A Spectrum Sharing Algorithm Based on Spectrum Heterogeneity for Centralized Cognitive Radio Networks

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***Abstract*—Spectrum sharing is envisaged to allow multiple cognitive radio (CR) nodes to jointly use the vacant spectrum resource for opportunistic transmission. Most previous work on the spectrum sharing did not take into account the spectrum heterogeneity, such as different transmission ranges, error rates, etc. In this paper, a spectrum sharing algorithm is presented that accommodates spectrum heterogeneity for centralized CR networks, meanwhile the individual users are free to be mobile. Each node is uniquely assigned a channel while considering its channel occupancy time, the location of the node, and the fairness of channel access opportunity. Each of these metrics contributes in part to a larger optimization problem and the final objective is to maximize the total utility of system. Simulations results reveal significant improvement in reducing spectrum handoffs.**

Keywords- cognitive radio; spectrum sharing; spectrum heterogeneity; spectrum handoff

I. INTRODUCTION

The rapid growth of wireless communication networks in the recent years has been fuelled by the ever-increasing demand for high-speed connectivity. However, according to the Federal Communications Commission (FCC), a significant amount of the licensed spectrum remains unutilized. Moreover, the spectrum utilization exhibits temporal and geographical variations from 15% to 85%, and this trend is also time-dependent [1, 2]. Fixed spectrum policy is unable to address these issues, as vast tracts of the frequency spectrum lie under-utilized. Therefore, cognitive radio (CR) technology has been proposed to solve the spectrum inefficiency problem. In the CR networks, the unlicensed user or secondary user (SU) can use the spectrum in an opportunistic manner as long as the primary user (PU) of that spectrum is not affected.

There are two types of CR networks in terms of network architecture: CR infrastructure-based networks and CR ad hoc networks [2, 3]. In CR infrastructure-based networks, a central entity is required, such as a CR base station (CR-BS). Through CR-BSs, SUs are more likely to communicate with other remote terminals. We consider this model in our paper.

Spectrum sharing is one of the main challenges in CR networks. In centralized CR networks, many spectrum sharing works are based on spectrum pooling, in which licensed users or primary users (PUs) can allow portions of their owned spectrum to be used by SUs [4,5,6,7,8]. However, spectrum pool requires negotiation between SUs and PUs and SUs must pay a certain amount of rent to use the leased spectrum. Previous work in this area has defined that channels have similar propagation and channel quality characteristics, i.e., defined as *homogeneous*. But in CR networks, channels may be located in widely separated frequency bands and would show significant heterogeneity in transmission range, channel error rate, path-loss, link layer delay, etc. In [9], Ma and Tsang firstly assumed the different channels support different transmission ranges on the spectrum sharing, and found the performance of spectrum sharing is highly dependent on the channel heterogeneity. But their SUs were assumed to be static and the set of available channels at each SU, once assigned, did not change with time.

In this paper, we propose a spectrum sharing algorithm based on channel heterogeneity for CR infrastructure-based network. SUs may be static or mobile. Spectrum pooling is not adopted, and the CR base station (CR-BS) detects the spectrum holes in a manner similar to the function undertaken by the SUs. Because of different transmission ranges, a channel can be used by a SU to communicate with CR-BS only when it is available at the locations of both SU and CR-BS, and also, the SU must be within the transmission range of the CR-BS for that particular channel. Compared with static SUs, moving SUs require more channel handoffs. In order to decrease the amount of channel handoffs and promote fairness for the SUs distant from the CR-BS, channel occupation time, position weight and fairness factor are used as spectrum sharing criteria. These metrics are used to define a utility function, and the final objective of dynamic channel allocation is to maximize the total utility of system. The simulation results show that the proposed spectrum sharing algorithm can remarkably decrease the amount of handoffs and the spectrum utilization can be guaranteed.

The rest of this paper is organized as follows. In Section II, the CR system model and functionality analysis are presented. The channel sharing algorithm is described in Section III. Section IV presents the numerical results. Finally, Section V concludes the paper.

II. SYSTEM MODEL AND FUNCTIONALITY ANALYSIS

A. System Model

In the centralized CR network, CR-BS is adopted as the centralized entity. The network architecture is given in Fig. 1. In the system, different types of channels have different transmission ranges. Both CR-BS and SU are required to detect the channel. SUs can be mobile or static, and can only communicate with CR-BS in a single hop.

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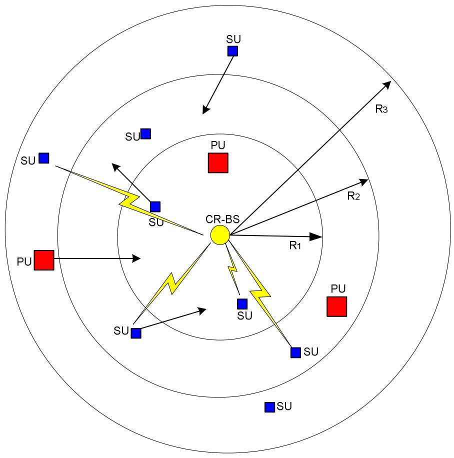

Figure 1. The structure of the centralized CR network with $L=3$

There are M channels, denoted by the set of C and the cardinality $|C| = M$. All these channels are classified into L types according to different transmission ranges. The set of each type of channels can be indicated by C^l, where $l = 1, 2, \cdots, L$. Meanwhile, all these channels can be detected by each SU and CR-BS at any position in the network. Let C_i denotes the set of available channels observed by SU i and M_i denotes the number of available channels detected. We have $C_i \subseteq C$ and $|C_i| = M_i \le M$. The C_i can be further divided into C_i^l , where $C_i = \bigcup_{l=1}^{L} C_i^l$.

In the rest of this paper, variable $\boldsymbol{l}$ denotes a given type of channels with a certain transmission range R_l, variable $\boldsymbol{i}$ denotes a given SU or PU. A channel only serves a user.

In addition, there are L types of PUs in the network and the PUs of type l can only use channels of type l accordingly. Thus, each of the available channels may be reclaimed by the PUs. When a PU of type l is active in a given position and there is no idle channel of type l, if there is a channel of type l used by a SU near the PU, the SU must vacate the channel for the PU immediately.

B. *Functionality Analysis*

For the sake of analytical convenience, we define L=3, the transmission ranges of three types of channels are R_1, R_2, R_3, respectively, which is described in Fig. 1. It is clear there are three layers for the CR-BS, which are: outside layer, intermediate layer and insider layer.

From the Fig.1, it is apparent that although SU i at the outside layer detects that there are many available channels C_i, only the set of C_i^3 with the longest transmission range can be used to communicate with CR-BS. But if SU i is at the inside layer, all the three types of channels can be allocated to access to CR-BS, which are C_i^1 , C_i^2 and C_i^3 . So, with increasing distance from CR-BS, the SUs have fewer channels to communicate with CR-BS. In order to offer comparatively fair opportunity to these SUs far from CR-BS, a location weight will be set in the system.

SUs are static, slow moving and fast moving. If there is a channel available for both a mobile SU and CR-BS, and the distance between the SU and CR-BS is less than the transmission distance of the channel, then the channel can be used. For example, if a SU at the inside layer is moving towards the outside layer and using a channel of C^1, channel handoff will be required quickly. Therefore, apart from the appearance of active PUs, the mobility can also result in channel handoffs. In order to decrease the total amount of channel handoffs as much as possible, channel occupation time will be calculated before allocation, and the channel with longer occupation time will be prior to be allocated.

III. SPECTRUM SHARING ALGORITHM

A. *Channel Occupation Time*

At the wireless hot-spots, efficient frequency reuse by dividing a large (macro) cell into number of small (pico) cells is one of the most effective ways to increase system capacity [10, 11]. As a result, the transmission range of spectrum in small cells is short. Taking into account this, the moving direction and velocity of mobile SU during communication are assumed to be unchangeable in the CR network.

For a given available channel, the transmission range is R. α is the angle between the moving direction of SU and CR-BS, where $0 \le \alpha \le \pi$; s is the distance between SU and CR-BS, where $0 < s \le R$; variable d denotes total travel distance using the given channel, where $0 \le d \le 2R$. The velocity of SU is v.

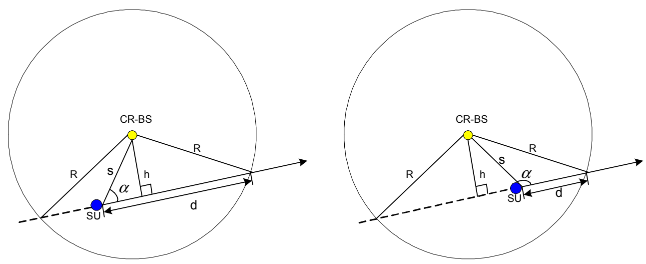

Figure 2. Model of moving distance calculation

According to the Fig. 2, the channel occupation time t_c with transmission distance R can be computed by

$$h = s \cdot \sin\alpha , \quad 0 \le \alpha \le \pi \tag{1}$$

$$d = \sqrt{R^2 - h^2} + s \cdot \cos\alpha , \quad 0 \le \alpha \le \pi \tag{2}$$

$$t_c = d / v \tag{3}$$

In the later part of this paper, the channel allocation is mainly based on the occupation time t_c. Through the above t_c calculation equation (3), when a SU is static, v =0, then $t_c = \infty$. As a result, the mobile SUs will be ever allocated channels after the static SUs, which is unfair to mobile SUs. So the t_c of static SUs must be set to a reasonable value. Because the minimum velocity will be set to be 1m/s in the simulation and the longest travel distance is $2R_3$, so the longest occupation time for a mobile SU can only be $2R_3$. Therefore, we use the following approach to calculate t_c.

$$t_{c,i}^{l} = \begin{cases} d/v, & if \quad v \geq 1m/s \\ 2R_3, & stationary \end{cases} \tag{4}$$

Where *i, l* denote the code number of SU and the type of channel, respectively. The channels of same type have same t_c.

B. Location Weight

From the functionality analysis in the Section II, we know that SUs at the outside layer have few available channels to communicate with CR-BS compared with the SUs at the middle layer and inside layer. In addition, once the channels of C^3 are allocated to the mobile SUs moving from the inside layer toward the outside layer, the SUs far from CR-BS have fewer channels to use. So channel allocation should be related to the position, and hence, the concept of *location weight* is introduced in the channel allocation algorithm.

The location weight is defined as w_p^l, where l indicates the type of channels, p is the location code number of SU, $p = 1, 2, 3$, which present inside layer, middle layer and outside layer, respectively. If a SU is at the outside layer, p=3, only C^3 can be used to access to CR-BS. If a SU is at middle layer, p=2, C^2 and C^3 can be used. However, for a SU at the middle layer, in order to give opportunities to SUs at outside layer to communicate, C^2 maybe have priority to be allocated. So at a given position, the SU's different types of channels detected have a certain values of w_p^l. For the three types of channels in this system, the values of w_p^l at three different layers give a weight matrix $\boldsymbol{w}$, the dimension of which is 3×3. The row indicates position p and column is the type of channel.

$$w = \begin{bmatrix} 1 & 0.5 & 0.25 \\ 0 & 1 & 0.5 \\ 0 & 0 & 1 \end{bmatrix}$$

C. Fairness Factor

The calculation of t_c for static SUs and location weight can positively solve access fairness problem to some extent. However, if the channel allocation is implemented completely according to the t_c, the static SUs and the SUs near to CR-BS still have more opportunities to be allocated channels. Hence, a fairness factor f_i is defined to further improve the fairness.

$$f_i = \frac{N_{block} + 1}{N_{access} + 1}$$

where N_{access} indicates the times of successfully obtaining channels to connect to the CR-BS, and N_{block} has opposite meaning. If a static SU has connected to CR-BS several times, the value of f_i is small, then the next time this SU has low chance to obtain channel. When $N_{block}= N_{access}$, which means f_i =1, then let $N_{block}= N_{access}$ =0.

D. Utility Function

In terms of distance between SU and CR-BS, we define ϕ_i^l to present whether the available channels of type l detected by SU i can be used to communicate with CR-BS or not.

$$\phi_i^l = \begin{cases} 1, & if \quad d_{i \to CR-BS} \leq R_l \\ 0, & if \quad d_{i \to CR-BS} > R_l \end{cases}$$

where $d_{i \to CR-BS}$ denotes the distance between the SU i and CR-BS, R_l is the transmission range of channels of type l.

If the channel occupation time t_c is very short, the channel handoff will appear quickly. So the amount of handoffs will increase in the system accordingly. Define β_i^l and set an occupation time threshold t_{th} to avoid this type of channel handoffs as much as possible.

$$\beta_i^l = \begin{cases} 1, & if \quad t_{c,i}^l \geq t_{th} \\ 0, & if \quad t_{c,i}^l < t_{th} \end{cases}$$

From the expression, for a given SU i, only the occupation time of channel of type l is not shorter than the threshold time, the type l can be possibly allocated to the SU i.

Only when a given channel j belonging to type l is detected available by SU i and CR-BS simultaneously, the channel j will be possibly allocated to SU i, which can be presented by

$$\gamma_i^{l,j} = \begin{cases} 1, & if \text{ channel } j \text{ is available for both SU } i \text{ and CR - BS}, \\ 0, & otherwise \end{cases}$$

According to these defined parameters, only when $\phi_i^l = \gamma_i^{l,j}$ =1, the channel j of type l can be used. In fact, this also denotes that only parts of the detected channels can be allocated. If SU i has a set of available channels detected, where C_i composed of C_i^l, the amount of channels $C_{i,avai}$ that can be practically used to communicate with CR-BS in single hop will be

$$C_{i,avai} = \bigcup_{l=1}^{3} \left[\bigcup_{j \in C_i^l} \left(C_i^{l,j} \cdot \gamma_i^{l,j} \cdot \phi_i^l \cdot \beta_i^l \right) \right] \tag{5}$$

At last, the utility function of channel j of type l for the SU i is defined as

$$u_i^{l,j} = \phi_i^l \cdot \gamma_i^{l,j} \cdot \beta_i^l \cdot w_p^l \cdot f_i \cdot t_{c,i}^l \tag{6}$$

E. Channel Allocation

For SU i, the aim is to find the channel j^* with maximum utility value.

$$j^* = \arg\max\left(u_i^{l,j}\right)$$

For the whole system, the aim is to maximize the total utility of system, which is

$$\max \sum_{j\in C_{CR-BS}} u_i^{l,j}$$

Thus, the CR-BS needs to find out the optimum approach to allocate available channels C_{CR-BS} to different SUs.

IV. NUMERICAL RESULTS

In this section, we employ a simulation model to evaluate the performance of our spectrum sharing algorithm. In the centralized CR network, PUs randomly appear in a 4000× 4000m^2 area and there is a CR-BS located at the central of this area. There are 12 channels classified into 3 types with the transmission range set as 100, 300, 1000 m, respectively. Among each type of channels, only half channels are licensed channels and other half are unlicensed channels. There are 30 SUs distributed around the CR-BS at the radius of 1000 m. The probability of moving SUs is 1/2, the velocity of mobile SUs is uniformly distributed from 1m/s to 20m/s. The range of moving direction α is $[0, 2\pi)$ and the probability of α is $1/2\pi$. When SUs move toward outside and reach the remote edge, they can change the velocity and direction to be kept in the range. The occupation time threshold t_{th} is 10s.

The arrival of SUs and PUs follows a Poisson distribution with the mean λ. The call holding or "on" time is assumed to be exponentially distributed with a fixed mean of $1/\mu = 60s$.

The spectrum sharing algorithm presented in this paper is henceforth called as *scheme 2*. For comparison purposes, we present another spectrum sharing method called *Scheme 1*, in which only position weight is considered, but the channel occupation time and fairness are not employed.

From Fig. 3, we find that if λ_{PU} is fixed and λ_{SU} changes, the cumulative amount of handoffs required by SUs increases along with the simulation time, and the amount of handoffs in scheme 2 is lower than that in scheme 1. This is because in scheme 2 the allocated channel will be used for a comparatively longer time, which causes the aggregate handoffs to decrease. Fig. 4 shows that the times of handoffs forced termination in scheme 2 is also lower than the times in scheme 1.

In scheme 2, a channel satisfied $t_c \geq t_{th}$ can be allocated to a new SU. In Fig. 5, as a cost, the blocking probability of new SUs in scheme 2 is higher than that in scheme 1, but overall, it is just a bit lower. In terms of channel utilization, scheme 2 and scheme 1 have almost same performance, which can be seen from Fig. 6. From these experiment results, it can be found that the proposed spectrum sharing algorithm can efficiently decrease the amount of handoffs and guarantee the spectrum utilization.

In Fig. 7, for the scheme 2, when λ_{PU} increases and λ_{SU} is fixed, the amount of channel handoffs required by SUs will increase accordingly. This is because more PUs is active, SUs need to vacate more channel for PUs and also demand channel handoffs to keep the communication with CR-BS. However, in Fig. 8, when λ_{SU}=0.3 and λ_{PU} increases, the blocking probability of SUs does not increase in same order. In addition, from Fig.9, we can find that when more PUs are operational, the channel utilization will be higher. This is because some PUs can use same channels of type 1 and 2 simultaneously around CR-BS.

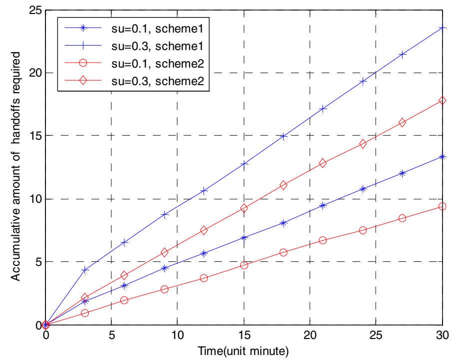

Figure 3. The accumulative amount of handoffs required by SUs when λ_{PU}=0.1

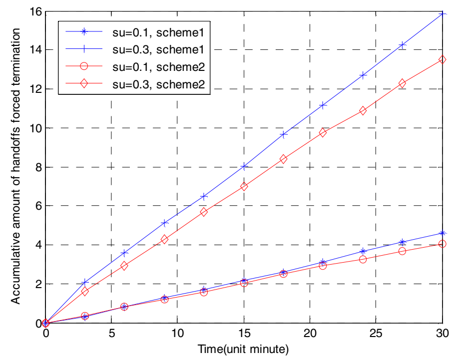

Figure 4. The accumulative amount of handoffs forced termination for SUs when λ_{PU}=0.1

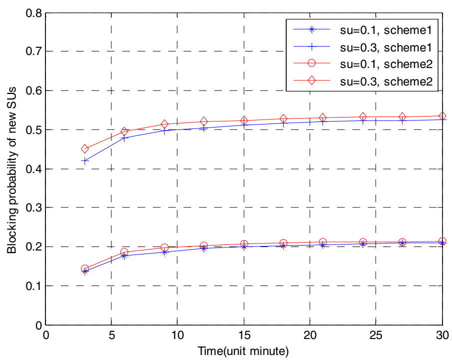

Figure 5. The blocking probability of new SUs when λ_{PU}=0.1

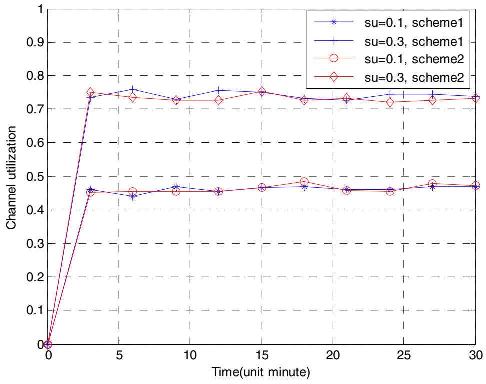

Figure 6. The channel utilization when λ_{PU}=0.1

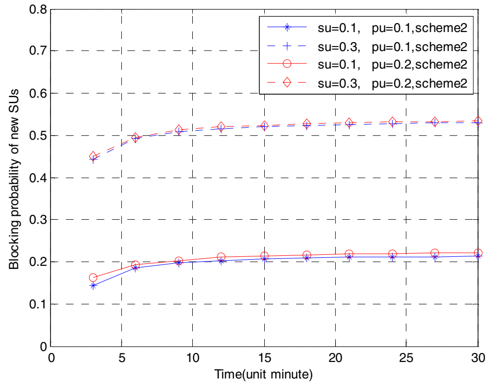

Figure 8. The blocking probability of new SUs in scheme 2 when both λ_{PU} and λ_{SU} change

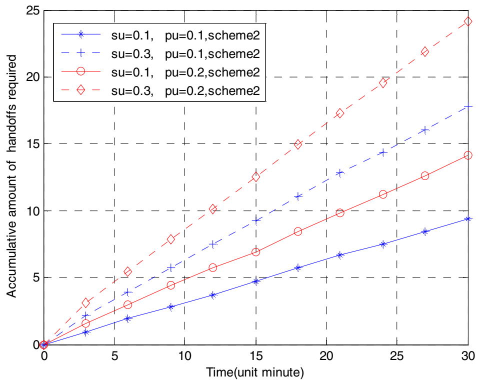

Figure 7. The accumulative amount of handoffs required by SUs in scheme 2 when both λ_{PU} and λ_{SU} change

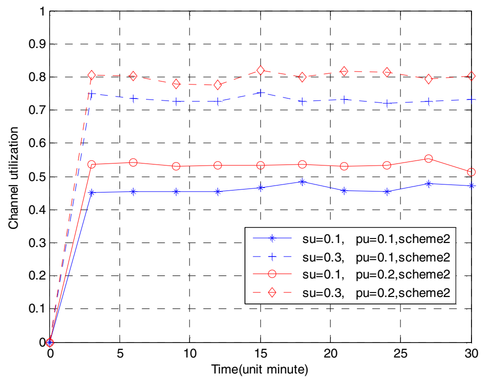

Figure 9. The channel utilization of scheme 2 when both λ_{PU} and λ_{SU} change

V. CONCLUSION

In this paper we proposed a spectrum sharing algorithm for centralized cognitive radio networks. In the CR networks, spectrums have different transmission ranges and SUs are static or mobile. The utility function considered the channel occupation time, position and fairness factor. CR-BS allocated the available channels to obtain the maximum total utility of system. Experiments results showed that the presented scheme can decrease the amount of spectrum handoffs, and other performances can also be guaranteed. The limitation of the centralized network is that the SUs far from CR-BS have less available channels. In the next step of this research we will employ jointly CR ad hoc technology in the centralized CR networks, in which out-of-range SUs can communicate with the nearest in-range node over multi-hop, leading to heterogeneous ad hoc and infrastructure CR network.

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