Channel Access Protocols for Multihop Opportunistic Networks: Challenges and Recent Developments

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Abstract

Heavy traffic over the unlicensed portion of the spectrum along with inefficient usage of the licensed spectrum gave impetus for a new spectrum allocation policy, the main purpose of which is to improve spectrum efficiency through opportunistic spectrum access. Cognitive radios have been proposed as a key enabling technology for such an opportunistic policy. One of the key challenges to enabling multihop CR communications is how to perform opportunistic medium access control while limiting the interference imposed on licensed users. In this article we highlight the unique characteristics of multihop cognitive radio networks, discuss key MAC design challenges specific to such networks, and present some of the work that has been done on MAC design for CRNs.

Recently, cognitive radios (CRs) have emerged as a promising technology to enhance spectrum utilization through opportunistic on-demand spectrum access. Traditionally, the radio spectrum is statically licensed to different organizations. Spectrum measurements by FCC and other organizations (e.g., XG DARPA initiative) indicated significant temporal and geographical variations in the utilization of the licensed spectrum, ranging from 15 to 85 percent. As an example, the actual measurements taken in Chicago for the frequency bands below 3 GHz indicate severe underutilization in the spectrum [1]. Specifically, the average spectrum utilization during the measurement period (two days) was 17.4 percent. These measurements motivated the need for a more efficient and adaptive spectrum allocation policy. In response to such measurements, the FCC has been revising its regulations to allow opportunistic access to the spectrum. CR technology offers such opportunistic capability. CRs are mainly characterized by their cognitive capability and reconfigurability. The cognitive capability provides spectrum awareness, whereas reconfigurability enables a CR user to dynamically adapt its operating parameters to the surrounding radio frequency (RF) environment. More specifically, the CR can be programmed to transmit and receive over widely separated frequency bands, adapt its transmit power, and determine its optimal transmission strategy.

A typical CR network (CRN) environment consists of a number of primary radio networks (PRNs) that are licensed to operate over orthogonal spectrum bands[1] and one (secondary) CRN. All networks coexist within the same geographical space. Figure 1 shows a conceptual composition view of a multihop CRN environment. Primary radio (PR) users that belong to a given PRN share the same licensed spectrum. CR users form an opportunistic network. They can opportunistically access the entire spectrum available to all PRNs. An important characteristic of a CRN is that users must operate using relatively low transmission power to avoid degrading the performance of PR users.

The above peculiar characteristics of CRNs distinguish them from traditional multichannel wireless networks. Although many medium access control (MAC) protocols have been proposed for traditional multichannel wireless networks, these protocols are not well suited to the unique characteristics of CRNs. Specifically, the absence of PR users in multichannel wireless networks makes their protocols fundamentally different from CRN MAC protocols. In order to design a good MAC protocol for multihop CRNs, the following attributes are required:

- The protocol should be transparent to PR users (i.e., does not require coordination with them).
- The protocol should provide guarantees on PRNs' performance.
- The protocol should allow cooperation among neighboring CR users at the MAC layer to improve spectrum efficiency and fairness among them.
- The protocol should make efficient sensing and spectrum assignment decisions to explore both unused (white) and partially used (grey) spectrum *holes*. These decisions should account for channel dynamics due to PR users.
- The protocol should provide an effective distributed coordination scheme for exchanging control information without assuming a predefined dedicated control channel.

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[1] *The terms band and channel are used interchangeably in this article.*

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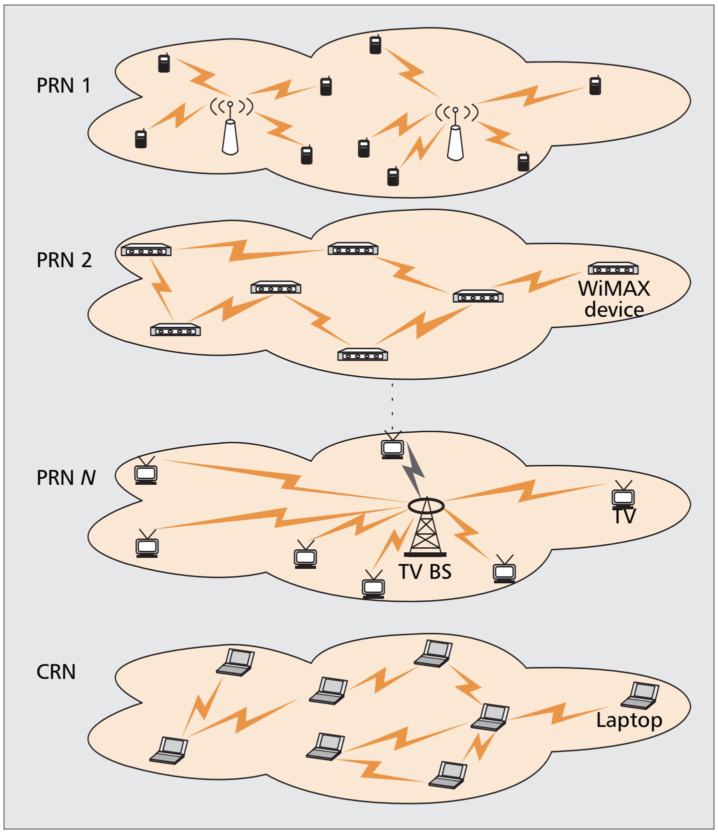


■ Figure 1. *Opportunistic access environment containing one CRN and* N *PRNs.*

Many researchers are currently engaged in developing efficient MAC protocols that attempt to address the above design requirements. In this article we present a survey of spectrum access protocols proposed thus far for multihop CRNs. Our aim is to give a better understanding of the current research issues in this emerging field. We start by discussing the key design issues in developing MAC protocols for such networks. Then we present recent progress in MAC protocol design for CRNs. The article concludes with a discussion of open research issues.

Design Challenges

Novel spectrum access/sharing protocols and algorithms are needed to effectively tackle the unique resource constraints and dynamic operating environment of CRNs. In this section we discuss the main challenges in designing such protocols and give an overview of recent developments in this domain.

Control Channel Dilemma

In a multihop CRN environment a reliable mechanism for exchanging control information (transmitter-receiver handshake, sensing information exchange, etc.) is needed. Typically, in order to support such a mechanism, a licensed common control channel (CCC) is often dedicated for control information exchange. A number of MAC protocols for CRNs were designed assuming the existence of such a channel. While this approach is simple, it is contradictory to the opportunistic nature of CRNs and can cause a single point of failure. In addition, the CCC can become a performance bottleneck under high traffic load. To solve this issue, various solutions have been proposed, none of which are totally satisfactory. In the following we classify these solutions into three different classes.

Non-Dedicated CCC — Many MAC protocols for CRNs were designed assuming a predetermined non-dedicated CCC that is known to all users. This control channel can be implemented as a channel in an unlicensed band (e.g., ISM band) or an underlay ultra-wideband (UWB) channel [2]. UWB is a radio technology that can transmit at a very low power density (in watts per hertz) in a short range by spreading the signal over a large portion of the spectrum. Therefore, its impact on PRNs will be very negligible.

The aforementioned non-dedicated schemes have major design issues that make their practicality questionable. Specifically, using UWB leads to a small control transmission range, which might jeopardize CRN connectivity. On the other hand, using a fixed CCC can cause a single point of failure, become a performance bottleneck, and raise security issues. Worse yet, in a multihop environment, a CCC may not be available to all CR users (because non-neighboring CR users may have different views of spectrum availability).

Dynamic Local Control Channel — Neighboring CR users typically have a similar view of spectrum conditions. Accordingly, grouping (i.e., clustering) algorithms can be used to enable reliable coordination between CR users. Each group dynamically selects a local CCC for exchanging control information [3]. However, applying such an approach in multihop CRNs is daunted by several deployment challenges, such as ensuring connectivity (i.e., different groups adopt different local control channels), determining group sizes, identifying the members of each group, and selecting the optimal frequency for a new CCC (i.e., due to the dynamic nature of CRNs, local CCC renegotiation is very frequent).

Hopping-Based Control Channel — A hopping-based control channel is a promising technique to overcome the need for a CCC and alleviate the control channel bottleneck problem. According to this approach, CR users hop across all licensed channels according to a predefined channel hopping sequence. During hopping, a CR transmitter-receiver pair exchanges control information to decide which channels to use for data transmission. When they successfully exchange control information, the communicating CR users stop hopping and start data transmission. Once done, both transmitter and receiver resynchronize back with the hopping sequence. The main difficulty with such an approach is its synchronization requirements. Specifically, this approach requires stringent time/channel synchronization between CR users.

CR Transmission Power Control

Coexistence of CR and PR users in the same area poses a new challenge regarding protecting PR performance. In a mixed CRN/PRN environment, three types of interference need to be accounted for: CR-to-CR interference, PR-to-CR interference, and CR-to-PR interference. The latter is the most critical, because of its direct influence on PRNs' performance. Thus, CR transmission powers over the various PR bands need to be regulated such that the PR users' reception is not negatively affected by CR transmissions.

To address this issue, a *frequency-dependent power mask* on the CR transmissions is often adopted (Fig. 2). This mask reflects the maximum permissible transmission power vector of a CR user. Depending on whether or not a CR transmission can overlap with PR transmissions, existing solutions for regulating CR transmission power can be classified into two types: binary and multilevel.

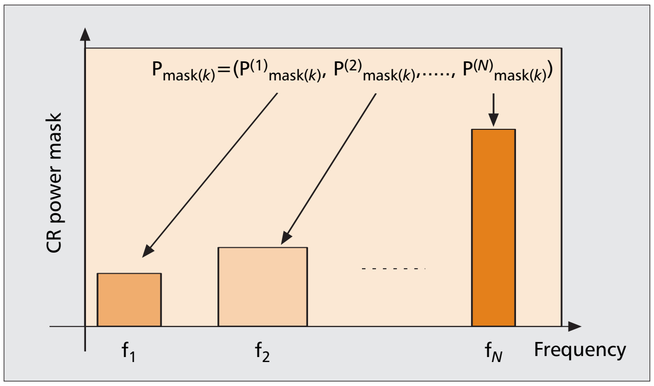


Figure 2. *Frequency-dependent power mask for CR user* k.

Binary-Type Power Mask Model — Most MAC protocols for CRNs focus on identifying and avoiding interference with PR transmissions [4–6]. In these protocols CR users can only exploit white spaces that are free of PR interferers. This type of opportunistic spectrum sharing requires a CR user to perform sensing before attempting to transmit. Accordingly, the CR user identifies whether or not a given PR band is idle. If so, the CR user can transmit. Under the assumption of perfect sensing, this approach ensures nonoverlapping (collision-free) band occupancy between CR and PR users. In this case the corresponding power regulating scheme can be viewed as a binary-type power mask over each PR band. Formally, for band i, $i = 1, \ldots, N$, the CR transmission power is 0 if any PR user operates on band i, or $P^{(i)}_{\max}$ if none of them is active. $P^{(i)}_{\max}$ is the smaller of the FCC regulatory maximum transmission power over that band and the maximum power supported by the CR's battery. However, the efficiency of this type of scheme depends heavily on the ability to predict/detect the presence of PR signals over various bands (i.e., the scheme requires a robust algorithm for determining white spaces). If CR users are unaware of the location and transmission technology of nearby PR users, detecting and identifying white bands is still a major challenge. Binary-type power mask can also result in nonoptimal spectrum utilization. It has been shown that allowing CR users to exploit both white and grey bands gives much better spectrum utilization [7].

One example of binary-type power control for CRNs is given in [5], where the authors proposed two random access schemes to exploit the white band opportunities under given constraints on the CR-to-PR collision probability and overlapping collision time. Under such constraints and assuming perfect sensing, the authors provided closed-form expressions of the capacity limit of CR users.

Multilevel Power Mask Model — Using a multilevel power mask allows for simultaneous spectrum sharing between neighboring CR and PR users, which can potentially lead to better spectrum utilization. According to this approach, CR users can exploit both white and grey bands. This model presents a general form of spectrum opportunity and provides a generalization of the widely used binary-type power mask. Thus far, both *static* and *dynamic* power masks have been used in developing MAC protocols for multihop CRNs. In the case of a static power mask, the mask is assumed to be fixed and the same for all CR users. However, this assumption is hardly true for a generic multihop CRN (because spectrum utilization may significantly vary in time and space). As a result, for a generic multihop CRN, the design of a good MAC protocol should be based on an adaptive/dynamic power mask.

Determination of the Power Mask — The determination of an appropriate power mask is certainly an important topic. The proposed spectrum sharing protocols in [7, 8] were designed such that the maximum transmission powers of CR users over various bands are dynamically computed based on the PR's interference margins and local traffic conditions. In [8] the authors provided a *neighborhood-dependent* adaptive power mask on CR transmissions that ensures a statistical (soft) guarantee on the performance of PRNs. The proposed solution guarantees that the outage probability (p_{out}) of a PR user, defined as the probability that the total interference power at a PR receiver exceeds the maximum tolerable interference, is less than a given bound β. The authors provided closed-form expressions for the resulting power mask. Simulation results in [8] show that the proposed MAC protocol improves spectrum utilization and statistically guarantees the performance of PR users under different traffic loads and for different values of β.

The FCC defined the *interference temperature model* in 2003, which provides a metric for measuring the interference experienced by PR users. It has been shown that using this model to constrain the CR transmission power results in very poor performance [7]. Based on this fact, Clancy proposed alternate usages for interference temperature that attempt to improve the CRN throughput without negatively impacting the PRNs' performance. The basic idea is to constrain the CR transmission power over partially used (grey) PR bands using the interference temperature model while leaving the CR transmission power over idle (white) bands unconstrained. This can be achieved by using a controllable transmission waveform whose power spectral density is non-uniform. However, the proposed scheme does not provide explicit guarantees on the performance of PRNs. It is worth mentioning that due to the lack of specific technical rules to implement the interference temperature model, the FCC abandoned this model in 2007 [9].

Spectrum Access/Sharing

As mentioned before, spectrum access/sharing schemes for traditional multichannel wireless networks are not well suited to the unique features and application requirements of CRNs. These schemes are often based on a *greedy strategy* that selects the best available channels for a given transmission. When such greedy assignment is employed in a CRN, the blocking probability for CR transmissions can increase, leading to a reduction in the CR network throughput [2]. Hence, new spectrum sharing algorithms are needed to improve the performance of CRNs. Research in this domain includes both

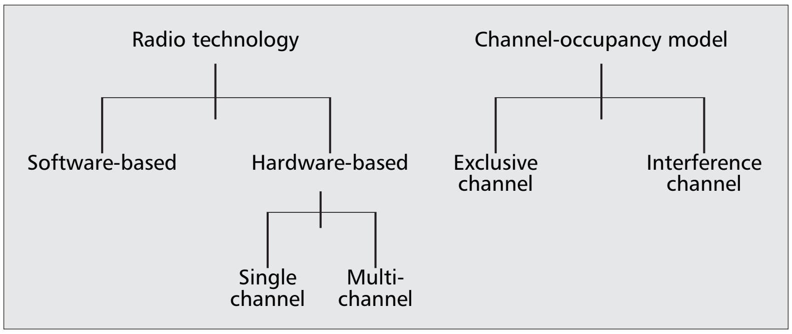
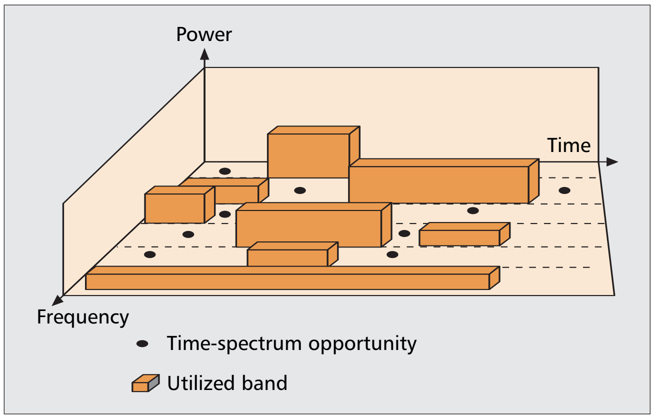


Figure 3. *Categorization of spectrum access techniques in CRNs according to the employed radio technology and channel occupancy model.*

centralized and distributed algorithms. We focus on distributed approaches in this article, as they are more suitable for multihop ad hoc networks. The optimal spectrum sharing (assignment) problem in CRNs that maximizes the spectrum utilization is known to be NP-hard. Hence, the proposed algorithms are heuristic in nature.

In general, existing spectrum access/sharing protocols in CRNs can be classified according to two aspects: the radio front-end technology and the spectrum-occupancy model (Fig. 3). In the following we describe the various categories of spectrum access protocols and give an overview of the main ones proposed in the literature. It should be mentioned that some of these protocols belong to more than one category. However, for simplicity we list them only under one category.



■ Figure 4. *Variable time-spectrum opportunities.*

Classification Based on Radio Technology

Hardware-Based Schemes — Several spectrum sharing solutions for CRNs have been designed assuming hardware-based radio technology. In these schemes the number of parallel channels that can be simultaneously used at a CR user is limited by the number of the available transceivers. Based on this number, approaches belonging to this category can be further classified into two groups: single-channel and multichannel assignment.

Single-Channel Assignment — A number of CRN MAC protocols that assume a single radio per user have been proposed. In these protocols a CR user can only transmit/receive over one of the available bands at a time. One example is in [6], where the authors discussed the hardware limitations of practical CRs, including partial spectrum sensing and single-radio constraints. They investigated how to conduct efficient and distributed spectrum sharing design under such hardware constraints. They formulated the spectrum sensing/sharing process as an optimal stopping problem. Both optimal and approximation stopping rules were obtained. According to the obtained rules, each CR user selects the best channel that maximizes its throughput.

Multichannel Assignment — MAC protocols that support multichannel parallel transmissions can significantly improve CRN performance [10]. In practice, to support parallel transmissions the radio system typically has multiple radio transceivers that can be used simultaneously. Each transceiver is tuned to a given carrier frequency with fixed bandwidth, allowing a CR user to choose from a fixed number of channels. This hardware-based implementation is referred to as multichannel multiradio (MC-MR) technology. It is worth mentioning that many multichannel spectrum sharing solutions in the context of CRNs are based on MC-MR technology. The potential benefits of using multichannel parallel transmission in CRNs were demonstrated in [10]. The carrier sense multiple access (CSMA)-based MAC protocol in [10] considers multiple transceivers per CR user, which has been shown to achieve considerable throughput improvement over its single-channel counterpart. The proposed protocol jointly optimizes the channel/power/rate assignment according to the surrounding interference, assuming a given power mask. It explores different channel combinations to seek the optimal one that has the minimum number of channels and requires the minimum transmission power while satisfying the imposed power mask and the rate demand constraints.

Software-Based Schemes — A common assumption in MC-MR networks is that there is a set of *common channels* available for every CR user, each with fixed carrier frequency and bandwidth. Consequently, MC-MR technology allows a CR user to choose from a fixed (limited) number of common channels. However, such an assumption is hardly true for a generic multihop CRN, where the spectrum availabilities may significantly vary in time, frequency, and space. To deal with this issue, software-defined radio (SDR) has been developed to provide a multichannel transmission capability with tunable parameters (tunable carrier frequency, bandwidth, number of channels, etc.). SDRs are more powerful and flexible than hardware-based radios. Specifically, the number of multiple (contiguous or non-contiguous) bands that can be used by a *single* SDR is typically much larger than that supported by MC-MR. More important, SDRs have the capability of enabling CR communications with variable-width bands [11]. In some sense, hardware-based CRNs can be considered a special case of SDR-based CRNs.

Several spectrum access protocols in CRNs have been proposed with the assumption of variable spectrum assignment. Variable assignment strategies facilitate the design of efficient spectrum sharing protocols in CRNs, have great potential to improve overall spectrum utilization, and account for spectrum heterogeneity in multihop CRNs. The need for adaptive variable spectrum sharing protocols was investigated in [4]. The authors introduced the concept of *variable width time-spectrum blocks* to model spectrum sharing/reservation in CRNs. A time-spectrum block is defined as a unit of spectrum reservation (Fig. 4). Based on this concept, the authors formulated the spectrum allocation/reservation problem as packing of time-spectrum blocks in a two-dimensional time-frequency space such that the rate demands of all CR users are satisfied as well as possible. Both centralized and distributed protocols were proposed. The simulation results in [4] show that variable spectrum assignment schemes significantly outperform fixed-bandwidth assignment schemes.

Classification Based on Channel Occupancy Model

Depending on the system setup and the resulting interference relationships between CR users (i.e., CR-to-PR, PR-to-CR, and CR-to-CR), spectrum access protocols for CRNs can be classified into two categories: protocol and physical.

Protocol Model — Under the protocol model, the CR-to-CR interference is eliminated by enforcing *exclusive channel occupancy* between CR users, whereby a channel occupied by a CR user cannot be simultaneously allocated to another CR user *in the same vicinity* (Fig. 5a). Consequently, only the PR-to-CR and CR-to-PR interferences are accounted for. MAC protocols belonging to this group generally follow the CSMA with collision avoidance (CSMA/CA) paradigm, with extensions to allow for the control packet handshake between communicating CR users. Communicating CR users perform a

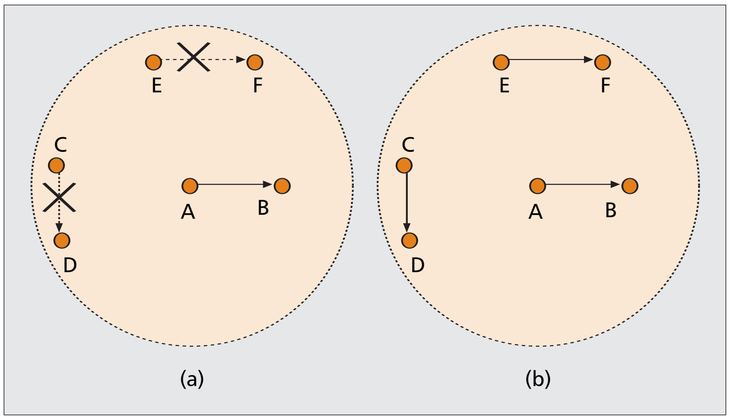


Figure 5. *Scenarios in which CR transmitters* C *and* E *can/cannot reuse the channels assigned to* A*. The dashed circles indicate* A*'s control-transmission range: a) exclusive channel occupancy; b) interference channel model.*

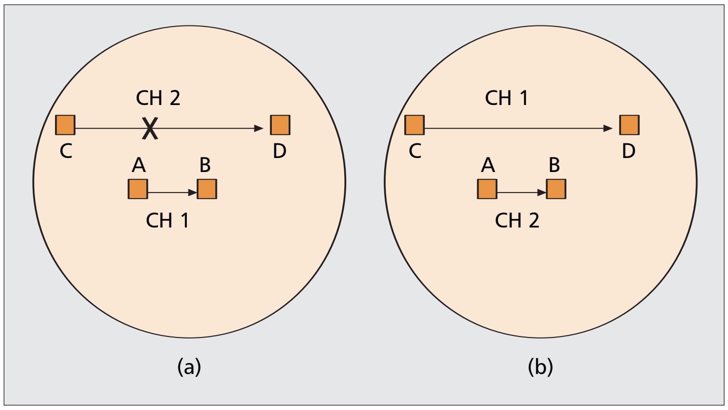


Figure 6. *Scenarios in which two CR transmissions can/cannot proceed simultaneously [2]: a) traditional channel assignment; b) distance-dependent channel assignment.*

three-way handshake over a CCC. During the handshake process, the communicating CR users exchange control information (the list of *currently available channels* at the transmitter, rate demand, etc.), conduct the channel assignment, and announce the outcome of the channel assignment and the duration of the transmission to their neighbors.

An interesting consideration of the dependence between the RF signal attenuation model and the transmission distance when assigning channels for CR transmissions was introduced in [2]. This distance- and traffic-dependent approach has great potential to improve spectrum utilization. To illustrate, consider an environment with two PRNs and one CRN. PRN 1 operates over a low-frequency band ($CH1$), while PRN 2 operates over a high-frequency band ($CH2$). Suppose that PRN 2 introduces a higher average PR-to-CR interference. Consequently, a CR receiver experiences a higher average signal-to-interference-plus-noise ratio (SINR) over $CH1$ than over $CH2$. Assume that two CR users, A and C, need to send data to CR users B and D, respectively (Fig. 6). Suppose that the distance between A and B (d_{AB}) is less than that between C and D (d_{CD}). Figure 6a shows that when the CR users employ the traditional multichannel greedy approach, transmission $A \rightarrow B$ uses $CH1$, whereas transmission $C \rightarrow D$ uses $CH2$. $A \rightarrow B$ is allowed to proceed because it operates over a low-carrier-frequency channel with low PR-to-CR interference for a short transmission distance. On the other hand, $C \rightarrow D$ requires relatively higher transmission power to overcome the high attenuation associated with the high-frequency/high-interference channel and the long transmission distance. If the required transmission power exceeds the specified power mask, $C \rightarrow D$ cannot proceed. However, both $A \rightarrow B$ and $C \rightarrow D$ have much better chances of proceeding simultaneously if each CR transmitter selects channels while keeping in mind the constraining power mask of the other transmitter (Fig. 6b). The simulation results in [2] show that distance- and traffic-aware MAC protocols can significantly improve CRN throughput while preserving fairness.

Physical Model — One common limitation of protocol-model-based MAC protocols is their sole reliance on CSMA/CA for accessing/reserving the shared wireless spectrum. Although CSMA/CA is fundamentally needed to reduce the likelihood of CR collisions due to the hidden terminal problem, such a mechanism may significantly degrade spectrum efficiency. Specifically, it negatively impacts spectrum utilization by *not allowing multiple concurrent CR transmissions* within the same neighborhood to overlap in frequency. Various attempts were made to develop MAC protocols for CRNs that assume an *interference channel* model. According to this model, neighboring CR users have the same channel access rights and may share the same channel simultaneously. This category accounts for all three possible interference relationships in the MAC design. Little is known about the optimal achievable rate region for such a setup.

We use the example in Fig. 5 to illustrate channel access under the physical model. Assume that CR users A, C, and E need to send data to CR users B, D, and F, respectively. According to the exclusive channel occupancy policy, transmissions $A \rightarrow B$, $C \rightarrow D$, and $E \rightarrow F$ cannot overlap in their data channels (Fig. 5a). The three transmissions can proceed simultaneously only if nonintersecting channels can be found to support their rate requirements. On the other hand, under the physical model, transmissions $A \rightarrow B$, $C \rightarrow D$, and $E \rightarrow F$ may overlap in their data channels if each CR transmitter selects its transmission power while keeping in mind its interference to unintended receivers (Fig. 5b). As an example, the CRN MAC protocol in [12] attempts to improve the spectrum efficiency by allowing multiple neighboring CR transmissions to overlap in frequency bands. It allows neighboring CR pairs to be first involved in an admission phase, then iteratively negotiate their transmission powers and channel assignment through a distributed price-based iterative water-filling algorithm.

Summary and Open Issues

Providing an efficient distributed MAC protocol for multihop CRNs is a challenging problem. The design of MAC protocols for such networks should leverage the unique capabilities of CRs and the peculiar characteristics of their multihop environment. This article gives a broad overview of the key design challenges in developing efficient MAC protocols for CRNs. It also surveys and classifies the recently proposed MAC protocols in the literature. We surmise that the most compelling challenges are how to provide effective distributed coordination between CR users without relying on the existence of a prespecified CCC, how to compute an appropriate neighborhood-dependent power mask that provides guarantees on the performance of PR users, and how to provide an optimal spectrum sharing scheme in order to maximize the spectrum utilization.

Many interesting open problems remain to be addressed. To deal with the spectrum heterogeneity in multihop environments, the discussions provided in this survey strongly advocate a dynamic neighborhood-dependent power mask approach as a good candidate to address the CR transmission power issue. The practical aspects of such an approach is yet to be explored. The design of an effective coordination scheme is still an open problem. Various solutions have been proposed in this domain, none of which are totally satisfactory. Because of the dynamic nature of CRNs, we believe that the design of an effective distributed coordination scheme must be based on a *transmission technology/coordination technique* that provides reliable CR communications, security, connectivity, and PR user protection. Variable bandwidth assignment schemes are promising, but their feasibility and design assumptions need to be evaluated. For instance, most of the proposed protocols are best effort and do not provide any QoS guarantees on CRN performance.

Although many interesting approaches have been proposed, most of them only cover a subset of the challenges related to CRN MAC design. Hence, for efficient MAC design, more research is needed to address the issues along the lines introduced in this survey.

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