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A survey on MAC protocols for cognitive radio networks

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ABSTRACT

In cognitive radio (CR) networks, identifying the available spectrum resource through spectrum sensing, deciding on the optimal sensing and transmission times, and coordinating with the other users for spectrum access are the important functions of the medium access control (MAC) protocols. In this survey, the characteristic features, advantages, and the limiting factors of the existing CR MAC protocols are thoroughly investigated for both infrastructure-based and ad hoc networks. First, an overview of the spectrum sensing is given, as it ensures that the channel access does not result in interference to the licensed users of the spectrum. Next, a detailed classification of the MAC protocols is presented while considering the infrastructure support, integration of spectrum sensing functionalities, the need for time synchronization, and the number of radio transceivers. The main challenges and future research directions are presented, while highlighting the close coupling of the MAC protocol design with the other layers of the protocol stack.

1. Introduction

Cognitive radio (CR) is a promising technology geared to solve the spectrum scarcity problem by opportunistically identifying the vacant portions of the spectrum and transmitting in them, while ensuring that the licensed or primary users (PUs) of the spectrum are not affected [2,10,3]. This necessitates adapting to the dynamically changing spectrum resource, learning about the spectrum occupancy, making decisions on the quality of the available spectrum resource, including its expected duration of use, probability of disruption caused by the PUs, among others. Thus, CR networks help to make efficient use of the available spectrum by using bands, such as television broadcast frequencies below 700 MHz, that have been recently marked for CR operation [29]. In addition, frequencies reserved for public service may experience intermittent use and the frequent quiet periods may also be used for CR transmission. However, in each of these cases, an important consideration is the prevention of performance degradation to the licensed users of the band used for CR transmission. This motivates the research in CR MAC protocols, with an aim for providing efficient means of sensing the channel to determine its occupancy, and sharing the spectrum among the other CR users[2] to maintain tolerable interference levels to the PUs that have a priority usage.

The design of CR MAC protocols has followed two approaches – (i) standardization efforts leading to the formation of the IEEE 802.22 working group [5], and (ii) application/scenario specific protocols. The former approach is mainly focused on infrastructure-based networks, in which a centralized coordinator or base station manages the spectrum allocation and sharing among the CR users. The CR users, however, may participate in the spectrum sensing function and provide channel information to the central controller. The standardization efforts lead to a uniformity in design and policy, thereby allowing multiple independent CR operators to coexist. On the other hand, application or scenario specific protocols are opti-

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[2] In this work, the terms secondary users (SUs), cognitive radio (CR) users, or nodes may be used interchangeably.

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mized for a particular type of environment, or user specified application goal. This approach has been increasingly used in distributed CR MAC protocols, that operate without the support of a centralized controlling entity. As an example, nodes in an ad hoc network may exhibit high degrees of mobility with coarse time synchronization that makes sensing coordination difficult. For such cases, the MAC protocol may leverage the mobility to determine which regions (covered by the node during its motion) exhibit high levels of PU activity. The spectrum availability in a region may be *learnt* by the node over time, such that the choice of the transmission spectrum can be improved. Moreover, as the information collected by a node is mostly based on its own observations, the dedicated sensing duration in the initial stage of the learning process may be higher than that compared to useful data transmission time. While this provides higher protection to the PUs in the long run, it results in reduced throughput that must still meet the quality of service (QoS) requirements set by the user. Thus, the MAC protocol operation must be adaptive to the environment and suited to the application needs, that makes standardization efforts particularly challenging.

The CR MAC protocols are differentiated from their classical MAC schemes based on the close coupling with the physical layer and the hardware support on the device. As an example, the carrier sense mechanism at the MAC layer may not reveal complete information regarding the channel owing to its inability to distinguish between the energy radiated by other CR users and the active PUs in the spectrum. In addition, packets may be simply re-transmitted in the event of a collision with other CR users, while the transmission must cease immediately if the packet loss is due to PU activity. To differentiate these causes, the physical layer may support the MAC layer in the implementation of the sensing strategy, and identifying the origin of the radiated power by baseband analysis of the spectrum shape. A general framework of the spectrum functions and the inter-layer coupling is shown in Fig. 1. Based on the radio frequency (RF) stimuli from the physical layer *RF environment*, the *sensing scheduler* at the MAC layer can determine the sensing and transmission times. The availability of the spectrum, whenever a data packet needs to be sent, is coordinated by the *spectrum access* function. The *spectrum sensing* block plays a crucial role, both in terms of long term channel characterization and ensuring that the channel is available at the time of actual data transmission.

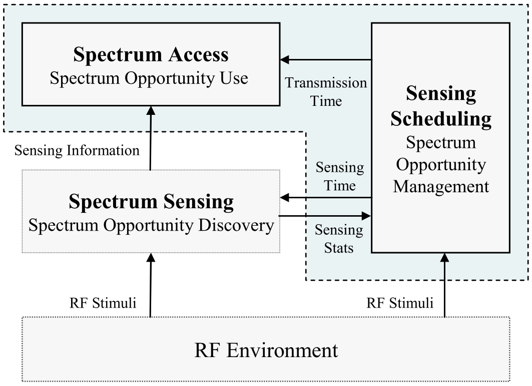

Fig. 1. Spectrum functions at the CR MAC.

While the scope of this survey is limited to CR MAC protocols at the link layer, it is interesting to note that there exists a significant interaction between the network and transport layers with the link layer. This helps in the other higher layer CR functions of joint spectrum and route decisions, congestion-free end-to-end reliability, spectrum and node mobility, among others. While many of these functions can be located at the central CR controller in infrastructure networks, distributed CR ad hoc networks need further interaction between the different layers of the protocol stack, as well as cooperation among the different users. A comprehensive treatment of the challenges faced by CR ad hoc networks is presented in [1].

The rest of the paper is organized as follows. In Section 2, we overview the main issues related to scheduling the spectrum sensing and transmission. In Sections 3 and 4 we focus on spectrum access MAC protocols for the CR infrastructure-based and ad hoc networks, respectively. Finally, Section 5 draws the conclusions and lists the future directions for research on CR MAC protocol design.

2. Spectrum sensing

Spectrum sensing is one of the key enabling functions in CR networks that is used to explore vacant spectrum opportunities and to avoid interference with the PUs. The two main approaches for spectrum sensing techniques for CR networks are [2]: *primary transmitter detection* and *primary receiver detection*. The *primary transmitter detection* is based on the detection of the weak signal from a primary transmitter through the local observations of CR users. The *primary receiver detection* aims at finding the PUs that are receiving data within the communication range of a CR user. Usually, the local oscillator (LO) leakage power emitted by the radio frequency (RF) front-end of the primary receiver is exploited, which is only feasible in the detection of the TV receivers. Thus, most of current research on spectrum sensing, described in this section, have mainly focused on primary transmitter detection. In addition to providing sensing coordination support at the MAC layer, the issues that are investigated are – (i) how long the optimal sensing and transmission durations must be, and (ii) the order in which the spectrum bangs must be searched to minimize the time for finding the available spectrum [12,13,15].

2.1. Optimization of spectrum sensing and transmission duration

The choice of the spectrum sensing time followed by the transmission time deals with two main parameters optimized by the MAC protocol, as shown in Fig. 2. While higher sensing times (T_s) ensure the correct detection of the spectrum, this may result in a comparatively smaller duration for actual data transmission (T_t) in the total time for which the spectrum may be used (T_f), thereby lowering the throughput. We discuss these functions further

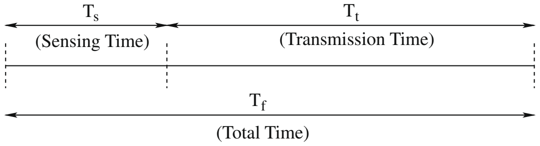

Fig. 2. Optimization of the sensing and transmission times.

depending on whether they are undertaken independently of each other, or in a joint optimization framework.

2.1.1. Independent sensing duration optimization

In this approach, the main objective is to find the sensing that minimizes the *missed detection* probability, i.e. determining the spectrum to be unoccupied when there is an active PU, and conversely, the *false alarm* probability, i.e. incorrectly inferring the presence of a PU in a vacant spectrum band. The sensing time (T_s in Fig. 2) optimization problem is studied in [25] while keeping the transmission time (T_t) constant. Here, the channel efficiency is defined as the amount of the time that the idle channel can be utilized by the CR user for data transmission to the total time in a frame (T_f). From this definition, it is clear that the higher channel efficiency (or throughput) obtained by longer transmission time needs to be balanced with the detection accuracy. Towards this aim, the false alarm probability is derived in [25] based on classical detection theories. Moreover, a numerical optimization framework is proposed to solve the sensing time allocation problem, when the detection samples are uncorrelated.

In [8], apart from the sensing time on a single spectrum band, the time for searching multiple spectrum bands is also optimized. The operation is as follows: After transmitting within a certain spectrum band for the duration T_t, the CR user will undertake spectrum sensing. If there is no PU detected, it will continue to transmit in the same spectrum band. If indeed the CR user infers the presence of a PU, it has to search for a new spectrum band. For this, the node tunes its transceiver to another channel and starts spectrum sensing. If the spectrum is detected to be busy, the CR user needs to repeat this procedure on another band till a vacant spectrum band is identified. Thus, this process of sensing multiple spectrum bands in succession introduces significant delay, which must also be incorporated in the optimization program. In [8], an independent and identically distributed ON/OFF random process is assumed for the primary traffic. The search time for the vacant spectrum is minimized, thereby achieving maximum throughput for the CR network.

2.1.2. Independent transmission duration optimization

The optimal transmission duration (T_t) is derived in [21] while keeping the sensing duration (T_s) constant. The problem is formulated as a collision-throughput tradeoff problem, which finds the optimal value of the frame duration (T_f) for the CR operation. It integrates the minimum desired sensing time requirement and the traffic pattern of the PUs in its transmission time optimization function. The objective of the optimization is to maximize the throughput of the cognitive radio network while keeping the packet collision probability for the primary network under a certain threshold. For this, the authors assume exponential on-off traffic model for PUs but present a simplified treatment for the optimal frame duration.

2.1.3. Joint sensing and transmission duration optimization

In [15], a theoretical framework is proposed for jointly optimizing the sensing and transmission parameters in order to maximize the spectrum efficiency subject to interference avoidance constraints. With the goal of exploiting multiple spectrum bands, a spectrum selection and scheduling method is proposed, where the best spectrum bands for sensing are selected to maximize the sensing capacity. An adaptive and cooperative spectrum sensing method is also proposed that considers the number of cooperating users in a multi-user and multi-spectrum environment. In particular, sensing and transmission are performed in a periodic manner with separate observation and transmission periods. We believe that this approach is best suited for CR networks, as it best balances the tradeoff between sensing accuracy and the spectrum utilization efficiency. However, this approach is inherently more complex, and issues such as obtaining a solution to the optimization problem in real-time and the computational overhead must be considered.

2.2. Spectrum search sequence optimization

The order in which the spectrum bands are chosen for sensing for the presence of PUs, called as the spectrum search sequence, determines the overall time used for searching the vacant spectrum. The performance of several such spectrum search schemes are investigated in [17]. An interesting approach is the consideration of correlated spectrum band occupancy models, in which it is more likely to detect a PU transmission in the neighboring spectrum of a band that is already known to be occupied. In addition, PUs may use several spectrum bands at a time, depending upon the way these bands are structured for use by the licensed users. Random and serial search schemes are investigated in [17], and a general n-step serial search scheme is proposed at the best solution.

In [12,13], both sensing duration and spectrum search sequence optimization problems are jointly studied. The aim here is to discover as many spectrum opportunities as possible in advance, while minimizing the average time taken to detect a vacant spectrum band. The authors assume a semi-Markov traffic model for the PU spectrum usage and propose an estimation technique to learn the traffic pattern exhibited by the PUs. Moreover, the problem of deciding on an on-demand sensing schedule, as opposed to using periodic sensing, is investigated.

2.3. Research challenges

The spectrum sensing involves several research challenges that are described as follows:

- *Sensing coordination*: For accurate sensing, the measurements on the channel must be undertaken during *quiet* periods, when the other CR users in the neighborhood can be silenced. This ensures correctly attributing the measured power to the radiation caused by the PUs alone. However, in the absence of time synchronization, especially in distributed networks, this coordination is difficult to achieve at the MAC layer.

- *Sensing information dissemination*: For accurate sensing, the measurements from several different CR users may be integrated. However, the exchange of this information constitutes an overhead and may possibly interfere with the data packets sent by the other CR users.
- *Optimal sensing duration*: Allocating the sensing and transmission time at the MAC layer is an important tradeoff between ensuring protection to the PUs, as opposed to maximizing the data throughput [15]. These durations must be carefully balanced to meet the user QoS requirements and prevent performance degradation to the PUs at the same time.
- *Integration of sensing with other transmission parameters*: The sensing results must be closely associated with the choice of transmission parameters, leading to adaptive modulation and power control techniques. In [22], a secondary transmitter adapting its transmit power according to the sensing metric is considered. Here, the SNR or the resulting capacity of the CR user is maximized satisfying its peak transmit power constraint and average interference constraint at the primary receiver. However, a more general class of sensing-dependent optimization techniques are needed that consider different possible transmission parameters.

After identifying the available spectrum resource through spectrum sensing, the MAC protocol must now determine the spectrum access scheme. We next investigate this in the next section.

3. Spectrum access

Spectrum access enables multiple CR users to share the spectrum resource by determining who will access the channel, or when a user accesses the channel. While both time slotted and random access schemes may be used in infrastructure-based networks, the difficulty in maintaining network-wide time synchronization in mobile ad hoc networks makes it infeasible to adopt completely slotted protocols.

In this paper, we provide a thorough description of MAC protocols for both CR infrastructure-based and ad hoc networks. We classify the existing approaches into (i) random access protocols, (ii) time slotted protocols, and (iii) hybrid protocols, as shown in Fig. 3. In addition, the number of radio transceivers also decides the working of the MAC protocol. We explain the classification as follows:

- *Random access protocols*: The MAC protocols in this class do not need time synchronization, and are generally based on the collision sense multiple access with collision avoidance (CSMA/CA) principle. Here, the CR user monitors the spectrum band to detect when there is no transmission from the other CR users and transmits after a backoff duration to prevent simultaneous transmissions.
- *Time slotted protocols*: These MAC protocols need network-wide synchronization, where time is divided into slots for both the control channel and the data transmission.

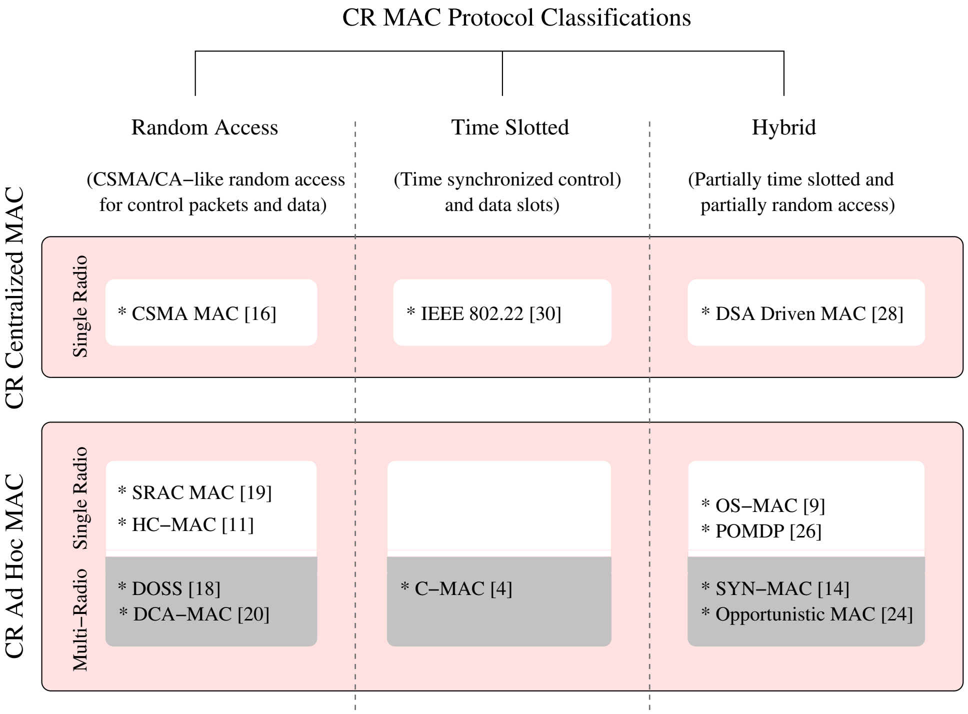

Fig. 3. Classification of CR MAC protocols.

- *Hybrid protocols*: These protocols use a partially slotted transmission, in which the control signaling generally occurs over synchronized time slots. However, the following data transmission may have random channel access schemes, without time synchronization. In a different approach, the durations for control and data transfer may have predefined durations constituting a superframe that is common to all the users in the network. Within each control or data duration, the access to the channel may be completely random.

The main research challenges for spectrum access are described next.

3.1. Research challenges

The challenges for efficient spectrum access are as follows:

- *Control channel design*: The spectrum access involves control signaling between the two CR users on either ends of the link. This messaging must be uninterrupted by the neighboring PU activity as it is used to exchange the sensing information, and coordinate the channel access. For this, reliable and dynamically changing control channels must be devised.
- *Adapting to PU transmission*: Some PUs have specific transmission patterns, such as pre-determined spectrum usage times and durations, such as television broadcast stations, or may have occasional random access to the channel, such as public service agencies. At these times, the CR MAC protocol may infer the nature of the PU and adapt its own transmission to avoid both interference to itself and also prevent conflict with the PUs. For this reason, dynamic power control and transmission scheduling schemes need to be devised.

4. MAC Protocols for CR infrastructure-based networks

These protocols need a central entity, such as a base station, that manages network activities, synchronizes and coordinates operations among nodes. However, the central entity is static and generally forms a single hop link with the mobile CR users that are within its coverage area. This architecture helps in the coordination among the CR users for collecting the information about the network environment, and allows the spectrum decisions to be localized.

We classify the existing works for such infrastructure-based or centralized networks based on the random access of the channel, time slotted behavior, and a hybrid approach that partially combines both of the previous access schemes, as shown in Fig. 3.

4.1. Random access protocols

A CSMA based protocol is proposed in [16] that uses a single transceiver and in-band signaling. This protocol ensures coexistence among the CR users and the PUs by adapting the transmission power and rate of the CR network. Here, the CR and the PU base stations are separate, though they may have overlapping coverage areas. The CR users and the PUs establish direct single-hop connections with their respective base stations. The proposed MAC protocol allows simultaneous transmission of the CR users even when the PUs are detected, as long as the interference caused to them is contained within a predecided threshold. The operation of the protocol is as follows: The primary network follows classical CSMA, in which the PU undertakes carrier sensing for period τ_p before sending a request to send (RTS) packet to its base station. The primary base station may reply with the clear to send (CTS) if it is available for the data transaction. However, the CR users have a longer carrier sensing time (τ_s, where $\tau_s >> \tau_p$) so that priority of spectrum access is given to the PUs. Based on the (i) distance of the CR users from the CR base station, and the (ii) noise power, the base station decides the transmission parameters, namely the transmit power and data rate, for the current transfer. The CR user is allowed to send just one packet in one round of this negotiation in order to minimize the risk of interference to the other PUs.

Fig. 4 shows the detailed protocol behavior in four different cases (a-d) plotted against a horizontal time axis:

- Case (a): Here, the PU gains the access to the channel after carrier sensing and backoff (or by retransmission following a prior collision), and sends its data. The CR user senses the channel for a period τ_s, and on finding the channel vacant (i.e. assuming the transmitting PU and the CR user are separated by a large distance), the CR user contends to gain the access to the channel through the RTS–CTS handshake. It then starts transmitting data with the power and rate suggested by the base station so that the concurrently occurring PU transmission is unaffected.

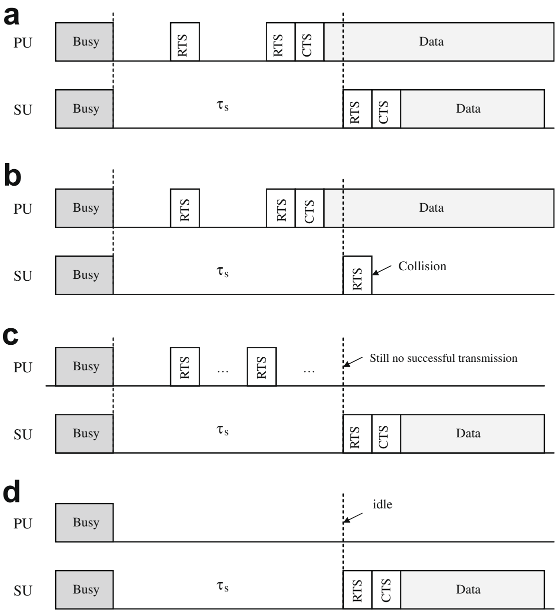

Fig. 4. CSMA based protocol with four-way handshaking procedure.

- Case (b): In this case, the RTS packet sent by the CR user experiences collision. The user must now wait for the next transmission opportunity after repeating the previous sensing process.
- Case (c): The PU sends repeated RTS packets but incurs collision each time. Here, the CR user can start transmission independently of the primary network, i.e. without adjusting its power and rate.
- Case (d): PU has no packet to send, thus the channel stays idle during the CR user's sensing period. Similar to the previous case, the CR user can start transmission without considering the primary network.

While coexistence is important, a significant interaction between the CR and the primary networks is implicitly assumed. The CR base station and users cannot determine if the PUs experience multiple failed transmission attempts (Case (c) above) without feedback from the primary network. Moreover, the transmission power for the CR users is only partitioned into two discrete levels (low or high) that does not reliably protect the PUs for all possible topologies. Moreover there is no clear assignment of the transmit power, coding scheme, transmission rate to the CR users, especially considering the interdependencies that exist in these parameters.

4.2. Time slotted protocols

IEEE 802.22 is a centralized standard that uses base stations for spectrum access and sharing [5,6] and this effort is directed by the working group [30]. The base station manages its own cell and all associated consumer premise equipments (CPE) or CR users in this case. In the downstream (DS) direction, 802.22 MAC uses time division multiplexing, while in the upstream (US) direction, demand assigned TDMA is utilized.

The standard specifies time slotted operation, with the frame hierarchy as shown in Fig. 5. At the apex, a *superframe* is defined, each of which is composed of multiple MAC *frames* preceded by the frame preamble. At the start of each superframe, there is also a superframe control header (SCH) that is used to inform the CR users of the current available channels, different bandwidths supported, future spectrum access time, among others. The MAC frame is formed by two parts in the frame structure, as shown in Fig. 6 – DS subframe and US subframe. The DS subframe contains a single packet burst from a given CPE, while the US subframe has multiple packet bursts, each transmitted from different CPEs. The different fields in these two subframes are as follows: In the DS subframe, the preamble deals with synchronization and channel estimation, the frame control header (FCH) contains the size of the DS- and US-MAP fields together with channel descriptors, and the DS/US-MAPs give the scheduling information for user bursts. In the US subframe, the urgent coexistence situation (UCS) notification informs of the incumbent licensees that have just been detected, while the other fields are used to derive the distance from the base station (ranging), and the individual bandwidth (BW) requests.

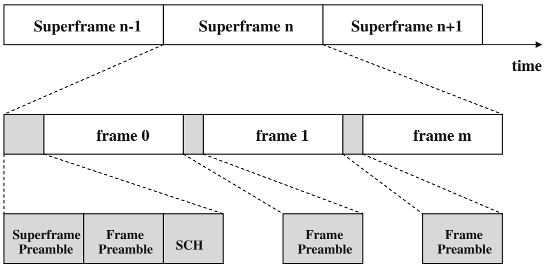

Fig. 5. Superframe Structure in IEEE 802.22 [6].

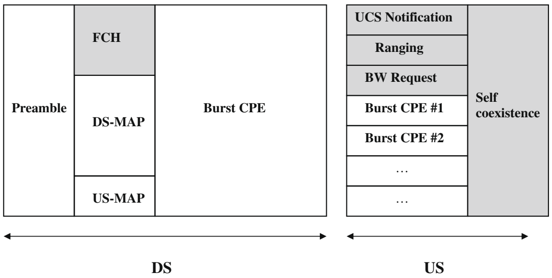

Fig. 6. Frame Structure in IEEE 802.22 [6].

The key features of the IEEE 802.22 standard are (i) extensive support for spectrum sensing, (ii) spectrum recovery, and (iii) coexistence of the different users.

4.2.1. Spectrum sensing support

The IEEE 802.22 protocol has a two-stage sensing (TSS) mechanism as shown in Fig. 7. To reliably attribute the source of the received power to the PUs, the standard enforces quiet periods throughout the CR network called as *channel detection time*. The TSS consists of two-stages which have different durations and goals:

- Fast Sensing: This is done at the rate of 1 ms/channel, and the sensing results are used to decide if a subsequent fine sensing stage is needed. The sensing is completed quickly though the accuracy is low.
- Fine Sensing: Fine sensing is performed on-demand, which allows CR networks to meet the strict quality of service (QoS) requirements by decreasing the rate of false alarms. The duration for this is much larger than the fast sensing, and gives a tradeoff for improving the sensing accuracy at the cost of transmission time.

4.2.2. Spectrum recovery

When a licensed user is detected, the incumbent detection recovery protocol (IDRP) is used, that enables the net-

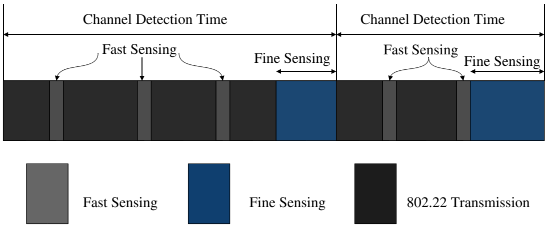

Fig. 7. Two-stage sensing (TSS) mechanism in IEEE 802.22 [6].

work to restore normal operation with minimal performance degradation. In IRDP, backup channels are used that allow to restore communication in case a channel needs to be vacated after PU appearance. These backup channels are kept in a priority list and are used whenever a CPE looks for a BS during the recovery procedure. This makes the protocol very efficient as both CPE and BS know in advance on which channels to recover the transmission when a PU is detected in their channel of operation.

4.2.3. Coexistence with users

The intra-network coexistence for CR network is achieved by the coexistence beacon protocol (CBP). The CR network may be composed of multiple base stations, which must regulate their transmission parameters based on the actions taken by each other. This requires communication between the cells, which is undertaken by the CBP beacons [6]. These beacons carry information about the cells and the DS/US bandwidth allocations for the users. CBP packets are allowed to be transmitted during specially marked periods called as a self-coexistence window. During this window period, contention-based scheme is used to access the spectrum band. As this protocol is also used for inter-base station communication, the latter have a higher priority than CPEs for spectrum access in this window period. This scheme allows the base stations to exchange information in priority over the general data traffic of the CR users.

The main drawback of this protocol is that the control header exchange is extensive, which may result in lower data throughput or reduced channel utilization. Moreover, the time synchronization is difficult to maintain between the different CR base stations, as well as CR users in a given cell.

4.3. Hybrid protocols

A game theoretic dynamic spectrum access (DSA) is proposed in [28]. The data transfer occurs in pre-determined time slots, while the control signaling uses random access scheme, making it a hybrid protocol. Moreover, this MAC is cluster based and the game policy in each cluster is managed by a central entity within the cluster. The proposed MAC protocol has high spectrum utilization, collision free spectrum access with QoS and fairness guarantees.

Four integral components can be recognized in the DSA-driven MAC framework, as shown in Fig. 8: (i) DSA algorithm, (ii) clustering algorithm, (iii) negotiation mechanism, and (iv) collision avoidance mechanism. Each of these functions is described in detail as follows.

4.3.1. DSA algorithm

The game theoretic DSA algorithm aims at pursuing a global optimization solution by reaching the Nash Equilibrium. In particular, the CR user behavior can be modeled as a repeated game model $\Gamma = \langle N, S_i, u_i, T \rangle$, where N is the set of players, S_i is the strategy of player i, u_i is the local utility function of player i, and T is the decision timing for the game. Therefore, each player keeps updating its strategy in order to maximize its own local utility function until the game converges to the Nash Equilibrium, after which a collision free channel access can be experienced. The utility function is composed of two components: the payoff or the gain obtained from the choice of the strategy, and the price the player should pay to the others for its strategy. The utility function may also take into account QoS and fairness requirement. From the networking viewpoint, the Nash equilibrium represents the assignment of spectrum access opportunities to all the CR users.

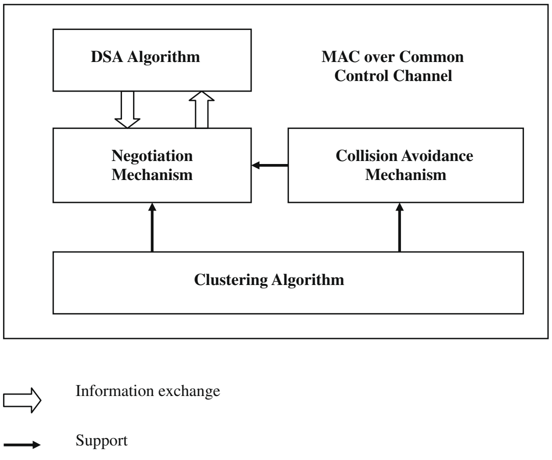

Fig. 8. DSA-driven MAC framework [28].

4.3.2. Clustering algorithm

For simplicity, a hexagonal cluster instead of a circular one is assumed. All the nodes within the hexagonal area are part of the cluster. The identity of each cluster is exclusively given by its position. When a node is added to the network, it can chose independently which cluster to join, based on the smallest distance from the cluster center. After joining a cluster, the node broadcasts with maximum power its coordinates and the cluster ID, so that all the other nodes within other clusters are aware of topology changes. The concept of virtual header (VH) is used, which is a packet unique to the cluster that also carries a token. The token contains the updated player list, i.e. accounts for the nodes joining/leaving the cluster. The beginning and termination of the VH propagation reflects the start and the end of one round of the game, respectively. The cluster head is the node to whom the VH is granted in that round.

4.3.3. Negotiation mechanism

The negotiation mechanism illustrated in Fig. 9 deals with the control message exchange and coordination of the actions of the CR users. This negotiation occurs over a CCC and is composed of two phases: (i) inquiry stage and (ii) formal negotiation stage. The aim of the inquiry stage is to identify the nodes that wish to start data communication. After this stage, the nodes that have packets to transmit will then become quasi-game players and will be considered in the formal negotiation stage.

When a node wants to start a new transmission, it sends a report packet to the VH node, thereby entering

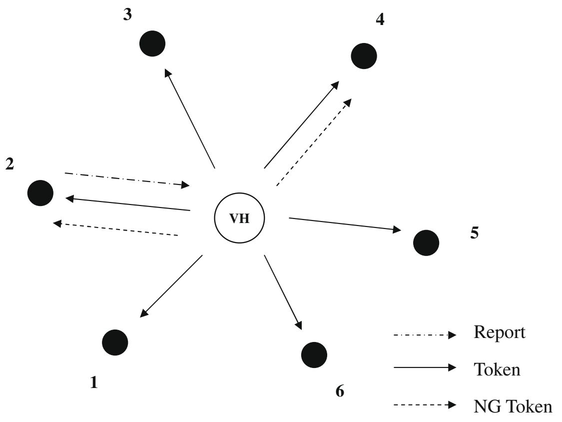

Fig. 9. Negotiation process in the DSA–MAC [28].

the inquiry stage. During this stage, all the cluster members build their player set and game strategy. Then, the VH is passed to the first player in the player set and the formal negotiation stage can start. The VH now carries the negotiation (NG) token which contains the dynamic game information required by the game players. In this way, the game players can update their local strategy and the related information in the NG token. The NG token is then passed to the next player in the list. The formal negotiation stage ends when convergence to the Nash equilibrium is achieved.

An example summarizing the entire negotiation mechanism is shown in Fig. 9. Node 2 wants to start a transmission and reports the request to the VH node. During the inquiry stage a token inquires all the cluster members but only nodes 2 and 4 become quasi-game players, as they have packet to transmit. Then, the formal negotiation stage is carried out in order to coordinate nodes 2 and 4 to process the formal game.

4.3.4. Collision avoidance mechanism

This mechanism aims at avoiding collisions during negotiations in different clusters and relies on out-of-band busy tones. Two different types of busy tones are exploited: *inside-cluster* and *outside-cluster* busy tones. Inside-cluster busy tone is set up by a node receiving a message to prevent other nodes external to its cluster from interfering with the ongoing negotiation. Outside-cluster busy tone is set up by a node overhearing messages from other clusters in order to avoid initiating a new round of negotiation within the cluster, as it may result in interference.

The time and the number of iterations taken to converge to the Nash equilibrium maybe prohibitively large. Moreover, the proposed scheme does not provide sensing support but assumes it to be readily available. Enforcing the quiet period necessary for sensing is difficult in such conditions. Another drawback of the above protocol is the low scalability as the negotiation delay increases with the number of players. The difficulty in maintaining synchronization and possible collisions in the game information packets are some of the other factors that affect the protocol performance.

5. MAC protocols for CR ad hoc networks

These protocols do not have a central entity for the operation of the network. Though the resulting architecture is scalable and has flexible deployment, the distributed spectrum sensing, sharing and access necessitate increased cooperation with the neighboring nodes. Maintaining time synchronization throughout the network and obtaining the information from surrounding nodes with minimum overhead are some of the factors that must be considered in the protocol design. We describe the existing works next based on the classification given in Fig. 3.

5.1. Random access protocols

This class of protocols is specially suited for ad hoc networks. Some of these protocols have support for multiple radio transceivers [18,20], while others use a single radio [19,11].

5.1.1. Dynamic open spectrum sharing (DOSS) MAC

Most of the works assume that a set of fixed non-overlapping spectrum bands are given, and a node can use only one of them at a time. However, if nodes are allowed to dynamically combine the available bands, it will result in better network performance. The dynamic open spectrum sharing (DOSS) MAC protocol provides an innovative solution to address the hidden node and exposed node problems [18]. Three radios are assigned distinctly to the control, data and busy tone band, respectively. The spectrum bands used for data transfer are mapped to the frequencies in the busy tone band. Thus, whenever a node transmits or receives data on a given channel, it also emits a busy signal in the corresponding busy tone band.

The DOSS MAC protocol consists of the following steps.

- *PU detection*: Since the CR users can use the spectrum only when the PUs are absent, the CR node continuously monitors the spectrum in its vicinity.
- *Set-up of three operational frequency bands*: First, the bands used for data transmission are determined, which could be a set of non-contiguous frequencies. Then, an out-of-band CCC is chosen for control signaling. The protocol proposes (i) traffic limiting, (ii) bandwidth ratio setting, and (iii) control channel migration techniques to alleviate the control channel saturation problem.
  - Traffic limiting: traffic which goes over the control channel is kept under a certain threshold.
  - Bandwidth ratio setting: the bandwidth ratio of the control channel and the data channel is adjusted to avoid the control channel to become a bottleneck.
  - Control channel migration: after fixing the initial control channel during the network setup, it can slowly migrate towards a better channel.

  Thirdly, a band is exclusively reserved for busy tones, the frequencies in which have a direct one-to-one mapping with the data transmission bands.

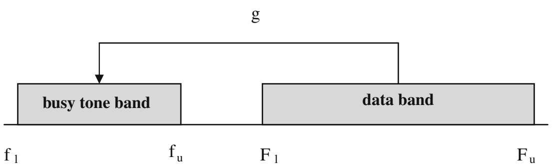

Fig. 10. Spectrum mapping in the DOSS MAC [18].

- *Spectrum mapping*: The mapping of the busy tones with the data transmission bands are done as follows. The busy tone band has a frequency range $[f_l, f_u]$, and the data band is contained in $[F_l, F_u]$, as shown in Fig. 10. The data spectrum is considerably larger, i.e. $F_u - F_l >> f_u - f_l$ and this linear mapping allows neighboring nodes to realize that the spectrum is actually used by another CR user by observing the corresponding busy tone.
- *Spectrum negotiation*: The sender sends a request (REQ) packet with the available spectrum bands at its end. The receiver then replies with a REQ_ACK packet containing the information of a mutually acceptable spectrum band. According to the spectrum mapping, it also issues the corresponding busy tone, telling its neighbors not to transmit on the chosen data spectrum band. Upon receiving the REQ_ACK, the sender tunes its data transmitter to the negotiated band.
- *Data transfer*: If a packet is correctly received, the receiver replies with DATA_ACK packet and turns off the busy tone. By receiving the DATA_ACK packet, the sender knows the transmission is successful. Otherwise, after a timeout, it will retransmit the data packet.

Apart from avoiding intra-CR network interference, we believe that this solution can also be applied to coordinate the MAC layer sensing. A node may sense on the channel which does not have a corresponding busy tone, thereby ensuring that the transmission of the other CR users are not mistaken for the PU activity.

The main drawback of this protocol is the use of separate and out-of-band spectrum for issuing the busy tones and for the CCC. Thus, the spectrum is not efficiently utilized. Moreover, the need for multiple transceivers is not justified as two of them are not used for data communication at all.

5.1.2. Distributed channel assignment (DCA) based MAC

A simple extension of the IEEE 802.11 CSMA/CA protocol using distributed channel assignment (DCA) is proposed in [20]. It uses multiple transceivers, with a dedicated out-of-band CCC for signaling. In addition, the proposed protocol also utilizes spectrum pooling which helps to enhance spectral efficiency by reliably detecting the primary network activity, thus serving as physical layer signalling.

The operation of the protocol is as follows:

- *Maintaining spectrum information*: Each mobile host maintains two data structures called the (i) current usage list (CUL), and (ii) the free channel list (FCL). Each node's CUL list records information of its neighbors including their addresses and the corresponding data channels utilized by them as well as the expected time of use. The FCL cannot be derived from the CUL and continuously updated to determine the available spectrum opportunity.
- *Data transfer*: This process is similar to the data transfer stage of [18], where the FCL is matched at both the sender and receiver ends using the RTS–CTS handshake. These messages also serve to silence the neighboring CR users, as seen in the classical IEEE 802.11 operation.

The use of a separate CCC results in wastage of the spectrum and may also become the bottleneck on the link. Moreover, there is no specific support for spectrum sensing or PU related adaptation that is required for CR networks. The protocol proposed in [23] has similar functioning and drawbacks, but uses a single transceiver that alternates between monitoring the CCC and the data spectrum bands.

5.1.3. Single radio adaptive channel MAC (SRAC) protocol

The single radio adaptive channel (SRAC) algorithm is proposed in [19] that adaptively combines spectrum bands based on the CR user requirement, called as *dynamic channelization*. In addition, it uses a frequency division multiplexing (FDM)-like scheme, called as *cross-channel communication*, in which a CR user may transmit packets on one spectrum band but receive messages on another. These two features are described as follows:

- *Dynamic channelization*: First, the basic spectrum unit (say, b) is decided, and the actual spectrum used is considered as an odd multiple of this unit (say, mb). Thus the number of possible transmission bands is much larger than the actual spectrum bands present, as the latter can be grouped differently by varying the multiplier m. Based on the spectrum demand, the usable transmission spectrum can be adaptively changed. Moreover, the spectrum bands are based on the observed load and the usage by the PUs.
- *Cross-channel communication*: In order to avoid frequency jamming and PU activity, a CR user may use different transmission spectrums for sending and receiving. This also allows for reserving larger spectrum for sending data, while the return acknowledgments may be received over smaller spectrum bands for efficient utilization of the spectrum. Each node maintains the list of spectrum bands used by the neighbors for receiving. Fig. 11 shows the case where node 1 has two neighbors A and B. Their receive channels are 2, 2, and 1, respectively. If the node 1's receive spectrum needs to be changed, it sends a notification packet in the receive bands of its neighbors (A and B) and immediately switches the spectrum. If the nodes hears acknowledgements (ACKs) from all its neighbors in the new spectrum band, the notification is completed. On the other hand, it continues to broadcast the new spectrum in the receive bands of the neighbor nodes (say node B) that has yet not replied till all the ACKs are received, or a retry limit is reached. The channel access is assumed to be CSMA with random wait.

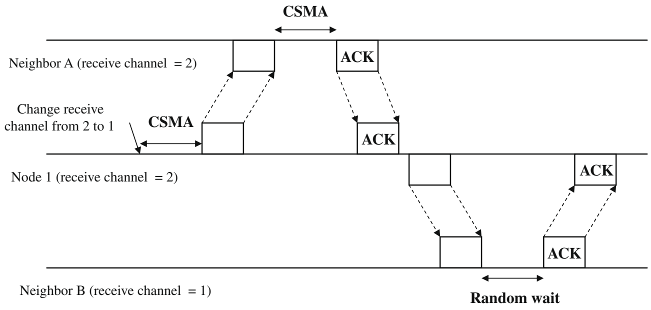

Fig. 11. The cross-channel communication in the SRAC–MAC [19].

However, this work does not completely address the means to detect the presence of a jammer and distinguish malicious activity from legitimate network conditions. Though this approach uses a single radio, it will result in significant *deaf* periods, where control messages not sent on the receive spectrum band of the node will not be monitored. Moreover, the signaling overhead for maintaining updated receive spectrum bands of all the neighbors continuously adds to the traffic.

5.1.4. Hardware constrained MAC (HC-MAC)

The hardware constrained MAC [11] protocol aims at efficient spectrum sensing and spectrum access by considering the hardware constraints, such as, the operational limitations of a single radio, partial spectrum sensing, and spectrum aggregation limits. It uses a CCC, but also has a single radio that simplifies the hardware requirements.

Hardware constraints can be divided into two classes given by (i) sensing constraints and (ii) transmission constraints. The sensing constraints concern the tradeoff between time taken for sensing and the resulting accuracy. As an example for *fine* sensing, a larger proportion of time needs to be allocated per channel, and hence a limited portion of the spectrum may be scanned. On the other hand, the transmission constraints are related to the limitations posed by the orthogonal frequency division multiplexing (OFDM) that decides the bandwidth range, as well as the maximum allowed number of the subcarriers. The distinct contributions made by this protocol are as follows:

- *Sensing decision*: In order to determine how many channels should be sensed, a *stopping* rule for successive channel sensing must be decided. By choosing a greater number of channels, the available bandwidth increases, leading to a higher data rate or reward. However, the cost of sensing, especially if the channel is found to be occupied and unavailable for use, must also be considered. The proposed finite horizon stopping rule chooses a time to stop channel searching such that the expected reward is maximized. The choice of how many channels to sense is also determined by the maximum allowed spectrum bandwidth that can be access by the transceiver at a given time, and also by the maximum number of permissible subcarriers that can be used from the available channels in this range. The authors propose backward induction to solve this problem, and complexity reduction techniques are given that reduce the computational time, especially if the number of channels is large.
- *Protocol operation*: The MAC protocol is constituted by the operations of (i) contention, (ii) sensing, and (iii) transmission. In the contention phase, the C-RTS and the C-CTS packets sent over the CCC are used for gaining access to the channel. The transmission pair that wins the contention then exchange S-RTS and S-CTS packets for each channel that is sensed. At the end of each sensing round, the decision is made on whether to initiate the sensing on a new channel, based on the stopping rule. After the channels are decided by the node pair, the data transmission begins and multiple channels found during the sensing may be used. Finally, the T-RTS and T-CTS packets are exchanged on the CCC signaling the end of this transfer and releasing the channel for other users.

A key difference of this protocol as against the previous work is that the sensing at either ends of the link is initiated *after* a pair of CR users win the contention on the dedicated CCC. However, the control messages used for channel negotiation may not be received by the neighboring nodes if they are engaged in their own data transfers. Moreover, the number of control messages is significant and may saturate the control channel earlier than classical single channel RTS-CTS based MAC protocols.

5.2. Time slotted protocols

5.2.1. Cognitive MAC (C-MAC)

The synchronized and time slotted cognitive MAC (C-MAC) [4] protocol is aimed at higher aggregate link throughput and robustness to spectrum change using multiple transceivers. C-MAC includes two key concepts: the rendezvous channel (RC), and the backup channel (BC). The RC is selected as the channel that can be used for the longest time throughout the network, without interruption among all other available choices. It is used for node coordination, PU detection, as well as multi-channel resource reservation. The BC, determined by out-of-band measurements, is used to immediately provide a choice of alternate spectrum bands in case of the appearance of a PU.

In C-MAC, each spectrum band has recurring *superframes* composed of a beacon period (BP) and a data transfer period (DTP), as shown in Fig. 12. The RC is used on a

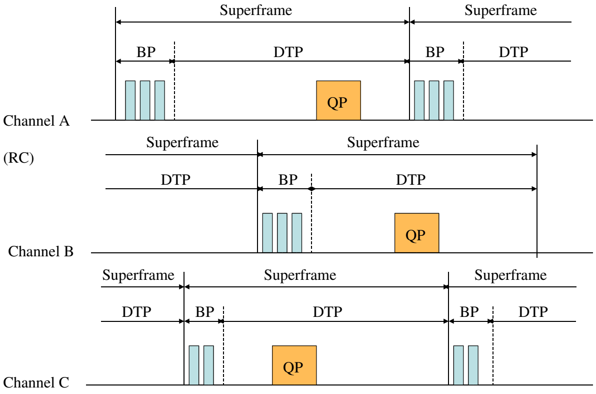

Fig. 12. Multi-channel superframe structure in C-MAC (each channel is structured in the form of superframes whose beacon periods (BPs) are non-overlapping across channels) [4].

network-wide communication, neighbor discovery, and sharing of load information for each band. Moreover, this is also used to exchange the schedules for the BP, so that the beacons are not simultaneously sent over all the spectrum bands. Upon power-up, each CR user scans all the available spectrum bands to determine the vacant spectrum resource. In these bands, if it hears a beacon, then it may choose to join that specific band and also set the global RC to the band specified in the beacon.

The working of the protocol is described in the following steps:

- *Distributed Beaconing*: Each BP is further time slotted so that the individual CR users may issue their beacons without interference. By re-broadcasting the received beacon information in its own beacon slot, a CR user helps to inform its neighbors of the other devices that are present at a distance greater than the transmission range.
- *Inter-channel coordination*: The CR users periodically tune to the RC and transmit their beacons. If they need to establish a new data spectrum band, this is communicated over these beacons. Any spectrum change that occurs in C-MAC must first be announced by the CR users over the RC, before using that band. In addition, the periodic tuning to the RC allows the CR users to re-synchronize and obtain the recent neighborhood topology information. The superframe structure (Fig. 12) is now used in the new spectrum band.
- *Coexistence*: The time slotted nature of the protocol allows the establishment of non-overlapping quiet periods (QP) for each of the spectrum bands (Fig. 12). This ensures that the PUs are differentiated from the CR users and correctly detected. Moreover, the beacons are transmitted with the most robust modulation and coding so that these packets that signal the presence of the PUs are reliably received. At this time, one of the spectrum bands from the BC is chosen, similar to the IEEE 802.22 protocol described in Section 4.2.
- *Load balancing*: The load balancing mechanism in C-MAC is achieved by accumulating the load statistics from the analysis of beacons, which carry the node traffic reservation information for the current superframe.

The main drawbacks of C-MAC are the following: All the beacons sent by the CR users must be accommodated in the BP of a superframe, which results in low scalability. Moreover, it is expected that the RC converges to a constant spectrum band over time, which cannot be guaranteed in distributed networks. Furthermore, the spectrum switching is not instantaneous - the information must first be disseminated to the other CR users in the beacon period of the RC. It is unclear how the non-overlapping nature of the BPs and the quiet periods are enforced without the presence of a central entity.

The limits associated with the use of a RC are circumvented by the distributed slotted protocol proposed in [27], which provides in-band signaling through a dedicated control window in addition to the beacon and the data transfer periods. Furthermore, during this window, the bridge nodes are allowed to use multiple channels, i.e. to access more than one coordination group in each superframe for optimizing the performance.

5.3. *Hybrid protocols*

5.3.1. *Opportunistic spectrum MAC (OS-MAC)*

The OS-MAC protocol uses pre-determined window periods for coordinating the choice of spectrum among the CR users and exchanging control information to separate the latter into groups [9]. However, within each window, the spectrum access is random, and hence this is a hybrid protocol.

The spectrum bands used for data communication are considered to be non-overlapping and a separate CCC is assumed for exchanging control packets between users on different bands. It uses a single radio that needs to switch between the data band and the CCC. The protocol operation is described as follows:

- *Network initialization phase*: Here the CR users form clusters, such that all the members of the same cluster wish to communicate with each other. The new user has an option of either forming its own cluster or joining one of the existing ones. During this entire stage of forming the cluster membership, the CR user keeps its radio tuned to the CCC. At any given moment, only one CR user is active in a cluster called the delegate.
- *Session initialization phase*: Here, the active delegate chooses a spectrum band for the group and communicates this to all the members of the cluster.
- *Data communication phase*: The members of the cluster use IEEE 802.11 DCF for accessing the spectrum band. At the same time, the active delegate monitors the CCC for collecting information of the spectrum environment. It then informs its own cluster members of a change in the spectrum band, if needed.
- *Update phase*: Each cluster delegate now sends the traffic information of its own cluster to the other delegates over the CCC, and returns back to the currently used spectrum band at the end of this transfer.
- *Select phase*: On learning of the spectrum usage statistics of the neighboring clusters, the cluster delegate may initiate changing of the spectrum used in the cluster. This

is done by using a smaller wait duration between consecutive packets, so that the delegate wins the contention and transmits the new spectrum choice with higher priority.

- *Delegate phase*: The role of the delegate is now passed onto another CR user in the same cluster for the next round of the protocol operation.

All these phases occur sequentially and have window durations determined by their respective timers. Moreover, these durations are flexible, and can be chosen so that each CR user in the cluster can access the spectrum band in a fair manner.

The OS-MAC protocol has several drawbacks. The membership of the CR users to the clusters is based on the assumption that each user already knows which cluster to join. As the clusters are formed based on group-communication needs, this is infeasible without exchanging detailed cluster information. Moreover, the CR delegate does not coordinate with the other clusters for efficient spectrum sensing, as each cluster operates independently without enforcing silent periods. Furthermore, there is no consideration of protection to the PUs either by adapting transmission, power control, among others.

5.3.2. Partially observable markov decision process (POMDP) based MAC

A partially slotted single radio MAC protocol based on the theory of partially observable markov decision process (POMDP) is proposed in [26]. A similar approach is also used in the cognitive radio access scheme in [7], where limited sensing capabilities of the cognitive radio imply that only one channel can be sensed at a time. In this case the system is also classified as partially observable and the analysis becomes involved.

The approach adopted in [26] integrates the design of spectrum access protocols at the MAC layer with spectrum sensing at the physical layer and traffic statistics determined by the application layer. The two main issues addressed are: (i) joint consideration of the spectrum sensing and spectrum access issues, and (ii) transmitter-receiver synchronization, i.e. ensuring that both the transmitter and receiver hop in the spectrum together without additional control overhead. The time is divided into slots, and in each slot the spectrum access follows a sensing-RTS–CTS–DATA–ACK schedule.

The POMDP is a generalization of a markov decision process and is addressed as partial because the network state cannot be fully observed due to partial spectrum sensing or due to sensing error. Here, time is divided into slots, and at the start of each slot, the protocol decides a set of spectrum bands for sensing, and another set of bands for transmission. These decisions are made with the aim of maximizing the throughput of the CR user while limiting the interference to the PUs and exploiting the past history of the spectrum band. During transmission, classical CSMA is assumed.

This work has the following novel approaches:

- *Performance metric*: As the protocol provides a decision on which spectrum bands to transmit based on the sensing, it proposes a new metric to measure the *reward* for the action. It is defined as the number of bits delivered when the user senses the spectrum bands during the sensing interval, and transmits in those bands that are deemed to be free of PU activity. The framework also integrates the cases where the sensing is error-prone and thus is a realistic representation. The above performance metric depends upon the network state and the reward is continuously added over time, and compared with the maximum value that could be cumulatively obtained for perfect decisions.
- *Learning support*: Unlike several previous works, the *cognitive* feature is fully integrated in the working of this protocol. The proposed MAC protocol in [26] accumulates the spectrum band history and learns which of these bands are best suited for long term use. No prior statistical traffic information for the PUs is known, and the probabilistic spectrum selection process converges to a value bounded within a constant error of the optimal solution, when observed over a sufficiently long time.
- *Synchronized spectrum switch*: For a given transceiver pair, the probability of choosing the spectrum for transmission is the same, as it is assumed that the spectrum environment seen over either ends of the link is similar. Thus, without an additional CCC, both the sender and receiver synchronously change the spectrum band, which is an important issue in CR networks.

The theoretical basis for the proposed MAC protocol assumes that the spectrum usage statistics remain unchanged for several time slots. As a result of this, the PU activity *pattern* is learnt over time and the protocol is strongly affected with frequent and random spectrum changes. Moreover, the optimal result is reached after very large time durations, and the protocol does not perform well in the initial stage.

5.3.3. Synchronized MAC (SYN-MAC)

The SYN-MAC protocol proposed in [14] does not need a CCC but has a dedicated radio for listening on the channel for control messages. A second transceiver is used for data traffic.

The main idea of the protocol is the following: Time is divided into time slots and each slot represents a particular data channel. The control signal exchange occurs in the channels represented by the slots while the data transfer can occur in any channel that is found suitable between a given node pair. Thus, the control signaling is similar to slow frequency hopping, in which the channel is switched periodically. At the beginning of each time slot, the CR users tune their dedicated control radios to the channel specified by it, and the users that wish to initiate a data transfer send out a beacon at this time. Interested neighbors respond with their own list of available channels, and further communication is carried out in one of those selected channels.

The protocol is explained in detail through the example shown in Fig. 13. There are five time slots, each representing one of the five channels. Consider two CR users *S* and *R* that wish to communicate, and have the free channel sets {1,2,5} and {1,3,5}, respectively. Node *S* chooses

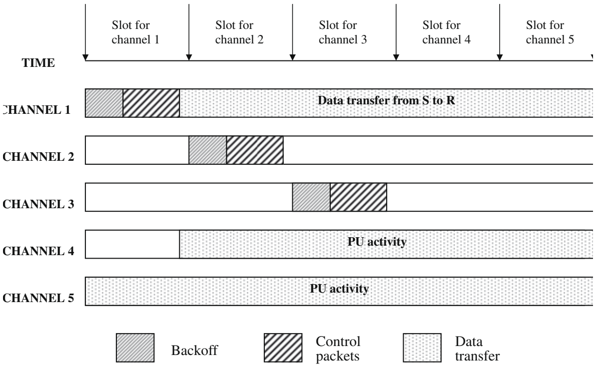

Fig. 13. Illustration of control and data packet exchange in SYN-MAC [14].

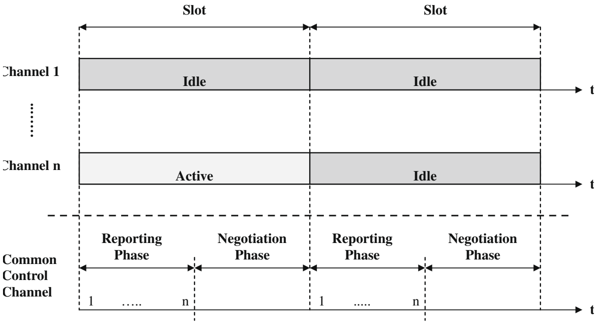

Fig. 14. Working principle of opportunistic MAC [24].

channel 1 and waits for the beginning of the related time slot to tune the listening radio to that channel. After a backoff period, *S* contends for the channel using an access scheme similar to the IEEE 802.11 distributed coordination function (DCF). If the contention is successful, it starts the data transfer.

Consider another example, in which four nodes *A*,*B*,*C*, and *D* form a linear topology. Their available channels are given by the sets {2,4}, {2,4}, {1,3,4}, and {1,3,4}, respectively. If node *B* detects PU activity on channel 4, it has to send a control packet to its neighbors informing of a change in its channel set. User *B* waits for the time slot dedicated to channel 2, the channel common with the neighbor (*A*), and sends this information after a backoff. A similar behavior is shown by node *C*, which has channel 3 in common with neighbor *D*. It waits for the related time slot to communicate its new channel set after detecting PU activity on channel 4.

The above protocol has the advantage of not using a dedicated CCC, and the dedicated listening also addresses the multi-channel hidden terminal problem. However, this approach does not guarantee protection to the PUs, as their arrivals are notified only in specific time slots to the neighbors. In addition, the channel may not be utilized efficiently, as it can be used only once in a given cycle.

5.3.4. Opportunistic MAC

The opportunistic cognitive MAC protocol proposed in [24] uses two transceivers, one for a dedicated CCC, and the other that can be dynamically tuned to any chosen spectrum. As shown in Fig. 14, the time is slotted for the data transfer over the licensed channels, while the CCC operation is partly slotted, followed by a random access negotiation phase. Thus, it is a hybrid protocol.

The detailed explanation of the working of the MAC protocol is described below with reference to Fig. 14. The CCC has the following two phases:

- *Reporting phase*: The reporting phase is further divided into *n* mini-slots, where *n* is the number of channels. At the beginning of each time slot, the cognitive user senses one of the channels. If the *i*th channel is perceived to be idle, it sends a beacon over the CCC during the *i*th mini-slot of the reporting phase. No beacons are sent if no PU is detected. These beacons serve to inform the neighbors of the PU activity.
- *Negotiation phase*: During the negotiation phase, the CR users negotiate via contention-based algorithms, such as those based on the IEEE 802.11 and p-persistent carrier sense multiple access.

To ensure that all the channels are sensed, each CR user independently chooses a channel with equal probability. If sufficient number of CR users are present, then all the channels can be covered with high probability. Moreover, the authors provide a detailed analytical treatment of the average number of channels available to the CR users, and the upper bound on their throughput.

Apart from the overhead of maintaining the time synchronization and the need of multiple transceivers, this work does not specify the exact link layer interactions between the nodes. As an example, multiple transmissions may be possible at the same time between different node-pairs, that may affect the sensing results. As the channel for sensing is randomly chosen, the neighboring nodes do not have a priori knowledge of this event and do not silence their own transmissions to improve the sensing accuracy.

6. Conclusions and future directions

In this paper, we present an overview of the state of the art for medium access protocols in cognitive radio networks. The existing works in the two main functions of the MAC protocol, namely the spectrum sensing and spectrum access were discussed. With respect to spectrum sensing, we believe that there is further work needed in devising accurate models that account for false alarm and missed detection probabilities in one framework. For this, the simplified ON/OFF PU traffic model may not be suitable in a practical environment where the licensed users may be cellular, contention-based, or have other possible access technologies. Regard the existing CR MAC solutions, several open issues remain that must be addressed. Firstly, the information from multiple layers must be seamlessly integrated in the working of the MAC protocol. As an example, the results of channel sensing and interference detection obtained from PHY layer can be used by MAC layer to build the channel occupancy history over time.

Most of the existing works do not completely integrate the sensing function. Hence, the sensing accuracy may be affected due to concurrent packet transmissions. There is also significant scope for devising protocols that adapt the CR transmissions based on the type of the interferer. As an example, the CR users may store packets to be transmitted during the off durations of duty cycled PUs. Newer performance metrics that capture the CR specific improvements should be devised and used for evaluating the different MAC protocols. Thus, we believe that MAC protocol design for cognitive radio is an open area of research and will be of interest to both the industry and the academia as this technology matures in the next few years.

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