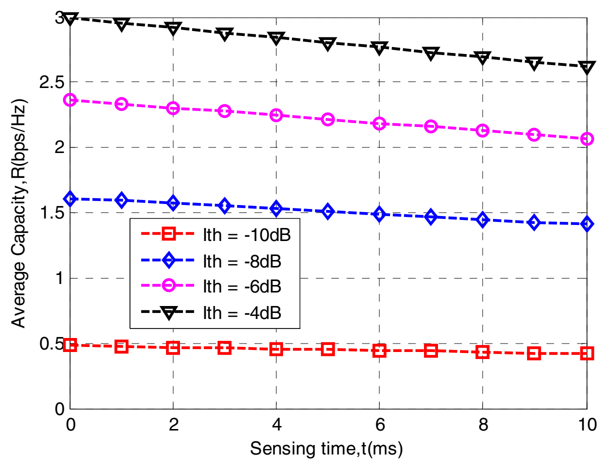

Fig. 3 Average capacity versus sensing time for different values of interference threshold

Furthermore, the influence on resource allocation performance from the imperfect spectrum sensing is considered in the following. Specifically, the impact from probabilities of detection and false alarm are shown in Fig. 4 and Fig.5, respectively. It can be clearly seen that the higher probability of detection and lower probability of false alarm can increase the average capacity. When the interference threshold is -10dB, the effect from imperfect spectrum sensing is not obvious. Besides, compared to the impact from the probability of false alarm, the impact of the probability of detection is significant.

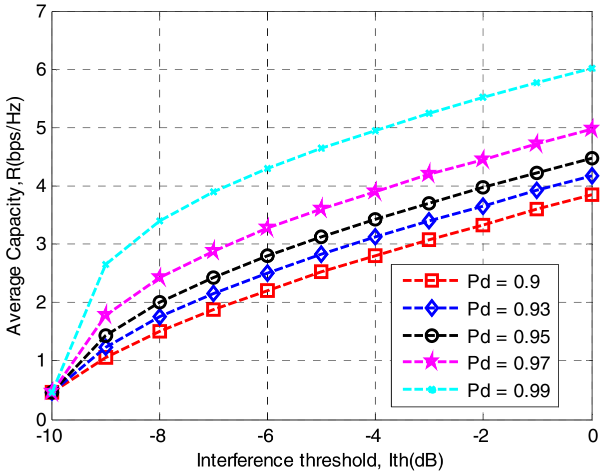

Fig. 4 Average capacity versus interference threshold for different values of detection probability P_d

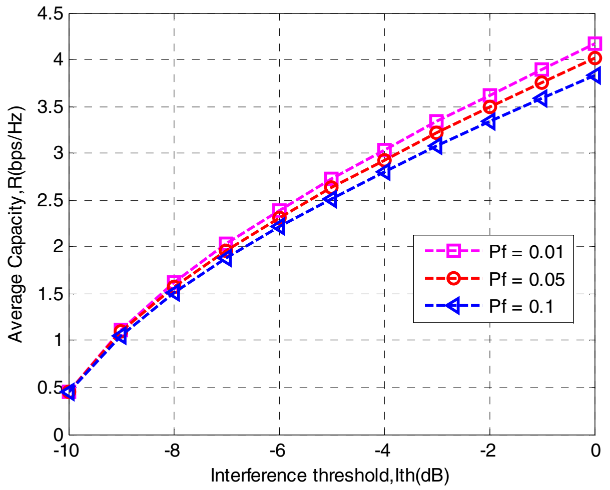

Fig. 5 Average capacity versus interference threshold for different values of false alarm probability P_f

V. CONCLUSION

In this paper, resource allocation strategy in cognitive radio networks is considered from viewpoint of imperfect spectrum sensing. In particular, the average capacity is maximized subject to the interference constraint of PU. Note that the heterogeneous services are taken into account. Our analyses and numerical results illustrate that the proposed allocation scheme can achieve significant improvements in spectrum utilization efficiency performance.

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