A Survey on MAC Strategies for Cognitive Radio Networks

Antonio De Domenico, Emilio Calvanese Strinati, and Maria-Gabriella Di Benedetto

***Abstract*—Dynamic spectrum policies combined with software defined radio are powerful means to improve the overall spectral efficiency allowing the development of new wireless services and technologies. Medium Access Control (MAC) protocols exploit sensing stimuli to build up a spectrum opportunity map (cognitive sensing). Available resources are scheduled (dynamic spectrum allocation), improving coexistence between users that belong to heterogeneous systems (dynamic spectrum sharing). Furthermore, MAC protocols may allow cognitive users to vacate selected channels when their quality becomes unacceptable (dynamic spectrum mobility). The contribution of this survey is threefold. First, we show the fundamental role of the MAC layer and identify its functionalities in a cognitive radio (CR) network. Second, a classification of cognitive MAC protocols is proposed. Third, advantages, drawbacks, and further design challenges of cognitive MAC protocols are discussed.**

***Index Terms*—Cognitive radio, Medium Access Control, Spectrum Sensing, Spectrum Sharing, Spectrum Mobility.**

I. Introduction

SPECTRAL resource demand has greatly increased in the last two decades due to emerging wireless services and products. While frequency allocation charts reveal that almost all frequency bands have already been assigned (see Fig. 1), traditional static spectrum allocation strategies cause temporal and geographical holes [1] of the spectrum usage in licensed bands. In addition, in recent years, Industrial, Scientific and Medical (ISM) unlicensed bands have allowed the development of technologies such as WiFi, Bluetooth, cordless phones, etc. The great success of this band has given rise to the problem of coexistence of heterogeneous systems that might interfere each other.

Cognitive radio emerges as a way to improve the overall spectrum usage by exploiting spectrum opportunities in both licensed and unlicensed bands. The cognitive cycle [2] begins with sensing the RF medium: radios are able to exploit information about the wireless environment to be aware of local and temporal spectrum usage. Opportunistic users may dynamically select best available channels, and adapt their transmission parameters to avoid harmful interference between contending users.

Manuscript received 1 December 2009; revised 20 June 2010.

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Digital Object Identifier 10.1109/SURV.2011.111510.00108

Nodes that are licensed to operate in a certain spectrum band are usually named as primary users. A primary network is not aware of the cognitive network behaviour and it does not need any specific functionality to coexist with it. Secondary users, which are typically not licensed, are responsible for avoiding interference with primary users transmissions. When a primary user is detected, secondary users should immediately react by changing their RF power, rate, codebook, used channel, etc. because their transmissions should not degrade primary users' QoS. Moreover, secondary users should coordinate their access to the available spectrum channel and avoid collisions between different cognitive radios.

Medium Access Control has an important role in several cognitive radio functions: spectrum mobility, channel sensing, resource allocation, and spectrum sharing [3]. Spectrum mobility allows a secondary user to vacate its channel, when a primary user is detected, and to access an idle band where it can reestablish the communication link. Channel sensing is the ability of a cognitive user to collect information about spectrum usage, and to maintain a dynamic picture of available channels. Resource allocation is employed to opportunistically assign available channels to cognitive users according to QoS requests. Spectrum access deals with contentions between heterogeneous primary and secondary users in order to avoid harmful interference.

Multi-channel MAC protocols for ad-hoc wireless networks have represented a first step in the development of MAC protocols for cognitive radio in unlicensed scenarios. These protocols address similar problems; they operate in a multi-channel context, and face the multiple channel hidden terminal problem [4]. A cognitive radio may exploit, however, increased sophisticated sensing functionalities; it distinguishes between primary and secondary users, and provides protection to licensed transmissions. The number of channels available at each user is fixed in a multi-channel network, while it varies with time and space in a cognitive network. Furthermore, the time-scale in which a cognitive radio operates is very different from that of an ad-hoc radio: secondary users must exploit periodical sensing to be aware of the wireless environment evolution, and must rapidly adapt their behaviour to reach QoS and comply with interference constraints.

A multitude of studies related to the cognitive radio MAC have been recently proposed. A few surveys have already been out in order to review existing work, and to assess the fundamental goals of cognitive radio. A general overview of critical issues in CR network spectrum management is provided in [5]. In [6], the authors discuss main characteristics of some existing multi-channel MAC protocols underlining

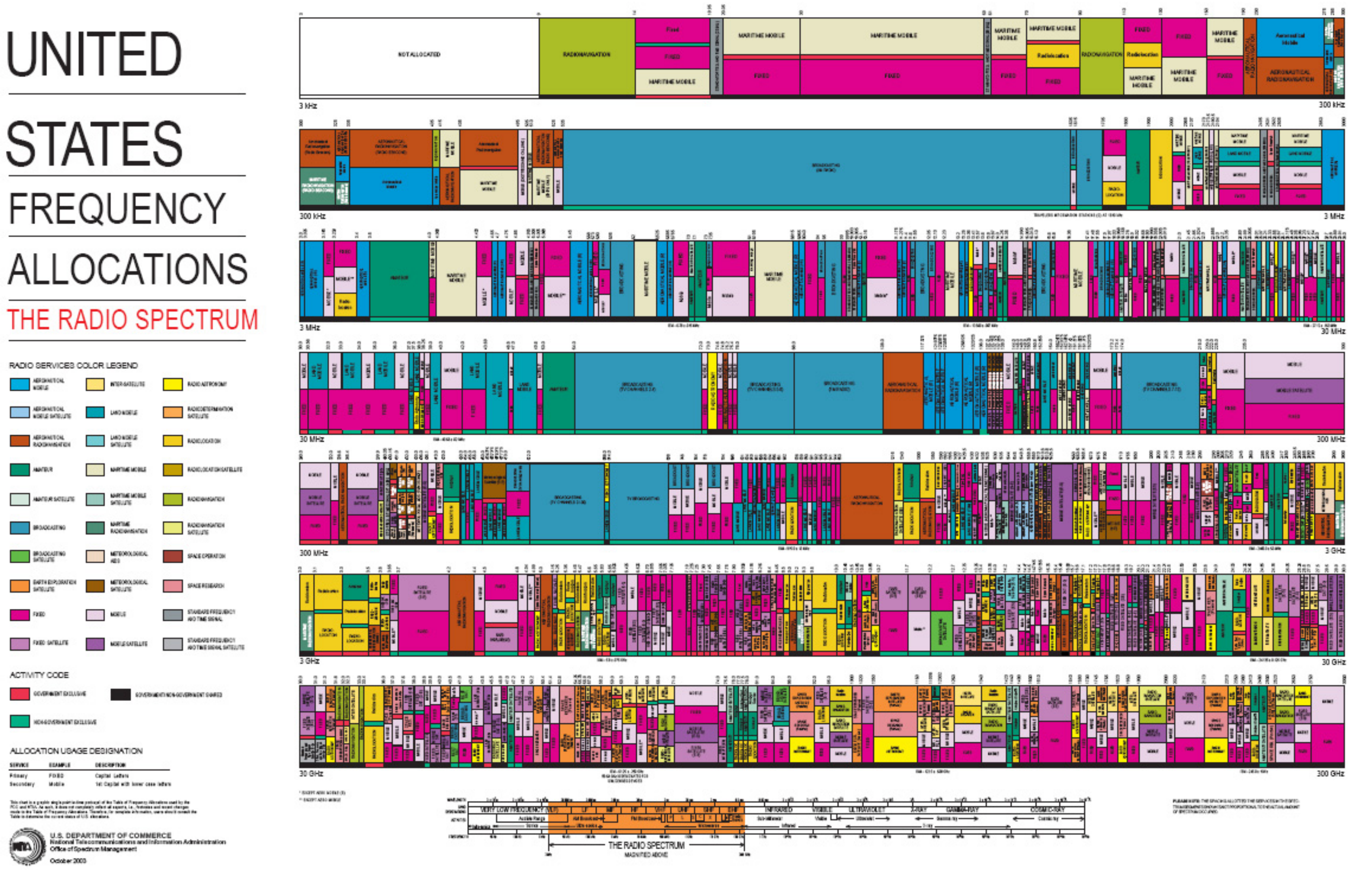

Fig. 1. U.S. Frequency Allocation Chart as of October 2003 (30 MHz to 30 GHz). Courtesy of the National Telecommunications and Information Administration (NTIA). http://www.ntia.doc.gov/osmhome/allochrt.pdf

the additional functionalities that each multi-channel protocol should offer to operate in the opportunistic context. Furthermore, CR MAC protocols are classified according to exploited mechanisms of channel negotiation/reservation. In [7], as well as [6], the authors discuss the main differences between classical multi-channel protocols and CR MAC protocols. Paper [7] presents, moreover, sensing policies and channel selection algorithms of some distinctive CR MAC protocols. In [8], MAC functionalities and current research challenges of Cognitive Radio Ad Hoc Networks (CRAHNs) are discussed. In [9], opportunistic networks are divided, according to the type of infrastructure, in centralized and distributed networks. Centralized networks are then classified depending on whether the controller takes part in data transmission among the secondary users. Otherwise, decentralized networks are classified according to how signalling and channel negotiation are managed into the network. Moreover, several CR MAC protocols are reviewed according to this classification. In [10], infrastructure-based and ad-hoc cognitive MAC protocols are classified according to the exploited medium access scheme and the number of exploited radio transceivers. In [11], CR MAC protocols are divided into four groups according to how control information is exchanged. Hence, in order to compare these groups from the throughput perspective, the authors of [11] exploit an extended version of the framework proposed in [12].

With respect to these previous surveys, the contribution of this work is, therefore, threefold. First, in an attempt to make order within different existing proposals, we present a global CR MAC protocols classification. Second, spectrum management issues and functionalities are discussed. Third, a comprehensive overview of classical and recent cognitive radio MAC protocols is presented. In particular, Section II introduces the proposed CR MAC protocol classification; Sections III, IV, V, VI, include CR MAC main issues and present existing algorithms dealing with spectrum sensing, opportunistic channel allocation, dynamic spectrum sharing and spectrum mobility, respectively. Finally, we conclude the paper by discussing same important spectrum management open issues in Section VII.

II. Classification of MAC protocols for cognitive radio

A general presentation of cognitive MAC protocols can be obtained by following the approach proposed in [13], where protocols are classified according to the following features:

1) complexity;
2) protocol architecture;
3) level of cooperation within the network;
4) how signalling and data transfer are managed during communication.

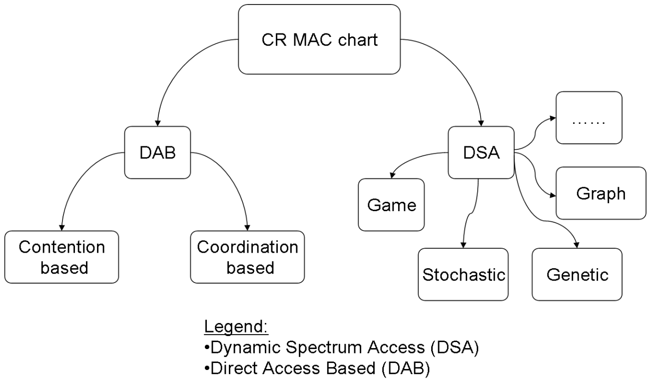

Fig. 2. Cognitive radio MAC protocols chart.

Figure 2 shows that two main MAC protocols categories can be distinguished: Direct Access Based (DAB) and Dynamic Spectrum Allocation (DSA). DAB protocols do not allow any global network optimization since each sender-receiver pair tries to maximize its own optimization goal. Moreover, resource negotiation is classically addressed with a sender receiver handshake procedure (see, for instance [14] or [15]), and a simple protocol architecture limits computational cost and latency. DSA classification refers to protocols that exploit complex optimization algorithms to achieve a global purpose in an adaptive fashion. Both DAB and DSA protocols can be implemented in centralized or distributed architecture. As well known, distributed protocols are more robust since they do not rely on reliability of the central node (also indicated as clusterhead or cluster leader), whereas in centralized protocols, a single node coordinates control information exchange and radio access. The latter architecture can potentially be more efficient in resource usage, by exploiting coordination and global information on network status. Moreover, the cluster leader often has access to complementary information on the wireless environment that permits to improve coexistence with primary users (e.g the DIMSUMNet architecture [16]) or the *Cognitive Pilot Channel* (CPC) scheme [17].

A. Control information exchange in CR networks

The amount of signalling information exchanged in a CR network is substantially larger than in a classical wireless network. Thus, most of CR MAC protocols exploit an out-of-band control channel to perform resource negotiation and share results of spectrum sensing. This channel is physically separated from the in-band channel where data transmission occurs. A dedicated control channel, moreover, may allow network synchronization and broadcasting. Two strategies are suitable for the selection of the out-of-band control channel: it can be a dedicated licensed channel (see, for instance [15]) or a shared channel ([18], [19]). While a licensed channel is often assumed to be interference free, in the latter solution heterogeneous networks may coexist on the same channel. Both solutions have drawbacks; in the first case, the common channel bandwidth should be adaptable to traffic load to limit resource wasting, or saturation, as the number of users increase. In the second case, the common channel should be continuously monitored because collisions of negotiation data could drastically affect system performance. When channel quality or its availability varies, it is necessary to vacate the selected channel and select a better one. Moreover, several protocols assume that a global control channel (e.g. [14], [20]) is available, while the probability that an opportunistic channel is available for all nodes in a cognitive network might be dramatically small. A local common channel is proposed in [21], [22] to overcame this drawback, and two approaches are proposed in the literature to manage the out-of-band control channel: the *Common Control Channel* (CCC) scheme and the *Split Phase* (SP) scheme.

Common Control Channel: users share a dedicated channel to exchange signalling information, sensing outcome, and perform channel selection. This scheme does not require time synchronization, hence, in order to avoid that network nodes miss control messages, a dedicated transceiver should be tuned on the common channel ([20], [19]).

Split Phase: this approach permits to exploit only one transceiver, but with a cost in terms of synchronization overhead. SP protocols divide time frames into two parts: a first part named *control phase* and a second part named *data phase* (see for instance [18], [23]). During the control phase each terminal overhears control messages to be aware of the network status; then in the data phase, transmissions are performed. Hence, free data channels are wasted during the control phase, and system efficiency is reduced, while, the control channel can be used for data transmissions during the data phase.

In order to overcome the out-of-band control channel drawbacks, several solutions have been proposed to handle signalling exchange and data transmissions over the same channel (in-band signalling). In IEEE 802.22 [24] a logical in-band control channel is exploited, while in [25] sensing results are piggybacked over data transmissions. Similarly, the *Frequency Hopping Sequence* (FHS) strategy is used in [26], [27]. In FHS, cognitive radios share a hopping list and keep moving from one channel to the other, until they are involved in a communication. In this approach, transmissions are more reliable because resource negotiation accuracy does not depend on the status of a single common channel. Frequency hopping requires, however, a tight synchronization among network nodes. Furthermore, to be suitable to a licensed scenario, it is necessary that the hopping sequence list may dynamically adapt to channel availability. This adaptation relies on spectrum usage prediction and its reliability affects system performance. Additionally, sensing output time-space dependence affects the possibility that different cognitive users may share a common hopping sequence and communicate.

Figure 3 highlights the main differences between the CCC, the SP, and the FHS approaches.

As already underlined, the *Common Control Channel* scheme requires two radios to efficiently manage signalling and data transmissions; the use of only one radio decreases device costs and energy consumption but imposes to interrupt data transmissions to perform sensing and signalling exchange. Moreover, a MAC protocol with a single transceiver has to address the multiple channel hidden terminal problem that may cause collisions between packets transmitted by different users. A user equipped with a single transceiver can in fact

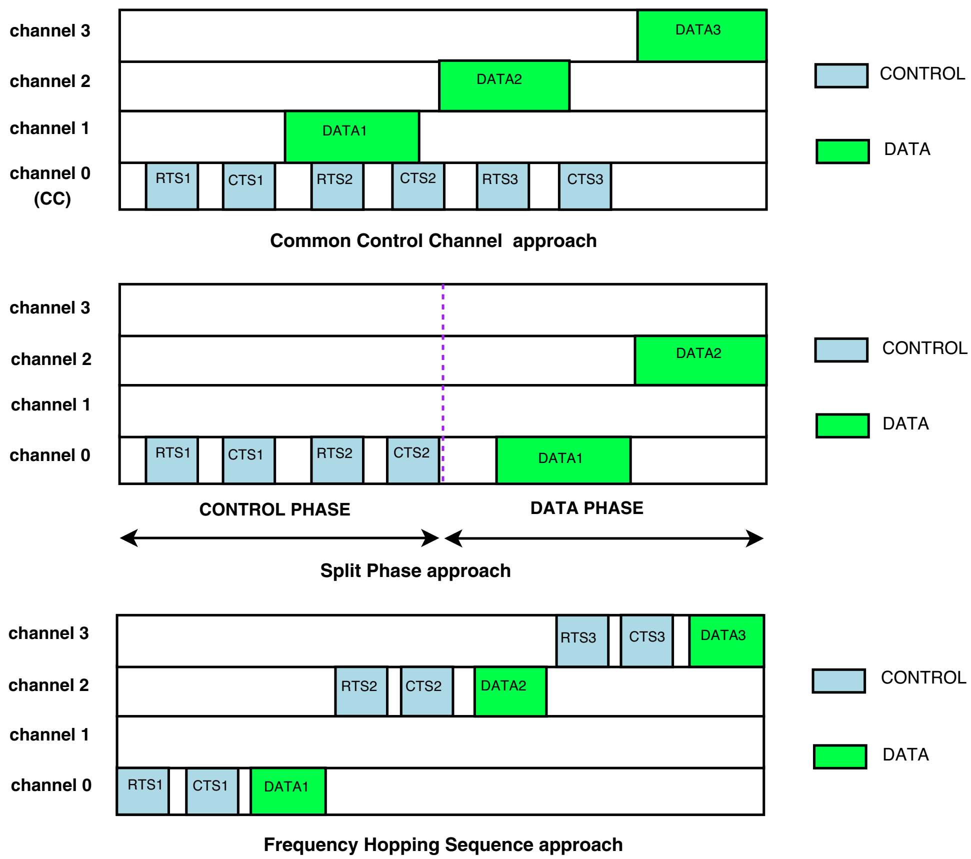

Fig. 3. Dealing with signalling and data transmission in multichannel CR networks.

only transmit or listen over one channel at a time. Thus, when a node is listening at a particular channel, it cannot hear communication taking place on a different channel. Consider for instance, the scenario of Fig. 4: node A wants to send a packet to node B and starts the RTS/CTS handshake on the control channel (channel 1). After negotiation, channel 2 is selected and node A starts communication. Node C does not hear, however, the RTS/CTS messages because it is listening to channel 3, and decides to initiate a transmission on channel 2, causing a collision.

B. Direct Access Based MAC protocols

In general, each DAB protocol belongs to one of the two following groups:

- **contention based protocols:** first, cognitive senders and receivers exchange their sensing outcome by means of a simple handshake. Then, the pair compares available resource and negotiates the channel where to communicate. The entire procedure is referred to as *Channel Filtering Sender Receiver* (CFSR) handshake.
- **coordination based protocols:** each node shares its channel usage information with its neighbours to increase sensing reliability, and improve overall system performance.

DAB protocols reviewed in this paper are listed in Table I, following the presented taxonomy.

C. Dynamic Spectrum Allocation MAC protocols

DSA-driven MAC protocols exploit advanced optimization algorithms to realize intelligent, fair and efficient allocation of the available spectrum. Each opportunistic user adapts its transmission parameters, such as modulation and coding, power transmission, and antenna configuration, to changes of the wireless environment, in order to efficiently exploit the available resource. Finding the system optimum that takes into account all the constraints of a cognitive system, requires, however, for practically relevant systems, prohibitively computational cost and a complete knowledge on the network status. Hence, although DSA algorithms promise global optimization and better performance than DAB strategies, they generally suffer from low scalability that affects negotiation delay and complexity. Therefore, in order to reduce complexity, decentralized approaches in which each node acts based on partial knowledge of network status (e.g. the localized variation of the island genetic algorithm [30]) have been proposed. Several approaches have been considered to model network interactions in DSA protocols, such as graph coloring theory [31], [32], game theory [33], [34], stochastic theory [35], genetic algorithms [36], and swarm intelligence algorithms [37].

Table II shows the list of DSA methods that will be examined in the following.

- **Graph theory algorithms:** a cognitive network can be modeled as a graph $G = (V, E)$ where V and E indicate the vertex vs. the edge sets. Two kinds of representations

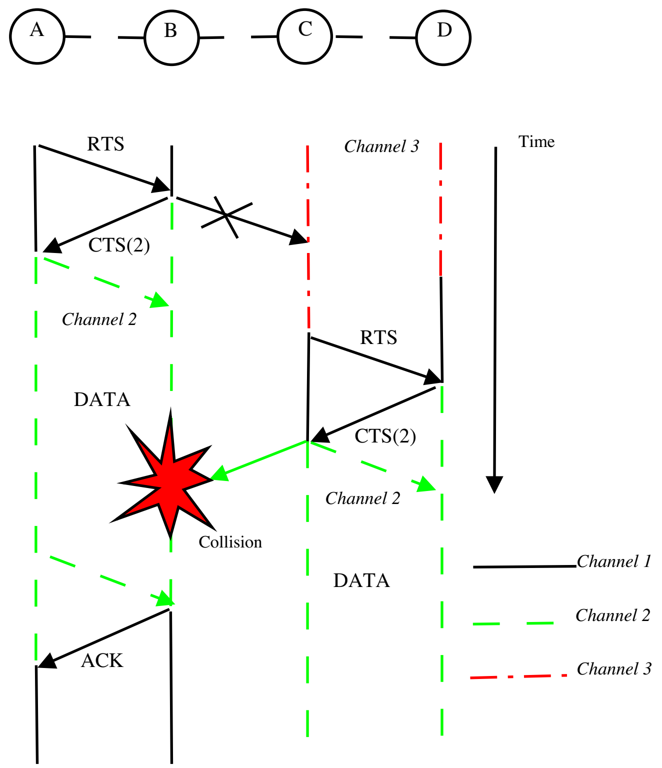

Fig. 4. The multichannel hidden terminal problem.

TABLE I
DAB CR MAC PROTOCOLS INCLUDED IN THIS REVIEW.

Protocol	Cooperation	Signalling	Reference
HC-MAC	contention-based	out-of-band	[14]
IEEE 802.22	coordination-based	in-band	[24]
C-MAC	coordination-based	out-of-band	[18]
MMAC-CR	coordination-based	out-of-band	[23]
SU08	coordination-based	out-of-band	[15]
DOSS	contention-based	out-of-band	[20]
SYN-MAC	coordination-based	in-band	[27]
HD-MAC	coordination-based	out-of-band	[22]
CogMesh	coordination-based	out-of-band	[21]
COMAC	contention-based	out-of-band	[28]
OS-MAC	coordination-based	out-of-band	[29]
Ghaboosi08	not addressed	out-of-band	[19]

are available: Node Contention Graph (NCG) and Link Contention Graph (LCG). In NCG, cognitive users are represented by nodes while edges indicate that two nodes are in the interfering range of each other. In LCG, the vertex set represents active flows, while edges represent a contention between different flows.

- **Stochastic algorithms:** the evolution of channel availability can be represented by a stochastic process. In particular, among the various proposed stochastic approaches, Markov chain formulation is the most applied. In these strategies, each node estimates channel usage based on the statistics of local spectrum sensing and its historical access experience. Hence, based on the observations, stochastic algorithm is expected to determine a strategy that maximizes the adopted utility function.
- **Game theoretic algorithms:** interaction between cognitive radios can be represented as a game. Game theory efficiently models the dynamics of a cognitive network: adaptation and recursive interactive decision process are naturally modeled by a repeated game. Moreover, with game theory each player may adopt a different utility function to pursue specific goals. Interactive behaviours among cognitive radios is represented as a game $\Gamma = \langle N, \{S_i\}, \{u_i\}\rangle$. N is the set of game players, each sender-receiver pair is an element of this set; S_i represents the strategy space (modulation and coding schemes, transmission power, antenna parameters, etc) of player i; u_i is the local utility function that models the scope of player i.
- **Genetic algorithms:** these are adaptive search algorithms based on the evolutionary ideas of natural selection. An iterative process starts with a randomly generated set of solutions called population. Best individuals are selected through the utility function (called here fitness function). Then, starting from this subset, a second population is produced through genetic operators: crossover and/or mutation. The new population shares many of the characteristics of its *parents*, and it hopefully represents a better solution. The algorithm typically terminates when it converges to the optimal solution or after a fixed number of iterations. Genetic algorithms are chosen to solve resource allocation problems due to their fast convergence and the possibility of obtaining multiple solutions.
- **Swarm intelligence algorithms:** Inspired by the collective behavior of social biological individuals, Swarm Intelligence (SI) algorithms model network users as a population of simple agents interacting with the surrounding environment. Each individual has relatively little intelligence, however, the collaborative behaviour of the population leads to a global intelligence, which permits to solve complex tasks. For instance, in social insect colonies, different activities are often performed by those individuals that are better equipped for the task. This phenomenon is called division of labour [37]. SI algorithms are scalable, fault tolerant and moreover, they adapt to changes in real time.

TABLE II
PRESENTED DSA CR MAC PROTOCOLS/ALGORITHMS.

Name	Algorithm	Signalling	Reference
DH	Graph coloring	not addressed	[32]
Zheng05	Graph coloring	not addressed	[31]
G-MAC	Game theory	in-band	[33]
Zou08	Game-theory	out-of-band	[34]
DC-MAC	Stochastic model	in-band	[35]
BIOSS	Swarm intelligence	not addressed	[37]
Nainay08	Genetic algorithm	not addressed	[30]

III. SPECTRUM SENSING

Spectrum sensing is the functionality enabling cognitive radios to be aware of spectrum usage and to detect spectrum opportunities. When two nodes want to communicate, source and destination are responsible for performing sensing; they select a set of channels to sense, they estimate channel availability, then channel filtering is performed, and a communication link is set up. Both reactive (on-demand) and proactive sensing may be exploited in a cognitive network. During data transmission, periodic in-band sensing is performed to detect incumbent primary users and avoid harmful collisions, while the sensing process dealing with the search of new opportunistic resources is referred to as out-of-band sensing. Different techniques have been proposed in the literature to process observations and detect primary users (energy detection [38], matched filter [39], feature detection [40]). MAC protocols are not necessarily aware of the adopted approach. The sensing outcome processing and available channel estimation can be realized in a distributed or centralized fashion. In the centralized approach, a leader fuses all sensing information according to a certain rule (for instance, AND, OR, or M-out-of-N rules [41]) and it evaluates spectrum opportunities. In the distributed solution, secondary nodes share observation data and independently take decisions regarding resource availability.

Sensing performance is limited by hardware and physical constraints. For instance, secondary nodes with a single transceiver cannot transmit and sense simultaneously. Moreover, users usually only observe a partial state of the network to limit sensing overhead. There is a fundamental trade-off between the undesired overhead and spectrum holes detection effectiveness: the more bands are sensed, the higher the number and quality of the available resource. This overhead is not only due to the sharing of the sensing outcome but also to the *Quiet Period* (QP) [24]. QP is the time during which a resource is not exploited for data communication in order to be sensed; transmission on the observed band is avoided during in-band sensing measurements in order to avoid intra-network interference. However, the overall system throughput is reduced when the network postpones scheduled transmissions to quiet the sensed channel.

A. Spectrum sensing in IEEE 802.22

The *IEEE 802.22* [24] working group task is to develop CR based Wireless Regional Area Network (WRAN) PHY and MAC layers in order to exploit idle TV spectrum bands. The proposed MAC protocol is a contention based DAB protocol with a centralized architecture. Each WRAN cell consists of a Base Station (BS) and its associated secondary users, named Consumer Premise Equipment (CPE). The BS and its CPEs are responsible for performing both in-band and out-of-band sensing. BSs indicate to each of their CPE the channel to sense, the sensing period and false alarm, and detection probability constraints. Measured values are feedbacked to the BS, which analyses them and takes appropriate action. IEEE 802.22 proposes a two sensing stages mechanism to realize in-band sensing, as represented in Figure 5. During fast sensing, rapid measurements ($\leq$*1 ms/channel*) are performed by each network node, and processed at the BS. Depending on the fast sensing process outcome, a BS may require a more reliable sensing on a specific channel. Fine sensing requires longer sensing period than fast sensing (for instance, *25 ms/channel* sensing is performed for primary users detection in the US DTV system), and exploits algorithms looking for particular signatures of licensed transmissions. Furthermore, in order to avoid intra-network interference during QPs, IEEE 802.22 exploits a synchronization algorithm permitting to BSs which operate in the same geographical region to perform reliable in-band sensing.

A *Dynamic Frequency Hopping* (DFH) strategy was proposed in [26] to increase IEEE 802.22 performance. In the DFH mode, a WRAN cell, while communicating on channel i (the in-band channel), observes channel availability on the next working channel j (the out-of-band channel). Then, to avoid collision with licensed users, the cognitive cell hops on channel j in order to continue transmission and starts sensing channel i. Each user is equipped with two transceivers; hence, sensing and transmission can be performed in parallel. This operation is referred as Simultaneous Sensing and Data Transmissions (SSDT), and represented in Figure 6. Guard bands separate in-band and out-of-band channels to mitigate interference during simultaneous sensing and transmissions. Hence, the DFH strategy increases system throughput by avoiding transmission interruption. Moreover, coordination between neighbor WRANs is proposed to avoid mutual interference during the sensing phase. A DFH Community (DFHC) is a set of N coordinated WRANs: each DFHC is managed by a community leader and its members exchange information through a coexistence window located at the end of the MAC frame. The leader is responsible of periodically generating and broadcasting the channel hopping pattern. Coordination permits the DFHC members to operate by transmitting and sensing without interruption using N+1 vacant channels, as long as the length of a single transmission is larger than the product N*QT (QT is the length of the Quiet Period).

In order to improve reliability of the DFH scheme, a Double Hopping approach is proposed in [32]. Figure 7 shows the Double Hopping operating mode for three neighbour IEEE 802.22 cells. The time at which a cell is allowed to consecutively transmit is indicated as T_{data}. The minimum amount of time required to perform sensing is T_{sens}. In order to limit interference, transmissions are not allowed on sensing channels during the QP. T_{quiet} defines for how long a frequency cannot be used because of the sensing process. Hence, in the DH operating mode each cell exploits a dedicated working frequency and shares a sensing frequency with all the cells within its network. Transmission starts on the working frequency, then when T_{data} expires, a cell hops on the sensing frequency to continue its communication while performing periodic sensing on its working frequency. After T_{quiet}, it can hop back on its working frequency and let the sensing frequency free. In Figure 7, the sensing slots for the working frequencies and the sensing frequency are referred to as N_{wf} and N_{sf}, respectively. The maximum number of neighbour cells that can share a sensing frequency and be supported by the double hopping strategy is $N_q = T_{data}/T_{quiet}$.

The DH approach permits to reduce the number of frequency channels exploited by each WRAN cell. In the classic DFH scheme each cell hops on N+1 channels (N is the number of cells in the network) according the pattern generated by the cell leader. Oppositely, in the DH approach, a CR cell hops between two frequencies only. This approach has some advantages: first, when a primary user appears on a working frequency only the cell attached to that channel has to shift to another channel; second, managing network coordination is simpler because cells share only the sensing frequency.

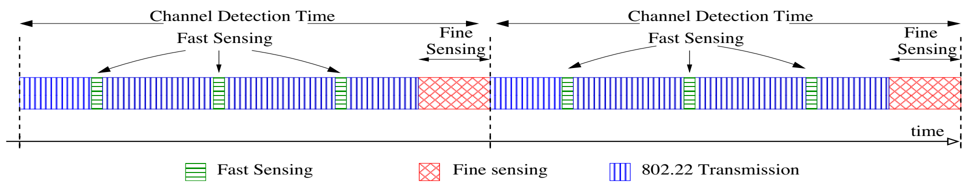

Fig. 5. The IEEE 802.22 two stage sensing [24].

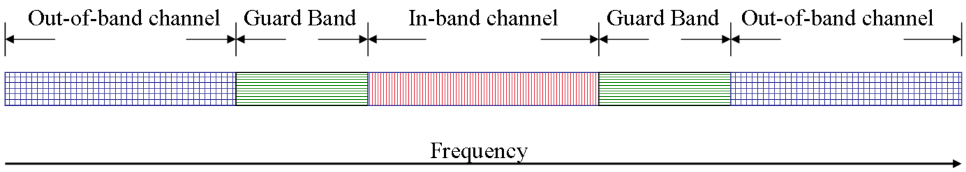

Fig. 6. Simultaneous Sensing and Data Transmission in 802.22 DFH [26].

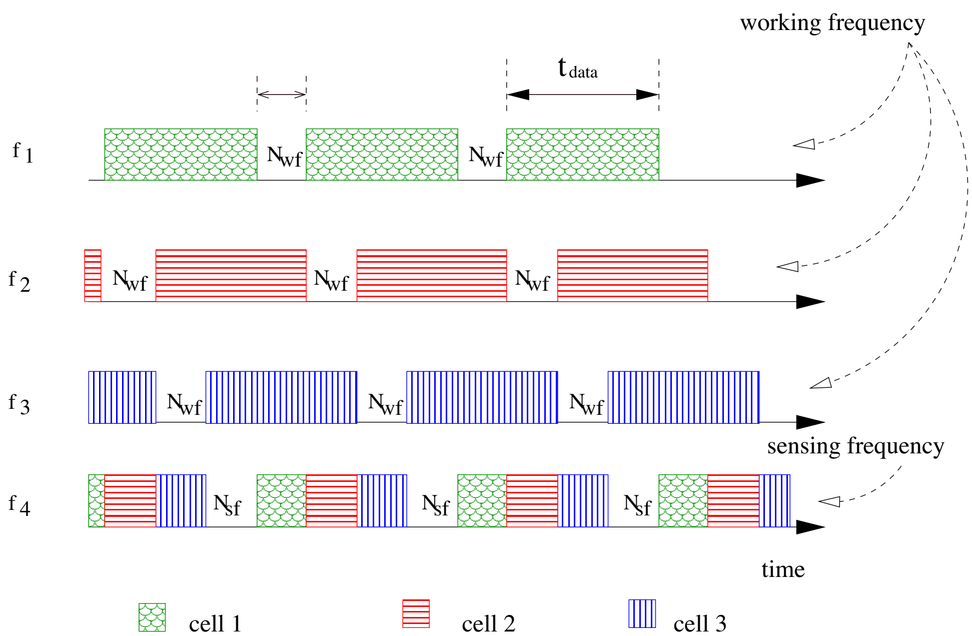

Fig. 7. Double Hopping operating mode for three neighbour cells [32].

B. Spectrum sensing optimization

In order to improve the spectrum sensing process, several CR MAC protocols have proposed different strategies to limit resource waste. A first approach is presented in the *Hardware-Constrained Cognitive MAC* (HC-MAC) [14]. HC-MAC is a contention based DAB protocol that represents the sensing process as an optimal stopping problem in order to determine how long a cognitive radio should observe the wireless bands to optimize its expected throughput. The stopping rule is defined by two objects:

- the observation sequence, modelled as random variable, $X_1, X_2 ...,$
- a reward sequence, which is a function of the observation, $y_0, y_1(x_1), y_2(x_1, x_2)....$.

After n observations, a cognitive radio can choose to stop sensing to collect corresponding rewards, or continue probing until it reaches its goal. The goal is to choose a time for stopping such that the reward is maximized. In Orthogonal Frequency Division Multiplexing (OFDM) radios, this decision is constrained by the maximum fragments number (the spectrum holes) that can be merged, and also by the limited width of the aggregated band. If there is a maximum number of channels that a radio can sense before taking the stopping decision, the stopping problem has a finite horizon. The finite horizon stopping problem can be optimally solved by the method of backward induction [42]. This solution has, however, an exponential complexity and it is thus necessary to reduce computational cost to a reasonable level, especially for large numbers of fragments. HC-MAC authors propose a truncated version of the optimal rule named $k-stage\ look-ahead$. This suboptimal algorithm computes, at stage n, the expected reward for sensing during $n+k$ stages. Hence, it decides whether to stop or to continue probing, comparing the reward function value with throughput constraints.

The optimization of the sensing period in order to maximize the discovery of spectral opportunities while minimizing sensing overhead is investigated in [43]. The authors consider a single hop cognitive wireless network coexisting with a

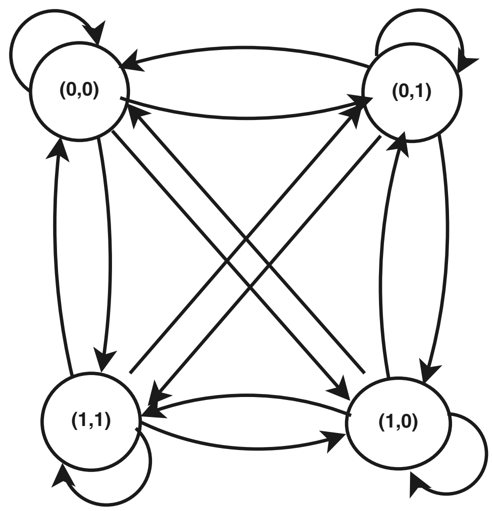

Fig. 8. The Markov model representing a network state transition {0(idle), 1 (occupied)}.

primary network. Each opportunistic user is assumed to be equipped with a single antenna, which can be tuned to any combination of N consecutive licensed channels. Hence, transmission and sensing cannot be performed at the same time, and communications have to be periodically interrupted. Channel sensing is performed during QPs in which nodes cooperatively participate in sensing to enhance primary users detection. Channel usage is modeled as an ON-OFF source; when a cognitive radio discovers an OFF period it can exploit all the remaining OFF period for its own transmission. Whenever an available channel is discovered, it is merged into a set with capacity equal to the sum of all available found channels. Then, nodes within the opportunistic network contend the exclusive access to the logic channel. Hence, the problem of finding the optimal sensing period for the N channels that minimize the unexplored opportunities (UOPP) and the sensing overhead (SSOH) can be expressed as

$$\underline{Tp^*} = \arg\min_{Tp} \left[\sum_{i=1}^{N} \left(SSOH^i(\underline{Tp}) + UOPP^i(\underline{Tp}) \right) \right] \qquad (1)$$

where $\underline{Tp^*}$ is the vector of optimal sensing periods. $UOPP^i(\underline{Tp^i})$ is defined as the average fraction of time during which channel i's opportunities are not discovered because i is sensed with a sensing period Tp^i. Moreover, $SSOH^i(\underline{Tp^i})$ is defined as the average fraction of time in which channel i's discovered opportunities are not exploited due to the QP.

In the *Decentralized Cognitive MAC* (DC-MAC) [35], [44], authors propose a channel sensing/access policy which considers the partial knowledge of licensed channels state at secondary users. Furthermore, this strategy handles spectrum sensing errors limiting interference to primary network. The proposed DC-MAC exploits the theory of Partially Observable Markov Decision Process (POMDP) where traffic characteristics of the primary users is represented as a Markov chain. Considering a band composed by N channels, the network can assume one of $M = 2^N$ state (Figure 8 shows a network state diagram for N=2). At the beginning of each slot, cognitive users, exploiting their knowledge of the network state, select the set of channels to sense in order to maximize the global reward collected in T slots, while limiting the primary user miss-detection probability. The optimal strategy represents past decisions and observations with the *belief* vector $\Lambda(t) = [\lambda_1(t), \ldots, \lambda_M(t)]$. $\lambda_j(t)$ is the conditional probability that the network state is j at the beginning of slot t, prior to the state transition. Action chosen at each slot affects the reward function in two ways: it gives an immediate reward (the access to selected channels), furthermore, it permits to update the *belief* vector according the observed state of the network. The optimal strategy defines a balance between gaining immediate rewards and achieve information to improve future behaviour. This strategy may, however, hardly be implemented because the dimension of the statistic $\Lambda(t)$ grows exponentially. Hence, the authors propose a sufficient statistic $\Omega = [\omega_1, \ldots, \omega_N]$ whose dimension grows linearly with N. This statistic can be exploited only when the N channels evolve independently. The element $\omega_j \in \Omega$ is the probability (conditioned to the sensing and access history) that channel j is idle at the beginning of a slot. Moreover, a suboptimal greedy approach that maximizes the expected reward per slot is presented.

Hence, the proposed DC-MAC operations are represented in Figure 9 and can be resumed as follows:

- At the beginning of each slot, transmitter and receiver select the channel a to sense according to the *belief* vector Ω. The two users exploit the same *belief* vector, this ensures that they tune to the same channel.
- If the sensed channel is available, the transmitter generated a random back-off time. In order to limit collisions with incumbent primary/secondary users, the sender continues to monitor the channel a during this period. If a remains idle, the transmitter starts a request to send/clear to send (RTS/CTS) handshake to verify if the sensed channel a is also available at the receiver side.
- The transmitter sends data over channel a. If the data are successfully received the receiver transmits an acknowledgement message. Finally, both the sender and the receiver update their belief vector.

DC-MAC is one of the few opportunistic MAC protocols that include sensing errors in its design, however, its implementation is limited by the assumption that the transition probability in the Markov channel model are known. In practice, this may not be available.

C. Cooperative detection

Licensed users detection effectiveness is compromised by noise uncertainty, lack of information about the primary receiver location, fading, and shadowing effects. The MAC layer optimizes the sensing strategy by dealing with these limitations and by taking into account possible sensing errors. Collaborative sensing allows different secondary users to share their sensing outcome. This strategy exploits inherent multiuser spatial diversity to improve detection, and decrease missing and false alarm probabilities [45]. Increased performance comes at the expense of increased latency and communication overhead. Cooperation can also solve the hidden terminal problem as well as reduce sensing observation time and bandwidth [46]. Furthermore, it also permits to decrease the effects of malicious sensing nodes [47].

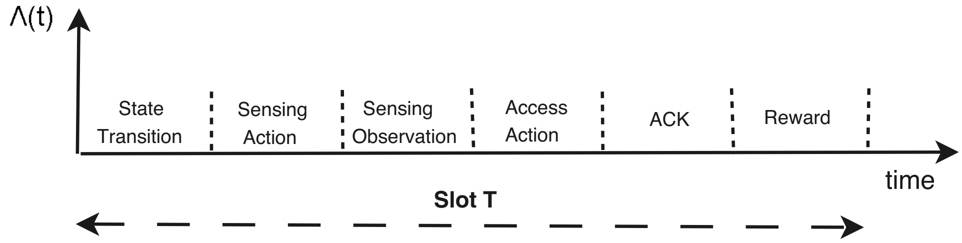

Fig. 9. The DC-MAC sequence of operations [35], [44].

In *C-MAC* [18] collaborative detection is implemented through beacons transmitted among network channels. C-MAC is a Split Phase distributed DAB protocol. It assumes that each cognitive user is equipped with a half duplex radio and that each channel is organized in superframe. The superframe is composed of two consecutive parts: Beacon Period (BP) and Data Transfer Period (DTP). In-band and out-of band sensing are performed during the QP of the corresponding channel. Primary users detection is notified through the beacon frame transmitted in each superframe. In order to allow cognitive users to decode the sensing output message even in presence of the primary user interference, the beacon frame is transmitted using the most robust modulation and coding scheme. Synchronization within the cognitive network allows different users to broadcast beacons without overlapping across all the available channels. During BPs secondary users switch among the network channels by listening beacon frames and acquiring information about channels state. Moreover, cognitive radios periodically visit a common channel, named *rendezvous channel* (RC), to gather information about primary and secondary users discovery and get resynchronized. Collected data are processed to realize a more reliable picture of spectrum usage.

In [23], the authors propose a MAC protocol for CR ad-hoc networks. The *Multichannel MAC* protocol (MMAC-CR) is a Split Phase protocol which takes advantages of a two stage sensing (fast/fine sensing) mechanism and a cooperative detection scheme. A dedicated control channel is used to perform network synchronization and common information exchange. In this protocol, time is divided into two phase: the Ad-hoc Traffic Indication Message (ATIM) window and the DATA window. During the first phase the following operations are performed:

- IEEE 802.11 timer synchronization function (TSF) [48] is run to permit tight synchronization within the network;
- CRs perform fast sensing;
- neighbour users share sensing outputs and update their local view of spectrum opportunities;
- medium access coordination is performed via a two way handshake.

During the second phase CRs

- exchange their data;
- perform fine sensing;
- enter in a doze state if they have not to data to exchange or channels to sense.

Communicating and sensing on different channels can be performed in parallel (i.e. one radio is dedicated to sense the spectrum medium), which significantly reduces the impact of sensing. When a user joins the network, it performs a fast scan on each channel and constructs the Spectral Image of PUs (SIP) vector. SIP[c] represents the spectrum usage estimation of the channel c:

- When no PU are active on channel c, SIP[c] is set to 0;
- When a PU is active on channel c, SIP[c] is set to 1;
- When the PU presence is uncertain SIP[c] is set to 2;

When the SIP of a channel is not 0, it will be excluded from the list of channels available for data transmission. Moreover, if the presence of PU on the channel is uncertain, a fine sensing will be performed on that channel during the DATA window. SIP values are periodically updated during the ATIM window through fast sensing. Primary user presence is estimated by implementing the OR fusion rule. Cooperative detection is performed during a mini-frame in the ATIM window. This frame is divided into C slots, one for each licensed channel. Cooperating nodes transmit a busy tone in the corresponding slot for every channel their SIP is not 0. If a slot is sensed as busy, then the corresponding channel is excluded for CR communication.

Synchronization within cooperating users is achieved through the Scan Result Packet (SRP), which indicates the beginning of the mini-frame. During the ATIM window, after the sensing process, each node will try to send an SRP frame to initiate cooperative detection. The access on the common control channel to transmit SRP packets is managed with the IEEE 802.11 Distributed Coordination Function (DCF) [49]. While MMAC-CR has the advantage to be energy efficient, it requires tight synchronism within the CR network. Moreover, MMAC-CR reliability strongly depends by the control channel quality.

In order to improve the cognitive network awareness on the spectrum usage, two sensing policies have been proposed in [15]. In the proposed coordination based cognitive DAB protocol each secondary user is equipped with two transceivers. The control transceiver, is used to exchange sensing information and contend the available channel on the dedicated control channel. The software-defined radio (SDR) transceiver is exploited to sense and transmit/receive data on the licensed channels. The control channel and licensed channels are time-slotted and synchronized. Furthermore, each licensed channel is modelled as an ON-OFF source and its state is characterized by a two state Markov-chain.

Time slots in the control channel are divided into two phases: a *reporting phase* and a *negotiating phase*. Reporting phase is still divided into n mini-slot, each one corresponding

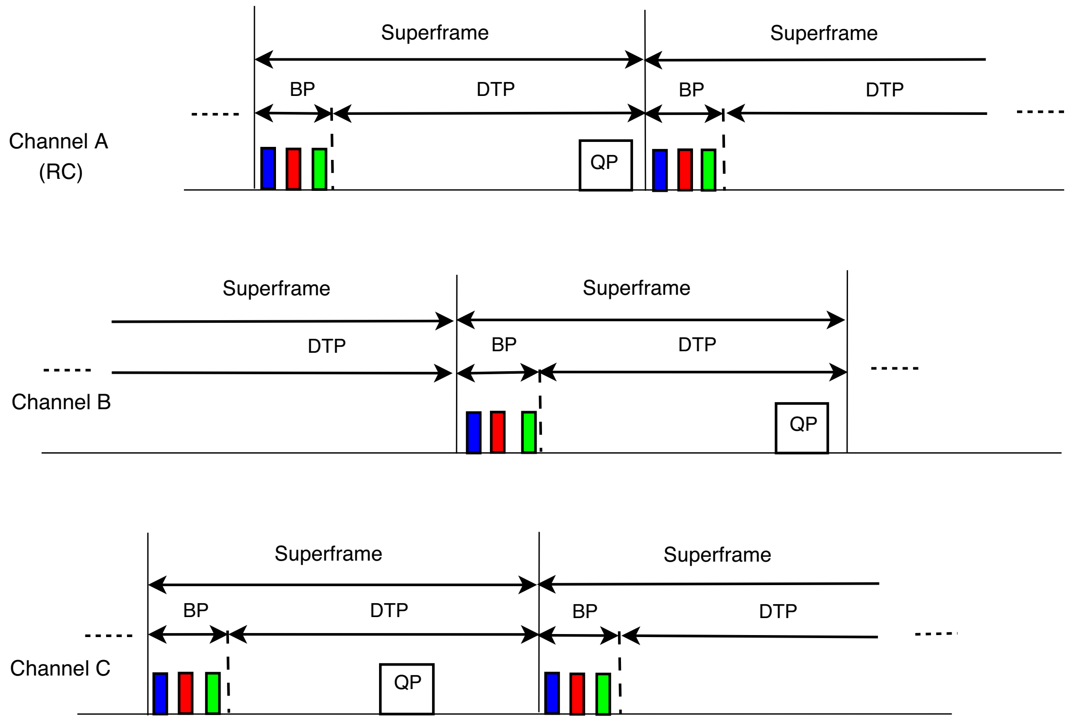

Fig. 10. Channel superframe structure in C-MAC [18].

to one of the licensed channels. This phase permits secondary users to share their sensing outputs. Negotiating phase permits cognitive users to contend the access to the overall set of available channels in the next time slot. The proposed scheme is illustrated in Figure 11.

According to the *random sensing policy* (RSP), at the beginning of each time slot, secondary users randomly sense one of the licensed channel. If the sensed channel is idle, the cognitive user transmits a beacon in the corresponding mini-slot within the reporting phase. Basically, the reporting phase, is a physical implementation of the AND rule. Clearly, the higher the secondary users number, the higher the number of the sensed channels. The basic idea of the *negotiating sensing policy* (NSP) is to let secondary users know which channel have been sensed by their neighbors, and then select different channels to sense in the next slot. During the negotiating phase, cognitive users include the information about the channels they sensed in the negotiating (RTS/CTS) messages. When a cognitive user discovers that it sensed the same channel of one of its neighbors, it selects a different channel to sense for the next time slot. The new channel is randomly picked from the set of channels for which the user has not received any beacon during the reporting phase. This set is made up by the channels that have been sensed busy and the channels that have not been sensed. Eventually, using the proposed negotiating sensing policy the number of sensed channels monotonically increases with time. It should be noted, however, that the implemented AND rule could be too aggressive with respect to the primary user. A more conservative approach has been proposed in [23].

D. Exploiting location awareness to improve spectrum sensing

A novel approach to perform spectrum sensing in a cluster-based mesh architecture is described in [25]. The proposed scheme permits to identify primary users' frequencies without any change to the IEEE 802.11 standard for Wireless Mesh Networks (WMNs). In the investigated architecture, a number of mesh routers (MRs) serve as access points for a community of Mesh Clients (MCs), which exchange data over the Internet. The access points form the backbone of the network and they forward traffic over the backbone, in a multi-hop manner, towards an Internet gateway. Both MRs and MCs are equipped with a single *IEEE 802.11b* transceiver, which can be tuned on both the ISM and licensed TV bands. In each cluster, MCs periodically piggyback sensing results over the data transmission to the cluster access point. The MR combines received information, and forwards it to the internet gateway where it is stored in a centralized database. Then, this data is regularly included by the gateway in the downlink stream and exploited at each cluster to optimize the MAC layer. Authors propose a sensing scheme that enables MCs to monitor licensed channels while avoiding MCs miss data packets transmitted on the ISM band. The proposed algorithm requires MCs to estimate their distance from primary station, when necessary. A cognitive node is allowed to perform spectrum sensing only when its operating channel is busy but the node is not the intended receiver. Whenever a MC hears a message over the cluster channel, it decodes the MAC layer header in the received message; if the node is not the packet intended receiver, it can hop to a licensed channel and perform spectrum sensing. All the *free* MCs within a cluster tune to the same licensed channel and evaluate the received energy. This energy is due to the superposition of signals emitted by different TV transmitters. These transmissions may lay on different carriers, and only a part of their power overlaps on the channel in which sensing is performed. Hence, MCs forward energy measurements and the estimated distances between each MC and primary receivers to the MR. Then, the MR estimates the carriers in which there are active transmissions exploiting the received information, the knowledge of the entire set of carriers available to the primary users, and the spectral overlap factor between licensed channels. Furthermore, authors propose a decentralized version of the proposed sensing scheme to equally share the computational cost among nodes within a cluster.

In [50], the authors propose a novel approach to improve coexistence between an infrastructure-based primary network and a cognitive ad-hoc network. The presented scheme can drastically reduce the need to perform spectrum sensing. Authors consider a scenario in which both primary and secondary users stay fixed or hardly move. Therefore, an opportunistic node that has location information about neighbour primary and secondary users can identify the coexistence region (R_{CT}) in which primary and secondary nodes can perform concurrent data exchange on the same frequency channels. R_{CT} can be computed as the area in which contemporary primary and secondary users transmissions are not in outage. In order to estimate this region, when a new node joins the ad-hoc network it should perform positioning and geographical routing to acquire its position and learn the position of its neighbours.

Therefore, authors believe that additional energy consumption and memory space due to the position and location update could be relatively small. However in [50], there have been not presented comparison between the proposal and the classical sensing techniques neither in terms of energy consumption nor in terms of computationally costs. Nevertheless, classic spectrum sensing is still necessary when a secondary sender receiver pair is outside the concurrent transmission region R_{CT}.

IV. Dynamic spectrum allocation

In traditional static spectrum assignment policies, the radio spectrum is divided into separate bands of fixed width, identified by their range of frequencies. A band is allocated to a licensee having the exclusiveness of using this resource. Quality constraints can be guaranteed because interference between heterogeneous systems is avoided. In a cognitive network, based on the sensing outcome, a resource allocation function assigns available channels to the contending users by attempting to maximize a utility function. Bandwidth and channel availability time-space dependency introduces, thus, new challenges with respect to classic wireless technologies.

A. Spectrum allocation in DAB algorithms

In DAB protocols, each sender-receiver pair selects channels to access according to personal constraints without considering network optimization.

COMAC [28] is a contention based protocol that tries to satisfy QoS constraints by limiting the number of used channels per user. Authors consider a scenario in which an ad-hoc cognitive network coexists with M primary networks. Each opportunistic user A maintains a list of its locally available channels *LAC(A)*, which is the set of channels that are not currently used by any of A's CR neighbours. LAC is continuously updated through the overheard of control packets. When an opportunistic pair wants to initiate a communication, the sender and the receiver exchange their *LACs* over the network control channel, and then the receiver selects channels where to communicate. Three parameters impact channel selection:

1) Spectrum state information;
2) Maximum allowable transmission power for channel;
3) Requested data rate.

According to these parameters, when the receiver B receives the sender A's RTS packet:

- It compares the set of its available channel *LAC(B)* with the sender's list *LAC(A)*. Then it computes $\Lambda \doteq LAC(A) \cap LAC(B)$;
- The channels within Λ whose received SINR is below a fixed threshold are removed from the list;
- Then the receiver sort the rest of available channels in descending order of their data rate;
- Selected channels are chosen from the sorted list until the the requested data rate is satisfied or the list is exhausted;
- If the data rate condition is satisfied the receiver transmits to the sender a CTS message including the list of the selected channels. Otherwise, B will not respond to A's RTS and the sender will reschedule its transmission.

A channel selection metric that jointly considers traffic load, connectivity, and interference is proposed in the Heterogeneous Distributed MAC (HD-MAC) [22]. HD-MAC is a modified version of the IEEE 802.11 MAC protocol proposed in [4] that permits distributed coordination of local clusters in a multi-hop cognitive radio network. In HD-MAC neighbour secondary users self organize in local group where coordination is handled through a local common channel. The MAC structure is organized in super-frames consisting in a Beacon Period (BP), a coordination window (CHWIN), and Data Transmission Period (DATA). During the CHWIN period users hop to the coordination channel to manage channels contention. Access during the CHWIN is realized according the CSMA/CA protocol. A general node u, maintains a score $w_u(c)$ for each channel c, defined as follows:

$$w_u(c) = \lambda_{in} Q_{in}(c) + \lambda_{out} Q_{out}(c) - \lambda_f Q_f(c) \tag{2}$$

where,

- Q_{in} represents the estimation of incoming traffic load on channel c,
- Q_{out} represents the estimation of outgoing traffic load on channel c,
- Q_f represents the estimation of traffic load that may interfere with neighbour's transmissions using channel c,
- λ_{in}, λ_{out} and λ_f represent the weight of each traffic type.

Q_{out} is updated at the beginning of CHWIN period based on the currently outgoing queue of node u, while Q_{in} and Q_f are estimated based on neighbour queues. In HD-MAC, each node includes its queue status in coordination messages. Channel negotiation is realized through CFSR handshake. When sender u transmits a channel request (CHRTS) to receiver v, it

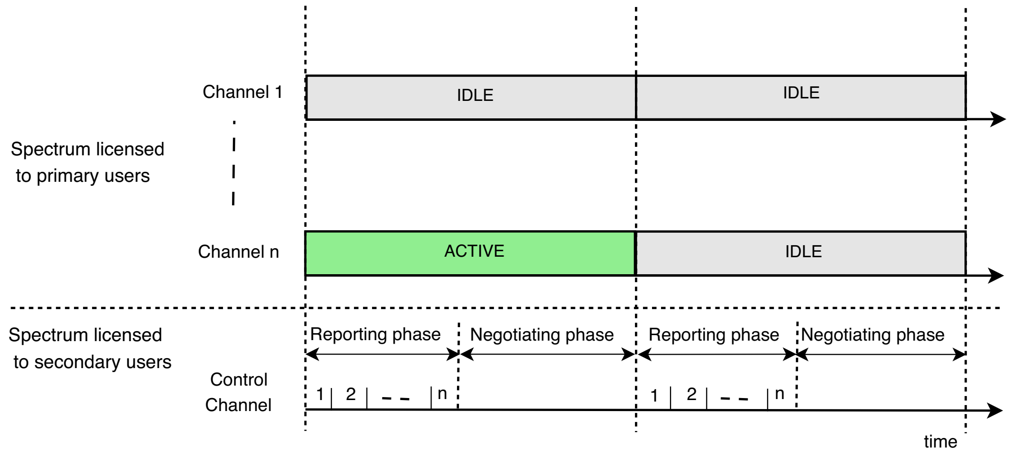

Fig. 11. Reporting and negotiation phases in [15].

includes its queue size related to v and a channel information message $\theta_u = \{c, w_u(c)\}_{c \in L(u)}$ related to its available channel list *L(u)*. The receiver chooses the common channel that maximizes $min\{w_v(c), w_u(c)\}$, and transmits to the sender a channel respond (CHRES) message that includes its selection and the volume of pending packets. If there is no feasible channel, the receiver sends a message of transmission failure. Upon receiving the CHRES message, u sends a channel confirmation message (CHCFM) to v. This message confirms the selected data channel and it includes the length of the pending packets. Neighbour nodes which overhear the CHCFM and CHRES messages obtain traffic information and update the channel score accordingly. Eventually, sender and receiver mark the selected channel as "outstanding". They will tune on this channel for all the DATA period, hence, their subsequent negotiations during the current CHWIN are based on the outstanding channel only.

In the MMAC-CR [23], channel selection is performed in order to minimize the expected interference. As explained in Section III-C, after the transmission of the scan result packet over the control channel, secondary users are aware of primary users activity on the observed band. The MAC frame is divided into two period: the ATIM window and the DATA window. During the ATIM window cognitive users that have buffered data perform a three-way handshake to realize data channel selection and inform neighbours about their traffic load. This handshake starts when the transmitter sends an ATIM packet on the control channel. This packet contains the selected channel and queue status of the transmitter. If the receiver agrees on the selected channel, it responds with a ATIM-ACK and then it waits for the beginning of the DATA window. Finally, the sender confirms the channel selection broadcasting an ATIM-RES frame on the control channel. Hence, cognitive users that overhear ATIM packets estimate the opportunistic traffic load on each channel and stocks this value in the Secondary users Channel Load (SCL) vector. When a user wants to start a communication, it selects the channel with the lowest SCL value.

B. Spectrum allocation in DSA algorithms

In DSA protocols the utility function is often made up of two components: a reward and a price. The reward describes the gain achieved by a certain node when choosing a particular channel, the price represents the cost that this choice implies for the overall network.

For instance, *GMAC* [33] is a game theoretic DSA protocol that exploits a function to maximize overall network throughput by limiting transmission power. Nash equilibrium is achieved through a distributed recursive game.

In [31] the authors propose different centralized and distributed strategies that optimize system throughput and fairness while minimizing interference. Frequency assignment is based on a graph coloring algorithm and the cognitive network is represented as a Node Contention Graph (NCG, see section II). Authors define a graph $G = (U, E_C, L_B)$ where U is the set of users sharing the spectrum, L_B represents the channel availability list at each vertex, and E_C the edges set modelling the interference constraints. For instance, given $u, v \in U$, if u, v interfere when using simultaneously a channel m, m is an element of E_C, and an edge labelled m is present between u, v. Figure 12 illustrates an example of a graph obtained according to this representation. In the proposed schemes channels assignment follows the order of the nodes that mostly contribute to maximize system utility.

Double Hopping (DH) [32] is a DFH scheme that proposes a distributed algorithm to generate a hopping pattern that minimizes the number of used frequencies. Maximizing the number of used channels for a transmission would reduce the interference to primary users. However, this may lead to channel overassignment and the system would not be able to guarantee QoS to secondary users. In [32], frequency assignment is again based on a graph coloring algorithm. Authors consider a scenario in which several CR cells contend the access to spectrum medium. Each cell consist of a BS and a number of associated terminals. The network is represented by an interference topology graph $G = (V, E)$. The elements of the set $V = \{v_1, ..., v_n\}$ are the cognitive cells and E is

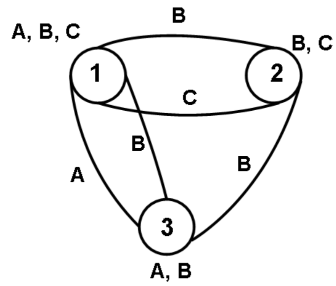

Fig. 12. A NCG representation of channel availability and interference constraints according to the model defined in reference [31].

the set of interference relationships between network cells. Additionally, the set of the neighbouring cells N_i is defined for each cognitive node i.

In order to generate hopping patterns, authors model the problem as an Integer Linear Program (ILP) and they present a centralized Optimal Frequency Assignment (OFA) algorithm that minimizes the number of used channels. Furthermore, they propose a distributed sub-optimal approach named as Distributed Frequency Assignment (DFA), which is based on the *Distributed Largest First* (DLF) [51] strategy. Accordingly, the order in which nodes choose channels depends on their interfering degree: a cognitive user does not choose its channel until it receives the decision of its neighbours with higher degree. While OFA scheme slightly outperforms the sub-optimal approach in terms of used channels, DFA computational complexity is lower and it requires a constant signalling overhead, which results in a better scalability.

A distributed approach to manage with channel allocation in cognitive radio network is proposed in [37]. The *BIOlogically-inspired Spectrum Sharing* (BIOSS) algorithm is based on the adaptive task allocation model of an insect colony. In this model, each element performs its task when the associated stimuli exceeds a fixed threshold. In the proposed algorithm, the stimuli associated to each channel is the maximum allowable transmission power. Instead, the response threshold is the required transmission power to achieve QoS constraints. Hence the probability P_{ij} that a cognitive user i access to the channel j is:

$$P_{ij} = \frac{P_j^n}{P_j^n + \alpha p_{ij}^n + \beta L_{ij}^n} \tag{3}$$

where

- P_j is the maximum permissible power on channel j;
- p_{ij} is the power that meets users requirements;
- $n \geq 1$ represents the steepness of the channel selection probability;
- L_{ij} is a learning factor which influences the access probabilities according to the perceived performance history;
- α and β are positive constants;

The learning factor is updated according to the performance experienced by cognitive users:

$$L_{ij} = \begin{cases} L_{ij} - \xi_0 & j \text{ does not not satisfy QoS constraints} \\ L_{ij} + \xi_1 & \text{elsewhere} \end{cases} \tag{4}$$

where ξ_1 and ξ_0 are the forgetting and the learning coefficients, respectively. Hence, the BIOSS algorithm works as follow:

1) each unlicensed user detects the set of available channels;
2) for each channel it estimates the maximum allowable power;
3) the learning factor, the forgetting and learning coefficients are initialized;
4) cognitive user computes the access probability for each available channels;
5) according to its QoS constraints the secondary user selects the set of channels with the highest channel selection probability;
6) finally, the learning factor is updated according to (4).

The access probability increases with the positive difference between the maximum estimated allowable power P_j and the minimum required power p_{ij}. The major drawback of the proposed scheme is that users with either tight or weak transmission constraints (p_{ij}) both prefer channels with larger permissible power. On the contrary, the overall spectrum efficiency could be increased if users with weaker power constraints would select available channels with smaller permissible power.

In [30], a genetic algorithm is used to solve a distributed channel allocation/power control problem for an ad-hoc cognitive radio network. The authors of [30] extends the work presented in [52] where an island genetic algorithm (iGA) is used to deal with the channel allocation problem. Moreover, while the algorithm proposed in [52] exploits a global knowledge about the network state, [30] presents a localized version of this algorithm which reduces the signalization overhead.

The proposed cognitive radio network model consists of a set of nodes N and each node $n_i \in N$ is able to simultaneously transmit and receive on different channels. Authors define L_i^C as the set of outgoing communication links originating from n_i and any node within its range of interference. Then, given a channel $l_{j,k} \in L_i^C$, $H_{j,k}^i$ and $Q_{j,k}^i$ are the set of the available channels and the set of the available power level for the link $l_{j,k}$, respectively. Finally, hq_i is the channel-power level assignment vector, where $hq_i \in \times(H_{j,k}^i \times Q_{j,k}^i)$. Hence, each user n_i try to optimize the fitness function

$$\max_{hq_i \in \times(H_{j,k}^i \times Q_{j,k}^i)} \left[f(hq_i) = \sum_{l_{j,k} \in L_i^C} \left(\frac{w_{j,k} \cdot p_{j,k}}{1 + | L_{j,k}^{hq_i} |} \right) \right], \tag{5}$$

where $w_{j,k}$ and $p_{j,k}$ are the bandwidth and the power assigned to the link $l_{j,k}$, respectively. $|L_{j,k}^{hq_i}|$ is the cardinality of the set of links that belong to L_i^C and can not be active at the same time as link $l_{j,k}$ under the assignment hq_i. In order to find the solution of equation (5) a genetic algorithm is implemented. Each node generates its initial population, consisting of M individuals. Each element of the population randomly allocates a channel-power level hq_i to each link $l_{j,k} \in L_i^C$. Hence, (5) is computed for each individual then, based on a parameters called as *keep rate*, the worst *[(1-keep rate)*M]* elements are eliminated and the remaining *(keep rate*M)* elements are selected to perform crossover and to generate

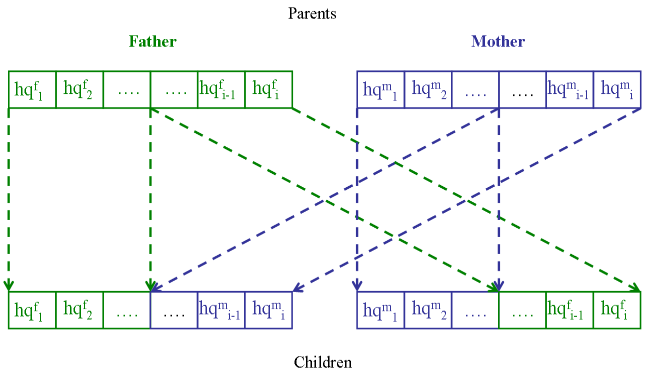

Fig. 13. One point crossover operation in [30].

new individuals. In order to perform crossover, first a triplet of parents is randomly selected, then the couple of parents with higher values of (5) exchanges part of their set hq_i. The crossover process is illustrated in Figure 13. Hence mutation is performed: according to the *mutation rate*, each element of the population, excluding the one with the best fitness, replaces part of values in hq_i with randomly selected couple of channel-power levels. Furthermore, after a fixed number of iterations (the migration interval) each node share hq_i values of its best individual with all the nodes within its interfering range. If the received information gives better fitness, it is included in all individuals of the node, otherwise the node merges the received data with only a part of its population. Finally, the implementation of the algorithm stops after a fixed number of iterations. The proposed localized iGA algorithm reduces the signalling overhead and computation cost in each node, hence it is more scalable; it needs, however, a larger number of iterations to converge.

In [25], authors investigate opportunistic spectrum access in a cluster-based mesh architecture. The presented COgnitive Mesh NETwork (COMNET) framework allows nodes within a cluster to shift working into the licensed TV bands. The goal is to equally distribute the cognitive network load between the primary and the secondary bands while limiting the generated interference. Each cluster is managed by a Mesh Router (MR), which acts as an access point for Mesh Clients (MCs) of its cluster. The region in which the mesh network operates is represented as a grid. MRs share information about the mesh network state (number of clients and positions of their access points) and the output of sensing stage (occupied primary channels) to estimate the interference generated by the mesh network at the center of the grid blocks. Hence, each MR autonomously selects the set of clusters that are allowed to shift into the free part of the licensed band and finds operating frequencies. All MRs have the same constraints and inputs, hence, they independently arrive at the same solution. This optimization problem is modelled as an Integer Linear Program (ILP) where selection is made in such a way as the total interferences in the primary band is limited. Furthermore, the mesh load is equally divided into the ISM and the licensed bands.

V. Dynamic spectrum sharing

The MAC spectrum sharing functionalities face the problem of coexistence between heterogeneous users accessing the radio resource. Typically, primary users are licensee owners of the spectrum resource and opportunistic users should not interfere with their transmissions. In [53], three different cognitive transmission access paradigms are presented: underlay, overlay and interweave. In underlay transmissions, secondary users are allowed to *operate while* generated interference stays below a given threshold. Due to the associated interference constraints, the underlay technique is mainly useful in short range communications [54]. In 2003 the FCC defined the *interference temperature* [55] as a way to measure and limit the interference perceived at primary users. However, implementation of this model results in poor performance compared to the amount of generated interference it can cause to primary users. Hence, this model has been abandoned by the FCC in 2007 [56]. In overlay transmissions, cognitive users exploit the knowledge of non cognitive user messages to either cancel or mitigate interference at both primary and secondary users side. In interweave transmissions, opportunistic radios transmit only in spectrum holes; if during in-band sensing a secondary user detects a licensed one, it vacates its channel to avoid harmful interference.

Contentions between secondary nodes can be avoided through coordinated access both in centralized (see, for instance IEEE 802.22 [57], [26]) and distributed architectures [18]. When coordination is absent, a random approach could be exploited to contend for access to available channels (see for instance [20], [44]). Otherwise, opportunistic users may exchange signalling messages in order to reserve the access to a data channel ([15], [28]). The control handshaking mechanism, however, does not completely solve the hidden terminal problem, hence the busy tone scheme is often exploited to prevent hidden nodes ([20], [34]).

A. Interweave Spectrum Access

Due to the lack of information on primary receivers, nowadays most of cognitive radio protocols are developed according to the interweave transmission paradigm. Secondary users avoid contention with incumbent primary nodes by performing periodically sensing on the occupied channels. If an incumbent is detected, the channel is vacated, transmission is interrupted, and a communication link is set up on a different channel.

In IEEE 802.22 [57] self coexistence of neighbour WRAN cells is realized with the *Coexistence Beacon Protocol* (CBP): at the end of each MAC frame, during a self-coexistence window, BSs transmit a beacon which permits communication and synchronization within a community of cells. The BSs receiving this beacon can schedule their transmissions in non-overlapping slots and avoid neighbour interference.

In the DFH proposition for IEEE 802.22 [26] the coordination of a DFH Community is realized by transmitting a broadcast announcement message (BSANN) on a Communication Management Channel (CMC). This message contains information about the state of the BSs, a list of neighbours, hopping channel list, and priorities. Each community leader periodically exploits the received information to update the community channel hopping pattern. Then, the leader broadcasts the new pattern to its community members. A DFH community can be rearranged by a leader in order to:

- reduce the number of used channels,
- reduce interference between neighbour communities,
- reduce communication overhead within a community.

In particular, a leader can:

1) permit to a community member to shift from one community to the others;
2) split its community and select two new leaders;
3) merge two communities in a new one.

Coexistence between neighbour communities is dealt through the BSANN messages that are exploited to mark used channels as occupied and avoid contentions.

In C-MAC [18], each terminal is requested to periodically broadcast a beacon during its BP. Each node receiving this beacon retransmits the embedded data by adding its own information about channel occupancy and the state of the network. In such a way, radios can coordinate the access and exploit information about the neighbours of their neighbours. This strategy overcomes the multiple channel hidden terminal problem, while increasing network overhead, which affects C-MAC scalability.

Another approach is proposed in the Dynamic Open Spectrum Sharing (DOSS) [20] that is a direct contention based DAB protocol. A data band, a control channel, and a busy tone band are exploited to manage communication, signalling, and contention, respectively. Spectrum negotiation is managed with a request to send/clear to send (RTS/CTS) handshake. A mapping rule is proposed to match the narrow band busy tones and the wide band data channels. Overhearing the busy tones, each node is aware of its neighbours communications and hidden/exposed terminal problems are avoided. DOSS effectiveness is impaired by the need for multiple transceivers and two separate bands to manage busy tones and common information exchange. Moreover, by increasing the allocated bandwidth, the probability that a primary user may be interfered increases: for instance, a data channel could be idle although its corresponding busy tone channel is unavailable.

Most DSA MAC protocols suffer from scalability issues. In large cognitive radio networks, it is necessary to limit the number of cooperating users to minimize overhead and delay of the optimization process. In the game theoretic DSA-driven framework presented in [34], the authors propose to introduce a clustering algorithm to overcome these issues and to achieve coordination among the game players. Moreover, a collision avoidance mechanism is proposed to protect the negotiation reliability from inter-cluster interference. Hence, four are the main components in this protocol:

1) the game;
2) the clustering algorithm;
3) the collision avoidance algorithm;
4) the negotiation mechanism.

Interactions among cognitive radios are modelled as a repeated game $\Gamma = \langle N, \{S_i\}, \{u_i\}, T\rangle$. N is the set of game players, where a game player represents the sender-receiver pair; S_i represents the strategy space (transmission parameters) of player i; u_i is the local utility function that player i wants to maximize; T is the players decision time indicating the time at which each radio can update its strategy. This clustering algorithm is geographical-position based. Each cluster is represented by a hexagon and identified by a cluster ID that depends upon the hexagon center coordinates. Arrivals and departures are handled with a *virtual header* mechanism. In this approach, the header of a cluster is not a node but a cluster-unique packet that is named virtual header. After a CR node chooses its cluster, it broadcasts its cluster ID and coordinates. Hence, each node obtains all the information about its neighbours. The proposed clustering algorithm is scalable, distributed and independent of the used DSA strategy. Collision avoidance mechanism is cluster-based and it exploits two busy tones to avoid interference and overcome exposed and hidden terminal problems:

1) *inside-cluster busy tone* (BT_i) is transmitted by the node that receives a message to prevent nodes outside its cluster to interfere.
2) *outside-cluster busy tone* (BT_o) is forwarded by the node that overhears the inside cluster busy tone to indicate that it is interfered by nodes belonging to a neighbour cluster. In such a way, the overhearing node prevents nodes within its cluster to communicate with it.

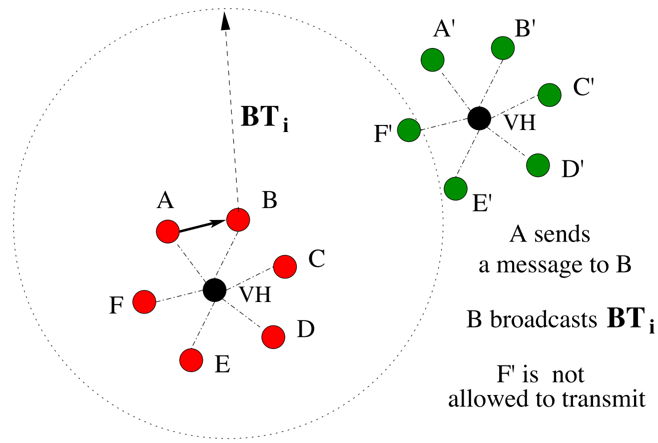

Fig. 14. The BT_i collision avoidance mechanism according to the game theoretic DSA-driven protocol [34].

Figure 14 and 15 represent the BT_i/BT_o collision avoidance mechanism.

Negotiation mechanism manages the control messages exchange and permit node synchronization during the game. This process is divided into two successive stages: the inquiry stage and the formal negotiation stage. In the first stage, each node within a cluster is queried of its intention to communicate by a token packet generated by the virtual header. At the end of the inquiry stage, the information collected by the token is exploited by game players to construct the game set and the strategy space. The advantages of a token based strategy is that it minimizes inter-cluster interference, and avoids intra-cluster interference during the negotiation process. Hence, during the formal negotiation stage, a negotiation token, which carries the dynamic game information is passed around the game players to update their local strategy. The process continues until the game converges to a Nash equilibrium.

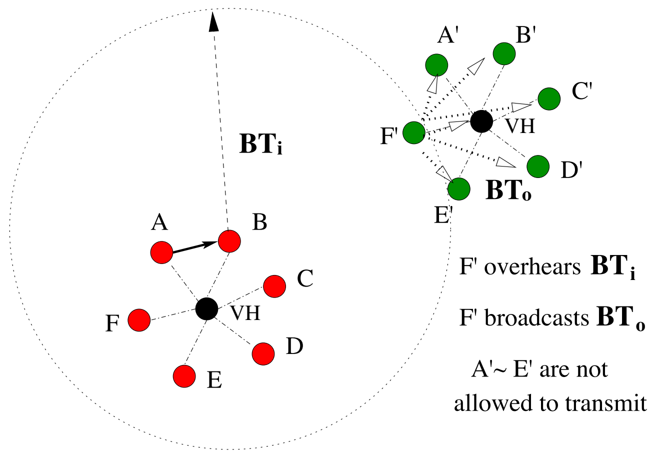

Fig. 15. The BT_o collision avoidance mechanism according to the game theoretic DSA-driven protocol [34].

In [15], the authors propose a MAC protocol which permits a secondary ad-hoc network to coexist with a primary network. Two sensing policies are exploited in order to enhance spectrum opportunities detection (see III-C). Moreover, the *p-persistent* Carrier Sense Multiple Access (CSMA) [58] protocol is used to manage reservation within secondary users. Negotiation is realized on the dedicated control channel which is licensed to the cognitive network. Each licensed channel is time-slotted and primary and secondary networks are synchronized. In the control channel, the slot is divided into two phases: the reporting and the negotiating phases. After the reporting phase each cognitive users is aware of the licensed channels that have been sensed idle by the nodes within its network. Then, secondary users with a non-empty queue negotiate the access to the overall set of available channels. Contention is managed during the control channel negotiating phase. In particular a sender listens to the control channel until it becomes idle. Then, it transmits a RTS packet with probability p. When the cognitive user successfully receives a CTS packet, it gets the reservation of all the available channels in order to transmit data in the next time slot. While the medium access scheme proposed in [15] is a simple procedure, which profits from the cooperative detection benefits, it can not guarantee fairness to the network opportunistic users. However, the scheme which would permit synchronization between primary and opportunistic networks is not investigated.

In [19] a cognitive MAC protocol for 802.11s wireless mesh networks is proposed. In this protocol, a mesh entity called as *cognitive extended service set* is defined. This entity can be either a Mesh Point (MP) or a Mesh Access Point (MAP). Moreover, Cognitive MP (CMP) and Cognitive MAP (CMAP) are defined as MP and MAP with opportunistic capabilities. While MP and MAP are able to operate only on the ISM band, CMP and CMAP can exploit also the licensed band. The licensed band is used by cognitive nodes to exchange data, while control signalling and transmission with non-cognitive nodes are realized on the ISM band. In this contention based protocol, cognitive users exploit two transceivers, which are dedicated to the control channel (ISM transceiver) and to data transmissions (non-ISM transceiver), respectively. After the sensing process, each cognitive node select a *long-term residency channel* (LTRC) and it tunes its non-ISM transceiver on this channel. Then, in order to inform all its next-hop neighbors, it transmits a channel switching (CHSW) frame on the control channel. Hence, when a cognitive source entity (CSE) wants to initiate a communication with one of its next-hop neighbours, due to the fact that it already knows the destination LTRC, the channel negotiation phase can be avoided. Therefore, the CSE transmits an *eRTX* on the control channel indicating the receiver identity and its LTRC. This message permits to reach two important goals: first, the sender asks the receiver to establish a link layer connection, then it informs its neighbors about the on-leave situation and the corresponding absence time duration. When the Cognitive Destination Entity (CDE) correctly receives the *eRTX* message, it responds by sending an *eCTX* on its LTRC. Otherwise, when the CSE has an incorrect a priori information about the CDE's LTRC, the receiver transmits the *eCTX* on the control channel, hence the sender can adjust its information and re-transmit the *eRTX* to avoid the distribution inconsistent information within the network. Upon reception of *eRTX* all neighbors of the sender are informed about the time period during which the CSE will not be present on its LTRC. Hence, those nodes that have already initiated a backoff cycle in order to start data transmission to the switching entity suspend the counting down until it will come back on its LTRC. The algorithm proposed in [19] limits the use of the control channel and allows reducing the possibility of saturation. Moreover, in comparison to the classic 802.11s it is more robust with respect to the hidden terminal problem, and reduces the resource wastage.

A frequency hopping DAB protocol for a multi-hop cognitive radio network (MHCRN) is proposed in [27]. This protocol, named Synchronized MAC (SYN-MAC) avoids the exploitation of a common control channel to overcome its inherent drawbacks (see section II). Each node is equipped with two radios: one dedicated to control signal exchange and the other to data transmission. Nodes divide each frame in N slots each one assigned to a different data channel. During the network initialization state, at the beginning of each time slot, nodes broadcast a beacon in all available channels to exchange information about channels set and to synchronize their radios. When this phase is completed, nodes that are not involved in transmissions, continuously listen their channel set to:

- detect primary users,
- receive signalling information,
- avoid the multi-channel hidden terminal problem.

When a node wants to transfer data, it first chooses one of the channels that it shares with the receiver. Then it waits for the time slot representing the selected channel, and starts a negotiation process similar to the IEEE 802.11 DCF [49].

While the proposed strategy has the advantage of avoiding a common control channel and solving the hidden terminal problem, it does not offer fast protection of primary users since their detection is notified to neighbours only in specific slots. Moreover, available channels are not efficiently exploited since they can only be used in one slot per frame.

On the contrary, HC-MAC [14] deals with medium access without requiring global synchronization or coordination among secondary users. The whole time frame consists in three phases: contention phase, sensing phase, and transmission phase. Secondary users contend the access in both control and data channel. During a contention window three packets are sent on the common control channel ch_0:

1) C-RTS/C-CTS are used to start the handshake of the sender-receiver pair and to inform neighbours that the common channel is busy,
2) S-RTS/S-CTS are used by sender and receiver to exchange the sensing process outcome,
3) T-RTS/T-CTS notify the end of the transmission process.

A node, wanting to transmit, waits a backoff period and then sends a C-RTS on ch_0. The receiver replies with a C-CTS on the same channel. Neighbours which overhear this packet defer their transmissions and wait for the S-RTS/S-CTS messages. After the handshake, sender and receiver are synchronized and sense each channel for the same amount of time. CFSR handshake is performed with the S-RTS/S-CTS exchange and permits the cognitive pair to agree on channel availability and to select the band where to communicate. After finishing transmission, the sender broadcasts the T-RTS and the receiver replies with the T-CTS: this packet exchange starts the next round of contention.

In order to reduce hardware costs, HC-MAC users are equipped with a single radio. The half-duplex radio, and the absence of a global synchronization, drive, however, to the multiple channel hidden terminal problem, which can cause collision during the transmission phase. Furthermore, a cognitive user may probe a channel where a hidden cognitive terminal is transmitting resulting in a false alarm event: authors refer to this problem as the *sensing exposed terminal problem*.

In a distributed CR ad-hoc network, it is desirable that nodes share a reliable control channel to provide the exchange of signalling information and to permit resource negotiation. Channel availability depends, however, on location and momentary conditions, and often a global control channel does not exist in the network. HD-MAC [22] adopts a distributed coordination scheme in which nodes self organize into local groups. Members of each group form a multi-hop network where a local common channel is exploited to realize coordination and communication. After neighbour discovery, each device shares its channel availability list and a common channel is elected through a voting process as the coordination channel. Only nodes into the same group can directly communicate with each other. Inter-group connection is realized through nodes located at groups boundaries: these nodes subscribe different coordination channels and act as *bridges* (see Fig.16).

Each user is equipped with a half duplex radio and time is organized in superframes. Each frame is composed by a BP, a coordination window (CHWIN), and a data transmission period. During the BP, two kinds of beacons are transmitted within the network: a global beacon and a group beacon. Each node broadcasts the global beacon over all its available channels to discover new users while the group beacon is transmitted within its group to permit coordination and exchange information about neighbour discovery. During CHWIN users negotiate access to data channels. Additionally, in order to easily implement connection among neighbour

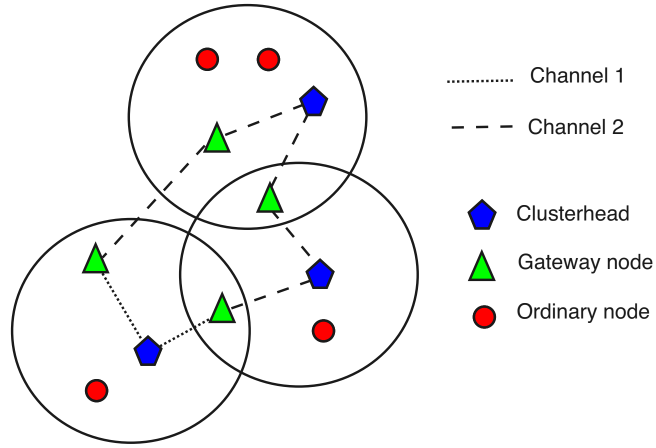

Fig. 16. Multi-hop cognitive network clusters connected by gateway nodes [21].

groups, HD-MAC divides *bridges* CHWIN structure in several slots, one for each coordination channel.

A decentralized MAC protocol for a CR based mesh network (CogMesh) is proposed in [21]. In CogMesh, a node forms a cluster on a particular channel and invites adjacent nodes sharing the same channel to join its cluster. The cluster leader and the common channel are named clusterhead and masterchannel, respectively. Clusterhead is responsible for intra-cluster channel access control and intra-cluster communication. Intra-cluster communication is realized through gateway nodes that act as *bridges*, as in [22]. The proposed MAC consists in a guaranteed access period to manage data transmission and a random access period to manage control message exchange. Channel access time is divided into super frames consisting of five periods (see Fig. 17). The beacon period is exploited by clusterheads to broadcast signalling information (resource allocation, synchronization, control messages, etc). The neighbor broadcast period is divided into mini slots in which each cluster node shares information about itself and its 1-hop neighbour list. During the data period, a TDMA approach is used to manage data communication. A quiet period is scheduled to quiet nodes within a cluster and realize spectrum sensing. The super frame is ended with a private RAP (random access period) and a public RAP which are used to manage intra-cluster and inter-cluster communications, respectively. Cluster formation, merging and termination processes are addressed in the proposed protocol. Eventually, a spread spectrum technique is proposed to realize the coexistence between different clusters and avoid the multichannel hidden terminal problem.

While both the strategies proposed in [22] and [21] address the global control channel problem, several problems still remain. In particular, network topology is affected by the presence of primary users, and the overhead due to continuous cluster set up may be critical. Moreover, HD-MAC suffers from the multiple channel hidden terminal problem.

The concept of *cognitive cloud* is introduced in [59] to represent clusters dynamic size changes in a CogMesh network. A cloud is a cluster that grows to cover as many secondary users as possible. Neighbours negotiate a common masterchannel to form fewer and larger clouds in order to simplify the exchange

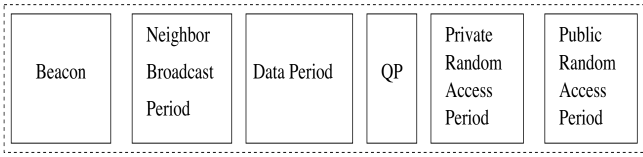

Fig. 17. CogMesh MAC superframe [21].

of signalling traffic through the network. A swarm intelligence approach is exploited to let nodes select as masterchannel a channel with sufficient quality, meanwhile being preferred by most neighbours. While this approach decreases the overall system overhead, it may, however, impair the reliability of transmitted control data: for instance, this may be unacceptable in a cooperative sensing scenario.

The Opportunistic Spectrum MAC (OS-MAC) [29] is a coordination based DAB protocol for CR ad-hoc networks. As in [21] and [22], cognitive users self organize in clusters to manage the access in both licensed and unlicensed spectrum. Each Secondary Users Group (SUG) is formed by a set of users which want to communicate with each other. The group leader is indicated as Delegate SU (DSU). DSUs acquire information about DCs traffic load and share this information within their SUG. In the OS-MAC, the authors suppose the existence of a global Common Channel (CC) which is used to perform clustering operation, and also to realize inter-cluster signalling exchange. Intra-cluster communication, on the contrary, is performed on the Data Channel (DC) selected by the cluster.

Secondary users are equipped with a single half-duplex transceiver; hence, they are not able to transmit and receive on different channels in parallel. At any time, in each SUG, only one node is allowed to broadcast data within its cluster. Nodes within a SUG which have buffered data contend the access to the DC using the IEEE 802.11 DCF access mode [49]. Moreover, in order to limit the channel load, only one receiver will acknowledge the message reception.

The OS-MAC divides time into periods which are named as Opportunistic Spectrum Periods (OSPs). Each OSP is further split into three phases: the Select Phase, the Delegate Phase, and the Update Phase. At the beginning of the OSP, each DSU transmits DCs traffic load information acquired in the Update Phase of the previous period. Then, during the Select Phase, based on this traffic information, the SUG selects an available DC. During the Delegated Phase, the first node which successfully delivers a message is elected as DSU. Finally, in the Update Phase, the DSU hops to the CC to inform other DSUs of its DC traffic load while nodes within its cluster continue to access to the DC. In order to reduce inter-cluster interference, the OS MAC implements a probabilistic channel selection mechanism which reduces the probability that different SUGs choose the same DC.

The main drawback in OS-MAC is that spectrum sensing and spectrum mobility functionalities are not addressed. Hence, a mechanism to protect licensed transmissions is not implemented. Furthermore, while the proposed inter-cluster information exchange scheme produces negligible overhead during the Update Phase, the CC may be mostly unused during the Select and the Delegate phases.

B. Underlay Spectrum Access

One of the few MAC protocols which exploit the underlay approach is the COMAC proposed in [28]. COMAC permits cognitive users to exploit licensed band while limiting the generated interference. However, in order to exploit the available spectrum more efficiently, COMAC does not assume any predefined power mask. The proposed mechanism ensures that cognitive transmissions do not harm licensed users with probability 1-β. More specifically, each secondary node determines the maximum transmission power over various channels such that primary receiver outage probability (P_{out}) is guaranteed to be below a constant β. Authors consider a scenario in which M primary networks coexist within the same geographical space of a secondary network. A stochastic model is proposed for the aggregate interference within each primary network and for the primary to secondary interference. The proposed model assumes that:

1) primary users are randomly located according a Poisson distribution;
2) the interference contribution to a generic opportunistic user is limited to all the active transmitters within a disk of radius r_c and centred at the cognitive receiver;
3) The M primary networks operate over M orthogonal bands;
4) There is a minimum distance between a primary receiver and the closest primary interferer within its network;
5) A channel occupied by a cognitive user cannot be simultaneously assigned to another secondary user in its vicinity. Hence, interference measured at a licensee user is mainly due at most one cognitive node.

Authors derive a close-form expression for the variance and the mean value of the two interferences. Furthermore they show through simulation that a lognormal function well approximates the distributions of these interferences. Hence, to guarantee primary users QoS, each cognitive user computes the upper bound on the transmission power which can be used on each licensed band. Each transmission power $P^{(i)}_{C,\beta}$ should satisfy the following condition:

$$P^{(i)}_{PR-PR,j} + g^{(i)}_{C,j} P^{(i)}_{C,\beta} \leq P^{(i)}_{L}, \tag{6}$$

where $P^{(i)}_{PR-PR,j}$ is the aggregated interference measured at the *jth* primary user generated by the transmitters within its network, $g^{(i)}_{C,j}$ is the gain between the cognitive user and the *jth* primary user and $P^{(i)}_{L}$ is the *interference power limit* of a user in the *ith* primary network. The $P^{(i)}_{L}$ value can be computed by the interference temperature limit which provides a metric for measuring the interference experienced by PR users. Following the methodology proposed in [60], the $g^{(i)}_{C,j}$ value is estimated based on the shortest distance between a primary receiver and cognitive transmitter. The proposed stochastic approach permits to mitigate interference perceived at primary users. However, contentions between secondary users are managed through a distributed CSMA/CA protocol. Signalling messages are transmitted over a specific control channel that is managed by a dedicated transceiver. In COMAC, each cognitive user A maintains a list *LAC(A)*, which consists of the data channels that are not currently used by A's cognitive neighbours. A transmission region is associated with each channel within *LAC(A)*: this region is the area where transmissions sent over selected channel can be correctly decoded. The transmission range of channel j depends on its SINR (signal to noise plus interference ratio) and is defined by its radius a_j. In order to limit the hidden terminal problem, COMAC requires the following constraint on the transmission range (r_{ctr}) of the control channel region:

$$r_{ctr}(A) \geq 2 \max_{j \in LAC(A)} a_j. \tag{7}$$

This constraint reduces the probability that cognitive neighbours may transmit over the same channels. Channels negotiation is managed with a sender-receiver handshake. Suppose that user A has data to transmit to user B at rate R_a. If A senses idle the control channel for a randomly selected back-off period it sends a RTS to user B. This packet contains *LAC(A)*, $P_{ctr}(A)$, $P^{(i)}_{C,\beta}(A)$ and the selected rate R_a. RTS refrains A neighbours to access on the control channel and permit to user B to check whether or not there exists a set of channel $\Omega \subseteq$ *LAC(A,B)* that supported the request traffic constraint. If it exists, B sends a CTS packet which includes the Ω set and the duration of the transmission T_{data}. CTS message refrains the receiver's neighbour to transmit to the channels within Ω during data transmission. Finally A responds with a *Decided-Channel-To-Send* (DCTS) message, which informs its neighbours about Ω and T_{data}, and then, it starts the transmission.

While this scheme permits parallel transmissions to take place in the same vicinity, multichannel hidden terminal is not completely solved due to possible collisions on the common control channel within neighbours users transmissions. Furthermore, as previously underlined, interference temperature implementation typically results in poor performance, hence, investigation of new interference metrics should form object for future research.

In [61], authors propose two *Detect and Avoid* (DAA) algorithms that mitigate the interference generated by an Ultra-wideband (UWB) network on UMTS and WiMAX systems. In DAA cognitive users implement the underlay paradigm through three operating modes: ranging, ordinary, and hold-off. During the ranging stage, UWB nodes perform all the signalling exchange, which is necessary to create a network. In the ordinary mode, users transmit data on a Time Division Duplex (TDD) basis. Secondary users can operate at a standard power W_a or at a limited power W_{prot}. W_{prot} is computed as the power which does not generate harmful interference to a primary user which is in the proximity of a secondary UWB terminal. Two time-out periods (T_{off} and T_{out}) are exploited to adapt power transmission to sensing results. During the hold-off stage cognitive nodes are idle in order to permit incumbent primary users to perform their first access to the primary network without being impaired by opportunistic users.

Coexistence with UMTS networks

UMTS networks operates in Frequency Division Duplex (FDD) mode. Hence, opportunistic UWB nodes periodically sense the uplink transmission to detect primary users presence and hence, they adapt their transmission power to mitigate interference generated toward the UMTS Base Station (BS).

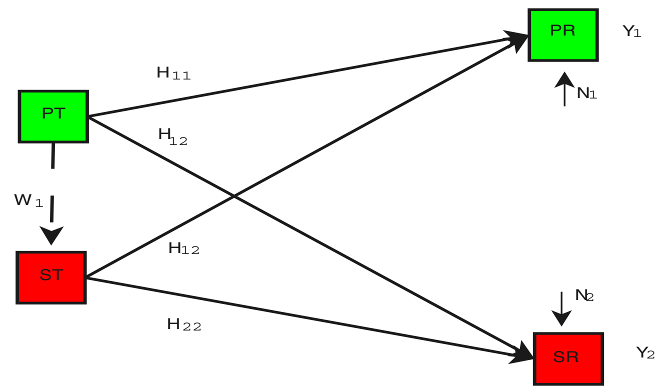

Fig. 18. Overlay interference model [54]. PT, PR, ST, and SR represent the primary transmitter, the primary receiver, the secondary transmitter and the secondary receiver, respectively. Dashed curve represents the a-priori knowledge of primary message W_1 at the secondary transmitter.

When the power measured in the primary band (P_m) is greater than a certain threshold (P_{thr}), UWB users are constrained to limit their power to W_{prot}. Otherwise, when opportunist nodes do not detect primary users for a time longer than T_{out}, the system supposes that there are not active UMTS terminals in the vicinity. Consequently UWB terminals are allowed to transmit with a power W_a.

Coexistence with WiMAX networks

Unlike UMTS, WiMAX terminals operate in TDD mode. Hence, subsequent frames are allotted for uplink and downlink transmissions. Two time-out periods are defined to efficiently operate in this scenario, T_{out} and T_{off}. When $P_m \geq P_{thr}$ a WiMAX terminal is assumed to transmit in uplink, thus the opportunistic node can set its power to W_a and it accesses the sensed band. Otherwise, when opportunist nodes do not detect primary users for a time longer than T_{out}, the system supposes that a WiMAX downlink transmission is active. Consequently UWB terminals are obliged to limit their power to W_{prot}. Furthermore, when primary transmissions are not detected for a time longer than T_{off} it is assumed that are not active primary users in the vicinity and, hence, transmissions are allowed at W_a.

C. Overlay Spectrum Access

In [54] the overlay access paradigm is investigated and this approach is compared with the classical interweave access. The assumption of the overlay model is that the secondary transmitter has a-priori knowledge of the primary user's message. Furthermore, all channel gains are known to both transmitter and receiver. The overlay model is represented in Figure 18. Two underlay strategies are suitable at the cognitive transmitter accessing the licensed spectrum: The *selfish* approach and the *selfless* approach. In the former strategy, the secondary transmitter uses all its available power to transmit data to the secondary receiver. Furthermore, the transmitter exploits the knowledge of the primary transmitter's message to null the interference at the secondary receiver side (i.e. using the dirty paper coding strategy [62], [63]). In the selfless strategy the secondary transmitter uses part of its available power to relay the primary transmitter's message to the primary receiver. The remaining power is exploited to transmit data to the secondary receiver. The power distribution is calculated to guarantee SINR constraints at the primary receiver. Moreover, the cognitive transmitter precode its data message to null interference at the cognitive receiver. The overlay technique has the further advantage to avoid primary hidden terminal interference because neighbour primary transmitters are allotted on orthogonal frequency bands. Simulation results presented in [54] show how the underlay technique can potential outperform the achievable secondary network throughput with the interweave technique. However, as the knowledge of the licensed user message can be available at the cognitive side only if the two transmitters are located in close proximity, the overlay performance gain is strongly affected by this distance. Moreover, complicated precoding techniques must be available at the cognitive transmitter, and cooperation between primary and secondary systems is necessary to estimate channel gains between transmitters and receivers.

VI. Dynamic spectrum mobility

In wireless licensed scenarios, channel availability and quality change with space and time. Cognitive radios coexist with primary users and interfering secondary users that dynamically access multiple channels. When a licensed user is detected, to realize seamless transmission, a cognitive radio vacates its channel and reconstructs a transmission link on a different channel. The procedure that permits this transition from a channel to another with minimum performance degradation is called *handoff*.

MAC scope is to design spectrum mobility to reduce delay and loss during spectrum handoff. The mobility management functionalities should be aware of the running applications and adapt to QoS constraints. For instance, FTP traffic requires tight constraints on packet error rate: a retransmission protocol should be implemented to refrain from outage. Voice communication permits, however, a maximum delay for the channel handoff of 150 ms to avoid call interruption. In presence of collisions or sensing errors, the receiver should follow the transmitter in a new available channel: secondary pair tight time and frequency synchronization is required for successful communication in a cognitive radio network.

IEEE 802.22 [57] and C-MAC [18] deals with the spectrum handoff with the Incumbent Detection Recovery protocol (IDRP). The IDRP allows the network to restore its normal activity maintaining an acceptable level of QoS. This procedure exploits a backup channel list that permit to reconstruct the communication link. In order to limit signalling and delay, the sender-receiver pair knows in advance where to restore their services if an incumbent is detected. Backup channels are identified by means of out-of-band sensing. Available channels are kept in a priority list used by devices during the recovery procedure. Users transmitting on the same channel share the same priority list to minimize signalling and rapidly recover communications.

In [8], spectrum mobility issues for a Cognitive Radio Ad Hoc Network (CRAHN) are discussed. Two different strategies are presented: proactive spectrum handoff and reactive spectrum handoff. In proactive strategies, users, while communicating, predict events such as mobility and channel quality degradation that could cause handoff. Meanwhile they search new spectrum bands where rapidly switching and minimizing performance losses and delay. Proactive sensing requires, however, complex algorithms in order to estimate network behaviour, and two radios to perform out-of-band sensing and transmission in parallel. Reactive strategies need rapid channel switching without any preparation and cause performance degradation due to high handoff delays. Reactive handoff is realized when unpredictable events, such as the primary user appearance, occur, or in those cases where devices can not afford proactive handoff due to energy or hardware constraints.

In [64], a fuzzy-based distributed strategy is proposed to limit the spectrum handoff event. This algorithm is realized through two Fuzzy Logic Controllers (FLC); cognitive radio is assumed to be able to evaluate, by means of spectral estimation techniques, the primary user bit rate and consequently its SNR (SNR_{PU}). FLC 1 takes as inputs SNR_{PU} and the signal strength from the primary user to the secondary one (SS_{PU}). Then, FLC 1 estimates the distance between primary and secondary users, and selects the allowed power for the cognitive radio. FLC 2 is in charge of taking decision about spectrum mobility. Spectrum handoff is initiated if the secondary user is in outage, or if its transmissions harmfully interfere with a primary user. In order to avoid spectrum mobility, cognitive radio power can be modified by trying to reduce generated interference. Reducing transmission power drives, however, a decrease in the secondary user transmission reliability, and a cognitive user could still decide to perform handoff.

In [43], a sensing-sequencing algorithm that minimizes the *channel-switching latency* (CSL), is proposed. The CLS is defined as the delay due to discovering of the first opportunity since the cognitive user has to vacate its channel. Authors propose to model channels as ON-OFF alternating sources and accordingly, they estimate the probability that a channel i would be idle (P_{idle}) at a certain time t based on its sensing history. Hence, the presented scheme proposes to compute P_{idle} for each licensed channel except the channel that has been vacated. Therefore, the optimal strategy is to sense channel according the descending order P_{idle}. Furthermore, when no channels have found to be idle authors recommend to avoid an instantaneous reply of the searching algorithm. A more energy-efficient strategy should consider a time T_{retry}, after which searching again for an idle channel.

VII. Conclusions and future lines of research

A comprehensive overview on MAC protocols state of art for cognitive radio network was presented. Spectrum sensing, resource allocation, spectrum sharing and spectrum mobility, were introduced and critically discussed. Table III synthesizes the analysed MAC protocols main features. The first column of Table III indicates MAC protocols names; according the taxonomy presented in Section II, the second column indicates the type of the protocol. The third column indicates with how many transceivers cognitive radios are equipped, and the fourth column indicates if the protocol exploits a dedicated common control channel; the fifth column describes protocol architecture, the sixth column shows if transmissions

TABLE III
CHARACTERISTICS OF ANALYSED CR MAC PROTOCOLS.

Protocol	Type	Trans.	Dedicated CC	Architecture	QP	MC-HT	Synch.
HC-MAC	DAB	1	Global	Distributed	Yes	Yes	No
IEEE 802.22	DAB	1	No	Centralized	Yes	No	Yes
C-MAC	DAB	1	Yes	Distributed	Yes	No	Yes
Ghaboosi08	DAB	2	Global	Distributed	No	No	No
DOSS	DAB	3	Global	Distributed	No	No	No
COMAC	DAB	≥ 2	Global	Distributed	No	No	No
SYN-MAC	DAB	2	No	Distributed	No	No	Yes
Su08	DAB	2	Global	Distributed	Yes	No	Yes
HD-MAC	DAB	1	Local	Distributed	Not addressed	Yes	Yes
CogMesh	DAB	1	Local	Distributed	Yes	No	Yes
DC-MAC	DSA	1	No	Distributed	Not addressed	No	No
MMAC-CR	DAB	2	Global	Distributed	Yes	No	Yes
OS-MAC	DAB	1	Global	Distributed	Not addressed	No	Yes
Zou08 [1]	DSA	1	Yes	Centralized	Not addressed	No	Yes
COMNET [1]	DSA	1	No	Centralized	Not addressed	No	Yes

interruptions are imposed during periodic incumbent detection, the seventh column indicates if the protocol suffers of the multichannel hidden terminal problem, the last column indicates if the protocol requires network synchronization.

While the cognitive principle has produced great expectation since its first appearance in [65], MAC protocol design for cognitive radio networks is still an open research field. With this paper we aim to underline some of the major issues on the domain:

- As explained in Section III, increasing the sensing time allows an increase of the number and the quality of the detected spectrum opportunities. However, in order to limit the sensing overhead, a cognitive user can observe only a limited part of the radio resource. Interestingly, only few MAC protocols implement a criterion (see, for instance [44]) to choose probing channels. Thus, this problem needs to be further investigated to improve spectrum sensing effectiveness.
- A major misconception in CR literature is that detecting primary transmitter signal is equivalent to discover spectrum opportunities [66]. On the contrary, even when primary signals can be perfectly detected, spectrum opportunities discovery is affected by three main problems: the *hidden transmitter*, the *exposed transmitter*, and the *hidden receiver*. A hidden transmitter is outside the sensing range of the cognitive sender but it is placed close to the cognitive receiver. An exposed transmitter is a primary sender that is located in the proximity of the cognitive transmitter, while the licensed receiver is outside the secondary transmitter interfering range. A hidden receiver is a primary receiver that is located in the interfering range of cognitive transmitter while the primary transmitter is outside the detection range of the cognitive users. While the hidden transmitter problem has been solved by performing spectrum sensing at both transmitter and receiver side, there are still no feasible solutions for the latter problems. In order to solve these issues, a cognitive user should be able to detect the presence of a neighbour primary receiver. In [67], the authors present a sensor which is able to locate a RF receiver measuring its Local Oscillator leakage power. However, this approach is only suitable in the detection of TV receivers [5].
- Cooperative sensing arises as a mean to greatly enhance the effectiveness of primary users detection in wireless fading channel. As stated in [47], [45] collaborative detection is, however, limited by the effects of spatially correlated shadowing. For a given SNR, a larger number of correlated sensing nodes is needed to achieve the same detection probability of few independent users. Future MAC protocols should consider correlation impact to develop more efficient cooperative sensing schemes.
- A common control channel (see section II) facilitates interaction and coordination among secondary users in a cognitive network. The common channel may however saturate when the number of secondary users or traffic load increase. Additionally, independent nodes may not observe the same spectrum availability and they may not be able to share the same channel. Additional dynamic strategies should be developed to realize a reliable exchange of signalling information, and permit synchronization within a neighbour cognitive radios.
- When an incumbent is detected, cognitive users interrupt transmission and hop in a new available channel to continue data transfer. Limiting packet loss and delay during the spectrum mobility process is a challenge. The backup channels list, introduced in [24] and [57], reduces latency and avoid performance degradation during the spectrum handoff. This solution should, however, be further investigated to increase the number of available channels and introducing QoS criteria to protect priority users.
- As explained in Section V the interference temperature model was an interesting but unsuccessful idea. Thus, in order to successfully implement the underlay transmission access paradigm new metrics that represent the performance degradation experienced by the primary system should be investigated.
- Apart from some exceptions, as [61], [68] and strategies based on *interference temperature* metric ([2], [28]), most of CR MAC protocols follow the interweave paradigm transmitting only on spectrum holes. Exploiting adaptive

modulation and coding (AMC) and power control techniques, new MAC protocols can be designed according to the underlay paradigm in order to improve the overall system capacity and efficiency. Furthermore, in order to jointly profit of the advantages of approaches presented in Section V-A and mitigate their drawbacks we believe that hybrid transmission schemes should be investigated.
- Classically, researchers have tried to develop bandwidth efficiency systems to deal with spectrum scarcity without consider the energy costs related to this approach. However, recent studies showed how scarcity is almost due to the static spectrum allocation strategies and that cognitive radio can be the way to improve the spectrum usage. Thus, *green* cognitive approaches should be investigated in order to save power consumptions, reduce interference, and improve battery life of customer's devices.
- Most of CR literature deals with opportunistic ad-hoc networks. However the impact of cognitive paradigms on cellular networks should be explored. In particular, we think that a cognitive approach is necessary to realize the coexistence of femtocells with macrocell users [69]. (Femtocells are low power access points introduced by the evolution of cellular systems to enhance indoor coverage).
- In order to optimize the radio resource management in CR networks, several DSA algorithms have been proposed (see Sections II-C and IV-B). Few MAC protocols, however, include these complex algorithms in their functionalities (see, for instance [44]). Hence, further investigations on DSA-based protocols to enhance the spectral usage in both primary and secondary network would form object for future research.

ACKNOWLEDGMENT

This work has been partially supported by the European Commission in the framework of the BeFEMTO project (ICT-FP7-248523) and by the French Agence Nationale de la Recherche in the framework of the Inter-Carnot project TEROPP (ANR 2007 P2IC 011 01).

MGDB work was supported by COST Action IC0902 "Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks", funded by the European Science Foundation and by FP7-ICT Network of Excellence ACROPOLIS - Advanced coexistence technologies for radio optimisation in licensed and unlicensed spectrum.

A special thanks goes to the reviewers for useful comments that have significantly improved the readability of this survey paper.

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