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# Medium Access Control Design for Cognitive Radio Networks: A Survey

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**SUMMARY** Designing a medium access control (MAC) protocol is a key for implementing any practical wireless network. In general, a MAC protocol is responsible for coordinating users in accessing spectrum resources. Given that a user in cognitive radio(CR) networks do not have priority in accessing spectrum resources, MAC protocols have to perform dynamic spectrum access (DSA) functions, including spectrum sensing, spectrum access, spectrum allocation, spectrum sharing and spectrum mobility, beside conventional control procedure. As a result, designing MAC protocols for CR networks requires more complicated consideration than that needed for conventional/primary wireless network. In this paper, we focus on two major perspectives related to the design of a CR-MAC protocol: dynamic spectrum access functions and network infrastructure. Five DSA functions are reviewed from the point of view of MAC protocol design. In addition, some important factors related to the infrastructure of a CR network including network architecture, control channel management, the number of radios in the CR device and the number of transmission data channels are also discussed. The remaining challenges and open research issues are addressed for future research to aim at obtaining practical CR-MAC protocols.

***key words:*** *cognitive radio, medium access control, MAC protocol, dynamic spectrum access, spectrum sensing, spectrum access, spectrum allocation, spectrum sharing, spectrum mobility, control channel, distributed wireless network, centralized wireless network, cooperative sensing, spectrum underlay, spectrum overlay, spectrum interweave, spectrum handoff*

## 1. Introduction

The wastage in using spectrum resource of the conventional static spectrum allocation policy [1] has motivated novel approaches to exploit the under-utilized spectrum, called white spaces, within licensed spectrum bands. Dynamic spectrum access (DSA) has been introduced as an effective method to enhance spectrum utilization by efficiently exploiting the white space and by increasing number of simultaneous users sharing a certain frequency band. In DSA, spectrum bands are first allocated to licensed or primary users (PUs) who have higher priority on spectrum accessing permission. Other users who are called unlicensed or secondary users can also dynamically access these spectrum bands as long as secondary user activity is invisible to primary users. As a result, secondary users can access a spectrum band either opportunistically whenever PUs are not using the spectrum bands or with limited transmission power under the interference temperature limit of PUs. In this way, the spectrum resource utilization is more efficient.

Cognitive radio (CR) has been developed to improve spectrum utilization efficiency by implementing white space DSA. To coexist with primary networks who possess the license to use the spectrum bands, CR networks equip their users called CR users with DSA functions. Spectrum sensing, spectrum sharing, spectrum allocation, spectrum access, and spectrum mobility are the five main DSA functions whose definition can be found in many previous works [2], [3].

First,the spectrum sensing function allows CR networks to discover spectrum holes by observing the spectrum environment. Spectrum sensing can be performed either individually or cooperatively.

Second, the spectrum sharing function defines the spectrum resource sharing modes. For sharing modes between primary networks and CR networks, spectrum sharing can adopt underlay, interweave, and overlay paradigms [4]. The description of these paradigms is detailed in Sect. 2.4. For spectrum sharing within CR networks, two spectrum sharing scenarios are considered: intra- and inter-network spectrum sharing. The former concentrates on spectrum allocation between the entities of a CR network, whereas the later deals with sharing solutions to enable multiple systems to be deployed in overlapping locations and spectrums.

Third, the spectrum allocation function is responsible for fairly allocating available spectrum bands to users in a CR network. Whenever a spectrum band is allocated, the information about the allocated spectrum band will be announced to other users. Either a cooperative or a non-cooperative manner can be used for spectrum allocation. The detailed discussion of the effect of these methods is in Sect. 2.3.

Fourth, the spectrum access function coordinates multiple CR users, who try to access the same spectrum simultaneously, so as to minimize access collision. In this paper, we focus on analyzing solutions in time domain spectrum access management. The detail is presented in Sect. 2.2.

Finally, the spectrum mobility function aims at providing seamless communications during transition to other spectrum bands in the presence of PUs.

In general, the medium access control (MAC) protocol is the core part for the operation of any network system. It is responsible for coordinating access of multiple users to spectrum channels. Therefore, designing an appropri-

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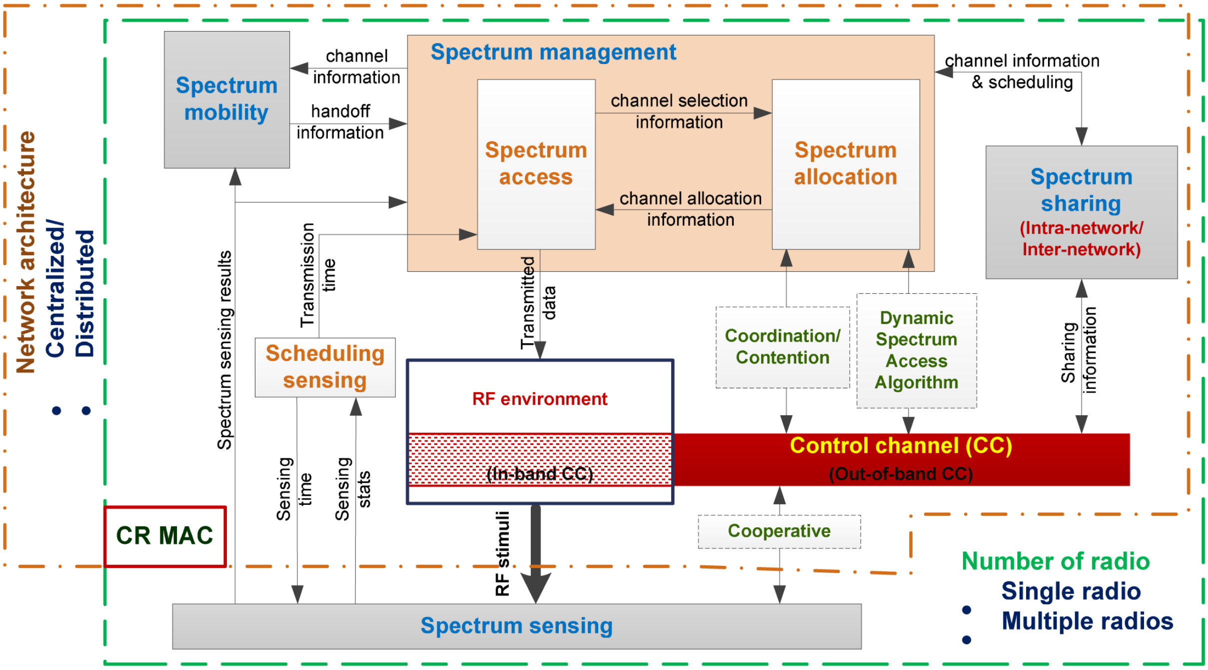

**Fig. 1** Components of a CR-MAC scheme.

ate MAC protocol is the main task for realizing white space DSA. A MAC protocol in conventional wireless network has to deal with a variety of problems such as network start-up, node joining, channel access collision, time synchronization, hidden/exposed-terminal and so on. A MAC protocol designed for a CR network (i.e., a CR-MAC protocol) has to face up to many more problems including many concerns related to DSA functions. As a result, CR-MAC protocols are more complicated than conventional MAC protocols. The factors affecting a CR-MAC protocol and its components are illustrated in Fig. 1.

Although much research has been conducted on CR-MAC protocols with many interesting publications, most of the issues have been presented separately. Some surveys focusing on some parts, i.e., some DSA functions or some infrastructures components, instead of an overall view, of CR-MAC design have been published. For example, a comparison between centralized and distributed approaches for spectrum management and a comprehensive overview of spectrum assignment are provided in [5], [6], respectively. In [5] the considered spectrum management for either centralized or distributed network mainly covers the spectrum access and spectrum allocation functions while not considering the spectrum sensing, spectrum sharing and spectrum mobility functions. Also, it does not consider the effects of control channel, the number of transmission channels and the number of radios on a user terminal. In [6], the authors presented an overview of the spectrum assignment, but did not covered other cognitive functions that a CR-MAC protocol needs to support such as the method to determine spectrum band characteristic through the spectrum sensing function, the method to avoid accessing collisions between different users through the spectrum access function, the method to manage spectrum handoff through the spectrum mobility function, and the method to perform spectrum sharing with primary systems through spectrum sharing function. There are also some previous surveys about CR-MAC protocols [7] and CR-MAC strategies [8]. However, these works aim at providing a list and/or classification of issues concerning CR-MAC protocols rather than a systematic construct of CR-MAC protocols.

Figure 1 illustrates the factors affecting a CR-MAC protocol and its components. It can be seen that many factors for designing CR-MAC protocols must be considered simultaneously. First, a designer must answer questions concerning network and hardware infrastructure such as: is the network organized in a centralized or a distributed paradigm? How many channels are used for data transmission? How to manage the control channel? How many radio units are equipped for each device? Answering these questions is necessary since a CR-MAC protocol could be only designed in accordance with the corresponding infrastructure.

Second, a designer must consider all the DSA functions since most of them mainly operate in MAC level. Despite the fact that the spectrum sensing function does not belong to a CR-MAC protocol, the schedule as well as the cooperation between users in a network for spectrum sensing is the responsibility of the CR-MAC protocol. Depending on the number of radio units on each device, sensing and transmission schedules will differ. Spectrum sensing results will provide information of available channels for the operation of spectrum access, spectrum allocation and spectrum mobility functions. Indeed, according to avail-

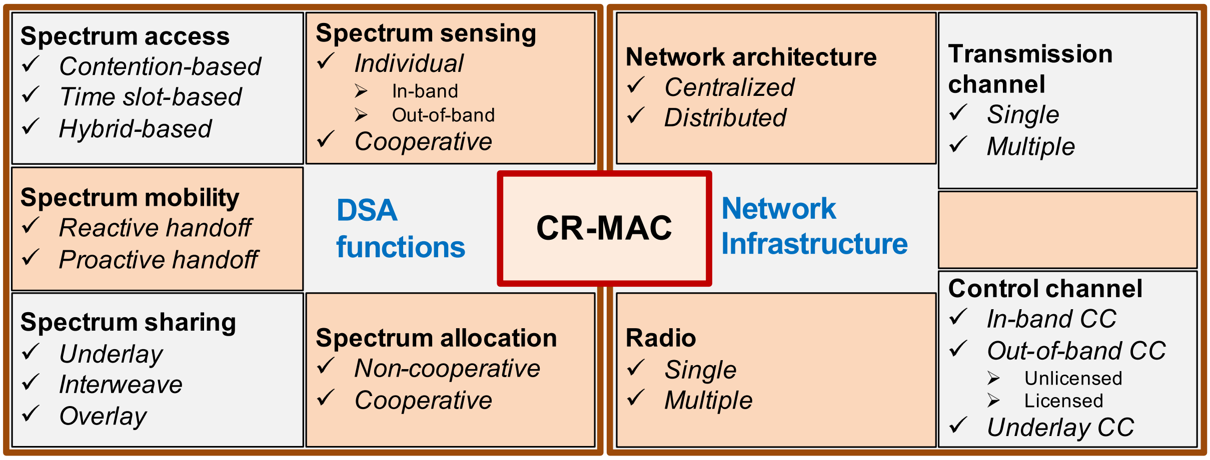

**Fig. 2** Classification of CR-MAC protocols.

able channel information, the spectrum allocation function of CR-MAC will adopt a coordination or contention protocol for a distributed CR network and a DSA algorithm for a centralized CR network to obtain a fair spectrum allocation for all the CR users. Information of allocated channels is transferred to spectrum access function in each user where a selection or negotiation or direct access procedure is accordingly performed depending on network architecture paradigm and spectrum accessing method to determine the transmitting channels. Information of allocated, used and available channels is then provided to the spectrum mobility function to prepare and ensure seamless communication during spectrum handoff due to primary network operation. Channel information and its use plan are also transferred to the spectrum sharing function, mainly focusing on inter-network spectrum sharing (intra-network spectrum sharing has been already performed in the spectrum allocation function).

It is obvious that the operation of DSA functions are closely associated with each other and are strongly influenced by the selection of infrastructure components of a CR network. Therefore, designing a MAC protocol, in principle, requires a general point of view which considers a MAC protocol as an entity including multiple associated functions and components. Any CR-MAC designation which separately considers the above functions and components can not obtain a complete solution.

In this paper, we present a review on components and factors that construct and influence on the operation of a CR-MAC protocol. To establish a systematic view, we divide these components and factors in two perspectives, i.e., DSA functions and network infrastructure, which will be discussed in detail in Sects. 3 and 4, respectively. A brief summary of the two investigated perspectives is presented in Fig. 2 for the convenience of reading. The remaining challenges and open issues for future research which aim at obtaining practical CR-MAC protocols are addressed in Sect. 5. Finally, we conclude the paper in Sect. 6.

## 2. DSA Functions for CR-MAC Design

### 2.1 Spectrum Sensing

Spectrum sensing is a prerequisite to enable CR users to identify spectrum holes which are not used by PU at a specific time and location. Spectrum holes can be localized through either the indirect spectrum sensing by primary transmitter detection or the direct spectrum sensing by primary receiver detection [3]. In general, secondary spectrum access is allowed if and only if it does not cause any interference to the primary system, and signal interference only occurs at receive ends. Spectrum holes are determined by the absence of primary receivers inside the coverage range of CR users. Therefore, primary receiver detection is considered as the direct spectrum sensing method.

There are some previous works investigating the direct spectrum sensing approach. In [9], the primary receiver can be detected by exploiting the local oscillator leakage power emitted from the RF front-end of the primary receiver. Another method proposed for primary receiver detection is proactive spectrum sensing [10]. In this method, CR user first sends a sounding signal and observes possible changes in the primary signal which is caused by the closed-loop power control. If there is an increment of primary signal power to compensate for interference power derived from the sounding signal, the nearby primary receiver can be sensed.

Another approach to identify spectrum holes is indirect spectrum sensing through primary transmitter detection. Observing the primary signal by CR users can provide information about the primary transmitter and spectrum holes. In principle, the presence of a primary signal means that there is no spectrum hole. However, its absence does not ensure the availability of spectrum holes. Indeed, spectrum holes may not be detectable due to receiver uncertainty or hidden terminal problem [3]. Receiver uncertainty is where a CR user's location is out-of-range of the primary transmitter and so can not detect the primary signal. Hidden terminal is where the location is affected by multipath fading and shadowing effect and so is unable to detect the primary signal correctly.

It can be seen that the direct spectrum sensing method has more limitations than the indirect since a local oscillator leakage power is too small to detect effectively and a sounding signal in the proactive sensing method causes interference to the PU. Therefore, most the current spectrum sensing methods are performed by indirect method through primary transmitter detection. The performance degradation of primary transmitter detection-based spectrum sensing due to receiver uncertainty and hidden terminal problem can be defeated by utilizing cooperative spectrum sensing among multiple CR users. Exploiting spatial diversity in cooperative sensing provides effective solutions for improving the sensing accuracy against receiver uncertainty or hidden terminal problems [11].

The main purpose of MAC protocol is to manage radio resource access. Furthermore, in CR networks, a spectrum hole is an opportunistic spectrum resource. Therefore, supporting a spectrum sensing function is necessary for a CR-MAC protocol to manage the opportunistic spectrum access effectively.

### 2.1.1 Scheduling for Individual Sensing

The design of CR-MAC components concerning spectrum sensing depends on the architecture of the network and the hardware of the CR terminal. If the network support an external sensing system [12] or a spectrum availability database [13], the CR-MAC has to ensure an effective access of CR terminals to spectrum resource status database. Availability of a control channel and network overheads will be the critical problem in CR-MAC design for this scenario.

In the case of performing spectrum sensing in each CR user, the number of radios on the device will decide the support level of MAC for spectrum sensing. For example, if CR terminals are equipped with multiple radios, the spectrum sensing process can be conducted in parallel with the data transmission process. CR user can observe status of the adjacent channels (the out-of-band channels) while communicating in the in-band channel [14]. This means that there is no influence on the utilization of spectrum due to spectrum sensing. The problem in that case is how to schedule the sensing time so that as many sensing channels are sensed as possible.

On the other hand, if the CR user is only equipped with a single radio, the spectrum sensing and spectrum access processes should be implemented alternately. The MAC layer must provide an optimal schedule so that the sensing time and spectrum access time are balanced [2]. One type of MAC organization is based on frame. There are two main issues that need to be addressed for spectrum sensing in frame-based CR-MAC with single-radio CR user.

- How long is the sensing period to maximize spectrum sensing accuracy while minimizing the sensing overhead?
- How frequent is the sensing process performed to detect active PU rapidly?

In general, sensing accuracy will be higher when the sensing phase is longer. The minimum period of time to conduct the sensing process is determined by the primary signal strength, and target probabilities of detection and false alarm. Moreover, all CR users have to keep quiet on the sensing channel during the sensing period to ensure no self interference. Therefore, the length and frequency of the sensing period should be considered carefully in order to optimize the tradeoff between spectrum utilization efficiency and sensing accuracy [15], [16]. In [17], a joint PHY-MAC spectrum sensing algorithm, which employs sequential probability ratio test in the PHY layer and a probability-based sensing scheduling mechanism in the MAC layer, is proposed to minimize detection delay with limited sensing overhead.

Under similar single radio constraints, in [18], a hardware constrained MAC protocol is proposed to improve the cognitive radio network throughput and overall spectrum utilization by considering the sensing process as a stopping problem. In [19] two optimization problems of sensing-period adaptation and optimal sensing-sequencing at channel switching are jointly considered. The goal is to discover as many spectrum opportunities as possible. A channel-usage pattern estimation technique was also proposed. In addition, instead of using periodic sensing, the authors considered making decisions based on an on-demand sensing schedule.

### 2.1.2 Cooperative Sensing

It is required that the spectrum sensing process is able to provide a high accuracy while operating under harsh conditions which may include noise uncertainty, deep fading and shadowing, lack of primary signal information and so on. Sensing accuracy can be improved by collaborating sensing outcomes of different CR users to exploit the spatial diversity [11]. In general, the cooperative sensing organization will depend on the network architecture, the hardware constraints and the availability of a control channel. This cooperative sensing method can be implemented either in a centralized or distributed network architecture. Depending on the number of radios on a CR user, the availability of a control channel and network architecture, there are other critical issues that a CR-MAC needs to manage to support cooperative sensing as follows.

- *Sensing cooperation*
  The main problem of CR-MAC design concerning cooperative spectrum sensing is how to perform cooperation. For cooperative sensing in CR networks with a single radio, the whole process generally includes two phases: a local sensing phase and a cooperative phase. CR users after observing a channel by the lo-

cal sensing phase will share their sensing outcomes to other CR users or a fusion center. A fusion process will be implemented for an overall decision of presence or absence of a primary signal. CR-MAC is responsible for the cooperative phase. In [20], the authors evaluate the performance of simple frequency hopping MAC for cognitive personal area networks integrated with a cooperative spectrum sensing process. It is demonstrated that there is a tradeoff between the accuracy of cooperative spectrum sensing and the node's ability to communicate. A design of MAC protocol which integrates sensing, reporting and data phases in cognitive radio networks has been considered in [21] where a dynamic ID number regulates access to the medium.

- *Sensing time synchronization*
  A tight synchronization between CR users is required so that all CR users keep quiet and sense the target channel at the same time. In [22], the authors propose a multi-channel MAC protocol for CR ad-hoc network in which a dedicated control channel is used for running IEEE 802.11 time synchronization function [23].
- *Communication overhead and time delay for cooperative sensing*
  The more local sensing data is combined, the higher sensing accuracy can be improved. However, collaborating sensing data requires a considerable communication overhead and time latency. Hence, there is an optimal number of nodes over which the sensing data should be collected so that the spectrum utilization is maximized under the constraint of a certain level of PU protection.
  In [24], a protocol called truncated time division multiple access that supports efficient distribution of sensing applies the 'K out of N' fusion rule. This sensing MAC aims at reducing the reporting overhead since for the 'K out of N' rule, a reporting operation can stop as soon as K one bits denoting PU presence are received. Another approach to resolve the optimal number of collected data is sequential fusion [25]–[27]. In [26] two ordered sequential reporting protocols are proposed for implementing a sequential fusion scheme in which local sensing data is transmitted in descending order of reliability. This method reduces cooperation resources while maintaining sensing accuracy. In [28], a group-based cooperative MAC protocol (GC-MAC) is proposed to address the tradeoff between sensing accuracy and efficiency. In GC-MAC, a targeted channel is jointly detected by a group of cooperative CR users. A CR user selection algorithm based on the channel dynamics and usage patterns is utilized to reduce the sensing overhead.
- *Imperfect reporting channel*
  A reporting channel for sensing results which may be imperfect degrades the accuracy of the cooperative sensing scheme [29], [30]. CR-MAC protocols are required to support a re-transmitting or error correction mechanism so that errors on reporting sensing results can be fixed.
- *Malfunction/malicious users in cooperative sensing*
  For both distributed and centralized collaboration, there is always the possibility that one or more CR user send a false local sensing result [31], causing the data collector to make a wrong spectrum-sensing decision. Faulty observations are either the results of intentional attack from malicious users or the malfunctioning software or hardware of malfunction users. This kind of security attack is called spectrum sensing data falsification (SSDF) attack [32]. Several previous works against SSDF attack based on historical data statistics [33], [34], or game theory [35] or bio-inspired consensus algorithm [36] can be found. CR-MAC protocols should support a further improvement on counteracting SSDF attack by an authentication scheme.

### 2.2 Spectrum Access

In the presence of multiple CR users trying to access the same spectrum band, a dynamically secondary spectrum access through CR-MAC protocol should be performed to avoid collision with PUs and also with other CR users. A negotiation mechanism for synchronizing transmission between CR transmitter and receiver is also required in CR-MAC protocol. According to different spectrum access modes, CR-MAC protocols could be categorized into time slot-based MAC, contention-based MAC, and hybrid MAC [7], [37].

#### 2.2.1 Contention-Based MAC

In the contention-based MAC protocols, the spectrum resource is accessed based on demand according to a contention mechanism. The contention mechanism is usually similar to the mechanism of carrier sense multiple access with collision avoidance (CSMA/CA) in IEEE 802.11 DCF standard. The CR user observes the spectrum band. If there is no transmission on the spectrum band from other CR users, the CR user will transmit its data after a backoff duration to avoid simultaneous transmission. The architecture of the contention-based protocols is simplest. However, the high collision rate causes inefficient spectrum utilization. This type of protocol can be found in several previous works [18], [22], [38]–[40].

#### 2.2.2 Time Slot-Based MAC

In the time slot-based MAC protocols, each CR user is assigned a unique control channel slot and a unique data transmission slot. Therefore, there is no collision and interference between CR user transmissions. Compared with the contention-based and hybrid protocols, the time slot-based protocol usually obtains better network performance. However, it is complicated to design this kind of protocol since there are many problems that are need to be handled, such as how to allocate slots and how to synchronize time at CR uses. The time slot-based MAC protocols are adopted in [41]–[45].

### 2.2.3 Hybrid MAC

Balancing tradeoff between the architecture simplicity of contention-based protocols and the spectrum utilization effectiveness of time slot-based protocols is the major purpose of the hybrid protocols. Superframe consisting of control and data transmission duration is usually predefined for all CR users in the network. However, contention-based mechanism is utilized for channel access within every control and data duration. Combining both protocols, a hybrid protocol provides higher spectrum utilization than a contention-based protocol and lower complexity than a time slot-based protocol. The hybrid MAC protocols are investigated in [46]–[54].

## 2.3 Spectrum Allocation

Dynamic spectrum allocation is a process to allocate available spectrum bands to CR users. Two approaches noncooperative and cooperative spectrum allocation should be considered [55]. A non-cooperative spectrum allocation protocol has much simpler architecture and lower computation complexity than a cooperative spectrum allocation protocol. The advantage of global optimization of a cooperative protocol is better performance compared with noncooperative protocols.

### 2.3.1 Non-Cooperative Spectrum Allocation

In non-cooperative spectrum allocation, CR users perform spectrum allocation by maximizing local performance such as throughput, delay, ... based on their own local measurement and decision [18], [22], [39], [46], [47], [52]–[54].

### 2.3.2 Cooperative Spectrum Allocation

In cooperative spectrum allocation, the cooperative spectrum allocation protocols aim at global optimization of spectrum utilization for the entire CR network in a cooperative manner. Approaches to solve the problem of cooperative spectrum allocation are as follows:

- *Stochastic algorithms:* A stochastic process such as Markov chain process is utilized for modeling channel activity. According to statistics of historical channel access data and current collected spectrum sensing results, the channel usage is estimated for executing stochastic algorithm to determine optimal allocation strategy. This type of algorithm can be found in [49], [56].
- *Game theory-based algorithms* Game theory provides a natural mathematical framework to analyze strategic interactions between several decision makers. As a result, the dynamic interaction of CR users can be considered as a game, and network interaction modeling and MAC protocol optimization in CR network can be archived by game theory. In detail, each transmitter is a player, the choice of its transmitting parameters is its strategy, and its utility function is described either in terms of its individual or network QoS parameters. Optimization techniques are adopted to find optimal strategies for spectrum sharing in this game theory-based approach. For example, in [57], the overall network throughput is improved through maximizing local utility functions by controlling the transmission powers according to outcomes of a distributed game that achieves Nash equilibrium. Similar game theory-based algorithms for optimizing dynamic spectrum allocation can be found in multiple previous works [58]–[62].
- *Bio-Inspired algorithms* Many challenges of cognitive radio networks such as self-optimizing, dynamic spectrum access, distributed and heterogeneous network architectures, and so on can be modeled and resolved by interesting characteristics such as autonomy, adaptation and collective intelligence of collaborative individuals of biological systems. As a result, bio-inspired algorithms have been developed to provide a new method for achieving decentralized spectrum sharing. In [63], the author proposed a biologically-inspired spectrum sharing (BIOSS) algorithm based on the adaptive task allocation model in insect colonies to perform decentralized spectrum sharing. BIOSS algorithm provides an efficient multiple spectrum band sharing without any coordination among CR users.

  In [64], the authors propose biological foraging-inspired communication (BFC) algorithm for the energy-efficient and spectrum-aware communication requirements in CR ad hoc networks. An autonomous decision-making mechanism is provided to optimize relay and channel selection without prior information requirements on node mobility and spectrum availability patterns. Therefore, Maximum overall spectrum utilization and minimum energy consumption are obtained by BFC.

## 2.4 Spectrum Sharing

CR-MAC protocol design strongly depends on the paradigm use to access the spectrum band. According to primary network information and environment awareness that CR users have, spectrum sharing approaches can be classified into three categories: underlay, overlay and interweave [4].

### 2.4.1 Spectrum Underlay

In the underlay approach, CR users are allowed to simultaneously transmit with PU if the transmission powers of

CR users are constrained below the interference temperature limit of PUs. Since the underlay CR users can access licensed spectrum band at any time, as long as generated interference is limited, spectrum sensing does not need to be performed. It is effective to adopt spectrum underlay protocols for the fast changing primary signal status scenario. Spread spectrum techniques such as CDMA and Ultra-wide band (UWB)transmission are able to be exploited for spectrum underlay access since only very low transmission power is required for obtaining a high data rate. Therefore, the major issue on CR-MAC design with spectrum underlay system is how to optimize power allocation for CR users that will not interrupt primary transmissions while maintaining other requirements of QoS or transmission rate.

In [39], the author proposes COMAC protocol that enables CR users to access licensed band through underlay approach. COMAC ensures the primary interference limit based on a statistical performance guarantee by limiting the fraction of CR transmissions interference time, instead of assuming a predefined power mask. In [65], a resource allocation framework is proposed for spectrum underlay in cognitive radio networks. Both constraints of interference for primary users and QoS for CR users were considered. The authors propose to implement admission control algorithms jointly with power control so that QoS requirements of all admitted CR users are satisfied while keeping the interference to primary users below the tolerable limit. In [66], an adaptive spectrum interweave and underlay sharing scheme for CDMA-based cognitive MAC in the uplink communications over centralized CR networks is investigated. The joint problems of channel sensing, data transmission, and power and rate allocations are considered. Due to adaption, the proposed scheme benefits from the advantage of longer accessing time of underlay access and the advantage of fully utilizing the entire vacant spectrum without considering any allowed interference of interweave access.

### 2.4.2 Spectrum Overlay

In the overlay approach, CR users are assumed to have the knowledge of primary user's transmission data. Therefore, interference can be reduced or even suppressed by using this prior knowledge. As a result, CR users can transmit simultaneously with primary users by assigning part of their transmitting power to assist or relay primary users. With the knowledge of transmission data, various coding schemes can be utilized to improve the data rate of both CR and primary users. Beside the problem of allocating transmitting power and implementing coding schemes, the main issue of the spectrum overlay paradigm on CR-MAC design is how to achieve the prior knowledge of the primary user's data and how to precisely estimate the channel gains between transmitters and receivers.

In [67], a two-phase overlay spectrum sharing protocol based on cooperative decode-and-forward relaying is proposed. The interference from the CR system to the primary system and vice versa can be completely canceled by using a space time block code (STBC) design in two time phases in the secondary system. In [68], the authors propose an overlay spectrum sharing scheme where the primary user leases half of its time slots to the CR user for cooperative relay. The primary user data is relayed based on the amplify and forward scheme. Antenna weights and power allocation are designed so that data rate and error criterion are satisfied.

### 2.4.3 Spectrum Interweave

In the interweave paradigm, CR users first identify spectrum holes, then exploit them for secondary transmission. Therefore, spectrum sensing is a prerequisite. If a primary signal is detected, the CR users must vacate the channel and try to establish the connection in another channel. Currently, most CR protocols are developed based on this type of approach [18], [38], [40], [42], [46], [47], [49], [52]–[54]. Compared with the two previous approaches, CR users are not required to have prior knowledge of the primary signal and restrict their transmission power in interweave paradigm. This paradigm is more appropriate for slow changing primary signal status scenario. In contrast, the spectrum utilization may be inefficient, since it is difficult to follow the fast changing primary signals without tracking them in a sufficiently large frequency. Therefore, the major issue of the spectrum interweave paradigm is how to optimize spectrum sensing.

## 2.5 Spectrum Mobility

In the spectrum mobility, CR users perform a process of vacating licensed bands when a primary signal is detected and maintaining seamless communication requirements during the transition to a better available spectrum band. This procedure is called *spectrum handoff*. CR-MAC design from the perspective of spectrum mobility mostly focuses on minimizing delay and loss during spectrum handoff. In principle, depending on QoS requirement level of application such as FTP, voice or video communication, etc, CR users will select a reasonable procedure for spectrum handoff.

In [41], the Incumbent Detection Recovery Protocol (IDRP) is investigated to perform spectrum handoff. This protocol utilizes a backup channel list, which includes a list of available channels identified by out-of-band sensing, for backup purposes. In this way, the recovery procedure can be performed with minimum time and signaling overhead. In [37], [69], the authors present two strategies for spectrum handoff: proactive and reactive.

- *Proactive handoff*
  CR users are allowed to maintain transmissions while conducting handoff procedures whenever proactive handoff events are detected. The CR users only switch to a new spectrum band after all decisions on the handoff are determined. In this way, channel switching is implemented with minimum time delay and connection loss. The proactive handoff, therefore, requires

**Table 1** Influence of infrastructure on CR-MAC design.

| | | Nework achitecture | | Transmission channel | | Control channel | | | Radio | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *Centralized* | *Distributed* | *Single* | *Multiple* | *In-band* | *Out-of-band* | *Underlay* | *Single* | *Multiple* |
| Spectrum sensing | *In-band* | o | o | o | o | - | o | o | o | o |
| | *Out-of-band* | o | o | o | o | o | o | o | x | o |
| | *Cooperative* | o | o | o | o | - | o | o | - | o |
| Spectrum access | *Contention* | - | o | o | - | x | o | o | o | o |
| | *Time slot* | o | - | o | o | o | o | o | o | o |
| | *Hybrid* | o | o | o | o | o | o | o | o | o |
| Spectrum allocation | *Non-coop.* | - | o | o | o | o | o | o | o | o |
| | *Cooperative* | o | o | o | o | - | o | o | o | o |
| Spectrum sharing | *Underlay* | o | o | o | - | o | o | o | o | o |
| | *Interweave* | o | o | o | o | o | o | o | o | o |
| | *Overlay* | o | o | o | - | o | o | o | - | o |
| Spectrum mobility | *Reactive* | o | o | o | o | o | o | o | o | o |
| | *Proactive* | o | - | o | - | x | o | o | x | o |
| Radio | *Single* | o | o | o | - | - | - | x | | |
| | *Multiple* | o | o | o | o | o | o | o | | |
| Control channel | *In-band* | o | o | o | - | | | | - | o |
| | *Out-of-band* | o | o | o | o | | | | - | o |
| | *Underlay* | o | o | o | o | | | | x | o |

(o): *easy/efficient*; (-): *difficult/inefficient*; (x): *impossible*;

CR users to be equipped with two radios for simultaneously transmitting in-band data and performing out-of-band sensing, and a sophisticated algorithm for estimating network behavior which could necessitate spectrum handoff. Some examples of proactive handoff events are user mobility and cell overload. Thus, most conventional handoff schemes are proactive.

- *Reactive handoff*
  The communications of CR users have to be blocked immediately whenever reactive handoff events are detected. The decision on the handoff will be made and implemented later. As a result, high handoff delay could be introduced. This strategy is performed in the cases of hardware or energy constraints to conduct proactive handoff, or in the case that the primary user appears in the current spectrum band.

In addition, a spectrum-aware mobility management scheme is proposed for CR cellular networks in [69]. By considering CR user mobility in the CR cellular network, the author defines four types of handoff events: intracell/intrapool, intercell/intrapool, intercell/interpool and intracell/interpool. Herein, spectrum pool is a set of contiguous licensed spectrum bands, each of which consists of multiple channels, and intrapool and interpool are the switching of the current spectrum band to another spectrum band inside and outside of current spectrum pool, respectively. According to each type spectrum handoff event, either proactive or reactive handoff procedure are selected.

Another issue of spectrum handoff in CR networks is multiple spectrum handoffs caused by multiple interruptions from the primary users during the transmission period of a secondary connection [55]. In [70], [71], the author proposed the preemptive resume priority (PRP) M/G/1 queueing network for characterizing spectrum usage behaviors with multiple handoffs. This model helps to analysis and establish optimal procedure for both the proactive and reactive spectrum handoff.

## 3. Infrastructures for CR-MAC Design

The infrastructure of a network including network architecture, management of control channel, the number of radio on each CR user and the transmission models strongly affect the design of MAC protocol in a CR network. For each element, a corresponding MAC protocol must be investigated to satisfy all possible capabilities of practical network operation. Table 1 provides a summary of the influence of infrastructure on CR-MAC with three evaluation levels, firstly, to indicate which configurations are impossible (x) to design, and secondly, to indicate those which are either difficult/inefficient (-) or easy/efficient (o) to design. For example, using single radio devices, it is unable to perform out-of-band spectrum sensing and proactive spectrum mobility, difficult to design CR-MAC for cooperative spectrum sensing and overlay spectrum sharing, and inefficient to exploit multiple far-separated data channels. In the case of using multiple channels transmission, the design of CR-MAC to carry out contention-based spectrum access, underlay or overlay spectrum sharing mode, and proactive spectrum mobility requires more effort than implementing other options. Another example is the influence of network architecture. It is insufficient to adopt contention-based spectrum access and non-cooperative spectrum allocation for centralized architecture, whereas it is very difficult to design time-slot based spectrum access and proactive spectrum handoff. The detailed analysis of the infrastructure perspectives is presented in the following subsections.

### 3.1 Number of Radios

CR network is classified into *single radio-based* and *multiple radio-based* network. The number of radios affects the execution of most DSA functions and hence determines the format of CR-MAC protocol.

### 3.1.1 Single Radio

The advantages of using single radio devices are the low cost and power consumption. However, a CR network equipped with single radio user terminals is able to perform out-of-band spectrum sensing, and hence unable to support proactive spectrum handoff. Similarly, single radio users also do not allow simultaneous multichannel transmission.

To implement multichannel communication with single radio devices, channel aggregation techniques are required. Another problem with single radio networks is the multi-channel hidden terminal problem [72] since single radio users cannot simultaneously transmit and receive in multiple channels. Therefore, designing a MAC protocol that schedules appropriate slot to effectively perform signaling, sensing and transmitting data is a challenge, especially for the in-band control channel case. Many previous works consider CR-MAC protocol for networks equipped with single radio [18], [40], [41], [46], [56], [73].

### 3.1.2 Multiple Radios

In contrast with single radio devices, multiple radio users are equipped with more than one radio. Thus, the multiple radio users require higher cost and power consumption. However, it is possible to design CR-MAC protocols that utilize one separate radio for listening to control channel or for out-of-band sensing. As a result, packet collisions would be decreased and the multi-channel hidden terminal problem would not occur. Many previous works can be found in [39], [44], [47], [58], [60]. Obviously, the equipment of multiple radios would facilitate the design of CR-MAC in aspects of signaling, sensing and transmitting data, but issues of balancing hardware resource, power consumption and QoS would appear. For example, in [74], the authors propose a channel assignment scheme for CR networks in which nodes have multiple radios, each of which can be assigned to a channel. The proposed strategy for channel assignment balances the need for topology adaptation focusing on flow rate maximization and the need for a stable baseline topology that supports network connectivity. Similarly, more research work should be dedicated to considering the optimal allocation hardware, power and spectrum resources simultaneously under QoS requirement constraints.

## 3.2 Transmission Channels

One important factor that affects to communication techniques is the number of spectrum channels that are used for transmitting data. CR-MAC protocols can be categorized in single channel and multi-channel protocols.

### 3.2.1 Single Channel Protocol

The single channel protocol is quite simple in the architecture where the communication data is transmitted in only one channel for each transmitter and receiver pair. Therefore, the design of this single channel CR-MAC protocol is simple. Although the supported data rate with single channel communication is lower than that with multiple channels, the low requirement for spectrum resource results in a longer connection of secondary access. In addition, since this type of protocol includes single radio devices, the cost for it is usually low. Several previous works considered single protocol for CR network [22], [38], [41], [42], [47], [49], [75].

### 3.2.2 Multi-Channel Protocol

In a multi-channel communication scheme, each pair of transmitter and receiver is allowed to transmit data through multi-channel simultaneously. Generally, depending on the number of radios equipped on devices, there are two subclasses for multi-channel protocol, i.e., *multi-channel multi-radio protocol* [76] and *multi-channel single-radio protocol* [77].

In multi-channel single-radio protocol [18], [40], [44], [46], [50], [56], [58], [73], a CR device equipped with single radio will transmit data through multiple channels with the support of channel aggregation/bonding techniques [78]. However, it is difficult to perform the aggregation for non-contiguous channels with a single radio due to the limitation of radio technique. In contrast, multi-channel multi-radio protocol [39], [79] is adopted for networks equipped with multiple radio CR users, and each radio operates on one channel. Therefore, the multi-channel transmission can be conducted easily, even in the non-contiguous channels case. However the cost for CR devices will be increased.

Although the use of multiple channel increases the total throughput, it is complex to design CR-MAC protocol so that spectrum sensing, access control, etc could be performed efficiently. Algorithms on optimizing power and channel allocation, QoS and fairness control and so on should be considered.

## 3.3 Control Channel

Management control signaling on CR network is a critical issue for designing CR-MAC protocol, since a CR network requires a larger amount of control signaling than a conventional network. Beside signaling on establishing connection, CR networks have to manage control signaling on implementing dynamic spectrum access functions. There are three possible approaches to manage control information in CR network: out-of-band control channel(CC), in-band CC and underlay CC. The two first approaches adopt interweave access mode, whereas the third approach utilizes underlay access mode.

### 3.3.1 Out-of-Band Control Channel

In principle, wireless communications systems usually adopt an out-of-band CC, which is separated from in-band data channels, for exchanging only control information. However, it is difficult to obtain such a free from interference CC for a CR network since CR users have to perform opportunistic secondary access to a licensed band. Thus, there are two possibilities for a dedicated CC: licensed out-of-band CC [46] and unlicensed out-of-band CC [41].

- *Licensed out-of-band CC*
  This approach is obviously more convenient to design a CR-MAC protocol including network start-up, node joining, and information exchange since a licensed channel ensured availability and free from interference. However, a licensed dedicated CC requires more cost and may be saturated when the number of users increases or wasted when the number of users decreases.
- *Unlicensed out-of-band CC*
  In an unlicensed out-of-band CC protocol, CR networks select an available unlicensed channel for CC. Unlike licensed dedicated CC, an unlicensed out-of-band CC is not fixed, it may hop in time according to primary user operation. Therefore, designing the protocol require more efforts, especially for designing network start-up and node joining procedures.
  In general, an unlicensed out-of-band CC can be a global CC for the whole network [18]. However, the adverse effect on colliding signaling because of primary user operation may severely degrade the network performance. Thus, global unlicensed out-of-band CC is proposed to be replaced by local unlicensed out-of-band CCs on small groups or clusters [80], [81]. This will help to limit the bad effect of CC unavailability to a small group of CR users instead of the whole network.

There are two approaches to manage out-of-band CC: Split phase and common control channel.

- *Split phase-based CC*
  A rendezvous channel is assigned, and channels are slotted into super-frames. A super-frame includes a beacon period and a data transmission period [22], [41]. All CR users operate on rendezvous channel for exchanging control signaling during beacon period. After that, CR users can exchange their data in their data channel. Obviously, this method is suitable for single radio device. However, this method leads to a waste of spectrum utilization during beacon period and requires a strict time synchronization for users operation.
- *Common CC*
  Unlike split phase method, control messages can be exchanged in a dedicated CC along with the operation of data channels. The CR user needs to be equipped with more than one radio to continuously observe the CC. However, CR users do not need to be strictly synchronized on the whole network.

### 3.3.2 In-Band Control Channel

It is difficult to obtain a commonly available channel between nodes since the available spectrum resources of different CR users may be totally different. Moreover, a saturation problem, which is the overload status of CC due to a large number of accessing users, may occur in out-of-band control channel schemes and often degrades network performance. Another approach for managing control information which solves the above problems is in-band signaling, i.e., transmission data and control messages are exchanged in the same channel. Therefore, control messages can be exchanged without any common CC. This type of signaling is suitable for distributed/ad-hoc CR networks since it is difficult to obtain a commonly available channel between nodes. Channel-hopping for both transmission data and control message [47], [48] is an example for this in-band CC method.

- *Hopping-based CC*
  In hopping-based CC, CR users can exchange the control packets on all in-band data channels according to the pre-defined hopping sequence. In this way, the CC saturation problem can be mitigated. However, hopping-based CC requires a strict synchronization on all CR users and a well-designed CR-MAC protocol to handle the control messages exchanging mechanism, which will considerably increase the complexity and cost of the CR network. There are some examples for CC using channel hopping that can be applied for CR network: Common Hopping [82], SSCH [83], and Mc-MAC [84].

### 3.3.3 Underlay Control Channel

Another promising approach to fulfill the requirement for a highly available CC is underlay CC, i.e., it utilizes underlay spectrum access mode for the control channel. In this underlay CC approach, control messages are transmitted in low power over a large bandwidth so that it appears as noise to the primary user. For example, in [85], the exchange of sensing information among CR users is proposed in a UWB signaling network. Compared to previous approaches using interweave access mode, this underlay CC is more reliable since the availability of CC is very reliable. The main drawback of this approach is the requirement of a complicated power control algorithm and particular hardware for spread spectrum communication. Furthermore, the transmission range of the underlay CC is also a issue.

## 3.4 Network Architecture

Generally, the type of network architecture is the first and major factor which should be considered before designing a MAC protocol. There are two categories of CR network architecture: centralized and distributed CR network. In this subsection, we consider the influence of network architecture on the design of CR-MAC protocols.

### 3.4.1 Centralized CR Network

A centralized CR network is equipped with a center to collect and process all network information. In general, the center will require every CR user to inform their states and objectives, then make the decision for all DSA functions based on system objectives [44], [45], [86]–[93]. There are two designing approaches for CR-MAC protocol in a centralized CR network: optimization approach and coordination/contention-based approach.

In an optimization-based approach, optimization techniques [90] (e.g. graph theory, linear programming, convex optimization, etc.) are used to solve the formulated problems of DSA functions such as cooperative spectrum sensing [25]–[30], time slot-based spectrum access assignment [45], cooperative spectrum allocation [44], etc. Executing optimal decision outcomes by the network center is imposed on CR users to ensure global optimization objectives.

In an coordination/contention-based approach [86], [87], the center can play a role of an arbitrator, and CR users perform contention to obtain their objectives. Some problems such as contention-based or hybrid spectrum access, cooperative spectrum allocation, proactive handoff problems [69], etc. can be categorized in this designing approach, and game theory can be used to balance objectives.

### 3.4.2 Distributed CR Network

In contrast to a centralized CR network, distributed CR networks in many scenarios such as in CR ad-hoc networks do not include a center [38]–[41], [45], [49], [50], [52], [53]. Therefore, CR-MAC protocols have to ensure mechanisms for collecting exchanging network information in every CR users independently. CR user need to be equipped with an autonomous decision making capability for independent operation which obtains local optimization objectives. According to the individual behavior of CR users, there are two types of CR-MAC protocol for distributed CR network: cooperative protocol and non-cooperative protocol.

In a cooperative protocol, CR users implement a collaboration process to exchange network information with each other, then make decisions on DSA functions according to network or group objectives. The decisions in this circumstance is oriented more towards overall benefit than individual benefit. Optimal and fair decision could be made based on cooperative game theories or optimization.

On the other hand, in a non-cooperative protocol, a CR user uses collected information about the network environment to make decisions which maximize its own benefit. The collected information about the network environment may derive from either its local observation or neighboring collaborated data. Coordination/contention-based procedures are the main approach for designing CR-MAC in this circumstance.

## 4. Challenges and Open Research Issues

### 4.1 Challenges and Issues on Spectrum Sensing

As mentioned above, spectrum sensing is a key function for implementing CR. Therefore, optimal sensing remains a challenge in CR-MAC design.

- *Joint sensing and resource optimization:*
  In some previous works, optimal frequency and period of sensing was scheduled such that the primary user can be detected immediately and accurately while balancing the spectrum utilization time. More research on the optimal spectrum sensing in various scenarios should be investigated. For example, it is possible to consider a joint optimization of accessing and sensing time, power transmission level and detection threshold under constraints of allowed interference temperature of primary user. The detection threshold and sensing time determine the sensing accuracy. Accessing time decides the utilization of spectrum resource. Since both sensing accuracy and transmission power affect the interference level of CR signal to primary signal, there is an optimal solution to balance the above factors. Similarly, we can consider a joint optimization of interval and frequency of sensing, secondary data rate, and QoS or throughput requirement under constrains of allowable sensing error level and a specific primary signal operation pattern.
  Spectrum sensing could be also combined with a prediction process of primary user operation to increase the sensing accuracy. This kind of spectrum sensing and optimal sensing scheduling in out-of-band multiple channels or wideband scenario can be adopted to optimal sensing strategies for the proactive spectrum handoff, or spectrum aggregation. Finally, it is worth noting that network infrastructures including the number of radios, control channel type and network architecture strongly affect the deployment of spectrum sensing. The design of CR-MAC on spectrum sensing has to consider these factors carefully.
- *Cooperative sensing:*
  Designing CR-MAC with cooperative sensing is required to solve the cooperative overhead and reporting bandwidth. Although some previous works try to solve the problem by adopting optimal sensing number, sequential fusion scheme, etc while maintaining sensing accuracy, more research should be conducted to obtain practical cooperative sensing protocols.
  Currently, most cooperative sensing research concentrates on an assumption that CR networks have a smaller size than the primary network. As a result, the overall decision by fusing local sensing results is more reliable than a local decision. However, in the reverse case where the primary network size is smaller than the CR network, the overall fused decision is not reliable since the primary signal does not cover all CR

user positions. Therefore, a new strategy for cooperative sensing should be considered. It is possible to combine geographical position information (proposed in IEEE 802.22 WRAN [43]) and the local sensing result to establishing a coverage map of the primary signal. This map can help tracking primary transmitters in mobility cases, and hence the primary frequency band can be reused in areas where a primary signal cannot cover. CR-MAC design for such circumstances should be studied more.
Other issues of security and time synchronization between CR users for cooperative sensing will be discussed in the following subsections.

### 4.2 Challenges and Issues on Spectrum Access

- *Collision avoidance mechanism:*
  For contention-based and hybrid spectrum access, the main challenge on CR-MAC design is how to obtain an effective collision avoidance mechanism between CR users and between CR uses and primary users. Conventional carrier sense multiple access with collision avoidance (CSMA/CA) mechanism is not suitable for CR network, where the priority for using the channel belongs to primary users and there are some hidden/exposed terminal problems such as multi-channel hidden terminal, hidden primary transmitter, hidden primary receiver and exposed primary transmitter problems which CSMA/CA can not take into account properly. It should be noted that new collision avoidance mechanisms have to operate with many control channel possibilities. Sometimes, signaling packets may not be exchanged due to the unavailability on unlicensed control channels.
- *Time synchronization:*
  Beside cooperative sensing, time synchronization between CR users is also required for time slot-based spectrum access protocol. Usually, network-wide time synchronization can be obtained through synchronization signaling on the control channel. However, due to the difficultly of allocating a common CC in a CR network, time synchronization is a critical issue in a time slot-based spectrum access protocol.
- *Multi-flow CR-MAC protocol for a distributed CR network*
  In a distributed CR network, it is possible to organize a multi-channel multi-radio multi-hop CR network where multiple data channels are utilized for transmitting simultaneously through multiple radios equipped in a CR user with multiple communications hop. As a result, there are multiple data flows exchanging in the network at the same time. CR-MAC design on this scenario have to deal with a huge amount of control signaling which requires an effective CC management method. Bio-inspired system may be a good solution for this scenario.

### 4.3 Challenges and Issues on Spectrum Allocation

- *Channel negotiation*
  In distributed CR networks, each pair of transmitter and receiver exchanges their lists of available channels which may be different due to the difference of transmitter and receiver spacial position and sensing accuracy. This negotiation process will determine in allocated channel to exchange data since there is no center in a distributed CR network. As a result, designing an effective negotiation mechanism is necessary for distributed CR-MAC protocol. The negotiation process requires a control channel for exchanging signaling packets and time synchronization between CR users.
- *Cooperative channel allocation*
  In a centralized network, a center will perform channel allocation for CR user in order to optimize the system parameters. Obviously, in this circumstance, the formulations of the optimization problem and its solution is necessary. More research should be conducted in this direction. There are many techniques that can be exploited such as game theory, genetic algorithm, optimization, bio-inspired-based techniques. The common problem is how to maximize the total network throughput while balancing fairness channel allocation and QoS guarantee for each CR user under some constraints such as hardware, power consumption, primary user protection level, etc.

### 4.4 Challenges and Issues on Spectrum Sharing

- *Underlay adaption access*
  Currently, most research on CR networks focuses on interweave opportunistic spectrum access. However, underlay secondary spectrum access is also promising due to the availability. One possibility of using underlay access mode is for a common control channel. The main issue of underlay spectrum access is how to control the interference of CR users affecting primary signal. It is possible to utilize a combination techniques of spectrum sensing, localization, adaptive modulation and coding (AMC), and transmission power control for an underlay adaption access protocol. In detail, spectrum sensing and localization techniques determine the position of primary users if they are present. AMC and transmission power control adjust the transmitted power so that it is under allowable interference level of the primary user.
- *Interweave adaption access*
  A similar combination of techniques can be adopted for adaptive transmission when the primary network is smaller than the CR network.
- *Hybrid adaption access*
  Another approach is to use both underlay and inter-

weave spectrum access alternately. Whenever a primary signal is detected, the CR network will change its operation mode from interweave spectrum access to underlay spectrum access. In this way, the CR users' communication is guaranteed.
- *Overlay access*
  CR-MAC protocols which support overlay access mode should be developed by considering a cooperative communication scheme. The key issue here is how to obtain primary data information at CR users without modifying primary network protocol.

### 4.5 Challenges and Issues on Spectrum Mobility

The ultimate objective of spectrum mobility is to perform a seamless handoff procedure which minimizes delay and packet loss. Preparation and prediction for handoff events are two key processes to implement an effective spectrum handoff protocol. There are still challenges to achieve such an efficient spectrum handoff protocol for both centralized and distributed CR networks.

### 4.6 Challenges and Issues on Control Channel Management

A control channel which is continuously accessible remains a key challenge for establishing CR networks.

- *Saturation problem of CC*
  The saturation of CC can occur in both licensed and unlicensed out-of-band control channel. There are many solutions such as reducing control traffic on CC, e.g., quantizing sensing data, adjusting the bandwidth ratio of CC over data channels, dynamic channelization, etc. However, a thorough solution for this problem remains a challenge.
- *Robustness to primary user activity*
  For unlicensed out-of-band CC or underlay CC, it is required to maintain signaling when a primary signal appears in the allocated CC. In interweave access mode of unlicensed out-of-band CC, the problem of disruption due to primary activity can be mitigated by a moving procedure where a pre-prepared channel list for CC could be adopted. However, it will be difficult for synchronization when establishing a new channel as CC. There is also an difficulty of controlling broadcast message, hence for new user to joint. Similarly, in underlay CC, the problem of designing an effective power control algorithm for ensuring underlay control messages transmission is not simple. In addition, the coverage of underlay CC also depends on the control message transmission power. Therefore, designing CC which is robust to primary user activity is a difficult issue.
- *Control channel security*
  A hopping-based CC is more secure than other types of CC due to its pseudo random to attackers. However, other types of CC are vulnerable to attack. Security in CC is also a big challenge.

### 4.7 Other Challenges and Issues

There are also many challenges and issues on CR-MAC design that need to be considered. A green CR-MAC which maintains a longer network life by focusing on power saving algorithms can be an open research issue. In addition, the security perspective on CR-MAC protocols should be also investigated in future research since CR networks are vulnerable and exposed to serious risks.

## 5. Conclusion

In this paper, we have presented a survey of perspectives related to the design of CR-MAC protocols. Several typical previous works are discussed to clarify two major perspectives on designing MAC protocols for CR networks: dynamic spectrum access functions and network infrastructure. Five DSA major functions including spectrum sensing, spectrum access, spectrum allocation, spectrum sharing and spectrum mobility are investigated through the view points of MAC protocol design. In addition, some important factors related to infrastructure of the organization of a CR network including network architecture, control channel management, the number of radios on CR devices and the number of transmission data channels are shown. The remaining challenges and open research issues are also addressed to obtain practical MAC protocols for CR networks in future.

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