# Spectrum Management in Cognitive Radio Ad Hoc Networks

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## Abstract

The problem of spectrum scarcity and inefficiency in spectrum usage will be addressed by the newly emerging cognitive radio paradigm that allows radios to opportunistically transmit in the vacant portions of the spectrum already assigned to licensed users. For this, the ability for spectrum sensing, spectrum sharing, choosing the best spectrum among the available options, and dynamically adapting transmission parameters based on the activity of the licensed spectrum owners must be integrated within cognitive radio users. Specifically in cognitive radio ad hoc networks, distributed multihop architecture, node mobility, and spatio-temporal variance in spectrum availability are some of the key distinguishing factors. In this article the important features of CRAHNs are presented, along with the design approaches and research challenges that must be addressed. Spectrum management in CRAHNs comprises spectrum sensing, sharing, decision, and mobility. In this article each of these functions are described in detail from the viewpoint of multihop infrastructureless networks requiring cooperation among users.

Current wireless networks are based on a fixed spectrum assignment policy that is regulated by governmental agencies. Although spectrum is licensed on a long-term basis over vast geographical regions, recent research has shown that significant portions of the assigned spectrum are utilized, leading to waste of valuable frequency resources [1]. To address this critical problem, the FCC recently approved the use of unlicensed devices in licensed bands. Toward this end, cognitive radio (CR) technology is envisaged that enables the identification and use of vacant spectrum, known as *spectrum hole* or *white space* [1]. In this article we focus on the challenges faced in CR ad hoc networks (CRAHNs), which do not have infrastructure support and must rely on local coordination for different CR functionalities.

Since most of the spectrum is already assigned, a key challenge is to share the licensed spectrum without interfering with the transmission of other licensed users (also known as primary users or PUs). If this band is found to be occupied by a licensed user, the CR user moves to another spectrum hole to avoid interference. In CRAHNs the distributed multihop architecture, dynamic network topology, diverse quality of service (QoS) requirements, and time and location varying spectrum availability are some of the key factors that must be considered in network design. These challenges necessitate novel design techniques that simultaneously address a wide range of communication problems spanning several layers of the protocol stack.

In CRAHNs CR users are mobile and can communicate with each other in a multihop manner on both licensed and unlicensed spectrum bands, as shown in Fig. 1a. Furthermore, due to the lack of central network entities, CRAHNs necessitate each CR user having all the spectrum related CR capabilities, and determining its actions based on local observation, leading to distributed operation [2]. In order to adapt to the dynamic spectrum environment, the CRAHN requires spectrum-aware operations, which form a cognitive cycle [1]. As shown in Fig. 1b, the steps of the cognitive cycle consist of four spectrum management functions: *spectrum sensing*, *spectrum decision*, *spectrum sharing*, and *spectrum mobility*. To implement CRAHNs, each function needs to be incorporated into the classical layering protocols, as shown in Fig. 2. The following are the main features of spectrum management functions:

- *Spectrum sensing*: A CR user should monitor the available spectrum bands, capture their information, and then detect spectrum holes. Spectrum sensing is a basic functionality in CR networks, and hence closely related to other spectrum management functions as well as layering protocols to provide information on spectrum availability.
- *Spectrum decision*: Once the available spectra are identified, it is essential that CR users select the best available band according to their QoS requirements [2]. Especially in CRAHNs, spectrum decision involves jointly undertaking *spectrum selection* and *route formation*.
- *Spectrum sharing*: The transmissions of CR users should be coordinated by spectrum sharing functionality to prevent multiple users colliding in overlapping portions of the spectrum. Spectrum sharing includes *channel and power allocations* to avoid interference caused to the primary network and a CR medium access control (MAC) protocol along with spectrum sensing.
- *Spectrum mobility*: If the specific portion of the spectrum in use is required by a PU, the communication must be switched to another vacant portion of the spectrum. This requires *spectrum handoff* and *connection management* schemes closely coupled with spectrum sensing, neighbor discovery in a link layer, and routing protocols.

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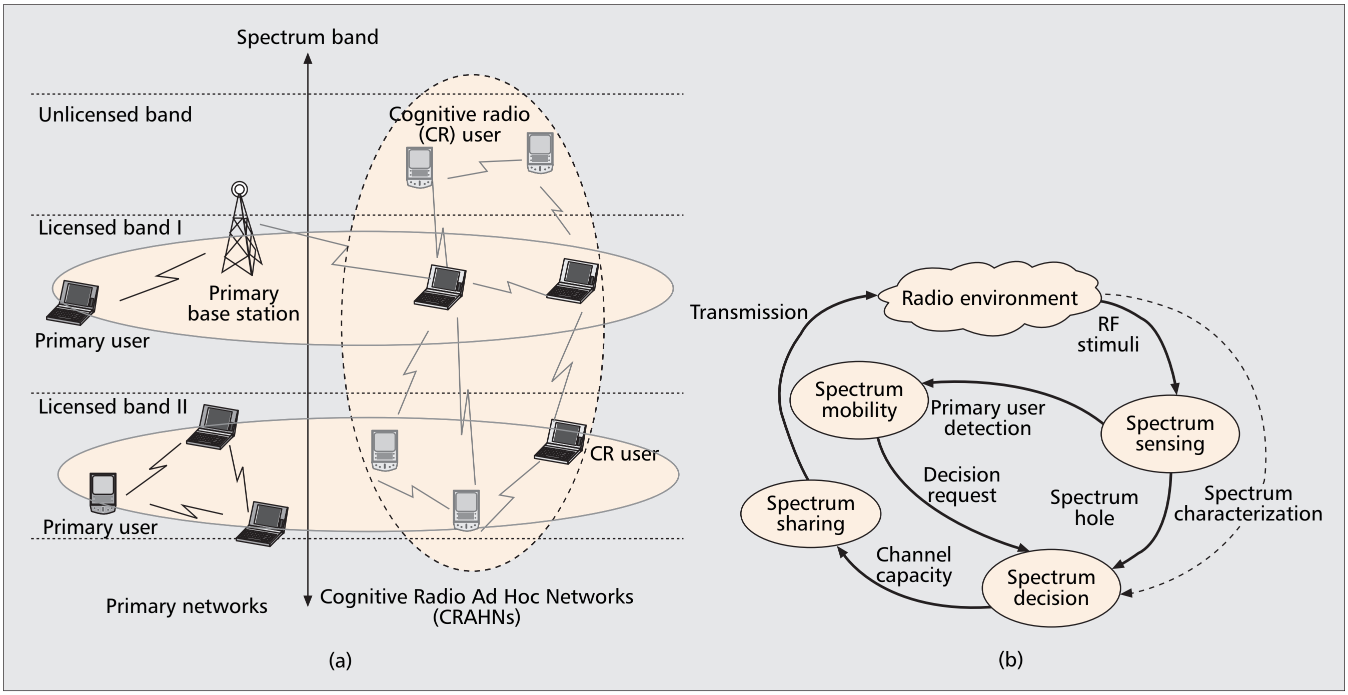

■ Figure 1. *The overview of CR ad hoc networks: a) network architecture; b) CR cycle.*

Each of the these spectrum management functions relies on exchanging information between CR users over a common control channel (CCC), which we describe in the next section.

## Cooperation and CCC

The interaction between CRAHN users leading to cooperation and the use of the CCC in spectrum management are important topics, which are explained first.

### Cooperation

CRAHNs lack centralized support, and hence must rely on local observation of each CR user to determine its actions. To overcome the drawback caused by the limited knowledge of network topology and spectrum availability, all spectrum management functions are based on cooperative operations, where CR users determine their actions based on observed information exchanged with their neighbors. As an example, CRAHNs require assimilation of information during sensing from several users to improve accuracy and for fair sharing of the detected spectrum resource through cooperation. Some spectrum management functions, such as spectrum decision and mobility, need reliable route formation and packet delivery over multiple hops in CRAHNs. For this, information regarding the likely PU interference over the length of the path and sensing schedules of the intermediate nodes needs to be available at the source node. In summary, cooperation is theoretically more advantageous in CRAHNs since the uncertainty in a single user's observation can be minimized through collaboration [2].

### CCC

To enable cooperation among CR users, a CCC is required for exchanging spectrum information and coordinating the spectrum access. A brief classification of the possible approaches for the CCC is provided in this section [2].

*In-Band CCC* — The control messaging occurs in the licensed channels used for data transfer. As spectrum availability changes with time, the in-band CCC is generally in effect for comparatively smaller durations. As an example, spectrum sensing is periodic and may occur at well defined epochs, during which the surrounding CR users may need to be silenced by informing them via the CCC. Moreover, the physical extent of the CCC is limited (*local coverage*), as the spectrum resource that may be used is different based on the location of the users. Although this approach has the advantage of using a single transceiver, it is subject to periodic disruptions and the associated overhead of new task-specific CCC formation.

*Out-of-Band CCC* — Here, a separate channel is used for the CCC that does not overlap with the licensed channels. The best performance results if a CCC has *global coverage* as new users joining the network can conveniently broadcast their presence on it without knowing the current state of the CR network. In addition, cluster-based architectures may use local coverage where the CCC is defined differently for each cluster of user and reflects the specific PU activity in their respective locations. However, as the data and control signaling are separate, more than one transceiver may be needed for dedicated CCC monitoring. For single radio devices, the cost of switching between the data band and the CCC, and the associated deaf period when the CCC is not sensed must be accounted for in the protocol design.

### Research Challenges

While information about the network environment greatly enhances the performance in CRAHNs, the messaging overhead must also be considered. The cost of collecting this information includes the link layer delay, energy consumption, and the rate of update messages to keep the state of the network current.

The channel for the CCC must be carefully chosen so that it is not interrupted over long periods of time. While this considerably simplifies CCC operation, the main difficulty is identifying a uniformly acceptable channel over large portions of the network. Moreover, care should be taken to ensure that the CCC does not lower the spectrum utilization efficiency in low-traffic scenarios, as spectrum for the control messaging is exclusively reserved.

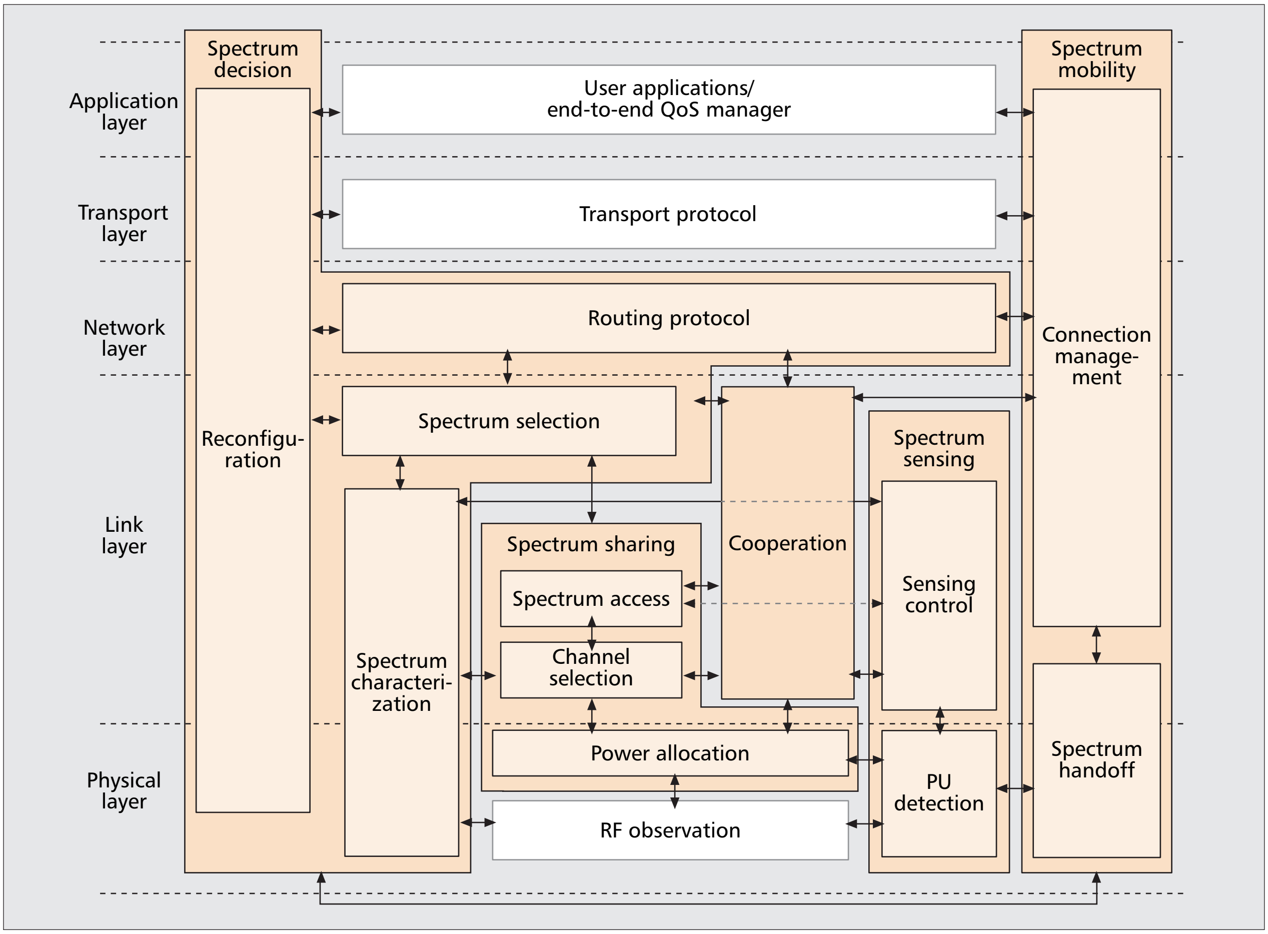

Figure 2. *Spectrum management framework for CRAHNs.*

## Spectrum Sensing

### Basic Framework

A CR is designed to be aware of and sensitive to the changes in its surrounding, which makes spectrum sensing an important requirement for the realization of CR networks. As shown in Fig. 2, the CRAHN necessitates the following functionalities for spectrum sensing.

PU Detection — PU detection is a capability to determine the presence of PU transmissions through the location observations of a CR user and identify the current spectrum availability accordingly. In CRAHNs energy and feature detection methods are the most commonly used for PU detection [3]. In the *energy detector* CR users sense the presence/absence of the PUs based on the energy of the received signals. While the energy detector is easy to implement, it cannot differentiate signal types. Thus, the energy detector often results in false detection triggered by unintended signals in CRAHNs. Furthermore, its performance is susceptible to uncertainty in noise power.

*Feature (or cyclostationary) detection* determines the presence of PU signals by extracting their specific features, such as pilot signals, cyclic prefixes, or modulation type, from its local observation. The main advantage of feature detection is its robustness to the uncertainty in noise power. Furthermore, it can distinguish the signals from different networks. Thus, this method allows the CR user to perform sensing operations independently on those of its neighbors without synchronization. Although feature detection is the most effective scheme for CRAHNs, it is computationally complex and requires a significantly long sensing time.

Furthermore, in CRAHNs spectrum sensing necessitates an efficient cooperation scheme in order to prevent interference to PUs outside the observation range of each CR user as well as to mitigate multipath fading and shadowing effects.

Sensing Control — The PU detection functionality is controlled and coordinated by a sensing controller, which considers two main issues:

- How quickly a CR user can find the available spectrum band over a wide frequency range for their transmissions
- How long and how frequently a CR user should sense the spectrum to achieve sufficient sensing accuracy during the transmission and detect the presence of transmission in primary networks so as to avoid interference

For fast and efficient spectrum discovery in CRAHNs, the out-of-band sensing scheme should have a coordination scheme to optimize its searching sequence and decide on the stopping rule for out-of-band sensing [4]. Furthermore, in in-band sensing a longer sensing time leads to higher sensing accuracy, and hence to less interference. Conversely, a longer transmission time increases the access opportunities, but causes higher interference due to the lack of sensing information [5]. Thus, how to select the proper sensing and transmission periods in a distributed manner is an important issue in CRAHNs.

### Research Challenges

Support of Asynchronous Sensing — Since each user has independent and asynchronous sensing and transmission schedules in CRAHNs, it can detect the transmissions of other CR users as well as PUs during its sensing period. However, with energy detection, which is most commonly used for spectrum sensing, a CR user can identify the presence of a transmission, but not the types of detected transmissions. As a result, the transmission of CR users detected during sensing operations causes false alarms, leading to decreased spectrum access opportunities. Thus, how to reduce these false alarms is a critical factor in determining the performance of CRAHNs but has still not been explored.

*Optimization of Cooperative Sensing* — Although cooperative sensing improves detection accuracy, it increases network traffic, resulting in higher latency in collecting this information due to channel contention and packet retransmissions. Furthermore, each cooperating user may have different sensing accuracies according to its location. Thus, CRAHNs are required to consider these factors to find an optimal operating point.

## Spectrum Decision

### Basic Framework

CRAHNs require capabilities to decide on the best spectrum band among the available bands according to the QoS requirements of the applications. This notion is called spectrum decision and constitutes a rather important but yet fully unexplored topic. The main uniqueness of spectrum decision in CRAHNs lies in the end-to-end route consisting of multiple hops with heterogeneous spectrum availability. The following are the main functionalities required for spectrum decision (Fig. 2).

*Spectrum Characterization* — Through *RF observation*, CR users characterize the available spectrum bands by considering the received signal strength, interference, and number of users currently residing in the spectrum. Unlike classical ad hoc networks, each CR user observes heterogeneous spectrum availability that is varying over time and space due to the PU activities, which should also be considered in the spectrum characterization.

*Spectrum Selection* — According to the observed spectrum availability, CR users allocate the best spectrum band to satisfy QoS requirements. Since the entire communication session consists of multiple hops with heterogeneous spectrum availability, spectrum allocation is closely coupled with routing protocols to determine the best combination of route and spectrum. However, since there are numerous combinations of route and spectrum between the source and destination, it is infeasible to consider all possible links for spectrum decision. Thus, in recent research route selection is performed independent of spectrum allocation [6]. Although this method is quite simple, it cannot provide an optimal route because spectrum availability on each hop is not considered during route establishment. Thus, a joint spectrum and routing decision method is essential for CRAHNs.

*Routing Protocol* — Current on-demand routing protocols, using CCC for the setup phase and the shortest route metric, need modifications before they can be used in a multichannel CR environment. First, new metrics and optimization functions need to devised that capture the collective spectrum opportunity for each of the candidate forwarding nodes. One such example metric is the *bandwidth-footprint product*, which measures the extent of the physical region that is unusable because of possible interference to the PUs in a given spectrum bandwidth. By minimizing this metric, the routes can be chosen so that the CR users in the path avoid the regions where large sections of the licensed spectrum are rendered unusable.

The main decision undertaken during *route setup* is choosing between allowing the path to circumvent the affected PU activity region, or switching the spectrum while maintaining the current direction of advance toward the destination. In addition, the type of channel access technology and underlying physical layer capability may also strongly influence routing choices. As an example, if a CR user device is equipped with a secondary ultra-wideband (UWB) radio, the routes may pass through the PU affected regions without any change in the spectrum. The UWB transmission is seen as *noise* by the PUs, but the limited transmission range increases the number of hops.

*Reconfiguration* — The protocols for different layers of the network stack must adapt to the channel parameters of the operating frequency. Once the spectrum is decided, CR users need to select the proper communication module such as modulation types, error control schemes, and upper layer protocols adaptively to application requirements as well as spectrum characteristics, and reconfigure their communication system accordingly. For example, the spectrum bands used by CR users may not have uniform bandwidths. When the spectrum is changed on a given link, it may become a bottleneck or exhibit a very large increase in capacity. Both these conditions affect the end-to-end delay, and in turn the transmission rate of the source decided by Transport Control Protocol (TCP). Thus, the congestion window (CW) needs to immediately reflect the bandwidth conditions of the spectrum on the link.

### Research Challenges

*Joint Spectrum and Route Formation* — Although the need to jointly identify the paths and the available spectrum is important, it is a nontrivial problem at the network layer. First, the RREQs may traverse independent paths to the destination on each channel, and new techniques are needed for combining these possibly disjoint paths for the best spectrum use. The arrival time of the RREQs in the route setup stage cannot be considered as the final measure of performance of the path. The estimated route latency needs to be further averaged with the possibility of PU disruption on the links that compose the path, and novel path quality metrics need to be formulated that use statistical knowledge of the PU information.

*Spectrum Dependency on Propagation* — Some spectrum bands provide longer propagation of the electromagnetic waves; thus, ranking of the available spectrum resources from the viewpoint of *connectivity* is important. The per-hop advance toward the destination is not uniform for all the spectrum bands, and this should be considered as a design factor when calculating the estimated number of hops in the route.

## Spectrum Sharing

### Basic Framework

Spectrum sharing provides the capability to maintain the QoS of CR users without causing interference to the PUs by coordinating the channel access as well as allocating communication resources adaptively. Thus, spectrum sharing is performed in the middle of a communication session and shares some functionalities with spectrum sensing. Figure 2 depicts its functional blocks for CRAHNs.

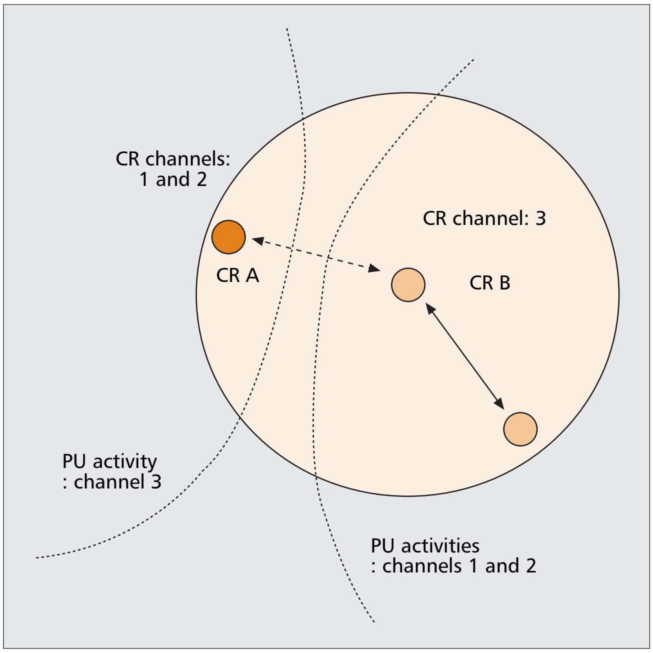

Figure 3. *Topology discovery challenge.*

*Resource Allocation* — Based on local observation, CR users need to perform channel selection and power allocation while choosing the best channel constrained by interference to other CRs and PUs. Cooperation among neighbors helps to enhance the performance of spectrum sharing, especially in power allocation, which should be aware of the PU activities in the transmission range.

Game theoretic approaches have been exploited to determine the communication resources of each user in CRAHNs. Each CR user has a common interest to use the spectrum resources as much as possible. However, CR users have competing interests to maximize their own share of the spectrum resources (i.e., the activity of one CR user can impact the activities of others). Furthermore, the rational decisions of a CR user must be undertaken while anticipating the responses of its rivals. Game theory provides an efficient distributed spectrum sharing scheme by describing the conflict and cooperation among CR users, and hence allowing each CR user to rationally decide on its best action. Although the game theoretic approaches can achieve the Nash equilibrium, they cannot guarantee the Pareto optimum, leading to lower network capacity.

*Spectrum Access* — Sensing and transmission intervals, determined by sensing control, influence the performance of spectrum access, as explained previously. This functionality forms the core of the MAC protocols [7]. However, in CRAHNs the sensing schedules are independent of each other due to lack of synchronization over all users. Furthermore, CR ad hoc users may adopt periodic or on-demand sensing triggered by only spectrum sharing operations (i.e., when CR users want to transmit or are asked for their spectrum availability by neighbor users). Based on the different spectrum access techniques, the design approaches for MAC protocols in CRAHNs can be classified as random access, time slotted, and hybrid. In random access schemes the channel may be opportunistically captured by any CR user for both control and data exchange. In time slotted protocols the control and data are assigned fixed durations, and prevent simultaneous transmission by multiple CR users. Finally, in a hybrid scheme there may be a fixed time duration for control packets followed by random access for capturing the channel before data transfer.

To aid CR users in properly accessing the spectrum and communicating with each other, the MAC layer has the following key considerations.

*Time Synchronization* — Some MAC protocols need rigid synchronization for both control and data channels (*slotted*), while others have assigned slots for control signaling alone (*hybrid*). Slotted protocols may need network-wide synchronization and have distinct slots in the beaconing period for each CR user. This is difficult to achieve due to the distributed operation in CRAHNs and incurs scalability issues. In addition, in some slotted protocols CR users hop over the channels broadcasting *hello* messages in a pseudo-random manner similar to Bluetooth. This results in a large coordination time and lowers spectrum utilization efficiency. As the spectrum is available only for short durations, periodic hopping without data communication wastes the resource. Thus, we believe that random access is best suited for CRAHNs if there is an accurate spectrum sensing mechanism supporting it.

*Spectrum Sensing Support* — To improve the accuracy of spectrum sensing, PU transmission must be distinguished from that of other CR users in the same neighborhood. If energy detection is used, one approach may involve establishing a silence zone up to two hops from the CR user currently performing sensing. Another approach is to use multiple radios that are assigned distinctly to the control, data, and busy tone band, respectively [8]. Whenever a node transmits or receives data on a given channel, it also emits a busy signal in the uniquely mapped busy tone band. Thus, during spectrum sensing, a CR user may first check the busy tone to verify that the channel is truly unused by other CR users. In carrier sense multiple access (CSMA)-based protocols, a CR user undergoes a backoff for a small duration when the channel is sensed busy due to transmission by other users. This time could be utilized for spectrum sensing since the CR user is idle as it counts down its backoff timer. Moreover, in CR ad hoc mesh networks, the different devices connected to the mesh router (MR) may piggyback their sensing results on the data packets and allow the MR to make a decision based on the collected information.

### Research Challenges

*Topology Discovery* — The use of nonuniform channels by different CR users makes topology discovery difficult. From Fig. 3 we see that CR users A and B experience different PU activity in their respective coverage areas and thus may be allowed to transmit only on mutually exclusive channels. The allowed channels for CR A (1,2) being different from those used by CR B (3) makes it difficult to send out periodic beacons informing the nodes within transmission range of their own ID and other location coordinates needed for networking.

*Distributed Power Allocation* — The CR ad hoc user determines transmission power in a distributed manner without support of the central entity, which may cause interference due to the limitation of sensing area even if it does not detect any transmission in its observation range. Thus, spectrum sharing necessitates sophisticated power control methods for adapting to time-varying radio environments so as to maximize capacity with the protection of the transmissions of PUs.

## Spectrum Mobility

### Basic Framework

CR users are generally regarded as *visitors* to the spectrum. Hence, if the specific portion of the spectrum in use is required by a PU, the communication needs to be continued in another vacant portion of the spectrum. This notion is called *spectrum mobility*. Spectrum mobility is closely related to time-varying network topology and spectrum availability, resulting in link failure on the end-to-end route. Compared to an infrastructure-based network, a CRAHN has a more dynamic and complicated topology depending on both spectrum and user mobilities. Here, we investigate the two main functionalities in spectrum mobility: spectrum handoff and connection management.

*Spectrum Handoff* — To provide seamless communications, spectrum mobility gives rise to a new type of handoff, the so-called spectrum handoff, in which users transfer their connections to an unused spectrum band. In CRAHNs spectrum mobility events can be detected as link failures caused by user mobility as well as PU activity. Furthermore, the quality degradation of the current transmission also initiates spectrum mobility. While route outages caused by node mobility are common in classical ad hoc networks, there is also a unique issue related to CR networks. Here, the route may still be connected, but the mobility of CR users may cause the original route, which was initially chosen to be unaffected by PU transmissions, to intersect regions under PU coverage.

When the link failure eventually occurs, the spectrum handoff stage comes into effect. A spectrum-related link failure caused by the arrival of PUs implies that link-layer recovery is ineffective as a large number of channels are affected, and no mutually acceptable channel exists on the link. In such cases local recovery is best suited, where a fresh RREQ may be transmitted by the users over the CCC in an attempt to join the two disconnected route segments on both sides of the affected PU region. In mobility-related failure the best design approach is to identify a new CR user closest to the initial location of the nodes that participated in the route setup process. The reason for this is that the route setup ensured that the path progressed through regions that were relatively unaffected by the PU activity. Given the frequent spectrum and mobility related disruptions that are possible in a CRAHN, the design of the network layer must aggressively seek local recovery mechanisms for reducing the recovery overhead.

*Connection Management* — The objective of a connection management function is to sustain the QoS of the ongoing transmission or minimize its quality degradation during spectrum switching by interacting with each layering protocol. Once the switching latency information is available, the connection management can predict the influence of the temporary disconnection on each protocol layer, and accordingly reconfigure each of them in turn. During spectrum switching, the protocols for different layers of the network stack should be transparent to spectrum handoff and the associated latency. Novel multilayer mobility management protocols are required to ensure that applications do not suffer from severe performance degradation. These protocols should support mobility management adaptive to different types of applications. For example, a TCP connection can be put in a wait state until spectrum handoff is over. For data communication such as FTP, the mobility management protocols should implement mechanisms to store packets that are transmitted during a spectrum handoff. Furthermore, mobility management protocols necessitate error control schemes for packets lost or corrupted during spectrum switching.

To avoid temporary disconnection, CR users can adopt multiradio transmissions where each transceiver tunes to different non-contiguous spectrum bands and transmit data simultaneously. Even if a PU appears in one of the current spectrum bands, the rest of the connections continue their transmissions unaffected.

### Research Challenges

*Switching Delay Minimization* — The spectrum switching delay is closely dependent on not only the hardware, such as an RF front-end reconfiguration time, but also algorithm development for spectrum sensing, spectrum decision, link layer, and routing layer decisions. Each time a CR user changes its frequency, the network protocols may require modifications on the operational parameters, which may cause protocol reconfiguration delay. Furthermore, to find the new spectrum and route, CR users need to perform out-of-band sensing and neighbor discovery, while minimizing searching delay through search sequence optimization. Thus, it is desirable to design a cross-layer spectrum mobility scheme to reduce the operational overhead and achieve faster switching times. The estimation of accurate latency in spectrum handoff is essential for reliable connection management.

*Adaptive Framework for Spectrum Handoff* — In a dynamic CR network, PUs may use the channels for intermittent durations, causing the need to change the routing paths. At such times, spectrum handoff is faced with the following options:

- Change the physical regions through which the existing path passes
- Switch the currently used spectrum band

Each method has a different influence on the QoS of the ongoing transmission. Furthermore, since a PU activity region is typically larger than the transmission range of CR users, multiple hops may be influenced at the same time when a PU is detected, which makes recovery time much longer than that in user mobility. Thus, the decision on switching strategy needs to be made adapting to the types of applications and mobility events, and must be closely coupled with the support provided by the link layer in terms of transmission adaptation, spectrum sensing information, and its own estimation of the PU activity with respect to the current time and geographical location, which is still an unexplored issue in CRAHNs.

## CRAHNs Based on the Commons Model

### Basics

The discussion so far has mainly focused on the so-called exclusive use model, in which CR users must operate under the strict guideline of limiting interference to the PUs that have priority access to the spectrum [9]. There is a growing interest in a different paradigm called the *commons* model, which relies on self-regulation and adherence to spectrum etiquette without special consideration of licensed users [9]. The commons model is of growing interest in defense research, as well as interaction between major telecommunication operators. It can be described by the following classification.

*Spectrum Etiquette and Standardization* — The problem of identifying a common set of rules becomes more involved in CR ad hoc networks belonging to different independent operators that may be present in spatially overlapped regions. Working groups such as the IEEE SCC41 P1900.5 aim to define a policy language along with consideration of the possible architectures for specifying interoperable vendor-independent control of networks.

*Mutual Spectrum Sharing through Cooperation and Selfish Competition* — Cooperation may involve choosing an optimal transmission power, channel bandwidth, transmission rate, and other parameters such that the user's own performance is maximized along with that of the overall network. In competitive approaches, each user may progressively increase its own usage of the spectrum resource and other communication parameters selfishly until its performance is affected by similar operation by neighboring users.

## Research Challenges

*Determination of Channel Structure* — The channel structure, bandwidth, and other specific transmission parameters need to be decided by CRAHN users. How a given spectrum block may be divided into smaller usable segments is an open issue.

*Misuse Detection and Penalty* — Some CR users may unfairly improve their performance at the cost of others, making it necessary to devise strategies to detect selfish behavior. In addition, penalizing misuse of the spectrum resource needs the presence of suitable external regulatory bodies, which is a significant design challenge in CRAHNs.

## Conclusions

The spectrum management functions integrated at the different layers of the network protocol stack play a critical role in realizing CRAHNs. They help with interaction among the CR users for spectrum sensing, selecting the spectrum band according to the history of PU activity, adapting transmission power and packet scheduling times to the presence of PUs, and ensuring that CR functions undertaken locally by the users seamlessly work in an end-to-end multihop scenario. While this article points out the key research challenges and emerging directions in CR research, a more descriptive treatment of the subject with additional issues explained can be found in [2]. We believe that research on CRAHNs should focus on leveraging cross-layer information and use cooperation among multiple users effectively to ensure protection to PUs as well as optimize CR network performance.

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