Joint Spectrum and Power Allocation for Inter-Cell Spectrum Sharing in Cognitive Radio Networks

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***Abstract*—Cognitive radio (CR) networking achieves high utilization of the scarce spectrum resources without causing any performance degradation to the licensed users. Since the spectrum availability varies over time and space, the infrastructure-based CR networks are required to have a dynamic inter-cell spectrum sharing capability. This allows fair resource allocation as well as capacity maximization and avoids the starvation problems seen in the classical spectrum sharing approaches. In this paper, a joint spectrum and power allocation framework is proposed that addresses these concerns by (i) opportunistically negotiating additional spectrum based on the licensed user activity (exclusive allocation), and (ii) having a share of reserved spectrum for each cell (common use sharing). Our algorithm accounts for the maximum cell capacity, minimizes the interference caused to neighboring cells, and protects the licensed users through a sophisticated power allocation method. Simulation results reveal that the proposed inter-cell spectrum sharing framework achieves better fairness and higher network capacity than the conventional spectrum sharing methods.**

I. INTRODUCTION

Today's wireless networks are characterized as a static spectrum assignment policy. Recently, due to the increase in spectrum demand, this policy is faced with spectrum scarcity at particular spectrum bands. On the contrary, a large portion of the assigned spectrum is still used sporadically leading to under-utilization of the significant amount of spectrum [1]. Hence, dynamic spectrum access techniques are recently proposed to solve these spectrum inefficiency problems.

The key enabling technology for dynamic spectrum access techniques is the cognitive radio (CR) networking that allows intelligent spectrum-aware devices to opportunistically use licensed frequency bands for transmission. In order to share wireless spectrums with the licensed (primary) users, the unlicensed (cognitive radio) users need to continuously monitor the spectrum for the presence of the primary users and reconfigure the RF front-end according to the demands and requirements of the higher layers. These capabilities can be realized by designing the following spectrum management functions [2]: (1) Determine the portions of the spectrum currently available (spectrum sensing), (2) select the best available channel (spectrum decision), (3) coordinate access with other users for this channel (spectrum sharing), and (4) effectively vacate the channel when a primary user is detected (spectrum mobility).

Among the above spectrum management functions, the spectrum sharing plays an important role in determining the performance of the CR network. Especially in the infrastructure-based CR networks, the total network capacity mainly depends on the spectrum allocation among base-stations, called *inter-cell spectrum sharing*. Recent research on spectrum sharing has explored two different sharing models: *exclusive allocation* and *common use*. The *exclusive allocation* allows the CR user to use the spectrum exclusively to its neighbor users. Although the exclusive approach is known to be optimal [3], it has unfair resource allocation, especially in CR networks where the spectrum availability varies significantly over time and location. On the contrary, the *common use approach* enables each CR user to share the same spectrum with its neighbors, mainly focusing on a sophisticated power allocation method [3], [4]. Although this method can mitigate the unfairness in resource allocation, it achieves lower total capacity than the exclusive allocation due to the existence of higher inter-user interference. Since most of the research on spectrum sharing has focused on only one sharing model (either exclusive or common use models), spectrum and power allocations have not been considered together to date. With either of these approaches, the infrastructure-based CR network cannot achieve its objectives, high spectrum utilization and fair resource allocation with interference avoidance.

To address these challenges, we propose an inter-cell spectrum sharing framework for infrastructure-based CR networks in this paper. More specifically, in this framework, each cell can exploit the exclusive and common use approaches dynamically according to the spectrum utilization in its vicinity. In the exclusive allocation, the base-station determines the spectrum band having the highest expected cell capacity. This is characterized by the permissible transmission power based on the primary user activities. If there is no spectrum available for the exclusive allocation, our framework switches to the common use approach where spectrum selection is based on the interference and primary user activities in the neighbor cells. This helps to realize 1) maximum cell capacity, 2) less influence to neighbor cells, and 3) interference-free uplink transmission. Furthermore, in order to protect the transmission of primary networks, the inter-cell spectrum sharing necessitates the sophisticated power allocation in both exclusive

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and common use methods. To this end, we propose a joint spectrum and power allocation method where transmission power can be determined so as to maximize the cell capacity as well as to avoid interference to primary networks through transmission power constraints.

The rest of the paper is organized as follows: In Section II, we describe the limitations of conventional spectrum sharing methods and motivate the joint spectrum and power allocation approach. Sections III and IV present the network architecture and our proposed framework for inter-cell spectrum sharing, respectively. In Sections V and VI, we propose the spectrum allocation methods for exclusive and common use models, respectively. In Section VII, we explain the proposed joint spectrum and power allocation method. Performance evaluation and simulation results are presented in Section VIII. Finally, conclusions are presented in Section IX.

II. MOTIVATION

In this section we present conventional spectrum sharing methods, and describe the practical considerations for inter-cell spectrum sharing which are the motivations of our proposed work.

A. Related Work

Spectrum sharing has been considered as the main functionality to determine the total capacity of CR networks [2]. There are two different classical approaches in spectrum sharing: spectrum allocation for the exclusive model and the power allocation for the common use model, which will be explained in the following subsections.

1) Exclusive Allocation Approach: The spectrum resource can be assigned to only one user to avoid interference to other neighbor users. In [5], a graph coloring based collaborative spectrum access scheme is proposed, where a topology-optimized allocation algorithm is used for the fixed topology. In mobile networks, however, the network topology changes due to the node mobility. Using this global optimization approach, the network needs to completely recompute spectrum assignments for all users after each change, resulting in a high computational and communication overhead. Thus, a distributed spectrum allocation based on local bargaining is proposed in [6], where CR users negotiate spectrum assignment within local self-organized groups. For the resource constrained networks such as sensor and ad hoc networks, a rule-based device centric spectrum management is proposed, where CR users access the spectrum independently according to both local observation and predetermined rules, leading to minimizing the communication overhead [7].

2) Common Use Approach: This solution allows multiple users to access the same spectrum at the same time. Thus, in this approach, power allocation is the most important part to increase the capacity with less interference to other users. Game theory has been exploited to determine the transmission power of each user [3], [8]. Although this approach can achieve the Nash equilibrium, it cannot guarantee the Pareto optimum, leading to lower network capacity compared to the exclusive allocation model. In [3], orthogonal power allocation, i.e., exclusive allocation, is shown to be optimal to maximize the entire network capacity. However, the common use model achieves more fair resource allocation, especially in networks with few available spectrums. In [4], a centralized power allocation method is proposed that uses a spectrum server to coordinate the transmissions of a group of links sharing a common spectrum. In [9], both single channel and multi-channel asynchronous distributed pricing (SC/MC-ADP) schemes are proposed, where each node announces its interference price to other nodes. Using this information from its neighbors, the node can first allocate a channel and in case there exist users in that channel, then, determine its transmit power. While both methods consider the spectrum and power allocation at the same time, they do not address the heterogeneous spectrum availability which is a unique characteristic in CR networks.

B. Considerations in Infrastructure-based CR Networks

Recent work on spectrum sharing has mainly focused on the distributed ad-hoc networks. However, the infrastructure-based CR networks have unique challenges which have been unexplored so far. Since infrastructure-based networks consist of multiple cells, we need to consider not only spectrum sharing inside one cell, i.e., among users, called *intra-cell spectrum sharing* but also spectrum sharing among multiple cells, called *inter-cell spectrum sharing*. Furthermore, the infrastructure-based networks require more strict fairness in resource allocation so as to provide communication channels to their users with the guaranteed service quality. Here are several practical issues we need to consider for the inter-cell spectrum sharing.

1) Heterogeneous Resource Availability: The main difference between conventional wireless networks and CR networks lies in the primary user activities. Since CR networks do not have spectrum license, they exploit the spectrum opportunistically and vacate the spectrum immediately when a primary user appears. According to the time and location, each cell experiences different primary user activities, leading to the heterogeneous resource availability. Also the number of neighbor cells influences the performance of spectrum sharing. Figure 1 shows the number of available spectrum bands at each cell in the network topology used for our simulations in Section VIII. The spectrum band is available only when all primary user activity regions in the cell are idle. Thus, the expected number of available spectrum bands at a cell j can be expressed as $\sum_{i=1}^{N}[\prod_{k\in\mathcal{K}_i(j)} P_i^{\text{off}}(k)]$ where N is the total number of spectrum bands, $P_i^{\text{off}}(k)$ is the probability that the spectrum i is idle at the primary activity region k, and $\mathcal{K}_i(j)$ is a set of primary activity regions in the cell j at spectrum i. This shows the spectrum availability of the common use approach. If the exclusive approach is used for spectrum sharing, the number of neighbor cells competing for the same spectrums should be considered as well. In [6], the lower bound of available spectrum resource, the so-called *poverty line*, is derived as $[\sum_{i=1}^{N}(\prod_{k\in\mathcal{K}_i(j)} P_i^{\text{off}}(k))]/(L+1)$ where L is the number of neighbor cells. As shown in Figure 1, according to the cell locations, the spectrum availability varies significantly. Furthermore, it shows different patterns in both common use and exclusive approaches. For the efficient spectrum utilization, we need to mitigate this heterogeneous spectrum availability by exploiting common use and exclusive approaches dynamically, i.e., in the limited spectrum environment, the common use approach helps to increase fairness in user capacity while the exclusive approach is much advantageous in the environment with sufficient spectrum resources.

2) Inter-Cell Interference: Since the interference range is generally larger than the transmission range [10], the transmission in the current cell influences its neighbor cells. For this reason, although the current cell does not detect any primary user activity in its transmission range, its transmission may cause interference in the neighbor cell detecting primary user activities. The simplest way to avoid this problem is not to use the spectrum where neighbor cells detect the transmission of primary networks. If we consider this constraint in the exclusive model, the available spectrum resources become lower as shown in Figure 1. Therefore, while the exclusive model is theoretically optimal, it shows an inefficient spectrum utilization in CR networks. In order to avoid this problem while satisfying interference condition, the exclusive allocation is also required to have a power allocation method adaptive to spatial and temporal characteristics of primary user activities.

3) Imperfect Knowledge of Neighbor Cells: Most of the power allocation schemes based on the common use approach assume that every CR user or a central network entity is aware of all radio information such as the channel gains of all possible links and all interference information in the networks [4], [9]. However, in the infrastructure-based networks, it is impossible to obtain all necessary information for power allocation since there is no direct communication channel among CR users located in different cells. In order to get the information of neighbor cells, inter-cell spectrum sharing requires a cooperation mechanism among the cells. In addition, for a more practical spectrum sharing method, we need the cell capacity estimation with the minimum amount of information exchanged with neighbor cells.

III. SYSTEM MODEL

A. CR Network Architecture

In this paper, we consider the infrastructure-based CR network which has centralized network entities such as a base-station in cellular networks or an access point in wireless LANs[1]. CR base-stations form a cell and have their own users which are uniformly distributed in their coverage. In order to detect the transmission of primary networks, all CR users observe their local radio information and report them to their base-station. Based on these local measurements, CR base-stations determine the spectrum availability and allocate the spectrum resource to CR users [11].

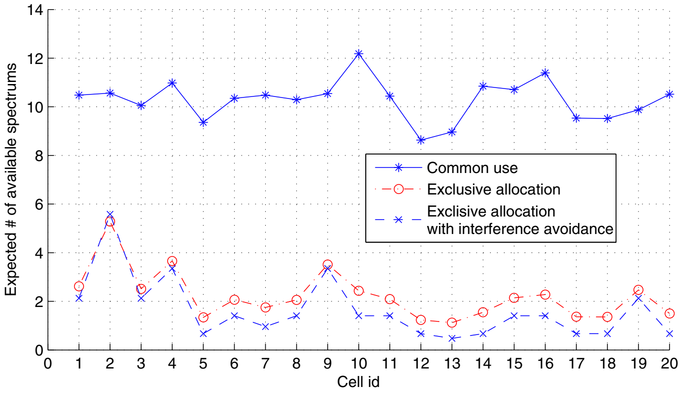

Fig. 1. Available spectrum bands at different locations

Figure 2 shows the network model we consider in this paper where each base-station j has its transmission range with radius $R(j)$. Here the transmission range (or cell coverage) is defined as the range within which a transmitted signal should be successfully received [10]. Each cell considers the cells in its interference range as its neighbors. The interference range is the area within which other unrelated users will be interfered by the transmission of the current cell [10]. In this architecture, each base-station is assumed to be aware of the information of its neighbors (radius, location of the base-station, etc) and capable of communicating with its neighbor base-stations.

For the bi-directional communication, we assume CR networks use time-division duplex (TDD) which has been adopted in an IEEE 802.22 [12]. Thus, CR networks have separate time frames for uplink and downlink transmissions in the same spectrum band. Furthermore, each base-station j has the transmission power budget $P^{\rm tot}(j)$ which can be allocated over its spectrum bands. Another important architectural issue in CR networks is how to establish a control channel. The control channel plays an important role in exchanging information regarding sensing and resource allocation. Several methods are presented in [13], one of which is assumed to be used as the common control channel in our proposed method.

B. Primary Network Model

All spectrum bands CR networks can access are assumed to be licensed to different primary networks. We assume that the PU activity of spectrum i at PU activity region k can be modeled as a two state birth-death process with death rate $\alpha_i(k)$ and birth rate $\beta_i(k)$. An ON (Busy) state represents the period used by PUs and an OFF (Idle) state represents the unused period [11], [14], [15], [16]. Since each user arrival is independent, each transition follows the Poisson arrival process. Thus, the length of ON and OFF periods are exponentially distributed [17]. Based on this model, busy and idle probabilities of the spectrum i can be obtained as follows:

$$P_i^{\rm on}(k) = \frac{\beta_i(k)}{\alpha_i(k)+\beta_i(k)}, \quad P_i^{\rm off}(k) = \frac{\alpha_i(k)}{\alpha_i(k)+\beta_i(k)} \quad (1)$$

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[1] In the remainder of the paper we will use the term base-station to refer to the central network entity

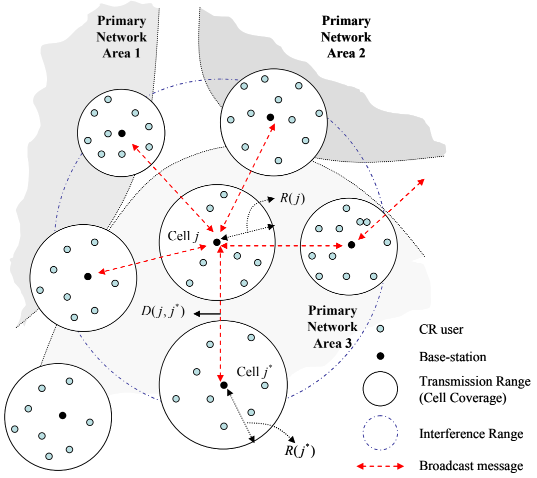


Fig. 2. Network Architecture

Here we assume that the CR network has M available licensed bands and is already aware of PU activities. Furthermore, each spectrum band can have multiple PU activities according to the location as illustrated in Figure 2.

IV. INTER-CELL SPECTRUM SHARING FRAMEWORK

A. Overview

As explained in Section II-B, infrastructure-based CR networks are required to provide two different types of spectrum sharing schemes: *intra-spectrum sharing* and *inter-spectrum sharing*. In order to share spectrum efficiently, CR networks necessitate a unified framework to support cooperation among inter- and intra-cell spectrum sharing schemes and other spectrum management functions. Figure 3 shows the proposed framework for spectrum sharing in infrastructure-based CR networks, which consists of *inter-cell spectrum sharing*, *intra-cell spectrum sharing*, and *event monitoring*.

1) Event Monitoring: The event monitoring has two different functionalities. One is to detect the PU activities, called *spectrum sensing*. Here we assume periodic sensing which has separate time slots for sensing and transmission [11]. In addition, CR users monitor the quality-of-service (QoS) of their transmission. According to the detected event type, the base-station determines the spectrum sharing strategies and allocates the spectrums to each user adaptively based on the radio environments.

2) Intra-Cell Spectrum Sharing: The intra-cell spectrum sharing enables the base-station to avoid the interference to the primary networks as well as to maintain the QoS of its CR users by allocating spectrum adaptively based on the event detected inside its coverage area. If a new CR user appears in this cell, the base-station determines its acceptance and selects the best available spectrum band if it is admitted. Furthermore, when some of its CR users cannot maintain the guaranteed QoS or lose their connections due to the PU activities, the base-station should re-allocate the spectrum resource to them immediately. Also a CR MAC protocol is required to allow multiple CR users to access to the same spectrum band. The intra-cell spectrum sharing has been widely investigated before [15], [12], [16], [18], [19] and is out of the scope in this paper.

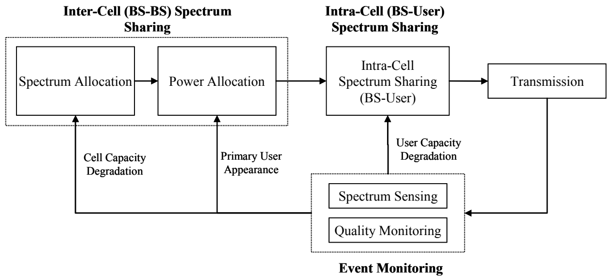


Fig. 3. Inter-cell spectrum sharing framework

3) Inter-Cell Spectrum Sharing: In CR networks, the available spectrum bands vary over time and space which makes it difficult to provide reliable spectrum allocation. In the infrastructure-based CR networks, the inter-cell interference also needs to be considered in spectrum sharing so as to maximize the network capacity. In the proposed framework, the inter-cell spectrum sharing is comprised of two subfunctionalities: *spectrum allocation* and *power allocation*. When the service quality of the cell becomes worse or is below the guaranteed level, the base-station initiates the inter-cell spectrum sharing and adjusts its spectrum allocation. In the *spectrum allocation*, the base-station determines its spectrum bands by considering the geographical information of primary networks and current radio activities. Here the inter-cell spectrum sharing exploits both *exclusive allocation* and *common use* approaches adaptively based on time-varying radio environment. After that, in the *power allocation*, the base-station determines the transmission power of its assigned spectrum bands so as to maximize the cell capacity without interference to the primary network. In this paper, we mainly focus on the inter-cell spectrum sharing among all functionalities described here.

B. Distributed Sharing Method

Since each cell has a base-station, intra-cell spectrum sharing can be implemented in a centralized manner. However, it is not practical to develop the inter-cell spectrum sharing as a centralized method due to the scalability problem. Furthermore, an additional network entity is required to coordinate resource allocation over the entire network. Instead, we introduce a distributed method for the inter-cell spectrum sharing.

For distributed sharing, each cell should be aware of the exact information of its neighbor cells. As mentioned in Section II-B, however, it is not feasible for the CR user to obtain all the necessary information from other users located in the other cells. Instead, in the proposed method, the base-station exchanges local cell information with its neighbor base-stations through the broadcast messages, called the distributed spectrum sharing messages (DSSMs). This message is assumed to be transmitted through the dedicated control channel.

Each base-station broadcasts the DSSM to its neighbor cells periodically. Any conventional distributed MAC protocols can be used for the transmission of DSSMs. The DSSM can be used not only to exchange sensing and interference information but also to announce the initiation of spectrum sharing. Once receiving the DSSM with spectrum sharing initiation, the cell prohibits itself and its neighbors from initiating another spectrum sharing procedure until it receives the sharing completion message, which enables the conflict-free sharing in the multi-cell environment. The following information are conveyed through the DSSMs:

- *Spectrum availability:* The base-station determines the availability of all spectrum bands in its transmission range by considering the sensing information of its users and broadcasts this availability to its neighbor base-stations. Furthermore, the base-station needs to announce its current spectrum utilization to its neighbor cells, which can be considered for their spectrum allocation.
- *Minimum busy interference $I_i^{\min}(j)$:* Local information measured in the neighbor cells is essential to estimate the influence on the neighbor cells when a current cell uses a certain spectrum. However, it is not practical to exchange all local information with its neighbors. To reduce the communication overhead, we use a single representative information among all sensing results. When the PU activity is detected in spectrum i, the base-station j sends the minimum signal strength among all sensing data observed in its users, which represents the primary signal strength plus interference at the border of the PU activity.
- *Maximum idle interference $I_i^{\max}(j)$:* If no PU activity is detected at spectrum i, the base station j sends the maximum value among the interference measured in its users. Unlike $I_i^{\min}(j)$, this value is observed during the transmission period, instead of the sensing period, and hence mainly comprised of the interference from other CR neighbors and noise. Since there is no interference source within its transmission range, the maximum idle interference is likely to be measured at the border of its coverage.

Above information are used for spectrum and power allocations which will be explained in Sections V, VI, and VII.

V. SPECTRUM ALLOCATION FOR AN EXCLUSIVE MODEL

In wireless communications, the interference range is known to be larger than the transmission range [10]. Thus, for the interference-free communications, spectrum band needs to be allocated exclusively to each cell not to be overlapped with the spectrums of its neighbors, which is the traditional approach to avoid interference in cellular networks. However, as described in Section II, the traditional exclusive approach is not suitable to CR networks, leading to inefficient and unfair spectrum utilization. To solve these problems, we propose a novel spectrum allocation to improve the spectrum availability in the exclusive model by considering the permissible transmission power derived from spatio-temporal characteristics of the PU activity. To simplify the representation, the important symbols used in the subsequent discussion are summarized in Table I.

TABLE I
SYMBOLS USED FOR THE ANALYTICAL MODELING

Symbols	Descriptions
N	Total number of spectrum bands
W_i	Bandwidth of spectrum i
$P^{\mathrm{tot}}(j)$	Total transmission power budget of CR cell j
$P_i^{\max}(j)$	Maximum permissible transmission power of CR cell cell j at spectrum i
$P_i^{\mathrm{pu}}(j,k)$	PU restricted power of CR cell cell j at spectrum i and region k
$P_i(j)$	Transmission power assigned to spectrum i in cell j
$R(j)$	Radius of CR cell j
$P_i^{\mathrm{off}}(k)$	Idle probability of spectrum i at region k
P_{temp}	Interference temperature of spectrum i
$I_i^{\max}(j)$	Maximum idle interference measured at spectrum i of cell j
$I_i^{min}(j)$	Minimum busy interference measured at spectrum i of cell j
$D(j,j^*)$	Distance between base-stations of cell j and j^*

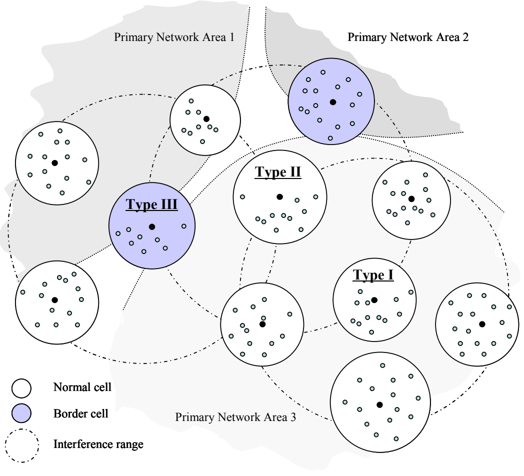


Fig. 4. Cell characterization

A. Cell Characterization

As we explained in Section II, even in the same spectrum band, PU activities show different characteristics according to the location. Based on this spatial characteristic of PU activities, the cells in CR networks can be classified as a *normal cell* and a *border cell*. While the normal cell has the same PU activity region inside its transmission range, the border cell is placed at the border of the PU activity region, and hence has multiple PU activities as shown in Figure 4. In the proposed method, according to the types of cells in the interference range, we classify three different scenarios for exclusive spectrum allocation as shown in Figure 4.

Type I. No border cell in the interference range: In this case, all cells in the interference range are placed in the same PU activity region, i.e., the spectrum availability is identical over all cells. If no primary user is detected in a type I cell j, the base-station can transmit on spectrum i with the maximum power $P_i^{\max}(j)$. Otherwise the transmission power is zero. Thus, the probabilities $\Pr(\cdot)$ of both cases can be derived as follows:

$$\begin{aligned} &\Pr(P_i^{\max}(j)) = P_i^{\mathrm{off}}(k') \\ &\Pr(0) = 1 - P_i^{\mathrm{off}}(k') \end{aligned} \tag{2}$$

where k' is the PU activity region in the interference range.

Type II. Border cells in the interference range: Some of the neighbors are border cells, which can restrict the transmission power of the current cell even though no PU activities are detected in its transmission range. If the cell j has n PU activity regions in its interference range, it can have n different permissible transmission powers including one maximum transmission power $P_i^{\max}(j)$ and $n-1$ powers $P_i^{\mathrm{pu}}(j,k)$ restricted by a region k.

Let $\mathcal{K}$ be the set of PU activity regions in its interference range, and k' be the region in the transmission range. In the type II, its transmission power can be $P_i^{\max}(j)$ when all PU activity regions in $\mathcal{K}$ are idle. If multiple PU activities are detected in the interference range at the same time, the transmission power is determined by the region which allows the cell to use the smallest transmission power so as not to violate the interference constraint of other regions (More details are explained in Section V-B). Here we define the dominant regions $\mathcal{K}_k^*$ as the set of PU activity regions which allow smaller transmission power than the region k when primary users are detected in all regions. Please note that k' is not included in $\mathcal{K}_k^*$. Then the probabilities of each permissible transmission power can be determined as follows:

$$\begin{aligned}
&\Pr(P_i^{\max}(j)) = \prod_{k\in\mathcal{K}} P_i^{\mathrm{off}}(k)\\
&\Pr(P_i^{\mathrm{pu}}(j,k)) = P_i^{\mathrm{off}}(k')\cdot \prod_{k^*\in\mathcal{K}_k^*} P_i^{\mathrm{off}}(k^*)\\
&\qquad\qquad\cdot(1-P_i^{\mathrm{off}}(k)) \qquad k\in\mathcal{K},\ k\neq k'\\
&\Pr(0) = 1-P_i^{\mathrm{off}}(k')
\end{aligned} \tag{3}$$

As explained in Eq. (3), if all regions in $\mathcal{K}_k^*$ are idle, the region k can determine the transmission power $P_i^{\mathrm{pu}}(j,k)$. In this case, the state of non-dominant regions does not affect the transmission power.

Type III. Border cell in the transmission range : The cell is placed at the border of region with multiple PU activities. The probability of $P_i^{\max}(j)$ is the same as that of Type II. Let the set of PU activity regions in its transmission range be $\mathcal{K}'$. Then the probabilities of $P_i^{\mathrm{pu}}(j,k)$ and zero power can be derived as follows:

$$\begin{aligned}
&\Pr(P_i^{\mathrm{pu}}(j,k)) = \prod_{k'\in\mathcal{K}'} P_i^{\mathrm{off}}(k')\cdot \prod_{k^*\in\mathcal{K}_k^*} P_i^{\mathrm{off}}(k^*)\\
&\qquad\qquad\cdot(1-P_i^{\mathrm{off}}(k)) \qquad k\in\mathcal{K}-\mathcal{K}'\\
&\Pr(0) = 1-\prod_{k\in\mathcal{K}'} P_i^{\mathrm{off}}(k')
\end{aligned} \tag{4}$$

In this case, the CR network can use the spectrum only when all regions in the transmission range are idle.

In the following subsection, we present how to determine the permissible transmission power explained above.

B. Permissible Transmission Power

For efficient spectrum allocation, the CR base-station should be aware of the permissible transmission power at each spectrum preventing the interference to primary networks. This permissible power can be estimated by considering the idle interference $I_i^{\max}(j^*)$ and the busy interference $I_i^{\min}(j^*)$ conveyed in the DSSMs.

When no PU activity is detected in any neighbors of the cell j at spectrum i, the maximum transmission power $P_i^{\max}(j)$ can be used in the cell. Let the power propagation function be $\mathcal{F}(.)$ which is the function of transmission power and the distance between a transmitter and a receiver. Then the maximum transmission power $P_i^{max}(j)$ can be obtained as follows:

$$I_{\triangle}(j^*) = P_{\mathrm{temp}}W_i - I_i^{\max}(j^*), \quad j^*\in\mathcal{N}(j) \tag{5}$$

$$P_i^{max}(j,j^*) = \mathcal{F}^{-1}(I_{\triangle}(j^*), D(j,j^*)+R(j^*)) \tag{6}$$

$$P_i^{max}(j) = \min_{j^*\in\mathcal{N}(j)} P_i^{\max}(j,j^*) \tag{7}$$

where $I_{\triangle}(j^*)$ is the available power for CR users at a neighbor cell j^*, $P_i^{max}(j,j^*)$ is the possible transmission power of cell j derived from $I_{\triangle}(j^*)$, and $\mathcal{N}(j)$ is the set of neighbors of the cell j. In the PU activity region, the total interference should be less than P_{temp}. From this constraint, we can obtain the interference margin, $P_{\mathrm{temp}}W_i - I_i^{\max}(j^*)$ available to CR networks. Since the current cell does not use the spectrum i currently, this interference margin is highly probable to be measured at the farthest border of the neighbor cell j^*. $D(j,j^*)+R(j^*)$ from the current base-station. From this, the maximum possible power $P_i^{max}(j,j^*)$ can be derived as Eq (6). In order to satisfy the interference condition in all neighbor cells, the base-station chooses the minimum transmission power among all $P_i^{max}(j,j^*)$ as shown in Eq. (7).

If some neighbors are border cells, the permissible transmission power can be determined according to the location of PU activity regions. In neighbor cells currently busy, $I_i^{\max}(\cdot)$ is not available. In order to estimate $I_{\triangle}(j^*)$, we instead use $I_i^{\min}(j^*)$, which includes the primary signal strength and interference components. Assume the primary network maintains the minimum SINR γ at its border in the presence of interference P_{temp}. The interference at the border of the neighbor cell $I_i^{\max}(j^*)$ can be estimated as the difference between the measured signal strength and the pure primary signal strength, $I_i^{\min}(j^*) - \gamma\cdot P_{\mathrm{temp}}\cdot W_i$. Then the available power can be obtained using Eq. (5).

In this case, the border of the PU activity can be considered as the nearest border of the neighbor cell j^* from the current base-station. Therefore the permissible transmission power can be determined so that the received power at the border of neighbor cell, i.e., $D(j,j^*)-R_{j^*}$ from the base-station, does not exceed $I_{\triangle}(j^*)$. Thus, the restricted transmission power can be obtained as follows:

$$P_i^{\mathrm{pu}}(j,k) = \min_{j^*\in\mathcal{N}_i(j,k)} \mathcal{F}^{-1}(I_{\triangle}(j,j^*), D(j,j^*)-R_{j^*}) \tag{8}$$

where $\mathcal{N}_i(j,k)$ is the set of neighbors of the cell j located at region k of spectrum i. Similar to $P_i^{\max}(j)$ in Eq. (7), the minimum transmission power needs to be chosen for $P_i^{\mathrm{pu}}(j,k)$ not to violate the interference constraint in any neighbor cells.

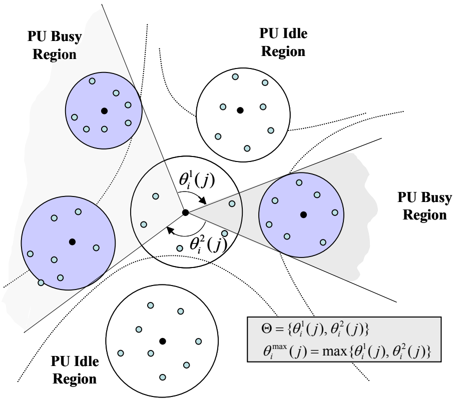


Fig. 5. Busy and idle regions based on primary user activities

C. Spectrum Selection

Based on the cell characterization and the permissible power, the capacity of each spectrum band can be estimated for spectrum selection, referred to as *opportunistic cell capacity*. The opportunistic cell capacity $C_i(j)$ is defined as the capacity of spectrum i at the boundary of the transmission range of cell j, which represents the minimum capacity to be provided by the base-station. According to the cell type, the opportunistic capacity can be derived as follows:

Type I:

$$C_i(j) = W_i \log_2(1 + \frac{\mathcal{F}(P^{\max}(j), R(j))}{I_i^{\max}(j)}) P_i^{\text{off}} \tag{9}$$

Type II & III:

$$\begin{aligned} C_i(j) = W_i[&\log_2(1 + \frac{\mathcal{F}(P_i^{\max}(j), R(j))}{I_i^{\max}(j)}) \cdot \Pr(P_i^{\max}(j)) \\ &+ \sum_{k \in \mathcal{K} - \mathcal{K}'} \log_2(1 + \frac{\mathcal{F}(P_i^{\max}(j), R(j))}{I_i^{\max}(j)}) \cdot \Pr(P_i^{\text{pu}}(j,k)] \end{aligned} \tag{10}$$

If the base-station has multiple available spectrum bands for the exclusive allocation, it selects the one with the highest opportunistic capacity.

VI. SPECTRUM ALLOCATION FOR COMMON USE MODEL

Although the exclusive sharing is known to be optimal in total network capacity, it is not suitable to CR networks due to the unfair resource allocation as explained in Section II. In the common use approach, the cell can share the same spectrum with its neighbor cells, which improves fairness but causes capacity degradation due to the inter-cell interference. To mitigate this effect, the following issues should be considered in the common use approach:

- *Cell capacity maximization:* The common use approach aims at finding a spectrum to enable the cell capacity to be maximized by exploiting spectrum bands adaptively to the PU activities.
- *Less inter-cell interference:* To avoid the capacity degradation due to the inter-cell interference, CR networks need to find the spectrum to cause less influence on neighbor cells.
- *Uplink transmission:* Unlike the downlink (from base-station to CR users), the uplink shows the different interference range according to the location of the users. Since the interference range of the uplink is extended much farther than that of downlink, the uplink transmission causes higher interference to the neighbor cells. Furthermore, the uplink transmission is highly probable to interfere with the PU activity detected in its neighbor cells.

To address these issues, we propose a two-step spectrum sharing for the common use model, which is explained in the following subsections.

A. Angle-Based Allocation for Uplink Transmission

As explained above, the uplink transmission can cause more significant interference to the PU activities at its neighbor cells. Figure 5 shows PU idle and busy regions based on the location of its neighbors who detect PU activities. When CR users in the busy region begin to transmit, they interfere with the transmission of primary networks in its neighbor cells. The best way to reduce interference in uplink transmission is to use the spectrum which does not have any PU activities in neighbor cells. If the base-station cannot find this spectrum, alternatively it can exploit the multiple spectrum bands to allow all directions to be covered with their idle regions, referred to as *angle-based allocation*.

Let $\Theta_i(j)$ be the range of angles for PU idle regions at cell j in spectrum i. Then, to avoid the resource shortage of uplink transmission, the cell should satisfy the following angle condition:

$$\Theta_i(j) = \{\theta | \text{no PU activity in the direction } \theta\} \tag{11}$$

$$\bigcup_{i \in \mathcal{S}(j)} \Theta_i(j) = \{\theta | 0 \leq \theta \leq 2\pi\} \tag{12}$$

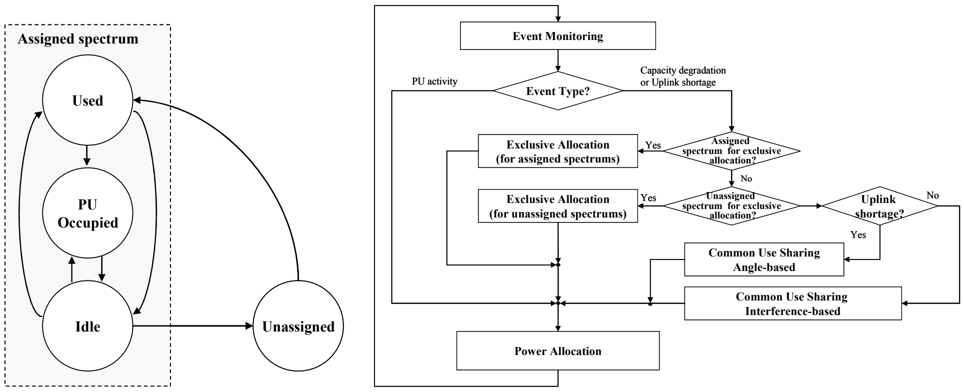
where $\mathcal{S}(j)$ is the set of spectrums assigned to a cell j. The angle of the idle region can be estimated by the base-station, which is aware of the location information of its neighbors.

If the cell does not satisfy the angle condition for uplink transmission, the base-station initiates the inter-cell spectrum sharing immediately and finds the proper spectrum band to satisfy the condition in Eq. (12).

B. Interference-Based Spectrum Allocation

If current spectrum allocation already meets the condition in Eq. (12), the CR network should consider the capacity maximization both in terms of the cell and the total network as explained in the beginning of this section.

The principle of the allocation is as follows: First, for the maximum cell capacity, the cell should find the spectrum with the lowest interference in its transmission range. However, in order to maximize the total network capacity, the cell needs to consider the influence on the neighbor cells when it determines a certain spectrum band. Optimally, we can allocate the spectrum to maximize the total network capacity



(a) (b)

Fig. 6. Joint spectrum and power allocation: (a) spectrum status diagram, and (b) flow chart.

if each cell is aware of the channel gain of all possible links to the users both in neighbor and current cells as well as the interference at those users, which is not practical in the infrastructure-based networks. Instead we propose a more practical and intuitive approach. Usually the cell with higher interference shows less influence on its capacity compared to the cells with lower interference. When new interference is added to the spectrum having low interference, it causes high capacity degradation. On the other hand, in case of the cell having higher interference, the degradation of capacity is relatively small even though additional interference is applied. If the capacity becomes below the threshold due to the additional interference, the base-station will initiate the inter-cell spectrum sharing procedure, and finally release the spectrum with low capacity, which helps to increase fairness in resource allocation as well as total network capacity. Thus, the cell needs to choose the spectrum bands with the highest interference in its neighbors. From these observations, we devise the selection criterion to consider both cell capacity and total network capacity together where the base-station chooses the spectrum so as to maximize the ratio of the interference in its neighbors $I_i^{\max}(j^*)$ to its own interference $I_i^{\max}(j)$.

Even though the cell satisfies the condition for uplink transmission in Eq. (12), it is highly probable that primary users will re-appear in the assigned spectrum which may violate the condition for uplink transmission. Thus, it is much advantageous for the cell to choose the spectrum with the widest idle angle range. By combining this idea with the above criterion, we can derive the following selection principle for the common use approach, called an *interference-based spectrum allocation*:

$$i^* = \arg\max_{i\in\mathcal{S}(j)} \frac{\theta_i^{\max}(j)}{2\pi} \cdot \frac{\min\limits_{j^*\in\mathcal{N}(j)} I_i^{\max}(j^*)}{I_i^{\max}(j)} \tag{13}$$

where $\theta_i^{\max}(j)$ is the maximum idle angle in spectrum i at cell j as shown in Figure 5. $\mathcal{S}(j)$ is the set of available spectrum bands at base-station j. Here, in order to consider the effect on all neighbors, the lowest $I_i^{\max}(j^*)$ is chosen among the interference measured in neighbors. If the neighbor cell is in the active region, we can use $I_i^{\min}(j^*) - \gamma \cdot P_{\text{temp}} \cdot W_i$ instead of $I_i^{\max}(j^*)$ as explained in Section V-B.

VII. Joint Spectrum and Power Allocation for Inter-Cell Spectrum Sharing

In the previous section, we introduced two different spectrum allocation methods. Once the spectrum is allocated, the transmission power needs to be determined to maximize the cell capacity. In power allocation, CR networks should consider the interference constraint to protect the primary networks. Furthermore, in order to maintain the fairness with less capacity degradation, inter-cell spectrum sharing is required to allocate the transmission power cooperating with both spectrum allocations for exclusive and common use approaches. In this section, we describe the power allocation combining with the spectrum allocation presented in the previous sections and propose a joint spectrum and power allocation method for inter-cell spectrum sharing.

A. Power Allocation

Once the spectrum is selected, the base-station determines its transmission power over all currently used spectrum bands. Generally a water filling is used to optimally allocate the power in the presence of noise where capacity is maximized when the sum of transmission power and interference are same over all frequencies in the spectrum band [20]. However, unlike the general water filling method, in the inter-cell spectrum sharing, each spectrum has an upper power limit according to the PU activities and spectrum utilization in the vicinity of the current cell. The upper limit can be obtained as follows:

First, if there is no activity of either primary or CR users in the neighbor cell j^*, the upper power limit $P_i^{\text{up}}(j, j^*)$ is the same as Eq. (6). Second, if a neighbor cell j^* has a PU activity, $P_i^{\text{up}}(j, j^*)$ can be obtained as $\mathcal{F}^{-1}(I_\triangle(j^*), D(j, j^*) - R_{j^*})$, which is explained in Eq. (8). Last, if the neighbor cell j^* currently uses the spectrum i, we need to consider the transmission of the cell j^* since $I_i^{\max}(j^*)$ does not contain its own signal strength. In this case, we can assume that the most portion of maximum interference $I_i^{\max}(j)$ measured in the current cell comes from the cell j^*. From this, the transmission power of the neighbor cell can be estimated as $\mathcal{F}^{-1}(I_i^{\max}(j), D(j, j^*) - R_j)$. Then, the total interference can be expressed as the sum of the interferences from outside cells, $I_i^{\max}(j^*)$, and interference from its own transmission. From this, the available power at the farthest border of the cell j^* from the base-station j can be obtained as follows:

$$\begin{aligned} I_\Delta(j^*) = &P_{\text{temp}} \cdot W_i - [I_i^{\max}(j^*) + \\ &\mathcal{F}(\mathcal{F}^{-1}(I_i^{\max}(j), D(j, j^*) - R_j), R_{j^*})] \end{aligned} \tag{14}$$

Then $P_i^{\text{up}}(j, j^*)$ can be derived using Eq. (6). Among all $P_i^{\text{up}}(j, j^*)$ obtained above, the base-station j chooses the minimum as an upper power limit of spectrum i, $P_i^{\text{up}}(j)$.

Based on the constraints of all assigned spectrums in $\mathcal{S}(j)$, we introduce the constrained water filling method for power allocation as shown in Algorithm VII-A. Here $\mathcal{S}^{\text{r}}(j)$ and $P^{\text{r}}(j)$ represent the set of remaining spectrums and remaining power, respectively. $\mathcal{S}^{\text{c}}(j)$ and $P^{\text{c}}(j)$ are candidate spectrums and the expected power for current water filling procedure.

Algorithm 1 Constrained Water Filling Method

```
$P^{\text{r}} = P^{\text{tot}}(j),\ \mathcal{S}^{\text{r}}(j) = \mathcal{S}(j),\ P_i(j) = 0, \forall i \in \mathcal{S}(j)$
while $P^{\text{r}} > 0$ and $\mathcal{S}^{\text{r}}(j) \neq \emptyset$ do
    $i^* = \arg\min_{i \in \mathcal{S}^{\text{r}}(j)} [(P_i^{\text{up}}(j) + I_i^{\max}(j))/W_i + N_0]$
    $\mathcal{S}^{\text{c}}(j) = \{i | I_i^{\max}(j)/W_i < (P_{i^*}^{\text{up}}(j) + I_{i^*}^{\max}(j))/W_{i^*}, i \in \mathcal{S}^{\text{r}}(j)\}$
    $P^{\text{c}}(j) = (P_{i^*}^{\text{up}}(j) + I_{i^*}^{\max}(j))/W_i * \sum_{i \in \mathcal{S}^{\text{c}}(j)} W_i - \sum_{i \in \mathcal{S}^{\text{c}}(j)} [(P_i(j) + I_i^{\max}(j)]$
    if $P^{\text{c}}(j) > P^{\text{r}}(j)$ then
        for $\forall i \in \mathcal{S}^{\text{c}}(j)$ do
            $P_i(j) = P_i(j) + (P^{\text{c}}(j) - P^{\text{r}}(j)) * W_i / \sum_{i \in \mathcal{S}^{\text{c}}(j)} W_i$
        end for
        $P^{\text{r}}(j) = 0$
    else
        for $\forall i \in \mathcal{S}^{\text{c}}(j)$ do
            $P_i(j) = (P_{i^*}^{\text{up}}(j) + I_{i^*}^{\max}(j)) * W_i / \sum_{i \in \mathcal{S}^{\text{c}}(j)} W_i$
        end for
        $\mathcal{S}^{\text{r}}(j) = \mathcal{S}^{\text{r}}(j) - \{i^*\},\ P^{\text{r}}(j) = P^{\text{r}}(j) - P^{\text{c}}(j)$
    end if
end while
```

In the constrained water filling method, the sum of the allocated power and interference cannot exceed the upper limit of the transmission power, which enables interference avoidance with primary networks while maximizing the cell capacity.

B. Spectrum Sharing Procedures

In the spectrum sharing, it is desirable that the spectrum allocation in the current cell has less influence on the transmission of other cells. In the worst case, spectrum allocation causes the capacity degradation due to the frequent interruption with the transmission of neighbors. Therefore, inter-cell spectrum sharing necessitates a coordination mechanism to reduce unnecessary influence on the entire networks.

To this end, we classify the spectrum as the *assigned spectrum* and *unassigned spectrum*. Figure 6 (a) shows the state-diagram for inter-cell spectrum sharing. The assigned spectrum bands are allowed to be accessed by the current cell while the unassigned bands are assigned to other neighbor cells. The assigned spectrum can have three sub-states, *used*, *PU occupied*, and *idle* according to its utilization. In *used* and *PU occupied* states, the spectrum is currently used by the current cell and by the primary network, respectively. Spectrum in *idle* state is assigned to the cell but is not currently used. The assigned spectrum can be released to the unassigned only when it is currently idle and is requested by the neighbor cells for their exclusive allocation. In the exclusive allocation, the base-station first considers its assigned spectrum bands. If it cannot find a proper one, it extends its search to the unassigned spectrum bands. If there is no idle spectrum band available for the exclusive use, it switches to the common use sharing. In this case, the base-station can choose any available spectrum regardless of its state. Instead, the proposed common use allocation provides the capability to select the less influencing spectrum band as explained in Section VI. Through this coordination, each cell has a priority in utilizing its assigned spectrum, which can reduce the unnecessary spectrum allocation.

Figure 6 (b) describes the flowchart of the proposed joint spectrum and power allocation method. Each cell continuously monitors the network status and radio environment through the local observations of its users. If one of the following events is detected, the base-station initiates the spectrum sharing procedure: 1) capacity degradation, 2) primary user appearance, and 3) resource shortage of uplink transmission. If the detected event is related only to the PU activities, the base-station turns off its transmission power on that spectrum. If the base-station detects the quality degradation or resource shortage, it performs the exclusive allocation for the assigned spectrum and then for the unassigned spectrum if necessary. If it cannot find the proper spectrum bands, it turns to the common use sharing. If the event is a resource shortage for uplink transmission, it selects the spectrum having the proper idle angle through the angle-based allocation. If the event is related only to capacity degradation, it performs the interference-based allocation. Once spectrum is allocated, each base-station allocates the transmission power over the assigned spectrum bands by considering the total power budget and transmission power constraints derived from spectrum allocation.

VIII. PERFORMANCE EVALUATION

In this section, we present simulation results on the performance of the proposed inter-cell spectrum sharing method.

A. Simulation Setup

In order to evaluate the performance of the proposed sharing method, we implement the network simulator to support the network topology consisting of multiple cells in 10km x 10km area. Figure 7 shows the network topology used in the simulation. Here we assume 20 cells which have different number of users from 20 to 40. The transmission range of each cell is uniformly distributed from 1 to 1.5km. The interference range is set to twice larger than the transmission range. Furthermore, we consider 20 10MHz licensed spectrum bands with different

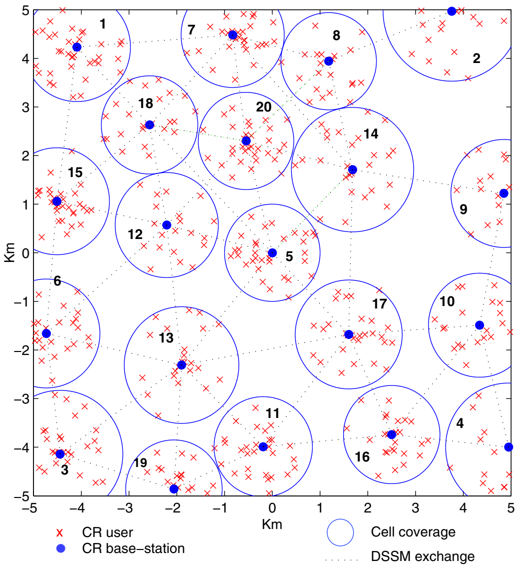


Fig. 7. Network topology for simulation

PU activities, α_i and β_i, which are uniformly distributed in $[0.1, 0.5]$. Each spectrum band has 2-5 PU activity regions. For the simplicity, each PU activity region on spectrum i is assumed to have the same α_i and β_i.

In this simulation, we use the free space power attenuation model where the channel gain is set to -31.54dB, the reference distance is 1m, and the path loss coefficient is 3.5. The base-station has 3000mwatt transmission power in total and can allocate up to 600mwatt to each spectrum. The transmission power of the CR user is set to 125mwatt. Noise power in the receiver is -174dBm/Hz. For the protection of primary networks, we set the interference temperature to 6dB greater than the noise power. The CR network uses the TDD with the same length of uplink and down link time slots. While base-stations can use the multiple spectrum bands at the same time, CR users can use only one spectrum for uplink and down link transmissions, respectively. For the intra-spectrum sharing, we use the proportional fairness principle, i.e., once users are assigned to the spectrum, each user is assumed to share the time slot fairly with other assigned users. Here the minimum QoS requirement for each user is set to 8Mbps.

To evaluate the proposed method, we use three different existing spectrum sharing methods as follows:

- *Fixed spectrum allocation:* Spectrum allocation can be obtained by the coloring method with a maximum proportional fairness criterion [5]. Here, each cell is assigned to the pre-determined spectrum bands and does not change them regardless of time-varying spectrum availability. Instead, this method considers the number of neighbor cells and PU activities.
- *Dynamic spectrum allocation:* This method is also based on the same coloring method used in the fixed allocation. However, in this method, spectrum allocation is dynamically updated over the entire network whenever spectrum availability changes, which leads to optimal performance in spectrum sharing.
- *Local bargaining:* In this method, each cell can negotiate with its neighbor to obtain spectrum bands when its capacity is below a threshold [6].

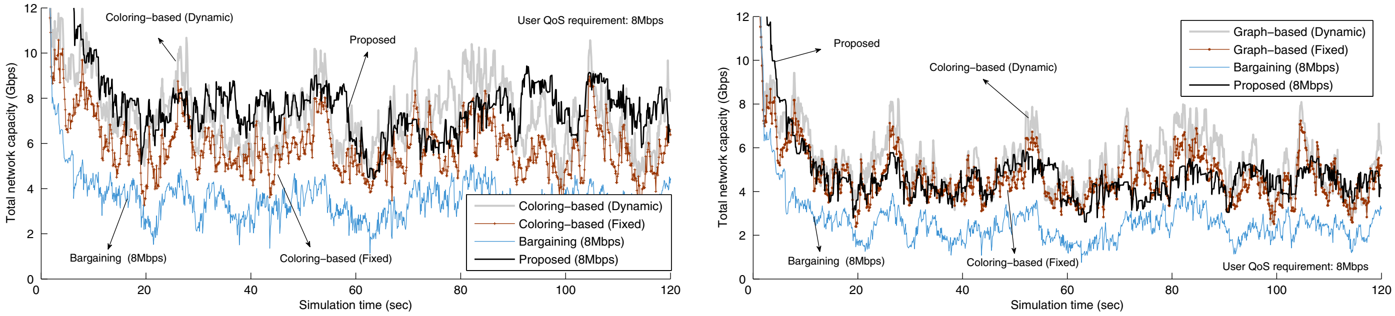
Here we do not consider existing common use sharing methods since they are not suitable for the infrastructure-based networks as explained in Section II-B.

B. *Total Capacity*

First we compare the proposed method with three existing methods mentioned in the Section VIII-A. Figure 8 shows total network capacity for both uplink and downlink transmissions. The dynamic allocation uses the graph-based optimization with global topology knowledge which leads to the highest capacity. While the fixed allocation does not require frequent optimization, it shows lower total capacity due to the lack of the channel adaptation. In the bargaining method, each cell takes the spectrum band from other neighbor cells if it cannot satisfy the QoS. However, since each cell cannot perform the spectrum allocation if its neighbors are currently involving in other bargaining process, the spectrum utilization becomes lowest than the others. Since the proposed method exploits the exclusive and common use model adaptively dependent on the network environments, it achieves a higher downlink capacity than the fixed allocation and bargaining schemes, and the same or slightly lower capacity compared to the dynamic (optimal) spectrum allocation while requiring less computational overhead as shown in Figure 8. One the contrary, the proposed method achieves the same total capacity as the uplink to the fixed allocation scheme due to the interference constraint imposed by Eq. (12).

C. *Fairness and QoS*

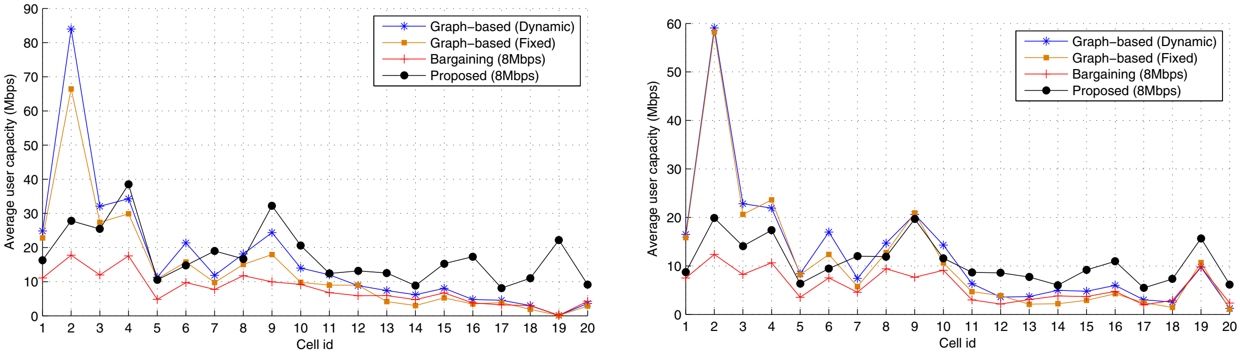
Here we investigate the capacity fairness, which is also an important objective in inter-cell spectrum sharing. As shown in Figure 9, existing methods show high fluctuation in their capacity, especially cells #12-#20 achieve significantly lower capacities than the other cells. However, the proposed method maintains better fairness in capacity over all cells than the other methods. Figure 10 depicts the dynamic adaptation between exclusive and common use modes according to the diverse QoS requirements. If the required capacity is relatively low, most of spectrum bands are used as the exclusive mode. As the required user capacity increases, the number of spectrums in common use mode increases. Through this dynamic adaptation between both modes, the proposed method can maintain fairness in capacity. In Figure 11, we observe the QoS violation ratio of each cell, which is defined as the fraction of time when the QoS of the cell is below the minimum requirement. The dynamic and fixed spectrum allocations do not have any QoS guarantee mechanism and just aim at maximizing total capacity and fairness under the exclusive sharing mode. On the contrary, the proposed method performs the spectrum sharing by considering the QoS condition of each cell. Figure 11 shows that the proposed



(a)

(b)

Fig. 8. Performance comparison in total capacity: (a) downlink, and (b) uplink.



(a)

(b)

Fig. 9. Performance comparison in capacity fairness: (a) downlink, and (b) uplink.

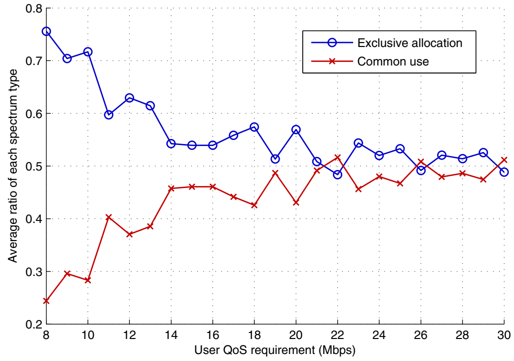


Fig. 10. Sharing modes under different QoS requirements

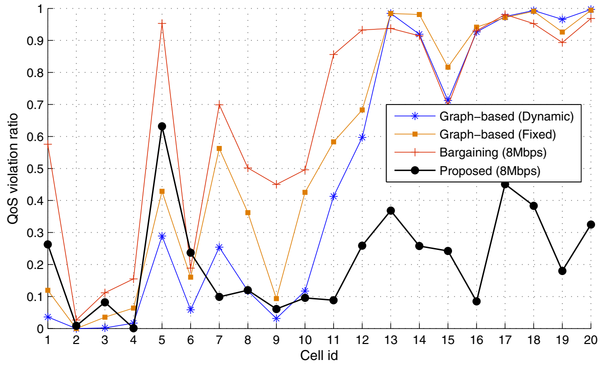
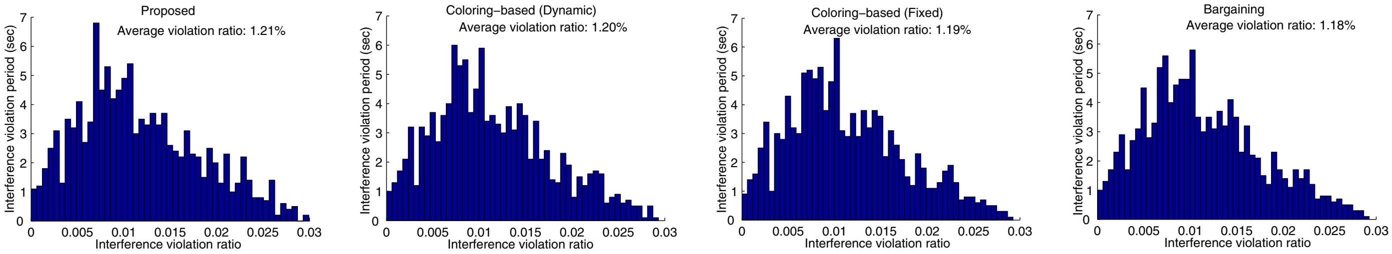


Fig. 11. Performance comparison in QoS violation ratio

method shows better performance in QoS guarantee. In cell #5, the proposed method shows higher QoS violation ratio than the other methods but achieves the same or slightly lower user capacity as shown in Figure 9. Even though the bargaining method provides QoS guarantees, it is based on the classical spectrum allocation and does not consider adaptive power allocation, which may lead to low spectrum utilization, and hence high QoS violation.

D. Interference Avoidance

Another important issue in CR networks is the interference avoidance with primary networks which has not been addressed in previous methods. Figure 12 shows the interference ratio under different sharing schemes, which is defined as the ratio of the area violating the interference temperature limit to total area occupied by primary networks. As shown in Figure 12, our proposed method shows similar interference ratio to other existing methods. In order to protect the primary networks, previous methods are assumed to adopt the same



(a) (b) (c) (d)

Fig. 12. Histogram for interference violation ratio: (a) proposed method, (b) dynamic allocation, (c) fixed allocation, and (d) local bargaining.

strategy used to avoid the inter-cell interference, i.e., CR cells cannot use the spectrum band on which some of their neighbor cells detect the PU activities, leading to inefficient spectrum utilization. However, since the proposed method determines the transmission power not to exceed the interference temperature, it achieves both higher capacity and better fairness while maintaining similar interference avoidance performance to other previous methods.

IX. CONCLUSIONS

In the paper we present a joint spectrum and power allocation method for inter-cell spectrum sharing in cognitive radio networks. Although the exclusive method theoretically achieves optimal capacity, this approach cannot guarantee the fair resource allocation which is also an important issue in inter-cell spectrum sharing. Furthermore, for the optimal allocation, it requires spectrum utilization and topology information of the entire network, which causes tremendous overhead and computational complexity. In order solve these problems, first, we proposed a novel spectrum allocation methods for both exclusive and common use models. To exploit the proposed exclusive and common use methods dynamically, we propose a joint spectrum and power allocation method where spectrum sharing mode and transmission power are determined according to the QoS requirements, primary user activities and current spectrum utilization. The simulation experiments show that the proposed sharing method achieves better performance in terms of both network capacity and fairness.

ACKNOWLEDGMENT

This material is based upon work supported by the US National Science Foundation under Grant No. CNS-07251580.

REFERENCES

[1] FCC, "Et docket no 02-135," *Spectrum Poicy Take Force (SPTF) Report*, November 2002.

[2] I. F. Akyildiz, W. Y. Lee, M. C. Vuran, and S. Mohanty, "Next generation / dynamic spectrum access / cognitive radio wireless networks: a survey," *Computer Networks Journal (Elsevier)*, vol. 50, pp. 2127–2159, September 2006.

[3] R. Etkin, A. Parekh, and D. Tse, "Spectrum sharing for unlicensed bands," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 3, pp. 517–526, April 2007.

[4] C. Raman, R. D. Yates, and N. B. Mandayam, "Scheduling variable rate links via a spectrum server," *in Proc. IEEE DySPAN 2005*, pp. 110–118, 2005.

[5] C. Peng, H. Zheng, and B. Y. Zhao, "Utilization and fairness in spectrum assignment for opportunistic spectrum access," *ACM Mobile Networks and Applications (MONET)*, 2006.

[6] L. Cao and H. Zheng, "Distributed spectrum allocation via local bargaining," *In Proc. IEEE Sensor and Ad Hoc Communications and Networks (SECON)*, pp. 475–486, September 2005.

[7] ——, "Distributed rule-regulated spectrum sharing.pdf," *IEEE Journal On Selected Areas In Communications*, vol. 26, no. 1, pp. 130–145, January 2008.

[8] Z. Ji and K. J. R. Liu, "Dynamic spectrum sharing: A game theoretical overview," *IEEE Communications Magazine*, vol. 45, no. 5, pp. 88–94, May 2007.

[9] J. Huang, R. A. Berry, and M. L. Honig, "Spectrum sharing with distributed interference compensation," *in Proc. IEEE DySPAN 2005*, no. November, pp. 88–93, 2005.

[10] M. G. K. Xu and S. Bae, "How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks?" *in Proc. IEEE Global Telecommunications Conferebce (Globecom) 2002*, pp. 72–76, November 2002.

[11] W. Y. Lee and I. F. Akyildiz, "Optimal spectrum sensing framework for cognitive radio networks," *IEEE Transactions on Wireless Communications*, vol. 7, no. 9, September 2008.

[12] IEEE 802.22 WG, "Draft standard for wireless regional area networks part 22: Cognitive wireless RAN medium access control (MAC) and physical layer (PHY) specifications: Policies and procedures for operation in the TV bands," *IEEE P802.22/D0.3.8.1*, September 2007.

[13] D. Cabric, S. M. Mishra, D. Willkomm, R. Brodersen, and A. Wolisz, "A cognitive radio approach for usage of virtual unlicensed spectrum," *in Proc. 14th IST Mobile and Wireless Communications Summit*, June 2005.

[14] C. Chou, S. Shankar, H. Kim, and K. G. Shin, "What and how much to gain by spectrum agility?" *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 3, pp. 576–588, April 2007.

[15] W. Y. Lee and I. F. Akyildiz, "A spectrum decision framework for cognitive radio networks," *submitted for publication*, 2008.

[16] Q. Zhao, L. Tong, A. Swami, and Y. Chen, "Decentrallized cognitive mac opportunistic spectrum access in ad hoc networks: A pomdp framework," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 3, pp. 589–600, April 2007.

[17] K. Sriram and W. Whitt, "Characterizing superposition arrival processes in packet multiplexers for voice and data," *IEEE Journal of Selected Areas in Communications*, vol. SAC-4, pp. 833–846, September 1986.

[18] T. Chen, H. Zhang, G. M. Maggio, and I. Chlamtac, "CogMesh: a cluster-based cognitive radio network," *in Proc. IEEE DySPAN 2007*, pp. 168–178, April 2007.

[19] J. Tanga, S. Misrab, and G. Xueb, "Joint spectrum allocation and scheduling for fair spectrum sharing in cognitive radio wireless networks," *Computer Networks Journal (Elsevier)*, vol. 52, no. 11, pp. 2148–2158, August 2008.

[20] C. E. Shannon, "Communication in the presence of noise," *Proceedings of the IEEE*, vol. 72, pp. 1192–1201, September 1984.