Spectrum Assignment in Cognitive Radio Networks: A Comprehensive Survey

Elias Z. Tragos, Sherali Zeadally, Alexandros G. Fragkiadakis and Vasilios A. Siris

***Abstract*—Cognitive radio (CR) has emerged as a promising technology to exploit the unused portions of spectrum in an opportunistic manner. The fixed spectrum allocation of governmental agencies results in unused portions of spectrum, which are called "spectrum holes" or "white spaces". CR technology overcomes this issue, allowing devices to sense the spectrum for unused portions and use the most suitable ones, according to some pre-defined criteria. Spectrum assignment is a key mechanism that limits the interference between CR devices and licensed users, enabling a more efficient usage of the wireless spectrum. Interference is a key factor that limits the performance in wireless networks. The scope of this work is to give an overview of the problem of spectrum assignment in cognitive radio networks, presenting the state-of-the-art proposals that have appeared in the literature, analyzing the criteria for selecting the most suitable portion of the spectrum and showing the most common approaches and techniques used to solve the spectrum assignment problem. Finally, an analysis of the techniques and approaches is presented, discussing also the open issues for future research in this area.**

***Index Terms*—channel assignment, spectrum assignment, spectrum selection, spectrum allocation, cognitive radio networks, dynamic spectrum management.**

I. INTRODUCTION

OVER the last few years, economical and technological driving forces have emerged and are expected to shape the design of future wireless networks. Everyday usage of wireless networks has increased significantly in the last decade and life without wireless devices (such as mobile phones, PDAs, smartphones, laptops etc.) seems impossible. The need for mobility and wireless connectivity has driven the widespread deployment of many wireless networks either in local areas (WiFi) or in metropolitan areas (WiMAX, 3.5G, etc.). The radio spectrum is a natural resource regulated by governmental or international agencies and is assigned to license holders on a long term basis using a fixed spectrum assignment policy [1]. This has an impact on the spectrum usage because recent measurements [2], [3], [4] have shown that for large portions of spectrum, the utilization is quite low, leading to a waste of valuable frequency resources.

To exploit the unused portions of spectrum, the concept of Cognitive Radio (CR) technology has been proposed by J. Mitola in [5], [6]. CR is based on Software Defined Radio (SDR) that was proposed in order to liberate the radio networks from the previous dependencies on hardware characteristics such as frequency bands, channel coding, and bandwidth [7]. SDRs add programmability to radio devices, increasing their flexibility to operate on different spectrum bands and with different modulations. An SDR transceiver is able to adapt its transmission parameters to the radio environment, which can vary over time. This ability allows users to access any portion of the free spectrum and not just a specific spectrum band, which is the case in current radios (i.e. 3G, 802.11, GSM, etc).

CR technology enables the reuse of the available spectrum resources. The basic limiting factor for spectrum reuse is interference, which is caused by the environment (noise) or by other radio transmissions. Controlling interference is essential to achieve maximum performance in wireless networks because interference directly affects the reception capabilities of clients [8], [9]. Actually, interference is a key factor that can lead to reduced capacity and performance because it reduces the achievable transmission rate of wireless interfaces, increases the frame loss ratio, and reduces the utilization of wireless resources. Furthermore, interference can be between links belonging to the same network or can originate from external sources.

Channel Assignment (CA) is one of the basic mechanisms that controls interference in a wireless network. CA in wireless environments aims to assign channels to radio interfaces of wireless devices in order to achieve efficient frequency utilization and minimize the interference that is caused by users that operate on the same channel [10]. CA influences the contention among wireless links and the network topology or connectivity between the nodes of a network. There is a trade off between minimizing the level of contention and maximizing connectivity and performance [11], [12]. Moreover, channel assignment determines the interference between adjacent channels; such interference exists not only for 802.11b/g, but also for 802.11a when the distance between antennas is small [13], [14].

Channel assignment is a key mechanism that aims to avoid performance degradation of a wireless network due to interference. In Wireless Mesh Networks (WMNs), which are mainly multi-hop wireless networks with fixed nodes, interference between the links causes severe performance degradation [15], [16] and efficient CA should be performed to avoid this issue. The use of multi-radio devices can increase the capacity of a WMN, but an efficient channel assignment algorithm is still necessary to minimize the interference among the multiple radio interfaces of each mesh node [17], [18].

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In CR networks (CRNs) due to the capability of CR users to access any portion of spectrum, significant interference may be caused not only to other CR users, but also to licensed users that are accessing the licensed spectrum bands. To avoid this issue, efficient Spectrum Assignment (SA) (also referred to as spectrum allocation and frequency assignment)[1] for CR networks has been a key focus of research. SA in CRs is the process of selecting simultaneously the operating central frequency and the bandwidth. This is quite different than CA in traditional wireless networks, where there is a pool of available channels with specific operating central frequency and bandwidth and the nodes select a channel among this pool. The simultaneous selection of frequency and bandwidth makes the SA in CR quite more complex. It is worth noting that up to now cognitive SA has been approached similarly than traditional CA, focusing mainly on selecting channels with specific bandwidth from a pool of available channels. Although this is contrary to the concept of cognitive radios, it simplifies the problem of SA and is widely used.

This work focuses on spectrum assignment in cognitive radio networks. We present an overview of the spectrum assignment challenge and describe the most basic approaches for modeling the SA problem. Furthermore, the criteria and the techniques that are used for solving the SA problem are also presented. The rest of the paper is structured as follows: in Section II we present an overview of CRNs. The problem of spectrum assignment in CRNs is discussed in Section III. In Section IV the basic techniques proposed so far in the literature for SA algorithms are presented. We present some challenges that must be addressed to enable efficient, robust spectrum assignment together with some open issues for future research in this area in Section V. Finally, Section VI concludes the paper.

II. COGNITIVE RADIO NETWORKS

The wireless spectrum is limited and the fixed spectrum assignment policies of governmental agencies result in wasting valuable spectrum resources. The proposed concept of CR technology envisages to exploit the unused frequency bands in an opportunistic manner. CR is a radio or system that can sense the environment and dynamically and autonomously adjust its radio operating parameters to modify system operation [2]. The Federal Communications Commission (FCC) proposed in 2003 the following term for "Cognitive Radio":

> "A cognitive radio (CR) is a radio that can change its transmitter parameters based on its interaction with the environment in which it operates. This interaction may involve active negotiation or communications with other spectrum users and/or passive sensing and decision making within the radio. The majority of cognitive radios will probably be SDRs, but neither having software nor being field reprogrammable are requirements of a cognitive radio." [19].

The term "cognitive radio" is very generic and should not be limited to SDR or field programming; nevertheless, SDRs are extensively used in the CR field, being almost the single available solution for CRs. There are several driving forces for cognitive radio technology, which include using spectrum efficiently, maximizing throughput, mitigating interference, facilitating interoperability, accessing secondary markets, etc. By exploiting these benefits, CR technology has opened new opportunities in sensing, accessing, and utilizing the available wireless resources, changing the current view on the operation of radio communications.

In CRNs the terms "primary users" and "secondary users" are often used. Primary Users (PUs) are licensed users that have been assigned spectrum for long-term usage, whereas Secondary Users (SUs) have no license for accessing spectrum bands and use CR technology to temporarily access the spectrum in an opportunistic manner [2], [20]. A radio device scanning the wireless spectrum at any specific location would observe:

- bands that are unoccupied most of the time,
- bands that are partially occupied some of the time,
- bands that are heavily occupied all of the time.

The unused portions of spectrum has led to the definition of the term "spectrum hole" (or "white space"), which is a frequency band that is assigned to a licensed user, but at a specific place and time is not being utilized [1].

Several standards for cognitive radio networks have been proposed by various organizations [21]. IEEE 802.22 [22] was the first proposed standard for wireless networks based on CR techniques. This standard aims to use the TV bands in an opportunistic manner, avoiding causing interference to licensed users. IEEE 802.22 is targeted at rural and remote areas and claims to achieve performance comparable to existing fixed broadband technologies such as DSL and cable modems. The TV bands were selected because of the very favorable propagation characteristics, which allow remote users to be serviced efficiently. IEEE 802.22 is a centralized system, in which a central base station is the entity that controls a cell and the Consumer Premise Equipments (CPEs) that are associated with this cell. In 2005 the IEEE Communications Society and the IEEE Electromagnetic Compatibility Society jointly established the IEEE 1900 Standards Committee, which standardizes the key issues in the fields of spectrum management, cognitive radio systems, and policy defined radio systems. IEEE P1900.4 is a working group that defined the architectural building blocks for optimized dynamic spectrum access in white space frequency bands [23], [24], [25]. Wireless services through cognitive radios operating in TV white bands are the reasons for various amendments of IEEE standards, like the IEEE 802.11TGaf [26], the IEEE 802.16h [27] and the IEEE802.19 [28]. Furthermore, the European Telecommunications Standards Institute (ETSI) has proposed several standards for the Reconfigurable Radio Systems (RRS), which are based on SDR and CR technologies [29]. Finally, the European Computer Manufacturers Association (ECMA) has proposed a standard called ECMA-392, entitled "MAC and PHY for Operation in TV White Space" [30], specifying the MAC and PHY layers for cognitive wireless networks operating in TV bands, targeting local area applications in houses, buildings

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[1] The terms "spectrum assignment" and "spectrum allocation" are used interchangeably in this paper. We also use the term "channel assignment", since this term is used in most of the works that we reference. We try to keep the distinction made above throughout the rest of this paper.

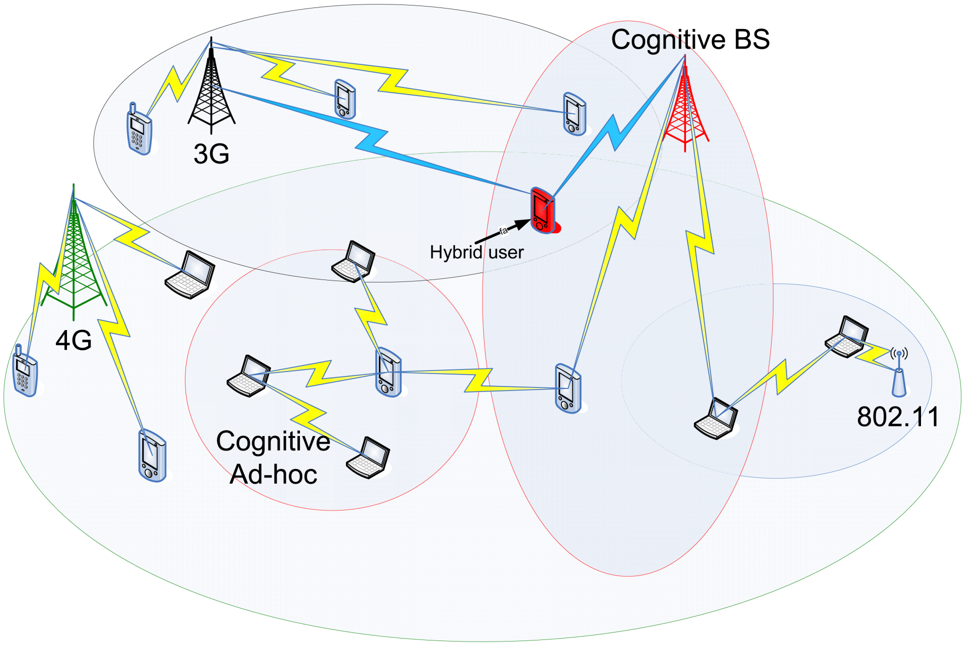

Fig. 1. Topology of a CRN co-located with primary networks.

and neighborhoods.

A. *CRN Architecture*

A CRN architecture basically consists of primary networks and secondary networks [1], [2], [20], [31]. A possible CRN architecture is depicted in Figure 1. Primary networks (PNs) are the existing wireless network infrastructures, such as GSM, UMTS, TV broadcast etc. that have been assigned licenses to operate in specific frequency bands. These networks consist of primary base stations and PUs. Primary base stations are used in infrastructure mode of wireless networks and hold a spectrum license for communicating with the PUs. Generally, the primary base stations do not have any functionalities for sharing the spectrum with secondary users.

The Secondary network (SN) is a cognitive network whose components do not have license to access any frequency bands. SNs can be split into infrastructure and ad-hoc networks that are operated by network operators or stand-alone users respectively. In infrastructure mode, secondary base stations provide one-hop communication to secondary users, have the ability to discover spectrum holes and operate in the most suitable available band in order to avoid interfering with the PNs. An example of infrastructure CRN architecture is the IEEE 802.22 network [22]. SUs are equipped with CR-enabled devices and access the spectrum dynamically, changing frequency bands when they detect primary transmissions. SUs are either connected to a secondary base station or to other SUs in an ad-hoc manner. *Spectrum servers* (or spectrum brokers) could be used for coordinating spectrum usage among different secondary networks.

Another type of cognitive users can emerge in the future in order to fully exploit the capabilities of CR technology and to the best of our knowledge, this type of users has not been considered in the literature up to now. This group consists of licensed users that are also equipped with a device with cognitive capabilities, hence can be considered as a hybrid between primary and secondary users. For example, these users can be equipped with laptops that have a 3G internet connection (thus are PUs in the licensed 3G spectrum), but also have a wireless cognitive radio device connected to the laptop (thus are able to connect to a secondary cognitive network) as shown in 1. These users will be able to access not only any primary network, but also secondary networks (even simultaneously, because they access each network through a different radio interface), maximizing their performance and the received Quality of Service (QoS), because they will execute different applications over each network and one connection will not affect the performance of other connections, since they operate in different frequencies. Considering a geographical area where multiple primary networks are operating together with several secondary networks, the hybrid users will be able to access any type of network (PN or SN) according to their preference (and the traffic load of the networks) or even access multiple networks at the same time (i.e. UMTS and an SN simultaneously). The advantage of the hybrid users is that they have higher priority than the SUs when accessing the primary networks. These users do not vacate the license band when other PUs transmit, since they are also primary users, but they can also exploit the available spectrum at other bands, such as when there is a high aggregate demand for throughput.

B. *Cognitive functions*

CR devices have the ability to interact with the environment and adapt to any changes, determining at any time the appropriate communication parameters. To enable dynamic adaptation of these parameters, several cognitive functions (referred to as the “cognitive cycle”) for managing the spectrum have been proposed [1], [2], [31].

Spectrum sensing is the basic functionality of CR devices,

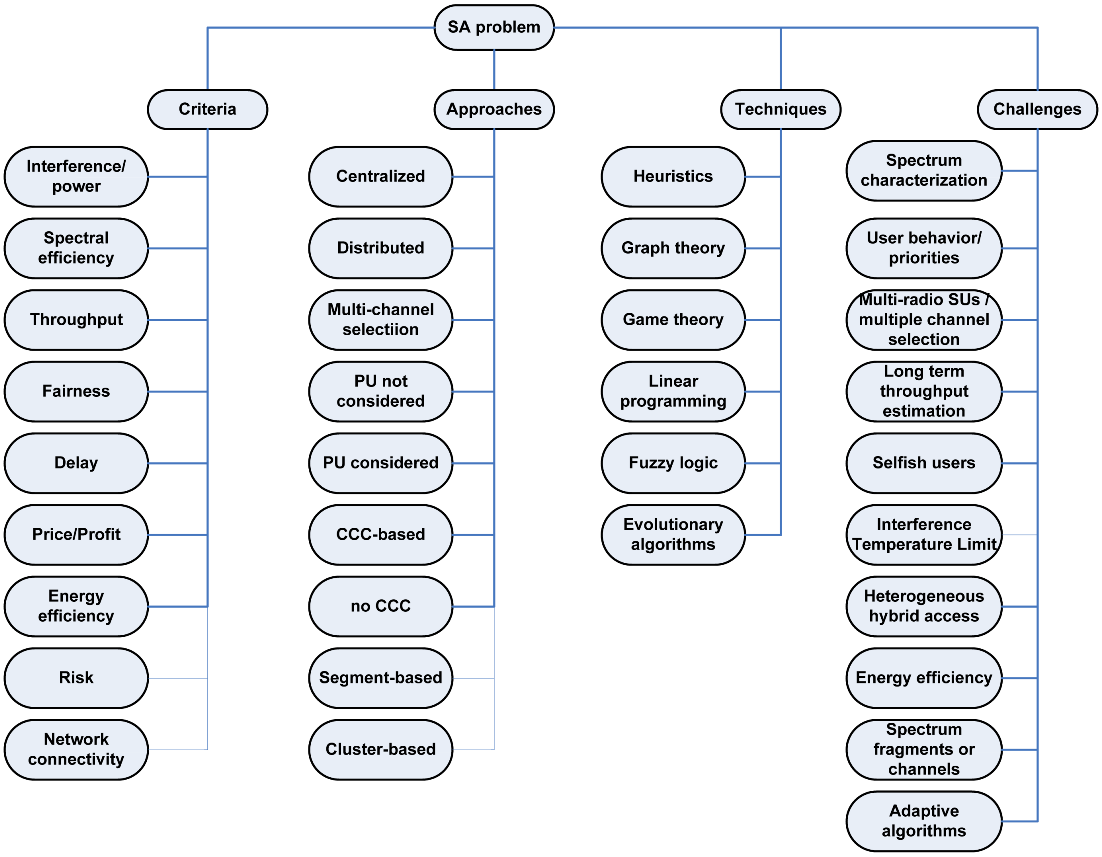

Fig. 2. Overview of the SA problem.

which monitors the spectrum bands at any given time, and detects the available spectrum holes. Spectrum sensing is closely connected to *spectrum analysis*, which determines the characteristics of the spectrum bands that are detected through sensing. After detecting and analyzing the spectrum holes, the *spectrum decision* (or *spectrum assignment*) function selects the best available band according to some criteria. In CRNs the SUs are able to access the available spectrum, but when their frequency bands overlap, this results in collisions and contention, which degrade the performance of the network. *Spectrum sharing* is a functionality that coordinates the spectrum usage among different SUs aiming at minimizing collisions and interference.

Once a suitable operating frequency has been selected, the communication can be started, but due to the high dynamicity of the mobile environment, after a while the selected band may become occupied by a PU. One basic characteristic of CR technology is the ability to change the operating band when the signal of a primary transmission is detected at the receiver. This functionality is called *spectrum mobility* and incorporates handover (or handoff) between spectrum bands, in order to avoid interfering with primary transmissions or to access another spectrum hole that can provide higher QoS to the SU.

III. SPECTRUM ASSIGNMENT IN CRNS

A. Problem definition

To maximize the performance of a CRN, one major challenge is to reduce interference that is caused to PUs, as well as interference among SUs. Interference results in additional noise at the receiver and lowers the Signal to Interference plus Noise Ratio (SINR), which in turn results in: (i) reduced transmission rate of the wireless interfaces, (ii) reduced utilization of the wireless resources, (iii) higher frame loss ratio, (iv) higher packet delay and (v) lower received throughput. In the absence of interference, a link should provide its maximum capacity, which depends on the available transmission rates and corresponding delivery ratios. Interference affects both the sender and the receiver of a link; the sender transmits at a rate less than its maximum, while there is a higher probability of unsuccessful packet reception at the receiver [98].

The interference that the CR transmissions create plays a key role in the operation of not only the CRNs, but also of the PNs that are operating in the same geographical area. A SU has the ability to operate in any frequency band, because that user is equipped with a reconfigurable device, capable of transceiving in any frequency (in practice the device will be capable of transmitting at a specific frequency range and not at the whole spectrum). Since SUs are unlicensed users, this capability may cause problems to licensed transmissions if the SU selects a licensed band. Thus, one basic requirement for CR technology is that SUs should not interfere with the

TABLE I
CRITERIA USED FOR COGNITIVE SA.

Criterion	Target Objective	Issues	References
Interference/power	Minimize interference between SUs and interference caused to PUs. Can be investigated jointly with power control. Minimizes interference in the network, which increases performance. Ensures minimum impact on PUs.	Does not necessarily ensure satisfaction of different user QoS demands.	[1], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51]
Spectral efficiency	Maximize spectrum utilization. Maximize number of channels used or number of SUs served, when each SU selects only one channel.	Does not consider different requirements of SUs. In multi-radio multi-channel SUs the complexity can be very high. Can be achieved only in centralized SA.	[41], [47], [52], [53], [54], [55], [56], [57], [58], [59]
Throughput	Maximize user or network throughput. Works in both centralized and distributed approaches.	Can increase interference in the network. Can cause unfairness and starvation to some SUs.	[39], [41], [49], [51], [52], [55], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70]
Fairness	Achieve fair throughput/spectrum distribution among SUs. Solves starvation problems.	Does not achieve maximum network performance. Does not take into account QoS requirements.	[53], [54], [60], [71], [72], [73], [74], [75], [76], [77], [78], [79]
Delay	Often considered jointly with routing, aims either to assign channels among paths for minimizing the total end-to-end delay or to assign channels for minimizing the spectrum switching delay.	Does not achieve maximum network performance and does not take into account the interference to the PUs.	[40], [44], [69], [80], [81], [82], [83], [84], [85], [86], [87]
Price	Each SU selects the channel according to the price of the channel and taking into account the reward for accessing this channel. Another approach is that network operators assign channels to SUs targeting at maximizing their own revenue.	SUs need to have a priori knowledge for the cost of each spectrum band or they should dynamically question the spectrum owners, which induces delays. Prices vary through network operators/spectrum owners.	[88], [89], [90]
Energy efficiency	Minimize energy consumption of SUs, meeting the QoS requirements	Does not achieve maximum performance. To be applied in centralized SA the nodes should have to continuously exchange their battery levels.	[53], [54], [65], [91], [92]
Risk	Minimize the probability that a path of a flow is blocked by emerging primary users.	Does not achieve maximum performance, although it aims to achieve less spectrum handovers. It splits the network into locations and assumes that only one channel is used at each location, something that does not achieve good spectrum utilization.	[93]
Network connectivity	Mainly used for CRAHNs, it aims to maintain the network connectivity and minimize interference within the cognitive network.	It does not ensure the QoS of the users, maximum network performance and maximum spectrum utilization.	[94], [95], [96], [97]

communication of PUs [2], [19]. This requirement makes the problem of interference management in CRNs even more complex than in traditional wireless networks, because another level of interference avoidance is included in the problem definition [32]. The SUs should not only avoid interfering with each other but also with PUs which have higher priority in accessing the licensed spectrum bands.

Spectrum assignment is a basic function of CRNs because it affects the normal operation of the network and is closely related to spectrum sensing, which provides information on the available spectrum. SA is responsible for assigning the most appropriate frequency band(s) at the interface(s) of a cognitive radio device according to some criteria (i.e., maximize throughput, fairness, spectral efficiency, etc.), while, at the same time, avoid causing interference to primary networks operating in the same geographical area. Spectrum holes that are discovered by spectrum sensing are used as input to spectrum assignment, in order to find the optimum spectrum fragment that the SU should use according to its requirements [2].

Cognitive spectrum assignment has some challenges that differentiate it from the conventional CA in wireless networks. In traditional primary wireless networks, the spectrum is split among channels that have fixed central frequency and fixed bandwidth. Thus, traditional CA is the process of assigning a channel (namely the central frequency for use) to each user. In CRNs there is no standard definition for “channels”. SUs can dynamically change the central frequency and the bandwidth for each transmission. As a result, the SA function for each SU should determine not only the central frequency, but also the spectrum bandwidth to be used by that SU (according its requirements), unless there is central node that selects frequencies/bandwidths for all SUs (in centralized SA). Moreover, the available frequencies and spectrum holes dynamically change with time and location. These additional challenges increase the complexity of the SA problem in CR networks compared to the CA problem in wireless networks, which is already NP-complete [99], [100]. A basic conclusion of this survey is that only very few past approaches (i.e.[52]) have considered spectrum assignment without the use of channels with the traditional meaning. In contrast to traditional wireless networks, where fixed, dynamic and hybrid CA algorithms exist, in CRNs, only dynamic SA techniques exist. A fixed scheme in CRNs would have no real application, because due

TABLE II
LIST OF NOTATIONS/VARIABLES.

Notation	Meaning
c	channel
$I^c_{i,j}$	Interference caused to node i from node j when they both use channel c.
I^c_i	Total interference caused to node i using channel c.
G_i	Transmission gain of node i
P	Transmission power
P^c_i	Transmission power of user i on channel c
h	Antenna height
d	distance
SL	System loss
γ	SINR
N_o	Average noise power
R	Data rate
r^c_i	Maximum data rate of user i on channel c
W	Channel bandwidth
s	Spectrum unit
a	Decay rate (path loss)
Θ	Transmission Range
M	Constellation size of M-QAM
η	Spectral efficiency
E	Consumed energy
Pb_x	Probability of variable x
$x_{i,c}$	Assignment of channel/spectrum unit c to node i
$s_{i,k}$	a value of 1 indicates that the spectrum band k is available for node i
Ds	Switching delay between frequency bands

to the dynamic characteristics of the spectrum, the available frequencies vary through time.

The procedure for solving the spectrum assignment problem in CRNs is usually split in three steps. First, criteria (which define the target objectives) are selected to solve the SA problem. The second step includes the definition of an approach for modeling the SA problem that best fits to the target objective. The third and final step is the selection of the most suitable technique that will simplify and help solve the SA problem. In the following subsections, these three steps are described and discussed in detail. Figure 2 gives an overview of the above three steps.

B. Criteria

There are several criteria for assigning spectrum to SUs in cognitive radio networks, and these vary according to the target objectives of each algorithm. Table I briefly presents these criteria. Furthermore, Table II presents the notations that are commonly used in the equations throughout the following sections. All other variables not presented in this table are explained in the text.

*1) **Interference/power:*** Cognitive radio networks have the constraint that the SUs should create no or limited interference to licensed users. Moreover, to maximize the CRN performance, interference between SUs should also be kept to a minimum. Thus, interference is the most common criterion for designing an efficient cognitive SA algorithm (i.e. [32], [33], [34], [35]). In the literature, many past efforts use interference caused by the SUs to the PUs as the only criterion. Other efforts disregard the PUs and consider only interference caused to other SUs, while others consider interference in both directions.

Many approaches (i.e. [1], [39], [40]) are based on the Interference Temperature Limit (ITL) at the PUs and assign channels to SUs in order to keep ITL under a predefined threshold. As defined by FCC [101], the ITL shows the amount of interference that is sensed by a receiver and can be calculated as the power received by an antenna (measured in Watts) divided by the associated RF bandwidth (measured in Hertz) and a term known as Boltzmans Constant (equal to 1.3807 Watt-sec/Kelvin)[2]. Limiting the interference temperature under a threshold is usually achieved via power control, in order to keep the transmission power of SUs and consequently the interference at PUs very low. This approach has a trade-off: decreasing the transmission power decreases the interference at PUs, but at the same time, decreases the SINR at the receiving SU. Thus, the transmission power should be selected very carefully in order to keep the SINR above the nodes' sensitivity for successful receptions.

Many works in the literature have explored joint frameworks for spectrum assignment and power control (i.e. [39], [40], [41]) for solving the spectrum assignment problem. However, these approaches do not always ensure maximum network performance or maximum spectrum utilization while in most cases QoS is also not taken into account.

In [41] several methods for channel assignment are proposed. One of these methods aims to minimize the transmission power given different data rates. To reduce the transmission power, the CR node with a large required data rate should use the channel with a large bandwidth and low interference level, which is the channel with the smallest interference over bandwidth ratio (I/W). The method assumes that the CR nodes exchange information for the required data rate on a channel selected for the communication.

A Dynamic Interference Graph is proposed in [42], [47] for capturing the interference between a pair of transmissions. Given a set of CR nodes and a particular channel, the authors construct an undirected graph with a number of vertices equal to the number of CR nodes. Each vertex (CR) is connected with another vertex if and only if the two CRs cannot be supported on that channel simultaneously. The channel allocation algorithm constructs at each step an interference graph (representing the interference between the unserved CRs), by considering also the aggregated interference caused by the already allocated transmissions in previous steps; thus, the interference graph is dynamically adjusted based on the aggregate interference. In [44] a method to calculate interference based on the path loss model is given. With S_i being the set of users in the interference range of node i that are operating on the same channel c, the interference of this CR user is calculated as the sum of interference of all other users in the set S_i

$$I_i^c = \sum_{j \epsilon S_i} I_{i,j}^c \tag{1}$$

and the interference of a node j to the node i that operates

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[2] Lately the FCC has abandoned the use of the term ITL, although many works still use it.

on the same channel c is calculated as

$$I_{i,j}^{c} = \frac{P_j \cdot G_j \cdot G_i \cdot ({h_j}^2 \cdot {h_i}^2)}{{d_{i,j}}^k \cdot SL}. \tag{2}$$

The authors consider the cumulative end-to-end interference as the sum of the interference caused to all CR nodes

$$I(t) = \sum_{i,c} I_i^c(t). \tag{3}$$

Many approaches (i.e. [33], [48], [49]) consider the SINR at each CR node in order to perform an efficient channel assignment. In [47] the SINR is calculated according to

$$\gamma_i^c = \frac{G_i \cdot P_i}{N_o + \sum_{j=1, j\neq i}^{N} G_j P_j}. \tag{4}$$

The authors assume that when $\gamma_i^c \geq \overline{\gamma}$, where $\overline{\gamma}$ is the minimum SINR to achieve a certain Bit Error Rate (BER), a reliable transmission towards CR i can take place. This seems quite reasonable, but should be calculated continuously, because new users may start transmitting after a while and the interference may increase, decreasing the SINR under the required threshold. To avoid this issue, a "safety net" for the SINR should be used, allowing the transmission towards i only if $\gamma_i^c \geq \overline{\gamma} + \kappa$, where κ is the "safety net", which is a constant value.

Common Assumptions: The common assumptions that are made in the works that aim to minimize the interference are the following:

- *Node cooperation*: The nodes are assumed to be cooperative and exchange data regarding their transmission power.
- *SINR*: The nodes are able to transmit with maximum power, if the SINR at the neighboring receivers is below a threshold, which assumes knowledge of the SINR at the neighbors.
- *ITL*: The nodes may transmit with maximum power given that the ITL at the neighboring PUs is below a threshold, which assumes the ability to measure the ITL at the PUs or that the PUs can exchange this information with the SUs.
- *Instantaneous channel information*: Many works are based on a local channel estimation and assume that channel gain information is available instantaneously.
- *Same set of channels*: Most works assume that the same set of channels is available for all SUs.
- *PUs known*: Almost all works assume that key characteristics of PUs, such as location and operating bandwidth, are known to the SUs.
- *Power control*: Many works have proposed a joint framework of SA and power control in order to minimize the interference to PUs and/or to other SUs.

2) *Maximize spectral efficiency/spectrum utilization:*

A key objective for the deployment of cognitive radio networks is to achieve better utilization of the available spectrum bands. Thus, maximizing spectrum utilization is another common criterion for designing an efficient cognitive SA algorithm (i.e. [52], [41], [47]). The goal here is to maximize either the number of channels assigned to SUs or the number of SUs that are being served in the CRN. Most previous works consider these two approaches to be equivalent (i.e. [59]), but in fact, this is true only in the case of single-radio SUs that use one channel at each radio interface. To maximize spectrum utilization there are usually several constraints, such as minimum interference to SUs and PUs, maximum transmission power, minimum SINR threshold, etc.

In [41] one of the proposed method aims to maximize the spectral efficiency, assuming M-ary Quadrature Amplitude Modulation (M-QAM) in the CR nodes. The spectral efficiency is calculated as

$$\eta = \frac{R}{W} = \log_2 M. \tag{5}$$

The problem of maximizing spectral efficiency is formulated as

$$\max \frac{1}{L} \sum_{j=1}^{L} \log_2 M^{(j)}, \tag{6}$$

where L is the number of possible simultaneous source-destination pairs. This function converts the problem of maximizing the spectral efficiency into maximizing the transmission power of each CR node. For this method to work, the CR nodes need to share their maximum allowed transmission power; however, this is not always feasible in CRNs. Furthermore, this method induces extra interference in the network, because transmitting with the maximum power causes higher interference to the nearby users and increases the energy consumption of the nodes. Thus, the attempt to maximize the spectral efficiency may result in lower quality of service, less battery lifetime or increased interference to the PUs.

In [54], the maximization of the spectrum utilization is achieved by allocating as fairly as possible the idle spectrum units using the target objective:

$$\max \sum_{i \epsilon V} w_i \ln(\sum_{s \epsilon S} x_{i,s}), \tag{7}$$

where w_i corresponds to the priority of CR i and V is the set of CR that request spectrum access. Considering that a fair allocation of spectrum units will remove possible starvation effects, this approach may indeed result in a good spectrum utilization, but fairness does not always achieve the maximum result.

In [53], the authors use two target objectives: (i) maximization of the total spectrum utilization and (ii) maximization of the bottleneck user's spectrum utilization. For (i) the objective function is calculated as

$$\max_{A \epsilon \Lambda_{N,K}} \sum_{i=1}^{N} \sum_{k=1}^{K} s_{i,k} \cdot b_{i,k}, \tag{8}$$

while for (ii) the objective function is

$$\max_{A \epsilon \Lambda_{N,K}} \min_{i<N} \sum_{k=1}^{K} s_{i,k} \cdot b_{i,k}. \tag{9}$$

A is a valid spectrum assignment allocation, $\Lambda_{N,K}$ is the set of all valid spectrum assignments given a set of N users and K spectrum bands and $b_{i,k}$ represents the maximum throughput that can be achieved by CR i in spectrum band k.

When multi-radio CRNs and multi-channel radios are involved, the complexity of maximizing spectral efficiency becomes much higher, which is something that, to the best of our knowledge, has not yet been fully investigated in the literature.

Common Assumptions: The common assumptions that are made in the works that aim to maximize spectral efficiency are the following:

- *Interference*: Many works assume that maximum spectral efficiency is achieved when channels with minimum interference are selected.
- *Single radio devices*: All works assume single radio devices, converting the problem of maximization of the spectrum utilization into maximization of the number of SUs that can be served.
- *Fixed set of channels*: All works assume a fixed set of channels, among which the SUs will select the one to use.
- *Rational users*: Most works assume that all users are rational and work together in order to maximize the overall network spectrum utilization. The users share their maximum allowed transmission power. There are no greedy users.

*3) **Rate/throughput of SUs:*** Throughput maximization is also a very common criterion for channel assignment schemes in both traditional wireless networks and CRNs (i.e. [52], [60], [61]). The objective is to maximize either the throughput of each individual SU or the total network throughput, based on several constraints:

- maximum transmission power for each SU on each channel ([41]),
- the link capacity using the Shannon theorem ([39], [55], [59]),
- the maximum interference-SINR ([49], [67], [68]),
- QoS requirements ([55], [69]),
- minimal impact to PU ([49], [102]).

Many works attempt to maximize the throughput of each individual SU and use a distributed SA algorithm where the users do not cooperate with each other [70]. This can lead, though, to contention when accessing the channels or to unfairness, because the first SU will be able to select any channel in order to maximize its performance, without taking into account the other SUs. Other works ([41]) have considered the sum of the throughput of SUs as a criterion and perform either a distributed (cooperative) or centralized SA trying to maximize the network performance, which can also lead to unfairness where some SUs are starved.

In [41] one of the target objectives is to maximize the total data rate of the CR nodes that use M-QAM. The maximum data rate of each user is calculated as

$$R = W \cdot \log_2(1 + \frac{1}{k_b}\frac{P_t}{I \cdot d^a}) \tag{10}$$

and the objective function as $\max \sum_{j=1}^{L} R^{(j)}$, subject to the constraint that each CR's transmission power is lower than a maximum value. d is the distance between the CR and its one-hop destination node and $k_b = -\frac{2}{3}\ln\frac{Pb_{ber}}{2}$. Using this target objective the result is that each user should use its maximum allowed transmit power for maximizing the data rate, something that is quite expected.

In [68] the authors use a different approach for throughput maximization, considering an OFDMA-based cognitive radio network. The CR nodes are assumed to borrow uplink subcarriers from a primary network. The maximization of the throughput is achieved using the target objective function $\max \sum_{k=0}^{|K|} g_{i,k}$ for all CR users, where k is the sub-carrier, $g_{i,k}$ is the allocated bits of CR i on sub-carrier k (if k is not used then the allocated bits are zero) and K is the total number of available sub-carriers,. The optimization is achieved under several constraints, such as maximum BER, minimum SINR and the minimum number of bits per CR.

Common Assumptions: The common assumptions that are made in the works that aim to maximize the throughput of the SUs are the following:

- *Fixed nodes*: The nodes are assumed to be fixed or moving so slowly that the network topology remains constant.
- *Interference*: Co-channel interference is the only source of noise at the receivers.
- *Single radio devices*: Almost all works assume that CR users have a single transceiver.
- *Bandwidth*: Some works assume that the bandwidth of a channel is sufficient to support more than one CR transmission.
- *Concurrent transmissions*: Here the previous works are divided between those that assume that only one transmission is allowed at each channel and those that allow concurrent transmissions with different spreading codes.
- *Channel conditions*: Almost all works assume stable channel conditions during the resource allocation period.

*4) **Fairness:*** The criterion of maximizing user or network throughput can create unfairness in the spectrum distribution among SUs, e.g. in cases where one SU can select multiple channels and others are left with no available spectrum (starvation). To avoid these cases, many works (i.e. [53], [54], [60]) have considered the criterion of maximizing throughput fairness among SUs, using several utility functions, e.g. by maximizing the minimum average throughput per SU , which leads to more fair results, or by using a fairness factor. Throughput fairness is often considered using a centralized approach and the goal is to assign channels to SUs, aiming to achieve a fair distribution of spectrum (and consequently of throughput). Although this approach solves starvation problems and unfairness, it does not consider the minimum throughput requirements of users receiving high-demanding applications. This can be solved by considering separate groups of SUs according to their QoS requirements or by using priorities of users according to different throughput requirements; to the best of our knowledge, this direction has not been fully investigated in the literature.

In [54] the fairness problem is considered jointly with maximizing the spectrum utilization, considering the objective to maximize the sum of the logarithms of the number of spectrum units that each CR uses. Many works (i.e. [71], [74], [75]) use the traditional target objectives for max-min fairness and proportional fairness. In *max-min fairness*, the target is to maximize the minimum share of resources among the CR users. In [71] the authors focus on infrastructure based CRNs and the target objective is to maximize spectral efficiency and fairness. The authors aim to avoid maximizing the rate of each CR user because this usually results in unfairness. For this reason they focus on the average bandwidth of flows and aim to maximize the minimum average per flow bandwidth for all the users at each cognitive base station by applying a version of max-min fairness. The objective function is

$$\arg\max U, \tag{11}$$

where the utility function is expressed as

$$U = \min_{0<n<N} R_n, \tag{12}$$

and R_n is the average per flow data rate of end-users associated with the cognitive base station n.

In *proportional fairness*, there is a trade-off between throughput and fairness. Several objectives for proportional fairness have been proposed, i.e. maximize the sum of the logarithmic utility functions or assign each user a data rate that is inversely proportional to its anticipated resource consumption. In [76] the authors propose a weight associated with the spectrum slice as $w_i = 1/m_i$, where m_i is the cost per data bit of using spectrum slice i. Then, the max-min algorithm is used, but instead of maximizing the spectrum demand sd_i, the authors use the variable sd_i/w_i for obtaining proportional fair allocation of resources. In [75] proportional fairness is achieved using the target objective:

$$max\ \ln(\prod_{i=i}^{N} R_i). \tag{13}$$

In [78] a variation of proportional fairness is proposed, called Collaborative Max Proportional Fairness (CMPF), calculated via

$$U_i = \frac{\max r_i^c/(D_{i,c}+1)}{\sum\limits_{c=1}^{C} x_{i,c} \cdot r_i^c} \cdot \Big(\frac{1}{\sum\limits_{c=1}^{C} s_{i,c}}\Big)^q \cdot \Big(\frac{1}{tag_i + 1}\Big)^u \tag{14}$$

where $D_{i,c}$ is the number of neighbors that cannot simultaneously use channel c with user i, and tag_i is the tag coefficient of user i, showing the number of channels that are already assigned for user i until now. Setting $q = u = 0$ in the above formula yields proportional fairness. Using this expression, the authors claim to be able to ensure the user's fairness of bandwidth gain and the user's fairness of channel assignment quantity.

In [79] the objective of the spectrum assignment algorithm is to maximize the sum of bandwidth of the CR users, with the constraint of achieving a fair spectrum distribution. In this respect they define the following fairness factor:

$$f_{i,k}(t) = \frac{\sum\limits_{j=1}^{N} 1(d_{i,j} \leq 2\Theta_{rs})}{\sum\limits_{k=1}^{K} s_{i,k}(t-1)}, \tag{15}$$

where t is the current allocation time, k is the current spectrum band, i is the CR node. This factor indicates the number of spectrum bands that are assigned to a CR user in relationship to the number of CR users that are within its transmission range and the authors try to assign an equal number of spectrum bands in neighboring CR nodes. This approach seems better to be specific in cases of large cognitive radio networks with many distant SUs. In this respect, the network operator (when centralized control exists) does not have to prevent some distant nodes from selecting more spectrum units than others when willing to have a "fair" distribution of spectrum units. Thus, using this equation, only the neighbor nodes will have to select the same (or quite close) number of spectrum units, allowing distant nodes to have more freedom in accessing the spectrum.

Common Assumptions: The common assumptions that are made in the works that aim to maximize the fairness of the SUs are the following:

- *Same channel capacity*: All channels are assumed to have the same capacity, so that the fairness can be measured by the number of channels allocated to each SU (simplistic approach).
- *single radio devices*: Almost all works assume the CR users to have a single transceiver.
- *Spectrum utilization*: Some works assume that fairness is closely related to spectrum utilization and aim to allocate channels among SUs as fairly as possible in order to achieve efficient spectrum utilization.

5) ***Delay:*** Spectrum assignment is also combined in several cases with another QoS criterion: the delay. Previous works in cognitive SA consider both the end-to-end delay and the switching delay for taking decisions regarding the spectrum bands they will select. End-to-end delay is the total time for the delivery of a packet measured from the source to the destination. In cognitive SA the end-to-end delay is considered in many approaches that combine spectrum allocation with routing. Especially in multi-hop CRNs, routing plays an important role in ensuring the performance of the network. *Switching delay* is the time that is needed for a CR user to move from one spectrum frequency to another. During the switching, the transmission/reception of the CR is interrupted, thus it induces extra delay in the flow of the user. As mentioned in [103], the switching delay may be of the order of 10ms for a 10 MHz change in the frequencies up to 3 GHz.

In [80], [87] the total delay of a flow is calculated by the sum of the delay of the existing flows plus the delay of the new flow. The first delay is called Node Delay (DN) and the second Path delay (DP). The goal of the paper is to assign channels to the node m in order to minimize the route-wide cumulative delay that is the sum of DP and DN. The switching delay Ds from frequency i to frequency j is calculated as in:

$$Ds_{i,j} = \sigma |Band_j - Band_i|, \tag{16}$$

where $\sigma = 10ms/10MHz$ is a positive constant mentioned in [103].

In [69] the authors present a framework for spectrum decisions in CRNs, taking into account the spectrum switching delay. A new metric is proposed for calculating the capacity of a CR user, namely the expected normalized capacity of a user k in spectrum c is given by

$$C_i(k) = \frac{T_i^{off}}{T_i^{off} + Ds} \phi_i c_i(k), \tag{17}$$

where T_i^{off} is the required transmission time without switching, ϕ_i is the sensing efficiency and $c_i(k)$ is a normalized channel capacity (measured in bits/sec/Hz) showing the user's datarate per each Hz of the spectrum band he uses. The sensing efficiency here takes into account the fact that the CR users do not transmit during spectrum sensing. The goal of this work is to find a spectrum assignment that maximizes the sum of the normalized capacities of the CR users. The approach assumes a constant switching delay, which means that it uses spectrum bands of a constant width, something that is not realistic for CRNs.

In [44] the authors propose a joint framework for channel assignment and routing in CRNs, considering metrics that combine the interference and the channel switching. This work proposes the Minimum cumulative Interference and channel Switching Delay (MISD) metric allowing a trade-off with different weights between interference and switching delay. The authors assign both channels and paths on each hop. The issue with this approach is that only the number of channel switches are taken into account and not the actual switching delay that is induced to the flow among its path. This approach would be useful only if the spectrum bands have the same width (thus each channel switching would induce a constant switching delay), which is restrictive.

Common Assumptions: The common assumptions that are made in the works that aim to minimize delay of the flows of the SUs are the following:

- *Routing*: Most works combine spectrum assignment with routing in order to find jointly the path for each flow and the channels of the intermediate nodes for minimizing the flow delay.
- *Switching delay*: Most works assume a constant switching delay, using spectrum bands with fixed width.
- *Channel switching*: Some works measure the switching delay by the number of channel switches, but once again this can give realistic results only if the channels have the same width, because the switching delay is proportional to the width that is the difference between the current and the new central frequency.
- *Cross-layer design*: Most works that combine SA with routing assume a cross-layer design, in which the routing module has knowledge regarding the spectrum opportunities (there is interaction between routing module and spectrum sensing module).

*6) **Price/profit**:*

Another (not so common) criterion used in the literature is the economic cost for transmitting over a channel by taking into consideration the reward or revenue that a CR node will receive from forwarding traffic over this channel. In [88] the spectrum is split in two types: TYPE I is shared between SUs and base stations of primary users, while TYPE II is shared only between SUs. Users are assumed to pay a predefined price for the spectrum they use. The price can be different for different spectrum bands, e.g., the 802.11 band can be free while the 3G band can be expensive. Additionally, by accessing each portion of TYPE II spectrum, the SUs can obtain a reward based on throughput, interference, power consumption, etc. The profit function for each SU is computed as

$$Prof_n(w_n) = Rev_n(w_n) - Cst_n(w_n), \tag{18}$$

where Rev, Cst is the revenue and cost for accessing the spectrum successfully and w_n is the spectrum size for each user n.

$$Rev_n(w_n) = U_n(w_n) + U_n(W - w_n) \tag{19}$$

and

$$Cst_n(w_n) = pr_n(U_n(w_n) + U_n(W - w_n)) - re_n U_n(W - w_n), \tag{20}$$

where $U_n(w_n)$ is the utility for accessing the spectrum TYPE I, $U_n(W - w_n)$ is the utility for accessing the spectrum TYPE II, pr is the price for accessing the spectrum and re is the reward for using spectrum TYPE II and W is the total available spectrum. The authors use the same utility function for simplicity, but discuss that any type of utility function can be used. Using these functions, network profit is defined as

$$Prof = \sum_{n \epsilon N} [pr_n(U_n(w_n) + U_n(W - w_n)) - re_n U_n(W - w_n)], \tag{21}$$

which is the total profit from the spectrum bought from the CRs. This approach introduces a trade-off between the spectrum that each user uses and the price the user pays. Thus, using this equation, the users can decide the portion of spectrum they need to use, according to their revenue for using it and the price they will pay. The most important issue here is to define the utility function, which can be of any type, as in the following work.

Another approach that considers a price function for spectrum assignment is [89], [90]. In this work, the SA problem is modeled as a game using a utility function that incorporates the profits of the secondary users and a price function. The basic idea here is the same as in the equation 18, namely that the profit is the difference between the revenue and the cost. However, the authors in [89], [90] consider specific utility functions. In particular, the profit of the SUs is given here by the following expression

$$Profit_i = r_i k_i w_i - w_i pr_i, \tag{22}$$

where r_i is the income per transmission rate of the user i, w_i is the spectrum fragment allocated to SU i, pr_i is the price per unit of spectrum and k_i is the spectrum efficiency $k_i = \log_2(1 + KSNR_i)$, in which SNR_i is the received SNR and $K = \frac{1.5}{\ln 0.2/BER_i^{tar}}$, with BER being the target bit error rate for the SU i. Using a definition for the price function given in [104], the utility function for the profit is given by the following expression

$$Profit_i = r_i k_i w_i - w_i[x + y(\sum_{j \neq i} w_j)^{\tau}], \tag{23}$$

where x, y are non zero constants and $\tau \geq 1$. After defining the utility function, the authors use game theory to find the optimum solution by Nash equilibrium.

Common Assumptions: The common assumptions that are made in the works that aim to maximize the revenue of the SUs/operators are the following:

- *Price*: All works assume that the SUs pay a specific price for the licensed spectrum they want to use and in some works the price is proportional to the amount of spectrum.
- *Reward*: Many works assume that by using the free spectrum they obtain a reward.
- *User groups*: Many works propose that not all users should pay the same price for accessing the spectrum and that different groups of SUs should pay different prices according to their spectrum requirements.

7) ***Energy efficiency:*** Another criterion for cognitive SA that has gained some attention lately is based on minimizing the energy consumption of the SUs [53], [54], [65], [91]. A distributed energy efficient spectrum access scheme is presented in [91], in which the system is assumed to operate in time slots. At each slot, the SUs that have a new traffic demand sense the entire spectrum and locate the available frequencies. This work proposes a distributed spectrum selection and power allocation algorithm for minimizing the energy consumption per bit over all subcarriers, since each SU is capable of selecting multiple subcarriers. The technique used for energy conservation is related to allocating the minimum energy per bit, guaranteeing the data rate and power constraints. Thus, the goal is to find the optimal number of channels that the SU can select and transmit with minimum power while guaranteeing its data rate requirements.

Another approach for energy efficient spectrum allocation in Cognitive Radio Ad Hoc Networks (CRAHNs) is described in [53]. Here, the channel access problem is formulated as a joint power/rate control and channel optimization problem, with the objective to maximize the total capacity and minimize the power consumption of the system. Thus, the energy efficiency problem is translated into minimizing the transmission power on the selected channels with the following constraints: (i) not to cause interference to PUs, by limiting the transmission power of a link on a specific channel with a power mask, (ii) not to select channel used by another SU and (iii) not to exceed the maximum battery power.

In [92] the problem of channel assignment in cognitive radio sensor networks is studied from the perspective of energy efficiency as the sensor networks are energy constrained by nature. The authors aim to minimize the energy consumption of the cognitive sensor nodes and prolong the lifetime of the network using an R-coefficient that is determined by sensor energy information and PU behavior, in order to predict the residual energy. The cognitive sensor network is split into clusters, assuming that the Cluster Head (CH) is rich in energy, so the focus is on the Cluster Members (CMs). The energy consumption of the data transmission is calculated via $E_{cir} + \varepsilon d^{\alpha}$, where E_{cir} is the Radio Frequency (RF) circuit energy consumption and ε is the amplifier energy required at the receiver, both calculated at each time-slot. Based on the previous expression, assuming the free space propagation model where $\alpha = 2$, if the cognitive sensor node i transmits for l continuous time-slots, the total energy consumption of the node is computed by:

$$E_i(l) = (E_{cir} + \varepsilon d_i^2)l, \tag{24}$$

where d is the distance between the CM and the CH. Since the transmissions of cognitive sensors are limited by the possibility of a PU transmission, the statistically expected energy consumption for a sensor i on channel j is computed as:

$$\widetilde{E_{ij}} = \sum_{l=1}^{L} E_i(l) Pb_j^l + E_i(L) Pb_j^{success}, \tag{25}$$

where $Pb_j^l = (1 - p_j)^{l-1} p_j$ is the probability that a sensor transmits only l time-slots due to collision with a PU and $Pb_j^{success} = (1 - p_j)^L$ is the probability that channel j is idle in L time-slots (p_j is the probability that channel j is busy). The R-coefficient representing the predicted *Residual Energy* is given by

$$Res_{ij} = Res_i^c - \widetilde{E_{ij}}, \tag{26}$$

where Res_i^c is the residual energy of the sensor node. This expression gives a prediction for the energy that will remain on the sensor node if it transmits on the channel j and can be used as a utility function for the channel assignment algorithm. This approach does not take into account the energy consumed when sensing the spectrum prior to transmission. Spectrum sensing consumes a significant amount of energy (i.e. for channel switching) and thus this energy should be incorporated within the previous equation.

Common Assumptions: The common assumptions that are made in the works that aim to maximize the energy efficiency of the SUs are the following:

- *Node cooperation*: Most works assume that neighboring nodes cooperate exchanging information for using the same transmission power.
- *Transmission power*: All works transform the problem of maximizing energy efficiency into the problem of minimizing transmission power of the SUs.
- *Power allocation*: Due to the previous assumption, the SA is very often combined with power allocation into a joint framework.

8) ***Risk:*** In [93] the concept of risk in cognitive radio network data flows is introduced. The reliability of a data flow is calculated as the probability that the path of the flow is blocked by emerging primary users, assuming that a SU is not allowed to transmit at the same channel with a PU. Thus, the basic goal here is to find the probability that a PU is accessing the spectrum and then select the channel with the minimum probability. The risk is calculated by

$$Risk(x) = 1 - \prod_{n=1}^{N} (1 - e^{-z_n}), \tag{27}$$

where

$$z_n = \sum_{i \epsilon C_n} \sum_{c=1}^{C} v_{i,c} x_{i,c} \tag{28}$$

and

$$v_{i,c} = -\log(1 - Pf_{i,c}). \tag{29}$$

In the above equation $Pf_{i,c}$ is the probability that channel c is not occupied by the SU i and $x_{i,c}$ is equal to 1 if channel c is assigned to the geographic location i (here the authors assign channels to geographic locations rather than standalone users). The goal of the paper is to find the optimal channel assignment that minimizes the risk given in equation (27) under the constraints that each location is assigned one channel and that each channel is assigned to only one specific location. The authors present both centralized and decentralized algorithms and perform risk analysis to study the redundancy allocation for multiple data flows, as well as with channel reuse.

Common Assumptions: The common assumptions that are made in the works that aim to minimize the risk of a PU accessing the selected channel are:

- *Channel independency*: The occupancies at different channels are assumed to be mutually independent.
- *Single channel transmission*: The SUs are able to transmit only on one channel, although they can sense multiple channels simultaneously.
- *Single channel allocation*: Each channel is assumed to be assigned to only one SU at a specific time.
- *Perfect knowledge*: The SUs are assumed to have perfect knowledge of the channel availability probabilities.

9) ***Network connectivity:*** Maintaining network connectivity is of paramount importance for traditional wireless ad-hoc or mesh networks in order to provide users with the requested QoS. If the communication links use the same frequency range, the distance of the nodes and the transmission power are the other two parameters that may affect the network connectivity. On the other hand, in CRNs and especially in Cognitive Radio Ad-Hoc Networks (CRAHNs), the network connectivity is affected not only by the transmission power and distance, but also by the frequency that the different links use. A study on the connectivity of a CRAHN is given in [105]. Two nodes may communicate if and only if they are within their transmission range, which is affected not only by the transmission power, but also by the frequency they select.

In [95] the authors investigate the impact of spectrum assignment on the connectivity of CRAHNs. The cognitive network is modeled by a graph and using graph coloring rules the authors evaluate the connectivity of the resulting network. Their results prove that the interference among SUs has a high impact on the connectivity of a CRAHN and different approaches have a different impact. Thus, when network connectivity is a criterion, appropriate graph coloring/labeling rules can be selected for spectrum allocation. In [96] the spectrum allocation problem is also investigated from the network connectivity perspective. The authors here also form a network graph with the network flows and the connectivity between the SUs and try to assign channels to the SUs (colors to the graph nodes) preserving the existing connectivity between the nodes, while minimizing the interference within the network.

The issue with the existing approaches using network connectivity as a criterion is that they focus exclusively on maintaining the network connectivity without considering other criteria. Although maintaining network connectivity is a major issue in CRAHNs, the quality of the links should also be taken into account in order to ensure delivering flows with high QoS. For example, the connectivity of the network could also be achieved by links with a very low throughput, but this may be unacceptable for most applications. Further work in this area should include multiple criteria for ensuring the QoS of the flows after the spectrum allocation.

Common Assumptions: The common assumptions that are made in the works that aim to maintain network connectivity are:

- *Fixed communication graph*: The CRN is assumed to have a fixed communication graph that is formed before the execution of the channel assignment algorithm.
- *Co-channel interference*: Most works consider only co-channel interference.
- *Stable channel*: The channel status is assumed to be stable for a short period of time during the SA execution.
- *Centralized*: All works consider centralized solutions, where a central node/module has all the necessary information to execute the SA.

C. Spectrum assignment approaches

In this subsection, the basic approaches for spectrum assignment are presented. Table III summarizes the characteristics of these approaches.

1) ***Centralized versus distributed spectrum assignment:*** Cognitive radio networks can operate in either centralized or distributed mode and so, spectrum assignment algorithms can also be classified in these two categories. Usually, centralized SA requires the existence of a central node that performs most of the actions and takes decisions on assigning the channels to the cognitive nodes. This central node may be a separate network entity called *Spectrum Server* or *Spectrum Broker* ([2]) or a central base station ([106]) that collects spectrum and radio information from all SUs either periodically or on demand. Centralized schemes have been considered in many works i.e. [35], [47], [49], [54]. A centralized SA scheme has several advantages due to the global view of the network that

TABLE III
BASIC SA APPROACHES.

Approach	Characteristics	Advantages	Disadvantages	References
Centralized	Spectrum server receives measurements from SUs and takes decisions.	Optimal decisions through the global view of network performance. Can achieve fairness between SUs. Integrates topology control and connectivity maintenance. Can use priorities for most important SUs	High signaling between SUs and the spectrum server. Not robust to spectrum server failures.	[35], [47], [49], [54], [55], [56], [58], [74], [76], [83], [106], [107], [108].
Distributed	SUs take decisions either as standalone or in cooperation with other SUs. Neighbor SUs exchange information for achieving good solutions. No central entity exists.	Faster decisions. High flexibility - can adapt quickly to network outages, node failures, etc. Low signaling overload.	Not optimal decisions (only locally). Very difficult to achieve fairness among SUs.	[41], [46], [53], [64], [65], [85], [91], [94], [109], [110], [111], [112], [113], [114]
Multi-channel selection	Spectrum aggregation. Capable of transmitting on multiple spectrum fragments (contiguous or not) with one radio interface.	Higher datarates. Maximum spectrum utilization.	Higher switching overhead. Transceivers may have short maximum span resulting in reduced spectrum utilization. Can increase interference when transmitting in multiple channels.	[44], [52], [115], [116]
PU not considered	Only SUs are taken into account. A set of available channels not utilized by PUs are assumed. The goal is to avoid interference between SUs and maximize their utilities.	Simplified approach.	Needs a predefined set of channels, but due to the dynamicity of the environment and the PU activities, these channels may become unavailable later.	[33], [53], [61]
PU considered	PUs' presence is included in the decision making process. Target is to avoid interfering not only between SUs, but also with PUs.	More realistic approach.	Needs cooperation with PUs to exchange measurements or needs knowledge of PUs' location and techniques to calculate the interference caused to PUs.	[38], [47], [49], [51], [102], [117]
CCC-based	Assumes or requires the existence of a common control channel for the coordination of the SA between the SUs.	Ensures the cooperation between SUs and is a simple approach.	Susceptible to DoS or jamming attacks. CCC may become congested if there are many SUs in the area. Needs a CCC allocation algorithm. Does not achieve maximum spectrum utilization.	[44], [61], [64], [80], [92], [112], [118], [119], [120]
no CCC	There is no CCC for the exchange of control messages between the SUs.	All channels are available for transmission, thus maximum spectrum utilization may be achieved.	Vulnerable to hidden node and deafness problems. May decrease the level of network connectivity.	[97], [121]
Segment-based	Network is divided into segments, the nodes of each have at least one common channel. Gateway nodes connect the segments.	Simple approach, achieves less channel switching.	Requires cooperation between nodes and an initial handshake between them, which is not defined how it should be done. Gateway nodes could be easily congested.	[81]
Cluster-based	Focuses on cognitive mesh networks, divided into clusters. At each cluster there is a cluster head gathering measurements from the nodes. Cluster heads exchange measurements and take decisions for spectrum allocation.	Achieves better load balancing distributing users into clusters. Reduces cooperation overhead.	Cluster heads can easily be congested. When a cluster head fails, the nodes should enter new clusters, which may not be always feasible and takes time.	[41], [59], [122], [123], [124]

the spectrum broker has: it is easier to maximize the overall network throughput and to minimize interference between SUs and in general the network performance. Furthermore, the spectrum server can also be used to achieve fairness in terms of either allocated spectrum or throughput minimizing the number of greedy users that use many spectrum bands to increase their throughput, causing problems to other users. The above targets cannot be achieved simultaneously, but the centralized SA can selectively achieve better results for these criteria. Centralized SA can integrate topology control using conflict graphs to minimize the interference between SUs. Connectivity maintenance is another key advantage because the global view of the network can help avoid disconnections. Moreover, the spectrum server can use priorities to links or nodes with constrained interfaces to ensure that these links will have high throughput, i.e. for links close to gateways. On the other hand, a major disadvantage of centralized cognitive SA is that it induces signaling overhead in the network, because of the need to exchange measurements between the SUs and the spectrum server. In addition, if the spectrum server fails due to crashes or power failures, then spectrum assignment will not be possible and each SU will choose its own channel(s) independently leading to contention and unfairness.

In distributed cognitive SA (i.e. [41], [46], [53], [64]), no central entity is responsible for assigning channels to cognitive users. In this case, users take decisions either by themselves or by cooperating with their neighbours, through the exchange of information, measurements and channel assignments with other SUs within a specified range (i.e. within 2-3 hops). In distributed channel assignment for traditional wireless networks ([125], [126]), each node calculates a metric, sends the information to its "neighbors", calculates the traffic load of each channel and then each node selects the channel with the minimum traffic load or the one that creates minimum interference to its neighbors (or according to some other metric). Distributed SA is usually more flexible, because it can quickly adapt to possible changes or network outages because only SUs in the affected area will have to make changes and exchange information. This is a much faster process compared to a centralized spectrum server, which may change the spectrum assignment of the whole network to react to changes or outages. Another advantage of distributed SA is that it incurs a lower signaling overload in the network, since only neighbor nodes have to exchange messages. Decisions are usually taken much faster, but are not optimal because the nodes have knowledge only for neighbor SUs and not for the whole network. However, fairness can only be achieved locally for a group of neighbor SUs and not globally for the whole network. Another issue with distributed schemes is that the decisions are based on the exchange of measurements between the SUs, thus inaccurate or misleading information can significantly affect the results. In this way, malicious users can send false information about spectrum holes in order to exploit them for their own benefit. Furthermore, there is an incentive for SUs to actually participate in the exchange of measurements. Distributed cognitive SA can usually take adequate decisions in cases of low traffic load, but in high traffic load situations, a centralized scheme, having knowledge of the traffic in the whole network, can take better decisions.

2) ***Multi-channel selection:*** In traditional channel assignment, the assigned channels have a central frequency and a specific bandwidth around that frequency. This means that "traditional" channels are contiguous in the spectrum and each one consists of contiguous spectrum fragments. In the case of multi-radio devices, each radio interface is assigned a separate channel, as in [115], where a multi-radio cognitive mesh network is considered. Recent advances in cognitive wireless radio technology have enabled simultaneous access to several spectrum fragments (i.e. with the use of Discontiguous Orthogonal Frequency Division Multiplexing - DOFDM), by aggregating these fragments into one channel, increasing each SU's bandwidth [52]. This results in better spectrum utilization, because separate small fragments (previously not suitable for use as standalone fragments) can now be aggregated into one channel, large enough to meet the bandwidth demands of a SU. Considering the use of multi-radio devices (i.e. in a cognitive mesh network) capable of accessing simultaneously multiple spectrum fragments, can dramatically increase the network capacity, giving users the capability of much higher data rates.

Although the use of spectrum aggregation seems promising for achieving better spectrum utilization and higher data rates, there are also some limitations, especially at the transceivers' side [52]. The transceivers cannot aggregate spectrum fragments that are far away, meaning that the span of the aggregated bands is not unlimited and there is usually a maximum span specified for each transceiver, e.g. 10 MHz. This means that if two spectrum fragments are separated by more than 10 MHz, they cannot be aggregated into one channel. This is important for the design of the SA algorithms, because the characteristics of each transceiver should be taken into account to assign the available frequency fragments efficiently. Moreover, the algorithms should avoid creating new small fragments that will not be able to be aggregated later. Spectrum aggregation based on the maximum span of fragments can aggregate portions of free fragments inside the maximum span, but leave smaller portions unutilized. For example, if the bandwidth demand is for 6 MHz, the maximum span is 10 MHz and there are two fragments of 4 MHz and 3 MHz separated by a used fragment of 4 MHz, the algorithm could take 2 MHz from the second fragment and leave 1 MHz unutilized. This could create problems when trying to utilize the remaining small fragment of 1 MHz later. In such a case, spectrum sensing can find other spectrum fragments that can be used in a more efficient way.

Another consideration when simultaneously accessing multiple channels is the overhead that is incurred by frequent channel switching, as this may prevent a SU from selecting a large number of multiple channels even if they are available [116]. Moreover, since each SU is not alone in the network, the optimal allocation of multiple spectrum fragments should be considered to avoid spectrum overutilization from some SUs and starvation of others.

In [44] the authors consider a multi-channel multi-radio cognitive radio network, stating that these characteristics result in a higher dimension problem in comparison to the single-radio networks. In this work the total available bandwidth is assumed to be split into K orthogonal channels with equal bandwidth. The concept of multiple channels at a link is simplified using the term "logical links". A physical link that transmits at K channels is broken down into K different logical links, each with a different channel between the same pair of nodes. In this way, the problem is transformed into a single channel problem and the spectrum assignment is jointly considered with scheduling, so that an assignment specifies which logical links transmit at each time.

In the literature so far there are only a few works on assigning multiple-channels or multiple spectrum fragments (either contiguous or not) in cognitive radio networks. A challenge for future works is to investigate algorithms for multi-radio cognitive devices capable of performing spectrum aggregation. This creates another level of complexity in the algorithms decisions, because the impact of interference of the multiple spectrum fragments among the multiple radio interfaces should be taken into account, because interference among the interfaces can dramatically decrease the performance of the network.

3) ***PU or not PU?:*** A basic dilemma when deciding to work on spectrum assignment in cognitive radios is whether the algorithm will take into account the presence of PUs within the core of the system model or not. Although one of the basic requirements for CR technology is that the operation of SUs should not affect the performance of primary networks, this is not always considered in the literature. Most works assume that the SUs have a fixed set of available channels which are separate from the channels of the primary users [33], [53], [61]. Based on this assumption, the target of the respective SA algorithms is to distribute the channels of this fixed set among the SUs according to some criteria. These approaches almost disregard the existence of PUs, because they only use them to limit the number of channels that the SUs are allowed to use, without directly considering the PU in the system model. Thus, these approaches are quite similar to traditional channel assignment in wireless ad-hoc or mesh networks, where the nodes have to select a channel from the available list of WiFi channels, according to some criteria.

Other works ([47], [49], [51], [102], [117], [38]) consider the PUs in the core system model and try to assign channels to SUs in such a way that the interference caused to PUs is kept to a minimum and under a certain threshold (which in the literature is mainly defined by the ITL). This approach requires either the cooperation of the primary network (distributing the measurements of PUs to the SUs) or that the SUs know the location of PU nodes so that they can calculate the interference they cause to them. In [51] the target is to protect the transmissions of the PUs from the transmissions of the SUs, taking into account the SINR at each primary receiver and ensuring it to be above a predefined SINR threshold $\overline{\gamma^p}$. Assuming that a primary transmitter operates on channel c, and transmits with power $\widetilde{P}^p_{i,c}$, then the following expression should be fulfilled.

$$\frac{\widetilde{P}_i^c \cdot G_{i,c}}{N_o + \sum\limits_{j=1, j\neq i}^{M} \widetilde{P}_j^c G_{j,c} + \zeta} \geq \overline{\gamma^p}, \tag{30}$$

where ζ is a positive constant, which defines the amount of extra interference that a SU can cause to the PUs, without severely degrading their performance. Thus, when the above constraint is satisfied, the CRN users can also use the licensed channels of the PUs in that area.

4) ***CCC or not CCC?:*** One of the most common requirements for spectrum assignment in CRNs is the existence of a Common Control Channel (CCC) for the coordination of the channel allocation between the SUs. CCC is a pre-defined channel used for exchanging control information between the SUs. There may be a global or a local CCC, depending on the network operator. The global CCC is the same for all SUs in a CRN, whereas the local CCC is dedicated to only a small geographical area. Although there are many works in the literature that investigate the allocation of a CCC in a CRN, these are out of the scope of this survey paper, because they are not related with the actual cognitive SA problem.

The SA approaches can be divided into two categories related to CCC: (i) those that assume (or require) the existence of a CCC for the coordination between the SUs and (ii) those that do not require the existence of a CCC. Most previous works in the literature belong in the first category (i.e. [64], [80], [112], [118]). The nodes are using at least one predetermined channel for the exchange of control data, which means that not all channels are available for data transmissions. On the other hand, this simplifies the coordination problem. Furthermore, the (known) CCC is vulnerable to a variety of attacks, such as Denial of Service (DoS) or jamming. That way if the CCC has limited or no functionality, the network performance may degrade dramatically. Moreover, the execution of efficient control channel assignment algorithms is required in order to find the optimum control channel in the geographical area of the cognitive network.

On the other hand, there are only a few approaches (i.e. [84], [97], [121]) that avoid using a common control channel for cognitive spectrum assignment. In [121] the problem of intra-cell channel assignment in a 802.22 cognitive network is investigated, assuming that there is no dedicated CCC. The authors assume that the SUs exchange control messages in the free channels and propose a heuristic for the channel allocation. The cognitive base station is responsible for the SA and informs the SUs of the free channels, using beacon broadcasts in all the free channels. The SUs listen to these beacons and form the set of free channels, from which they select the optimum according to some criteria. Although this process seems quite simple there are a number of issues it may face, including security holes (malicious users may jam the beacons of the base station so that fewer channels are available to the SUs) and a long time needed to finalize the channel allocation because the SUs have to switch to all channels in order to detect which channels are free.

In [84], [97] the authors propose to use a different mode of operation of the SUs in order to avoid the requirement of using a dedicated CCC. The proposed mode is the Tunable Transmitter - Fixed Receiver (TT-FR), which allows the SUs to transmit on any channel, but restricts them to receive only on one fixed channel (known to all their neighbors). Since all SUs know the channel for transmitting control information to another user, there is no need for a control channel. The goal of this work is to find the TT-FR allocation that serves the maximum number of SUs. The issues with this approach is that it is vulnerable to the hidden node and deafness problems and it may result in a decreased level of connectivity, because of the limitation in the use of channels for transmitting to the end users. Furthermore, the use of only one receiving channel limits the maximum performance of the SUs and the network as a whole.

5) ***Segment-based:*** In [81] the term “segment” is used for the spectrum assignment problem and is defined as the maximal set of connected nodes that have access to at least one common channel. Furthermore, the authors define the term “segment gateway nodes” as the nodes at the end of a link that connects two segments. Their strategy assigns the same channel to all nodes within a segment, which they call “operational channel”. The proposed approach includes a channel assignment scheme and an adaptive segment maintenance scheme. During an initial handshake, the nodes exchange the operational channel and the available channel list information in a round robin manner. However, the authors do not mention how this exchange is realized, i.e. if they use a control channel or not. The channel assignment scheme integrates channel assignment, segment formation, and route discovery. The segment formation is performed jointly with channel assignment, but due to the variable spectrum utilization, two scenarios for segment splitting and segment merging are also proposed. This approach is different from traditional cognitive radio approaches and is quite simpler, achieving less channel switching and having better performance results than traditional link-based and flow-based approaches. However, this approach was not compared with other CR-based approaches. Furthermore, it is assumed that the CR nodes have a single radio interface, which is not always the case.

6) ***Cluster-based:*** In [59], [122], [123], [124] the cognitive mesh network is divided into clusters. This approach is a hybrid solution between centralized and distributed spectrum assignment, which tries to avoid the disadvantage of each. The network consists of mesh routers which are fixed and mesh clients which can be mobile. The network is divided into M clusters, with each cluster having a router as a cluster head. Each SU sends its sensing results to the cluster head, which combines the results and generates a final spectrum allocation vector. The cluster heads exchange these vectors and then each cluster head decides which spectrum bands to use and broadcasts the decision to all cluster members. To address cluster head failures, when the SUs do not receive data from a cluster head for some period, then they assume that the cluster head has failed and subscribe to the closest cluster. This scheme has several advantages: it is robust to cluster head failures; it achieves better bandwidth utilization by distributing users into clusters and distributing the load into multiple channels; it reduces the communication overhead of distributed approaches, because the exchange of messages takes place only within each cluster and not in the whole network; it enables bandwidth reuse, in the same way as it is achieved in Global System for Mobile Communications (GSM) networks. A disadvantage of this scheme is that mesh routers can easily become congested, if they forward a lot of traffic from their cluster to another cluster. To avoid the congestion of mesh routers, the structuring of the clusters should be performed very carefully and dynamically adapt to the load. A cluster-based network is also considered in [41]. However, the approach followed is not much different from the case of traditional CRNs.

IV. TECHNIQUES FOR SOLVING THE SA PROBLEM

In this section the most common techniques that are used for solving the spectrum assignment problem in CRNs are presented. Table IV presents a summary of these techniques, listing their characteristics, advantages and disadvantages.

A. Heuristics

The problem of finding an optimal solution for cognitive spectrum assignment has often high complexity and determining good solutions quickly becomes very difficult. As mentioned in [156] the channel assignment problem belongs to the class of NP-complete problems. There is no known algorithm that can generate a guaranteed optimal solution in an execution time expressed as a finite polynomial of the problem dimension. To address this issue, *heuristic* methods are often used to speed up the process and find a good solution quickly in cases where an exhaustive search is impractical, because they do not require restrictive assumptions of the optimization routines and they permit the use of models that are more representative of the real-world problems [157]. Heuristic techniques can give a near-optimal solution at reasonable computational cost for algorithmically complex and time-consuming problems. Although some of the techniques described in this section, such as genetic algorithms and fuzzy logic are considered as heuristic algorithms, they are presented in different sections because of the specific characteristics that each of these methods has.

Since heuristic methods do not have a specific algorithmic solution, many works in the literature have presented their own simple algorithms (greedy or not) to solve the optimization problem of cognitive SA, e.g. [34], [43], [45]. Heuristic methods typically consider an iterative algorithm, which at each iteration finds the optimal solution, which can be, in our case, the SU that has the highest utility for accessing the spectrum, the channel with the highest SINR or lowest traffic, etc.

In [43] a heuristic channel assignment method is presented in order to lower the complexity of the optimization problem they present, which is $O(n^3)$, where n is the number of SUs that try to have spectrum access. The proposed algorithm selects randomly at each step a PU and a cooperating cognitive device, which scans the selected channel to obtain the transmission power of the PU and the channel state information. Assuming that the PUs are less than the SUs, after some iterations all the primary channels will be scanned and the cognitive users will select their channel.

In [127] the channel assignment problem is expressed as an Integer Linear Programming (ILP) problem and a heuristic scheme is proposed, claiming to provide a suboptimal solution with lower complexity. The key idea behind this scheme is to assign channels with low SINR to short-distance transmissions and to use local information for assigning more long-distance transmission channels. Two procedures are given, one for a static CRN with known traffic demands and one for a dynamic CRN with unknown traffic demands. The general idea is to divide the available bands into M sets and each CR user i constructs a preferable channel list for the other CR users according to the distance from i and the SINR of the channel, assigning the lower SINR channels to the closest users. The method assumes the existence of control channels and defines several control messages for the communication between the nodes.

The advantages of heuristics is that they are simple, they can be easily implemented and in many cases they can find high-quality solutions. Furthermore, they tend to be less sensitive to variations in problem characteristics and data quality [157]. A disadvantage of heuristics is that although, in theory, the solutions are problem-independent, most of the developed heuristic approaches are problem-specific and cannot be used for other problems. In addition, there is no analytical methodology to explain their convergence properties and they get stuck in local optimal solutions, which can be far from the global optimal solution.

TABLE IV
METHODS FOR SOLVING THE SA PROBLEM.

Technique	Characteristics	Advantages	Disadvantages	References
Heuristics	Iterative algorithms, finding at each iteration the best local solution , i.e. best available channel for SU, SU with higher utility, etc.	Simplicity, easy implementation, speed, can be insensitive to specific problem characteristics.	Most developed approaches are problem-specific. There is no analytical methodology for studying their convergence. Can be limited to “local minimas” and not to optimum solutions.	[34], [43], [45], [55], [58], [79], [113], [115], [127]
Graph theory	CRNs are visualized as graphs. Use conflict graphs, graph coloring or bipartite matching. Interference is modeled using conflict graphs.	Use existing solutions of graph theory.	Simplified assumptions. Cannot incorporate all parameters of CRNs, such as QoS requirements, ACI, etc.	[42], [43], [46], [47], [49], [51], [56], [57], [60], [71], [73], [74], [76], [78], [79], [83], [94], [109], [128], [129], [130], [131], [132], [133], [134], [135], [136]
Game theory	SA is modeled as a game where the SUs are the players. Solution is found through Nash equilibrium. Can use several utility functions, e.g. for selfish or cooperative users, fairness, to minimize spectrum handovers, etc.	Solid decision making framework. Can be used for both cooperative or non-cooperative approaches.	Difficult to structure the game in a way to guarantee equilibrium is always reached.	[32], [33], [36], [54], [60], [90], [82], [117], [137], [138], [139], [140], [141], [142], [143], [144], [145], [146], [147]
Linear programming	The join power control/SA problem can be modeled as a MINLP problem and then into a BLP problem that contains only binary parameters. It is solved using LP techniques.	Use of existing LP techniques.	Transformation from MINLP into BLP is not ensured and requires several assumptions, e.g. binary (0, max) transmission power.	[39], [42], [53], [61], [62], [66]
Fuzzy logic	Uses a set of rules for decisions, utility and membership functions for optimization and weights respectively.	Fast decisions based on the predefined rules. Learning techniques can improve the quality of the decisions.	Limited functionality because the rules are predefined. Needs a large number of rules to consider all parameters of CRNs. Dynamic nature of CRNs makes it hard to determine accurate rules.	[148], [149]
Evolutionary algorithms	Stochastic search methods that mimic evolution and social behavior. Chromosomes specify a conflict-free SA matrix. At each iteration a new SA is generated and it is evaluated using objective functions.	Can handle arbitrary kinds of constraints and objectives. Bad proposals for solutions are simply discarded.	Slow process for finding optimal solution. A possible risk includes finding local minimas.	[37], [63], [114], [150], [151], [152], [153], [154], [155]

B. Network graph based

Every network can be visualized as a graph, where the vertices correspond to the mobile devices or nodes and edges correspond to the connections between mobile devices. Network graphs have been extensively used in cognitive spectrum assignment, mostly for cases where the structure of the network is considered known a priori [158].

To solve graph-based spectrum assignment problems, several techniques can be used. The most common one is based on constructing the *network conflict graph* that captures the interference between neighbor SUs, i.e. [46], [60], [74]. Concurrent transmissions by neighbor nodes within the interference range in the same or neighboring channels cause interference that reduces the network performance. A conflict graph can be simple, weighted, multi-point or dynamic. A first step is to form the connectivity graph, which shows the connectivity and the communication between the network nodes. Figure 3 shows an example of how to construct a conflict graph. In Figure 3a an example network is given and Figure 3b shows the respective conflict graph and the interdependencies between the links of the network.

The vertices of a conflict graph correspond to the links between the nodes and the edges are drawn between links (vertices) that can interfere with each other when assigned the same or adjacent spectrum bands. In weighted conflict graphs, the weights on the edges represent the interference model or the required channel separation between the links. Multi-point conflict graphs can be used to simplify the conflict graph in cases where a single SU is transmitting to multiple receivers. Another approach uses dynamic conflict graphs to capture the possible changes in the interference due to the assignment produced in each step. Dynamic conflict graphs are formed at each step of the SA algorithms and take into account the aggregated interference effect [42], [47].

Conflict graphs are commonly used in centralized approaches where the spectrum server constructs the graph and assigns the channels. In distributed approaches, the SUs themselves form the sets of available channels and negotiate with their neighbors which spectrum bands to select in order to avoid interference between the links and maximize their performance. Although there are many algorithms proposed so far in the literature using conflict graphs, to our knowledge, they all consider a network with SUs only. Future works should be extended to include also PUs in the graphs, to limit the sets of available channels in links in the neighborhood of operating PUs.

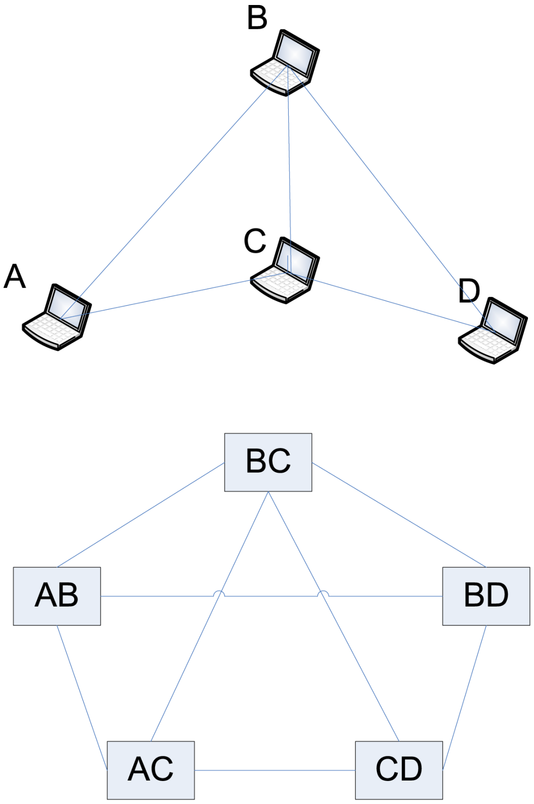


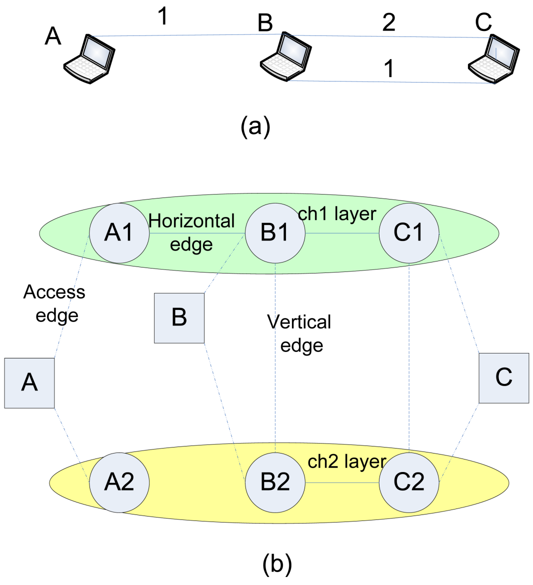
Fig. 3. An example of constructing a conflict graph.

Graph coloring is widely used in cognitive SA algorithms (e.g. [57], [71], [73], [74]), where the cognitive network is mapped to a graph, which is either uni-directional or bi-directional according to the algorithm's characteristics. The vertices correspond to the SUs that share the spectrum and the edges show the interference between the SUs. Some works also include the PUs in the graph, but these have been assigned a color a priori. The colors can be either at the vertices or at the edges, representing the spectrum bands that are assigned to the SUs or the links respectively. The spectrum assignment problem is equivalent to coloring each vertex (or edge) using various colors from a specified color list (spectrum availability list) to achieve a target objective. The basic constraint used in the literature is that two connected vertices (SUs) cannot be assigned the same color (spectrum band). Although this is generally accepted, it does not reflect the Adjacent-Channel Interference (ACI) that has been shown to cause severe performance degradation when links are close to each other. Future work in graph-coloring based cognitive SA should incorporate another layer in the color graph corresponding to the ACI and prevent connected vertices from using either the same or adjacent spectrum bands.

Many previous works have transformed the cognitive spectrum allocation problem into a *bipartite matching* problem (i.e. [42], [43], [49]), creating a bipartite graph with the available channels on the one side, the SUs on the other side and the connections between the two sides corresponding to the available channels. Common techniques such as the Hungarian algorithm can be used to solve the bipartite matching problem, but can lead to the starvation of some SUs. Thus, improvements have been proposed to solve the starvation problem, by specifying some restrictions to the decisions of the algorithm, such as, assigning, initially at each step, channels to the starving SUs. Although this approach does not give an optimal solution, it solves the starvation problem.

Another approach is given in [83], in which the construction of a layered graph to model the cognitive network is proposed. This layered graph models the channel information at each node and shows the interconnection between channel assignment and routing paths, resulting in much easier procedures for shortest path search. The constructed graph will have as many layers as the number of available channels and for each node, a subnode is associated at each layer. Three types of edges are defined: (i) access edges, connecting a node to its subnodes; (ii) horizontal edges, connecting the subnodes in the same layer representing the physical connection between the nodes; (iii) vertical edges, connecting subnodes of the same node (between the different layers) showing the data forwarding capability between different channels at a node. An example of layered graph construction is given in Figure 4. The authors claim that using a layered graph it is easier to find a path that connects two nodes, simply by performing a shortest path search. The nodes can choose different channels for the incoming and the outgoing links, reducing the interference between neighboring nodes on a path and improving spectrum utilization. As channel switching is induced to enable this approach, the authors include a "cost" at each node (the nodes need to switch between the receiving and the transmitting channel if single-radio nodes are considered). After constructing the layered graph, the authors propose a path-centric channel assignment method to find the optimal channels of the nodes. Although the method simplifies (as it claims) the problem of finding the optimal path between CR nodes in a network, it has several disadvantages that can reduce its performance. Using different transmitting and receiving channels could result in a much lower performance due to the channel switching delay. Furthermore, in large networks the construction of the layered graph may be a rather complicated and time-consuming procedure.

In [136] the construction of a factor graph is proposed to simplify the spectrum assignment problem. A factor graph models the interference between network nodes, which can include factor nodes and variable nodes. A factor node represents the interference relationship between two or more variable nodes and is usually represented by an edge between two nodes. The graph is directed because the channel for the link between two nodes is assumed to be different for the two directions. Furthermore, each link is assigned a weight, which depends on the transmission power and channel gain. After constructing the factor graph, the authors propose the Distributed Wave Algorithm (DWA) to solve the SA problem. The Maximum Interference Spanning Tree (MIST) is generated based on the factor graph, picking the node with minimum distances from all the leaves as the root node. Then, the nodes calculate a utility and after a two step process (starting from the leaves and starting from the root) select their channels aiming to minimize this utility.



(a)

(b)

Fig. 4. An example of constructing a layered graph.

C. Game Theory based

Game theory is a mathematical framework that has been widely applied to various engineering design problems, where the action of one actor/player impacts (and perhaps conflicts with) that of other components. In a multiuser network, wireless services are provided to rational users that seek to achieve the maximum performance. Therefore, game formulations can be used, and a stable solution for the players can be obtained through the concept of equilibrium. In the literature many works have applied game theory to solve the cognitive SA problem, e.g. [32], [33], [36]. The concept of game theory fits quite well with the cognitive SA problem, because the decision of one SU regarding the spectrum to allocate directly affects the performance of neighboring SUs [60]. There are two types of games; cooperative and non-cooperative, based on whether the users exchange information regarding their decisions or not, respectively. In the literature, most related SA algorithms formulate a game and try to find the optimal solution through the Nash equilibrium.

A cognitive SA game usually has three sets of elements: the players, the action space and the utility function(s). The players are the SUs or cognitive radios that take part in the game and contend for channel access. The PUs can also be active players, although their sets of frequencies may be constant and used only to avoid being selected by the SUs. The players have a set of functions, which is the set of available frequency bands and the action space is the cartesian product of the sets of actions of all players. Moreover, each player has a utility function that is used to translate the action space into the real world needs, namely the frequency bands to meet the SU requirements. The objective is to maximize each SU's utility function, by taking into account the impact of its decisions on the other players. For games with specific characteristics, a steady state solution always exists, and any unilateral change of a player results in a lower utility for that player. This solution is called the Nash Equilibrium.

A utility function may account for:(i) “selfish users”, evaluating each channel based on the level of interference perceived on that particular channel, or (ii) “cooperative users”, by additionally taking into account the interference to neighboring nodes [33]. Other utility functions account for fairness among the players (as in [60]) and target to maximize spectrum utilization by allocating spectrum units as fairly as possible, taking also into account the possibility to have different priorities for each SU. Another possible utility function may be used to minimize spectrum handovers (as in [82]). The utility function can also integrate two-way conflicts not only from the current device to the neighboring devices, but also from its neighbors to this device, by considering in the calculations parameters such as interference, bandwidth and holding time, with the possibility of having also the preference of SUs integrated in the function.

In [141] the problem of SA in cognitive radio networks is solved using a game theory technique called “stable matching”, using the Gale-Shapley theorem [159]. The stable matching theory was proposed for studying the stability of marriage and the one-to-one function that matches the preferences of men to the preferences of women and showed that for any two sets of preferences there is always a stable matching. A matching is stable if for any pair, the man prefers its partner over any other woman or the woman prefers its partner over any other man. The problem of channel allocation in [141] is studied using the stable matching theory, by assuming the users and the channels correspond to men and women respectively and the preferences could be expressed via a utility function, however without proposing a specific function. The authors present a decentralized version of Gale-Shapley assuming two sets of users: (i) roaming users that at each time-slot transmit to the best channel out of those not tried yet and (ii) non-roaming users that at each time-slot transmit to the same channel they transmitted in the previous time-slot. On each channel, the best user (according to a utility function) is declared as non-roaming, while all the other users are declared as roaming users. In that way, a matching between users and channels is constructed. After a number of time-slots (required by the Gale-Shapley theorem) the matching becomes stable and an equilibrium is reached. This approach does not consider the dynamic nature of cognitive radio networks, which results from the mobility of the users, users' dynamic service requirements and the existence of primary transmissions.

In general, game theory has been widely used in cognitive SA algorithms because it is a powerful decision making framework that can be used both for cooperative and non-cooperative decisions between SUs. The main disadvantage of this approach is that the utility function and the game formulation must be very carefully structured in a way to achieve equilibrium, because this is not always guaranteed. Furthermore, the performance in the equilibrium is also affected by the game formulation and the utility function.

Spectrum auctions/markets: Auction theory is an applied branch of economics studying the way that people behave in auction markets. It has been applied to the analysis of problems with conflicting objectives among interacting decision-makers. It can be considered as a specific branch of game theory, because it is a collection of game-theoretic models related to the interaction of bidders in auctions [142]. Spectrum auctions or spectrum markets have been widely studied in the literature as a solution for the spectrum assignment problem, e.g. [143], [145], [146], [147]. The SUs contend for the same channels and a regulator conducts an auction to sell the rights on a set of channels to primary and secondary networks. Several utilities are defined according to traffic demands and based on these, the SUs/PUs bid for the channel rights. The spectrum allocation problem is then solved by the regulator aiming either to maximize its revenue or the social welfare of the bidding networks [143]. To maximize the social welfare, the Vickrey-Clarke-Groves mechanism is most commonly used.

In [144] the auction framework allows SUs to share the available spectrum of PUs, which act as a resource provider announcing a price and a reserve bid allocating the received power as a function of the bids submitted by SUs. The SUs are the customers submitting the bids indicating which PU they use as a resource and how much they are willing to pay for a chosen amount of resource. Then a non-cooperative auction game is formulated, which is solved using the Nash Equilibrium.

D. Linear programming based

Linear programming is another commonly used technique for solving spectrum assignment problems in cognitive radio networks (e.g. [39], [42], [53]). More specifically, it has been proved that the joint power/rate control and spectrum allocation problem can be formulated as a Mixed Integer NonLinear Programming (MINLP) problem, which is NP-hard, meaning that the optimal solution grows exponentially with the size of the network [61]. The MINLP problem can be transformed into a Binary Linear Program (BLP) that contains only binary parameters and linear objective function and constraints. This transformation is possible because wireless communication systems are assumed to have a finite number of available channels (each one with a specific maximum power constraint) and the SU's multirate capability is discrete by nature. The transformation from MINLP into BLP is performed to simplify the BLP problem because it has a unimodular constraint matrix and can be solved in polynomial time using standard linear programming (LP) techniques.

A problem with this technique is that the transformation of MINLP into BLP requires some assumptions to transform continuous variables to binary, which may not always be valid. For example, in the literature it is proposed to have a binary-level transmission strategy where the SUs transmit with the maximum available power when the channel is idle and do not transmit when the channel is occupied by a PU. However, using maximum transmission power is not always a feasible solution. On the one hand, power control algorithms change the maximum transmission power in real time. On the other hand, when SUs transmit in PU bands, the SUs transmission power in most cases needs to be lower than the maximum, to avoid interfering with PU transmissions.

E. Fuzzy logic based

Fuzzy logic is a commonly used technique for decision making and optimization algorithms in SA [148], [149]. A Fuzzy Logic Controller (FLC) consists of four modules: a fuzzy rule base, a fuzzy inference engine and a fuzzification/defuzzification module. The fuzzy rule base consists of a set of rules, usually in the form of "IF - THEN", which can be based on prior knowledge, questionnaires or SU measurements. An example of a rule can be:

"IF spectrum utilization efficiency of the secondary user s_1 is F_1^x, and its velocity is F_l^v and its distance to the primary user is F_1^d , THEN the possibility that this secondary user is chosen to access the available spectrum is F_1^p".

The input to the fuzzy logic system can be the arrival rate of the PUs or SUs, the channel availability, the distance between users (either PUs or SUs), the velocity (if SUs are moving), the conflict graph (or any other model that captures the interference relationship between users), etc. These parameters are the input to the fuzzy controller, which takes decisions based on the set of predefined rules as to which SU will select which spectrum band. The rules use membership functions as weighting factors to determine their influence on the final fuzzy output sets regarding the spectrum utilization. Fuzzy logic is used mostly in cases where the configuration of the CRN is known a priori. Only in these cases, for a given set of values, the spectrum assignment can be performed automatically. Moreover, learning techniques can be used to improve the functionality of fuzzy systems. On the other hand, a fuzzy system is not scalable because a large number of rules is normally required for performing SA and considering all the different parameters that can affect the SA decisions, these rules are mainly subjective. All these parameters that should be used as input can make the formulation of rules very difficult. Finally, the membership functions can affect the results dramatically if not structured properly.

F. Evolutionary algorithms based

Evolutionary algorithms are stochastic search methods that mimic natural evolution and the social behavior of species, a category of which are the Genetic Algorithms (GAs). Genetic algorithms are random search techniques used for finding optimal solutions to problems such as cognitive SA ([37], [63], [150], [151], [152]). They are based on the principles of evolution and genetics and they are different from other optimization techniques because they are based on nature's notion of "survival of the fittest". This means that the "fitter" individual has higher probability to survive. To solve optimization problems, GA uses fitness functions and requires the parameters to be coded as chromosomes or finite-length strings over a finite alphabet, which are collected in groups called "populations". The populations are then divided into sets of feasible and infeasible solutions with the first being the channel assignments that satisfy the interference constraints or, in general, the requirements of the spectrum assignment. The procedure used in cognitive spectrum assignment based on genetic algorithms requires the definition of several parts, namely "population", "fitness function", "selection", "crossover", and "mutation". Chromosomes usually specify a possible conflict free channel assignment matrix, which is encoded in such a way to avoid redundancy of the elements. To evaluate the fitness of the chromosome, it should be mapped to the channel assignment matrix. For the initial population, the value of every bit in the chromosome is randomly generated and at each iteration, a new population is generated after applying selection, crossover and mutation functions. The evaluation of each chromosome is the objective of the optimizations, and several objective functions are used, such as maximizing throughput, fairness, etc.

The advantage of using GAs to solve the optimization problem of spectrum assignment in CR is that they can handle arbitrary kinds of constraints and objectives. Inefficient solutions are simply discarded by the algorithm. One major disadvantage associated with GA is that the process for finding the optimal solution is quite slow and there is always the risk of finding a local minima and not the globally optimal solution.

Another proposal for using an evolutionary technique is given in [153], in which the Harmony Search (HS) technique is used for finding the optimum channel assignment. The algorithm constructs a vector of channel assignments (called harmonies), which undergo intelligent combinations and mutations controlled by two parameters: the Harmony Memory Considering Rate (HMCR) and Pitch Adjustment Rate (PAR), both obtaining values in the range $[0, 1]$. The algorithm has three phases: (i) initialization, in which no a priori knowledge of the solution is assumed and the available assignments are drawn uniformly from the set of channel assignments; (ii) improvisation, in which the HCMR and the PAR are applied sequentially to produce a improvised set of harmonies; (iii) evaluation, in which the best harmonies (based on some metric values) are stored in the harmony memory and if all iterations are done, then the best assignment is selected from the memory. The authors of [153] also introduce a perturbation criterion to avoid local minimas.

In [114] swarm intelligence is used to solve the spectrum allocation problem in cognitive radio networks. The authors propose to use the following model: the broadcast message that carries the information about the probability of a successful transmission of a user is used as a pheromone; the SUs receive the broadcast message and adjust the channel according to the information included in the message. If the channel transmission probability decreases, then this SU will have a lower possibility of selecting this channel. The pheromones are not spread frequently among neighbor SUs to reduce the communication cost, something that may cause problems due to the dynamic nature of CRNs and could create problems if a PU wants to transmit unexpectedly in a channel. Channel state information is used to avoid conflict with other SUs and PUs. The proposed algorithm is distributed with each node selecting its channel according to the pheromones received by its neighbors. The target objective is to maximize the total probability of successful transmissions, something that does not guarantee the quality of service of the transmissions. A similar approach using Ant Colony optimization is also given in [154].

In [155] the SA problem is solved using the Artificial Bee Colony (ABC) algorithm, which is a swarm intelligent optimization algorithm inspired by honey bee foraging. The ABC algorithm introduces the concepts of employed bees, onlookers and scouts. Employed bees are equal to the number of food sources. Onlookers share the information of the food sources and explore. Scouts are employed bees that search new food sources, abandoning their own. The possible solutions are represented by the location of the employed bees or the onlookers, while the quality of the solution is represented by the nectar amount of food. For SA, the location of one bee or onlooker represents a possible channel assignment and the amount of nectar is the utility that is maximized.

V. CHALLENGES - ISSUES - DISCUSSION

Spectrum assignment is a key design issue for cognitive radio technology and many past efforts have investigated cognitive SA techniques from different perspectives. In the previous sections we have presented the overall view on the problem of SA in CR networks, giving a brief description of the most common approaches and techniques proposed so far by various researchers. Nevertheless, several open issues still remain that could be the basis for future research works.

A. *Spectrum characterization*

Most proposed efforts use a single criterion (i.e. SNR, SINR or throughput) to characterize the traffic load of the examined spectrum bands and choose the most suitable channel according to either the interference threshold or throughput requirements of the SUs. An open issue is the use of multiple QoS criteria to analyze and characterize the examined spectrum bands. Depending on each SU's service/application, there can be different QoS parameters, such as throughput, end-to-end delay, jitter, bit error rate, etc. Most cognitive SA algorithms consider only the throughput as a QoS requirement, but this is not enough for applications such as Voice over Internet Protocol (VoIP), which is delay-sensitive. Since various applications with different performance/QoS requirements may run simultaneously on the user device, the SA algorithms should incorporate methods that need to consider at the same time all the QoS parameters for the spectrum bands, so that optimal solutions can be achieved.

B. *User behavior/priorities*

User behavior is an aspect not considered in most past approaches in the literature. User behavior can be used to predict user requirements and mobility according to previous actions and this can help influence the decisions on spectrum selection. Furthermore, in the literature all SUs are assumed to have the same priorities for accessing the available spectrum bands and very few works have actually dealt with the issue of assigning spectrum to SUs that have different priorities. Priorities can be assigned to SUs based on their profile, their subscription, the service they request (mostly related to delay-sensitive applications), their QoS requirements, emergency requests, etc. Taking into account different priorities for SUs, the design and the functionality of efficient spectrum assignment techniques can change dramatically.

C. Multi-radio SUs / multiple channel selection

Selecting multiple channels or multiple spectrum fragments can lead to a huge increase of throughput of SUs and CR enables the selection of multiple channels that could be contiguous or not. This has been considered in only very few works until now and almost all focus on single radio devices. Multi-radio devices are also not very often considered in cognitive SA algorithms. In addition, the assignment of multiple spectrum fragments in such devices remains a very complex and open issue for future research. Multi-radio cognitive devices that can perform spectrum aggregation (or select multiple channels) will dramatically increase the performance of cognitive mesh networks and help avoid network congestion situations. This is a key open challenge for future research.

D. Long term throughput estimation

An estimation of the throughput of wireless links is used in many past contributions for selecting the best available channel to support the user demand. These approaches, though, mainly estimate the short term throughput of the channel, by taking into account the current measurements. The issue with these approaches is that the dynamicity of the cognitive wireless environment may result in severe changes in the throughput of links, i.e. due to interference, discontinuous PU activities, etc. When the SU has an application that will run for a long period of time, then calculating the short-term throughput and the short-term spectrum availability may result in frequent spectrum handovers. Using statistical data for tracking the history of channel availability, the long-term throughput of the examined spectrum bands can be calculated and users requesting constant throughput for a specific time period can benefit from such information and avoid performing frequent spectrum handovers which may result in low performance.

E. Selfish users in distributed SA schemes

The most common assumption in distributed SA schemes is that the SUs are willing to follow a strict protocol and exchange information regarding the spectrum holes with other SUs for taking a joint decision regarding spectrum allocation. However, as mentioned in [160] this assumption is not valid when selfish users exist in the CRN. These users want to maximize their profits regardless of the impact on the other SUs and may avoid sending information or send false/misleading information. The latter is a case of the Spectrum Sensing Data Falsification attack (SSDF) and much work has been done towards detecting the malicious users and excluding them from the SA process. An issue not covered in the literature is the investigation of incentives for the participation of selfish users into the SA schemes and how they can benefit (in terms of profit/performance) from the cooperation with other SUs in the SA process.

F. Interference Temperature Limit

Interference Temperature Limit (ITL) is a metric proposed in 2003 by the FCC [101] for limiting the interference caused by SUs to PUs. After a lot of research the FCC decided to abandon the concept of ITL because it has several drawbacks. Despite that, several approaches continue to use the concept of ITL. In 2012, the concept of Receiver Interference Limit (RIL) [161] was presented in a FCC workshop, aiming to overcome the drawbacks of ITL. Thus, newer approaches in cognitive SA should focus on the newly proposed RIL.

G. Heterogeneous hybrid access

One issue not covered in the literature so far is the case of having primary users equipped with cognitive-enabled radio devices in addition to their primary transceivers. These users will be able to connect to both primary and cognitive networks. When connected to primary networks, they will have priority in accessing the licensed spectrum compared to other SUs, but, when they access the cognitive network, they will have the same priority as other SUs and contend with them for accessing the spectrum. Consider for example a future heterogeneous wireless network where multiple primary networks (GPRS, UMTS, TV, 4G networks, etc.) co-exist with a cognitive network and a PU that has subscription to all the primary networks, but is also equipped with a cognitive-enabled radio device. An efficient cognitive spectrum assignment algorithm would consider the possibility to access any network or simultaneously access more than one network (included the cognitive network) for maximum performance. This can be exploited when a user device runs several applications and hence, can decide to simultaneously use multiple access technologies that are the most appropriate for each application.

H. Energy efficiency

Energy efficiency is the objective of minimizing the energy consumption and has received attention in wireless research only lately. Many works in the literature have focused on power control (which is also a form of energy efficiency) but is mostly used for minimizing interference and does not achieve a full energy efficient solution. In the current context of fight against climate change, the European Commission has set an optimistic target to reduce the carbon emissions by 20% until 2020 [162]. Our review has shown that there are few works that consider energy efficiency in the cognitive SA. The transmission power of an SU is directly related to energy consumption. Furthermore, for a fixed transmission range of an SU, the transmission power is inversely proportional to the selected frequency. Thus, the energy consumption of an SU is directly related to the selected spectrum band. Since most SUs are assumed to be mobile with limited battery lifetime, the spectrum assignment should attempt to minimize the energy consumption of the SUs to allow them to be connected to the network for a longer time. Furthermore, the complexity of the SA algorithms is also related to the energy consumption of the SU devices, thus to minimize the energy consumption of nodes, simple and fast SA algorithms should be developed. Finally, consideration of energy-awareness cannot usually be achieved by a simple modification or adjustment of the existing algorithms, but needs to be considered from the beginning in the development of energy efficient SA algorithms.

I. Spectrum fragments or channels?

The general description of cognitive radio technology does not specify what type of white holes a CR device can use, thus making the CR technology able to access any available portions of the spectrum, regardless of their frequency and bandwidth. However, this is not the case in most past approaches in cognitive SA. Almost all approaches assume that there are fixed-width channels available for the SUs and try to find the most suitable one for access. The "channels" are considered with the traditional meaning, namely they have a specific central frequency and a pre-defined bandwidth. Thus, most past works are indeed performing traditional CA in CRNs, which can be considered as a slight variation of the corresponding CA problem in traditional wireless networks. The problem of spectrum assignment in CRNs is more complex than the traditional CA. CRNs do not need to be restricted to fixed channel ranges and widths. The SUs sense the spectrum and find the white holes and try to access them according to some criteria. Thus, in CRNs spectrum assignment involves finding not only the central frequency, but also simultaneously finding and selecting the frequency and the optimal bandwidth of the spectrum that the SU wants to access. Only a few prior works has considered such an approach, which remains an open area for future research.

J. Adaptive algorithms

Another key challenge for the development of efficient SA algorithms is that the algorithms should be adaptive to varying conditions/scenarios in order to meet the requirements of a highly dynamic cognitive environment. All algorithms so far focus on a static scenario and network and try to find an optimal solution according to some criteria. In mobile environments, though, this is not the case because the environmental characteristics change significantly as a user moves through space (and time). For example, a user may at one time be part of a centralized CRN, but as the user moves he/she may leave the area of that CRN and enter the area of a distributed CRN. Another case can be when a user is in a high contention area and after a while enters a low contention area. Developing adaptive SA algorithms remains a key challenge for future research to provide efficient solutions for varying conditions and scenarios.

VI. CONCLUSION

Cognitive radio is a promising technology for future wireless networks. It aims to exploit the underutilized spectrum bands and solve the problem of overutilization of the free bands, enabling users access any unused portion of the spectrum rather than limiting their access to specific free frequencies, like the existing wireless networks. The basic feature of CR technology is that CR devices are able to sense the operating environment and adapt to real-time changes. This means that CR devices are able to find at any given time the available non-utilized spectrum bands and access them, while not interfering with licensed transmissions. Spectrum assignment is a key mechanism that ensures the efficient operation of both cognitive and primary networks. The objective is to assign spectrum bands to cognitive users in order to avoid interfering with licensed users and maximize their performance.

In this paper we present a brief overview of the problem of spectrum assignment in cognitive radio networks. We analyze the criteria for selecting spectrum bands, the different approaches and the several techniques that are used to solve the spectrum assignment problem. Finally, we have discussed several open issues and challenges that have not yet been fully investigated by the research community and can be the basis for future work in this area.

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