Spectrum Decision in Cognitive Radio Networks: A Survey

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***Abstract*—Spectrum decision is the ability of a cognitive radio (CR) to select the best available spectrum band to satisfy secondary users' (SUs') quality of service (QoS) requirements, without causing harmful interference to licensed or primary users (PUs). Each CR performs spectrum sensing to identify the available spectrum bands and the spectrum decision process selects from these available bands for opportunistic use. Spectrum decision constitutes an important topic which has not been adequately explored in CR research. Spectrum decision involves spectrum characterization, spectrum selection and CR reconfiguration functions. After the available spectrum has been identified, the first step is to characterize it based not only on the current radio environment conditions, but also on the PU activities. The second step involves spectrum selection, whereby the most appropriate spectrum band is selected to satisfy SUs' QoS requirements. Finally, the CR should be able to reconfigure its transmission parameters to allow communication on the selected band. Key to spectrum characterization is PU activity modelling, which is commonly based on historical data to provide the means for predicting future traffic patterns in a given spectrum band. This paper provides an up-to-date survey of spectrum decision in CR networks (CRNs) and addresses issues of spectrum characterization (including PU activity modelling), spectrum selection and CR reconfiguration. For each of these issues, we highlight key open research challenges. We also review practical implementations of spectrum decision in several CR platforms.**

***Index Terms*—Cognitive Radio, Primary User, Reconfiguration, Secondary User, Spectrum Characterization, Spectrum Decision, Spectrum Selection.**

I. INTRODUCTION

RECENT advancements in wireless technologies, such as software defined radios (SDRs), promise to address some of the major limitations experienced in legacy wireless communication systems. One of these limitations is inefficient utilization and management of the radio frequency (RF) spectrum in both licensed and unlicensed bands. Traditionally, RF spectrum is managed by the regulatory agencies through the assignment of fixed portions of spectrum to individual users in the form of renewable licenses. Although this regulatory approach ensures interference-free communications between radio terminals, it suffers from inefficient spectrum utilization. The available literature shows that spectrum utilization, on a block of licensed RF band, varies from 15% to 85% at different geographic locations at a given time [1]–[3]. As the demand for advanced broadband wireless technologies and services increases, traditional static spectrum regulation policies are becoming obsolete. To keep up with growing demand, there is a need for more efficient dynamic spectrum access (DSA) [4] technologies and regulatory approaches.

The need for DSA or opportunistic spectrum access (OSA) was first proposed for the United States by the Federal Communications Commission (FCC) in 2003 [1]. This need was mainly driven by the threat of lack of operating spectrum for future wireless technologies. This move was recently followed by another important decision by the FCC in 2008 [5] and the Office of Communications (Ofcom) in the United Kingdom in 2010 [6], to open up television white spaces (TVWS) for unlicensed utilization. TVWS refers to large portions of RF spectrum, in the very high frequency (VHF) and ultra high frequency (UHF) bands, that will become vacant after the switch-over from analogue to digital TV [7]. Alongside these developments, there has been a strong trend towards research and development of cognitive radio (CR) [8] technology to optimally access the usable spectrum opportunistically and dynamically. A CR is *"an intelligent wireless communication system capable of changing its transceiver parameters based on interaction with the external environment in which it operates"* [1]. CR is therefore seen as an enabling technology for efficient DSA.

While several approaches are proposed for achieving DSA (such as the dynamic exclusive use model, the spectrum commons model, and the hierarchical access model [4]), our focus in this paper shall be on DSA using CR technology.

The process of realizing efficient spectrum utilization using CR technology requires a dynamic spectrum management framework (DSMF). In this paper, we shall adopt the DSMF proposed in [2] due to its clarity and relevance to our discussion. This DSMF consists of *spectrum sensing, spectrum decision, spectrum sharing* and *spectrum mobility*, as shown in Fig. 1. Spectrum sharing refers to coordinated access to the selected channel by the secondary users (SUs) or CR users. (While the terms "SU" and "CR user" are used interchangeably, in this paper we shall only use the term SU). Spectrum mobility is the ability of a CR to vacate the channel when a licensed user is detected. Spectrum sensing involves identification of spectrum holes and the ability to quickly detect the onset of

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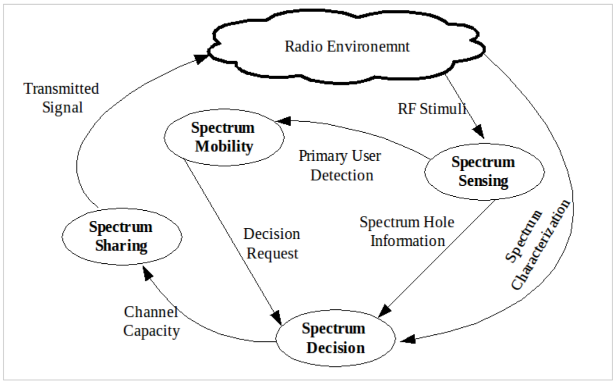

Fig. 1: Dynamic Spectrum Management Framework [2]

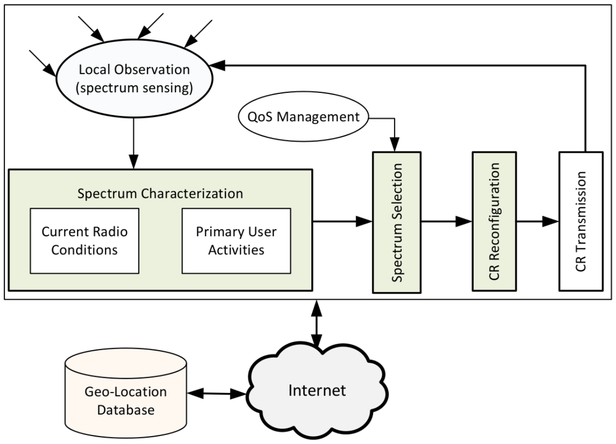

Fig. 2: Spectrum Decision Framework

licensed or primary user (PU) transmissions in the spectrum hole occupied by the SUs. Spectrum decision refers to the ability of the SUs to select the best available spectrum band to satisfy users' quality of service (QoS) requirements. In this paper we will focus on the spectrum decision component of the DSMF.

Spectrum decision involves three main functions [2]: *spectrum characterization, spectrum selection* and *CR reconfiguration*. Once vacant spectrum bands are identified (using spectrum sensing, geo-location databases or other techniques), each spectrum band is characterized based on local observations and on statistical information of the primary networks (which is normally called PU activities). The second step involves the selection of the most appropriate spectrum band, based on the spectrum band characterization. Thirdly, a CR should be able to reconfigure its transceiver parameters to support communication within the selected spectrum band. The required functions for the spectrum decision framework are summarised in Fig. 2. In order to perform these functions, the following questions need to be answered:

1. *How can the available spectrum be characterized?*
2. *How can the best spectrum band be selected to satisfy the SU's QoS requirements?*
3. *What is the optimal technique to reconfigure the CR for the selected spectrum band? (And how?)*

The above questions form the basis of spectrum characterization, spectrum selection and CR reconfiguration, respectively, as shown in Fig. 2. In this paper, we provide a comprehensive, up-to-date survey of the key research work on spectrum decision in cognitive radio networks (CRNs). We also identify and discuss some of the key open research challenges related to each aspect of the spectrum decision framework. This paper surveys the literature over the period 2003 to mid-2012 on spectrum decision in CRNs. This survey does not cover work done on spectrum sensing, spectrum sharing, spectrum mobility or geo-location databases.

We choose to focus on spectrum decision because of its importance in and centrality to the DSMF in CRNs and because it has received relatively little attention compared to other components of the CR DSMF (namely spectrum sensing, spectrum mobility and spectrum sharing). In many ways, spectrum decision represents the culmination of the DSMF in CRNs. We can limit our focus to this one aspect of DSMF based on the well-known communications engineering principles of modularity and abstraction, perhaps most famously and powerfully exemplified in Shannon's 1948 classic paper [9].

The remainder of this paper is arranged as follows. Section II provides the background of CR technology and the motivation for performing spectrum decision in CRNs. Section III outlines CR standardization and regulation activities which are related to spectrum decision in CRNs. Section IV discusses spectrum characterization, the first of the three major spectrum decision functions in CRNs. Section V focuses on spectrum selection, the second major spectrum decision function in CRNs. Section VI covers CR reconfiguration and reconfigurable parameters, the final major spectrum decision function in CRNs. Section VII presents related work on practical implementations of spectrum decision on CR platforms. Future developments in CRNs are reviewed in Section VIII. Section IX concludes the paper.

II. OVERVIEW OF CRNS

In this section we provide an overview of CR technology and different CRN topologies. We briefly mention generic problems affecting spectrum decision functions due to the time-varying nature and fluctuations of the available spectrum in CRNs.

A. *Cognitive Radio Overview*

Recently, CR has received considerable attention from the research community as an enabling technology for efficient management of RF spectrum. In order to achieve DSA, a CR should be both spectrum and policy agile [10]. A spectrum agile CR is capable of operating over a wide range of frequency spectrum; while a policy agile CR will be aware of the constraints under which it operates (such as the rules for opportunistically using the vacant spectrum bands). Practically, CR builds on the software defined radio (SDR) architecture with added intelligence to learn from its operating environment and adapt to statistical variations in the input stimuli for efficient resource utilization [11]. With the current threat of

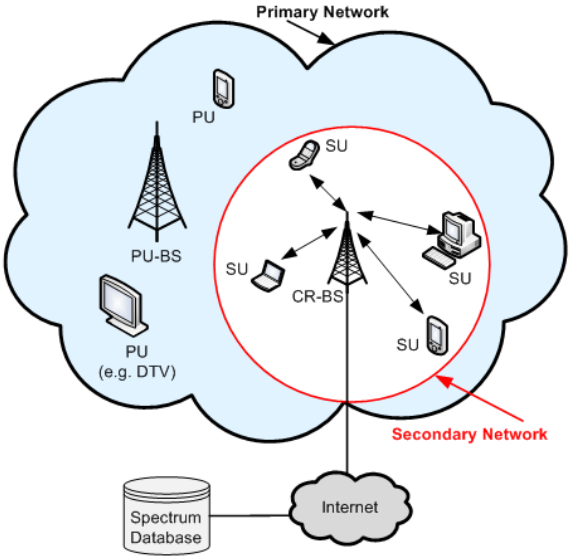

Fig. 3: Centralized CRN Topology

spectrum scarcity, CRs are widely proposed to build DSA-based secondary networks for lower priority users.

One of the major functions of a CR is to find spectrum holes and be able to access and utilise them without causing any harmful interference to the incumbent or PU. A spectrum hole is defined as a band of frequency assigned to the PU, but which at a particular time and specific geographic location is not being used by that PU [11]. In the absence of signalling between PUs and SUs, spectrum holes may be identified by performing direct spectrum sensing, using geo-location databases, beaconing techniques, or by combining spectrum sensing with geo-location database information [7], [12]. (For interested readers the latest developments on database based CRNs, known as “SenseLess CRNs”, are reported in [13].) A CR should also be intelligent enough to perform spectrum decision in order to select the most suitable frequency band to satisfy specific communication needs. Spectrum decision is a key function of CRs which requires greater attention in order to realize the practical implementation and deployment of CRNs. Consequently, the focus of this paper will be on spectrum decision frameworks in both centralized and distributed CRNs. Readers are referred to [2] and [11] for good introductions to spectrum agile CR technology.

B. *Cognitive Radio Network Topologies*

A CRN is a wireless communication network whose end-user nodes are CRs. Similar to traditional wireless networks, a CRN topology can be classified as either centralized (infrastructure-based) or distributed (infrastructure-less or ad hoc) network topology. These network types are depicted in Fig. 3 and Fig. 4, respectively. In this paper, we consider both centralized and distributed CRN topologies.

*1) **Centralized CRN Topology***

In the infrastructure-based CRN architecture, a central node such as a base station (BS) or access point (AP) is deployed with several SUs associated with it, as shown in Fig. 3. A typical example of a centralized CRN is a IEEE 802.22 wireless regional area network (WRAN) or a cellular network. For simplicity, we shall take the IEEE 802.22 WRAN as an example to discuss a centralized CRN. However, similar reasoning can be applied to more complex centralized CRNs. In a centralized network, a BS controls all the SUs (clients) or consumer premises equipments (CPEs) within its transmission range. The CRN operates within the transmission or coverage area of the primary network. Thus it uses DSA techniques to opportunistically access the primary network spectrum without causing any harmful interference. To do this, all SUs perform spectrum observation on specified spectrum channels and then send their observations to the BS, which acts as a fusion centre. Both the BS and its associated clients may be capable of detecting the presence of the PUs using different detection techniques (such as spectrum sensing, geo-location databases or beaconing).

In some cases [14], two physical channels are used: one for observing the primary channel and the other for reporting data by the SUs to the BS. Once available channels are gathered, a BS will build the final list of these available channels and their associated maximum transmission powers, and then decide on the best channels to be accessed. These channels will then be broadcast back to all or selected SUs for use. In the next subsection we discuss the distributed CRN topology.

*2) **Distributed CRN Topology***

In the distributed CR ad hoc network (CRAHN) topology, the SUs communicate directly with each other without any central or controlling node. As shown in Fig. 4, SUs share their local observations and analysis among themselves, as long as they are within each other’s transmission range. For database-based networks, each SU may have access to query the database for available spectrum bands. Using both its results and the results of other SUs, a SU can make a decision for an appropriate band using a local criterion. If the criterion is not satisfied, the process may be repeated again until a decision is reached.

It is clear that spectrum decision in CRAHNs does not rely on a central node. However, if SUs decide to cooperate, as in cooperative spectrum sensing, one node can be chosen as the head node and be used for making spectrum decisions. Unlike in infrastructure-based topologies, spectrum decision in CRAHNs also involves route selection, which is normally addressed as a joint spectrum and route selection problem. A noticeable new challenge in CRAHNs, which did not exist in traditional wireless ad hoc networks, is that channel availability is determined by the present behaviour of PUs, which may vary with location, time and frequency [15]. Another new challenge is the re-routing and switching to other available channels or links once the PU appears on the occupied channel [16]. Thus the wide range of operating or available spectrum makes it infeasible to transmit beacons over all possible channels. Section V discusses these and many other spectrum selection challenges experienced in both distributed and centralized CRNs.

In this section, we have provided a brief overview of

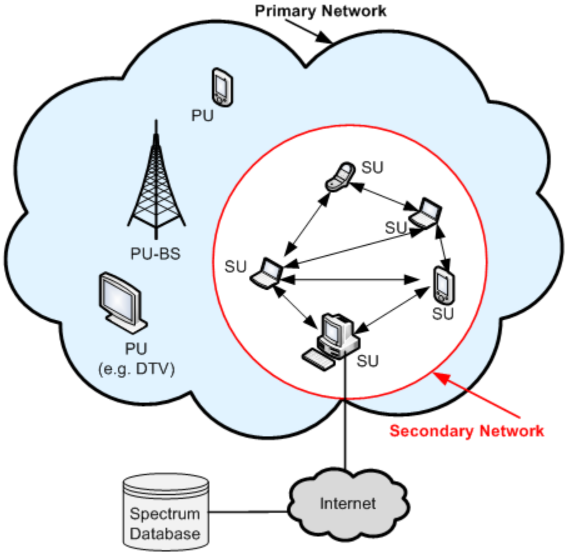

Fig. 4: Distributed CRN Topology

CR technology in relation to spectrum decision and the two most commonly deployed CRN topologies (i.e. centralized and distributed topologies). In the next section, we present standardization and regulation efforts around CR technology.

III. STANDARDIZATION AND REGULATORY EFFORTS

The introduction of frequency agile CR technology created a spark in numerous academic, industry, regulatory and standardization bodies worldwide. Like any other new technology introduced to the market, CR technology's success will depend on sound standardization and regulation efforts from standardization bodies, regulators and industry. It is important to note that initial research and development efforts on CR technology have been focused in the United States. This is mainly due to the FCC's adoption of CR as an enabling technology for efficient spectrum management. Since then, other standardization bodies and regulatory agencies around the world have become interested in the standardization and regulation of CRs for DSA. In the following sub-sections we will discuss standardization and regulatory efforts on CRs, focusing mainly on efficient frequency management.

A. Standardization

1) ***IEEE 802.22 Standard***

The global switch-over from analogue to digital TV will leave a considerable amount of VHF/UHF spectrum vacant. The TVWS spectrum has excellent radio propagation characteristics, and is now being proposed as the most useful spectrum for improving wireless broadband connectivity in rural communities [12], [17]. In order to take advantage of the TVWS spectrum, the IEEE 802.22 WRAN standard [18] was established, and the first official standard was released in July 2011. IEEE 802.22 is the first wireless air interface standard focused on the development of CR based WRAN physical (PHY) and medium access control (MAC) layers for operation in TVWS. It specifies a fixed point-to-multipoint wireless air interface where a BS manages its own cell and all associated CPEs. The IEEE 802.22 PHY layer is based on orthogonal frequency division multiple access (OFDMA) and can support a system which uses TVWS channels to provide wireless communication links over distances of up to 100 km. A typical use case for the IEEE 802.22 standard would be in sparsely populated rural areas [7].

The IEEE 802.22 standard supports incumbent or PU detection through spectrum sensing techniques with an option for geo-location databases. However, there are still technical difficulties in performing reliable spectrum sensing practically. Thus, some regulatory bodies such as the FCC and Ofcom prefer geo-location databases as the primary means for incumbent detection. A beaconing option is also provided for incumbent user detection in IEEE 802.22. In IEEE 802.22, both the CPE and BS have the capability to detect the incumbent, but spectrum decision is only managed by the central BS. The BS employs the CR capabilities for spectrum decision based on the TV channels' operating characteristics [19]. The BS actually performs the spectrum characterization and selection functions, while the CPE is responsible for the reconfiguration of its transceiver parameters.

2) ***IEEE DySPAN***

After realizing the importance of coordinated work around CR standardization, the IEEE P1900 Standards Committee was jointly established by the IEEE Communications Society (ComSoc) and the IEEE Electromagnetic Compatibility Society in the first quarter of 2005 [20]. On 22 March 2007, the IEEE Standards Association Standards Board approved the reorganization of the IEEE P1900 activities as Standards Coordinating Committee 41 (SCC41), called *Dynamic Spectrum Access Networks (DySPAN)*. The main aim of SCC41 is to develop supporting standards to address issues related to new technologies and the development of techniques for next generation radio systems and advanced spectrum management [21]. The SCC41 concentrates on developing architectural concepts and specifications for network management between incompatible wireless networks rather than specific mechanisms that can be added to the air interface.

In December 2010, the IEEE SCC41 was renamed the IEEE DySPAN-Standard Committee (DySPAN-SC). The IEEE DySPAN-SC consists of seven working groups (WGs), named 1900.1 through to 1900.7. Out of these WGs, the IEEE 1900.4's work has some elements of spectrum decision. This WG focuses on architectural building blocks enabling network-devices decision making for optimized radio resource usage in heterogeneous wireless access networks [20].

3) ***European Telecommunications Standards Institute***

In Europe, the European Telecommunications Standards Institute (ETSI) is also involved in the standardization of CR systems (called reconfigurable radio systems) under their Reconfigurable Radio Systems Technical Committee (RRS-TC) [22]. Cognitive radio principles within ETSI RRS-TC are concentrated on two topics: a cognitive pilot channel proposal and a functional architecture for management and control of reconfigurable radio systems. There are four WGs forming the ETSI RRS-TC, WG 1 to WG 4. Cognitive management and control falls under WG 3. This WG focuses on defining the system functionalities for reconfigurable and dynamic spectrum management and joint radio resource management. More information on ETSI RRS-TC can be found in [22].

B. Regulation

The International Telecommunication Union (ITU) is also involved in standardization efforts of CR technology through their ITU-R Working Party (WP) 1B and WP 5A [23]. These two WPs prepared reports describing the concepts and the regulatory measures required to introduce CR. The ITU-R WP 1B developed a working document towards draft text on World Radio-communications Conference 2012 (WRC-12) agenda item 1.19. Agenda item 1.19 reads: *"to consider regulatory measures and their relevance, in order to enable the introduction of software-defined radio and CR systems, based on the results of ITU-R studies, in accordance with Resolution 956 of WRC 07"* [24]. The ITU-R WP 5A is currently developing the working document toward a preliminary new draft report, *Cognitive Radio Systems in the Land Mobile Service* [25]. This report will address the definition, description, and application of CR systems in the land mobile service [23]. The regulatory technicalities on dynamic spectrum management and spectrum decision from the ITU's point of view should become clearer after the WRC-12, where they will be discussed under agenda item 1.19.

Now that we have presented the necessary background to assist in understanding CR technology, CRN topologies, and CRN-related standardization and regulation activities, in the following sections we will discuss the three major functions in the spectrum decision framework. These will be followed by additional sections on spectrum decision in CR platforms and future developments in CR technology.

IV. SPECTRUM CHARACTERIZATION IN CRNS

In CRNs, multiple spectrum bands with different channel characteristics may be found to be available over a wide frequency range [26]. In order to properly determine the most suitable spectrum band, it is crucial to first identify the characteristics of each available spectrum band. Spectrum characterization allows the SUs to characterize the spectrum bands by considering the received signal strength, interference and the number of users currently residing in the spectrum, based on RF observation. The SUs should also observe heterogeneous spectrum availability which varies over time and space due to PU activities. Heterogeneous spectrum availability refers to the availability of spectrum holes which fluctuate over time and location and have different characteristics. Thus, spectrum characterization should include both the current RF environment conditions and the observed PU activity modelling. In this section, spectrum characterization in terms of the radio environment and PU activity models is discussed along with some related work. The section ends with key open research challenges in spectrum characterization.

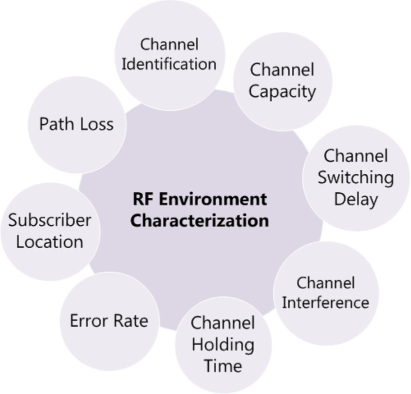

Fig. 5: Radio frequency environment characterization elements

A. Radio Frequency Environment Characterization

A CR is expected to continuously characterize radio environment usage in frequency, time and space. This is mainly due to the fact that available spectrum bands in CRNs always have different characteristics. Radio frequency (RF) environment characterization is a process that involves estimation of the following key elements or parameters: (1) channel identification, (2) channel capacity, (3) spectrum switching delay, (4) channel interference, (5) channel holding time (CHT), (6) channel error rate, (7) subscriber location, and (8) path loss [2], [27]. These elements are illustrated in Fig. 5 and analysed and discussed in the following subsections.

1) ***Channel Identification***

Primary channel identification is the first important step to be performed by each CRN. As research in CR evolves, different CRNs application areas are being introduced to the market. Some of these applications include: television (TV) white space networks, smart grid networks, machine-to-machine (M2M) networks, public safety networks, broadband cellular networks and wireless medical networks [28]. These applications or networks exhibit different traffic data patterns, either deterministic or stochastic.

In deterministic traffic, the PU is assigned a fixed time slot on a frequency band for communication. Once the PU stops communicating, the frequency band becomes available and can be used by the SUs. Examples of deterministic traffic data patterns occur in TV broadcasting (longer periods) and radar transmitters (shorter periods). Normally deterministic signals have fixed or predictable ON and OFF periods which can be determined by a mathematical expression, rule or table. Any future value for a deterministic signal can be calculated or predicted based on its past values, which makes it easy to predict future PU idle periods for CRNs.

On the other hand, stochastic traffic patterns can only be described and analysed using probabilities and statistics because their spectrum usage tends to exhibit greater variations in time and space [11]. Due to their randomness, stochastic signals are analysed using average values from a collection of primary signals. Examples of stochastic traffic data patterns occur in cellular networks. In order to improve the accuracy of stochastic traffic modelling, Haykin [11] suggested the design of a tracking strategy for PU idle period prediction models.

A prediction method for both deterministic and stochastic traffic patterns is proposed in [29]. This method is used by CRs to predict the primary channel idle time. In summary, channel identification is a crucial function for every CRN for learning its external environment, classifying primary traffic and applying the appropriate spectrum decision methods.

2) *Channel Capacity Estimation*

While many other parameters (such as the channel interference level, error rate, path loss, delay and holding time) are important for efficient spectrum characterization, a considerable amount of research has focused on channel capacity estimation. This is motivated by the fact that by estimating other (above) channel parameters, we can determine the channel capacity [2] (this means channel capacity can be derived from the above parameters). It has been shown that the traditional method of estimating channel capacity using the signal-to-noise-ratio (SNR) leads to non-optimal spectrum decision [30].

In an orthogonal frequency division multiplex (OFDM) system, each spectrum band i has a different bandwidth B_i, consisting of multiple subcarriers. A normalized CR capacity $C_i^{CR}(k)$ model of spectrum band i for user k is proposed in [26] for spectrum characterization in CRNs. This C_i^{CR} model defines the expected normalized capacity of user k in spectrum band i as:

$$C_i^{CR}(k) = E[C_i(k)] = \frac{T_i^{off}}{T_i^{off} + \tau} . \gamma_i . c_i(k) \tag{1}$$

where $C_i(k)$ represents the spectrum capacity, the term $c_i(k)$ (with small c) is the normalized channel capacity of spectrum band i in bits/sec/Hz, τ represents the spectrum switching delay, γ_i represents the spectrum sensing efficiency and T_i^{off} is the expected transmission time without switching in spectrum band i. Spectrum or channel switching delay is introduced within CRNs when SUs move from one spectrum band to another according to PU activity. More on channel switching delay is discussed in the next sub-section. Spectrum sensing efficiency arises due to the fact that RF front-ends cannot perform sensing and transmission at the same time, which inevitably decreases their transmission opportunities. When using spectrum sensing to detect spectrum holes, sensing efficiency is influenced by the observation time and transmission time [31].

3) *Channel Switching Delay*

In opportunistic or DSA network settings, radio nodes are expected to operate on different frequency channels in a given time without disrupting existing network connections [32]. This process is commonly known as dynamic channel switching (DCS). In CRNs, channel switching may be triggered by the detection of PUs on the operating channel, by degradation of the QoS due to interference, or traffic load in the current channel [18]. During the channel switching process, the SUs must dynamically switch from one channel to another idle channel, and during this switching process all SUs transmissions are temporarily suspended until the new spectrum opportunity or channel is found. Switching from one channel to another introduces additional delay to the CRNs, which is called switching delay. This switching delay may vary from one node to another since it depends on the hardware technology (e.g. time spent during RF front-end reconfiguration) and the algorithm used by the SUs or the overall CRNs to perform the spectrum decision process. The switching delay may also include the sensing time in cases where available channels are detected using spectrum sensing techniques. The ultimate goal is to keep the switching delay as short as possible to ensure that it does not affects the overall CRN performance.

Azarfar *et al.* [33] addresses the channel switching delay as an overhead that has the potential to decrease the useful time available for data communication. They consider channel switching delay as the sum of spectrum sensing duration plus the channel recovery time. Channel recovery time is the time spent by a SU to vacate the channel, to decide on the available channel (or signalling time for establishing new channels), and to select or access the available spectrum. Several techniques are proposed in [33] to reduce the channel switching delay. This includes the use of historical information of channel occupancy and channel quality index [33]. Historical information of channel occupancy becomes useful provided the SUs are aware of their operating location. For instance, a SU may use geographical coordinates of the previously explored areas to remember that spectrum band X was occupied or vacant and also to remember which technologies operate in that area. So when the SU approaches those areas (i.e. previously explored areas), it can save time by avoiding those spectrum bands which were found to be occupied during the previous visits. This will then reduce the channel recovery time, thereby reducing the channel switching delay.

In centralized CRNs such as IEEE 802.22 [18], the BS can decides to switch channels during normal operations by first selecting the backup channel from the backup or candidate channel list. Secondly, it must wait for a specified time to make sure that all the associated CPEs are prepared for the channel switch. This waiting time should be long enough for the CPEs to recover from an incumbent detection. Once all CPEs are prepared for channel switching, the BS can then schedule the channel switching procedure. Typical spectrum switching delay in IEEE 802.22 is less than 2 seconds [18].

Xu *et al.* [34] analysed a trade-off between higher bandwidth and switching overhead experienced in CRNs. In their paper, switching overhead is the sum of spectrum sensing time, channel evacuation time, and link setup time. The link setup and channel evacuation times are based on the radio hardware and the operating environment [34], and are modelled as a random variable for all SUs. It was found that using higher bandwidth in saturated traffic (i.e. where there is a large pool of idle PU channels to be sensed) with few SUs leads to more switching overhead due to an increased sensing time. However, in cases where a central node provides channel availability information to multiple SUs (i.e. SUs do not need to conduct spectrum sensing), the switching overhead reduces (it only consists of link setup and channel evacuation times).

In distributed CRNs, channel switching overhead on a node includes the switching delay, other flows' transmissions delay and the back-off delay (i.e. interference within a frequency channel) [35]. A delay based routing metric called cumulative delay for on-demand routing protocol is proposed in [35]. This cumulative delay is the total path delay derived from the spectrum switching delay and back-off delay. The back-off delay arises when more than two nodes contend for the spectrum resource. This delay will depend on the number of contending nodes on each spectrum band. Thus during spectrum characterization, the number of SUs in a distributed CRNs is important to estimate the switching delay.

An analysis of delay performance in CR sensor networks is presented in [36]. Two types of channel switching techniques are considered: periodic switching and triggered switching. In periodic switching, SUs switch to a new channel only at the beginning of each channel switching interval as defined in [36]. Periodic switching occurs if the occupied channel becomes unavailable (to the SUs) before the end of the channel switching interval. Channel switching can be caused by the sudden appearance of PUs or high interference on the channel due to adjacent channels. In triggered switching, the SUs switch to a new channel as soon as the current channel is no longer available [36]. It was found that bursty traffic experiences shorter delays when considering periodic switching techniques as compared to triggered switching techniques. This was mainly due to the fact that a channel is likely to be available in the earlier portion of the channel switching interval than in the later portion.

4) Channel Interference Estimation

In CRNs environment, SUs are expected to coexist with licensed or primary users (PUs). In some cases, several CRNs must also coexist within the coverage area of single or multiple primary networks. Such coexistence, if not controlled, can lead to harmful interference to the PUs. It is therefore crucial to accurately estimate and model interference generated by multiple active SUs in the network. In this subsection, different techniques for estimating, controlling and modelling channel interference caused by CRNs are discussed.

In [37], an opportunistic interference alignment scheme that allows multiple SUs to exploit the unused spatial dimensions of multiple-input-multiple-output (MIMO) PU channels is proposed. In this scheme, the primary transmitters maximize their rate by water-filling over the singular values of their channel matrix. By using singular values, PUs leave some eigen-modes unused, which allows the SUs to transmit at a significant rate by aligning their signals along the free eigen-modes of the PU channel. As a result, this scheme protects the transmission of the PUs while providing interference-free communication for the SUs.

An interference-aware radio resource allocation scheme is proposed in [38]. The paper studies PU interference caused as a result of: CR out-of-band (OOB) emissions and the interference that arises as a result of imperfect spectrum sensing. In OFDM-based primary networks, OOB emissions are due to power leakage in the side-lobes of transmitted signal. The amount of OOB interference power introduced in a PU sub-carrier due to SU transmission is modelled for both the uplink and downlink sub-bands. Finally, a computationally efficient algorithm for downlink and uplink subcarriers and power allocation in an OFDMA-based CRN is developed based on proposed OOB emissions and imperfect-spectrum-sensing-based interference models. To minimize the amount of OOB interference generated via non-contiguous multicarrier data transmission, multi-rate filter banks are suggested in [39]. In this approach, the multi-rate filter banks' sub-band spectra can be designed to be highly spectrally selective to limit the amount of intercarrier interference (ICI), which becomes advantageous in cellular systems that suffer from Doppler effects and frequency selectivity of the channels.

In [40], two interference detection schemes are proposed. The first scheme is based on pilot-aided interference detection for OFDM systems. In order to detect the presence of interference, this scheme requires at least two pilot symbols in a given subcarrier spaced in time. The pilot symbols are designed to ensure that their summation or subtraction is zero. For instance, two pilot symbols, x_1^p and x_2^p, can be selected as the two points in the Binary Phase Shift Keying (BPSK) constellation such that their summation is zero (i.e. $x_1^p + x_2^p = 0$). Although this pilot-aided scheme is simple in implementation, its weakness is poor interference detection in the sub-carriers where no pilot exists due to sparse placement of the pilot symbols. The second scheme proposed in [40] is based on a joint interference detection and decoding technique which does not require any pilot symbols. The decoder jointly performs erasure marking and decoding in order to erase the interference jammed symbols automatically during the decoding process. The decoding process consist of two steps: the first step determines the positions of the erasures, and the second step determines the number of erasures. However, this technique suffers from increased computational complexity and decoding delay.

Rabbachin *et al.* [41] proposed a statistical model for per-dimension (real or imaginary part) aggregate interference of a CRN which allows modelling of the CRN interference generated by SUs in a limited or finite region. In this model, two types of secondary spatial reuse protocols are considered: single-threshold and multiple-threshold protocols. For each protocol, the characteristic function of the CRN interference is expressed, and then used to derive its cumulants. The cumulants are used to model the CRN interference as truncated-stable random variables. The interference signal at the primary receiver generated by the i^{th} cognitive interferer is modelled as:

$$I_i = \sqrt{P_I} R_i^{-b} X_i \tag{2}$$

where P_I is the interference signal power at the limit of the near-far region (which is limited to 1m), R_i is the distance between the i^{th} cognitive interferer and the primary receiver, b is the amplitude path-loss exponent, and X_i is the per-dimension fading channel path gain of the channel from the i^{th} cognitive interferer to the primary receiver.

5) Channel Holding Time

Channel holding time (CHT) is the expected duration the SUs can occupy a licensed band before getting interrupted. Thus, the longer the holding time, the better the QoS for the SUs [2]. CHT can be determined by the type of secondary services served by the CRN or it can be determined by the regulator. It is useful in determining the RF environment characterization.

In [42], a Markovian model for finding the duration of the spectrum hole is proposed. This model builds on a CHT concept for the PU. Once the PU idle time is modelled as CHT, matrix-analytic techniques are applied to derive and analyse the duration of the spectrum holes which can be accessed by the SUs. One of the main drawbacks of this technique lies in its complexity.

Yuan *et al.* [43] introduced the concept of time-spectrum block to model spectrum reservation for CRNs. A time-spectrum block concept represents the time for which a SU occupies a portion of vacant spectrum without causing interference to the PUs. For a CRN of n nodes ($V = v_1, \cdots, v_n$), located in the two-dimensional Euclidean plane, let $d(v_i, v_j)$ denote the Euclidean distance between v_i and v_j. A time-spectrum block $B_{ij}^k = (t_k, \triangle t_k, f_k, \triangle f_k)$ is assigned to link (v_i, v_j) if sender v_i is assigned the contiguous frequency band $[f_k, f_k + \triangle f_k]$ of bandwidth $\triangle f_k$ during time interval $[t_k, t_k + \triangle t_k]$. Using the above definitions, the dynamic spectrum allocation problem can be viewed as dynamic packing of time-spectrum blocks into a three-dimensional resource, consisting of time, frequency, and space. Using a time-spectrum block B_{ij}^k, it is possible to find the time overhead of switching frequency or the time used for medium access contention in CRNs.

6) Channel Error Rate

In a communication link, error rate is defined as the rate of bits or data elements which are incorrectly received from the total number of bits or data elements sent during a specified time interval [44]. The average channel error rate is a useful parameter in estimating the RF environment characterization in CRNs. It depends on the interference level (interference to SU may be caused by the primary transmitters or other SUs), the available bandwidth, the frequency band in use and the modulation scheme (or access technology) [2]. Bit error rate (BER) and frame error rate (FER) are the most commonly used metrics. Error rate is usually stated relative to the channel's signal to noise ratio (SNR) values, and this makes the transmitted energy per bit an important metric in error estimation [44].

A closed-form average BER expression is derived in [45] to investigate SU's error performance for the binary phase shift keying (BPSK) modulation scheme. It was found that the channel error performance improves when the SU's SNR increases. Kaur and Sharma [46] analysed the bit error rate (BER) performance of the CR PHY layer over Rayleigh fading channels under different channel encoding schemes and channel conditions. They considered CRNs with both contention-based non-persistent carrier sense multiple access (CSMA) and OFDMA techniques.

7) Subscriber Location

Subscriber location also need to be determined when characterizing the RF environment. Generally, a SU can obtain geographical and environmental information using built-in global positioning system (GPS) coordinates, embedded information in packets exchanged between nodes or a central server that sends the most up-to-date global Radio Environment Map (REM) information [33]. IEEE 802.22 defines two modes which the SUs and BSs can use to find their geo-location: satellite-based geo-location (which is mandatory) and terrestrial-based geo-location (which is assisted by the CDMA ranging) [47]. By knowing its location, a SU can record a number of normal and abnormal events experienced in different locations and times. Such knowledge will be useful for future predictions of spectrum holes and characterization of the RF environment.

8) Path Loss

Path loss, the deterministic overall reduction of received signal power with distance between the transmitter and the receiver, is one of the factors affecting the radio propagation across wireless channels [11]. It is caused by the spreading of the electromagnetic wave radiating from the transmit antenna and the obstructive effects of the surrounding objects [44]. Path loss is normally obtained at the receiver side by dividing the transmitted power with the received power. Thus, transmission power can be increased to compensate for the increased path loss. However, this might cause higher interference for other SUs and PUs. According to Rappaport [48], the average path loss of a channel can be expressed using a path loss exponent (α). This path loss exponent α depends on frequency, antenna heights, and propagation environment. In free space loss, the path loss exponent α is equal to 2.

In [49], a low-complexity adaptive transmission protocol for CRNs, whose links have unknown and time-varying propagation losses, is proposed. This protocol adjusts its transmission modulation and coding as a mechanism for responding to changes in propagation losses. The transmitter power is increased only if the most powerful combination of coding and modulation is inadequate.

In this subsection we reviewed related work on RF environment characterization, which is the first step towards reliable spectrum decision scheme development. In the next subsection, we discuss PU activity modelling as another aspect of spectrum characterization.

B. Primary User Activity Modelling

Because there is no guarantee that a spectrum band will be available during the entire SU communication period, it is important to consider how often the PUs appear on the spectrum band. Using the learning ability of the CR, the history of the spectrum usage information can be used for predicting the future profile of the spectrum. This process is achieved through *PU activity modelling*. By considering the PU activity, the SUs can decide on the best available spectrum bands to be used for their transmissions. For a stable CRN, the spectrum decision framework must be aware of the available spectrum fluctuations, as well as the heterogeneous QoS requirements of the SUs [2]. It is important for the spectrum decision function to also consider the spectrum fluctuations because the SUs can transmit data only if they can accurately detect the spectrum holes. PU activity modelling also plays a crucial role in the design of communication protocols for CRNs [50]. For example: once we know that a PU favours a particular channel and tends to occupy it for a long period of time, that channel would be less likely to be available for a SU, as a result, sensing on such a channel would likely be a waste of time and energy [51]. Therefore, PU activity modelling will result in more effective spectrum usage for SUs, which in turn enhances CRNs performance [52]. Different techniques are used to model PU activities, and we discuss them in the next sub-sections.

1) *PU Activity based on Poisson Modelling*

There is a significant amount of research that models the PU activity as a Poisson process with exponentially distributed inter-arrivals [26], [53], [54]. The PU traffic is modelled as a two-state birth-death process with death rate α and birth rate β. In this approach, each user arrival is independent, and the PU transmission is assumed to follow the Poisson arrival process. As a result, the length of ON and OFF periods are exponentially distributed. An ON state represents the period used by PUs and an OFF state represents the vacant periods. An adaptive spectrum decision framework is proposed in [26] to determine a set of spectrum bands to satisfy the user requirements under the dynamic nature of RF spectrum bands. In this framework, each spectrum band is first characterized by jointly considering PU activity and spectrum sensing results.

For real-time applications, a minimum variance-based spectrum decision which minimizes the capacity variance of the decided spectrum bands is proposed. For best-effort applications, a maximum capacity-based spectrum decision scheme is proposed to maximize the total network capacity. However, based on a large-scale measurement-driven characterization of the PU activity in cellular networks investigated in [55], it was found that PU activity durations are non-exponential and high fluctuations ***of the PU activity*** may violate the Poisson assumption.

While the majority of studies assume that the PU activity follows the Poisson model, such assumptions were invalidated in [52], [56] based on the following reasons:

- The Poisson model approximates the PU activities as smooth and burst-free traffic. Therefore it fails to capture the bursty and spiky characteristics of the monitored data.
- The Poisson model does not consider correlations and similarities within data.
- The Poisson model fails to capture the short-term temporal fluctuations or variations exhibited by the PU activity.

Therefore the existing research which assumes the Poisson model derives PU activity models that have smooth and burst-free traffic in which short-term fluctuations are neglected [52]. A good illustration of the Poisson model's drawbacks can be found in [52], as depicted in Fig. 6. The Poisson model represents the ON period (which is the active transmission duration of a PU) and the OFF period (which represents the absence of PU activity). It can be observed from Fig. 6 that the actual PU activity fluctuates during the ON period, which is not tracked by the Poisson model. As a result, these durations are classified as part of the ON period, which leads to missed transmission opportunities. Based on these reasons, it is clear that Poisson modelling may lead to performance degradation in CRNs due to unidentified fluctuations in PU activities. In order to address the potential Poisson model drawbacks, the following subsections presents alternative mechanisms for PU activity modelling.

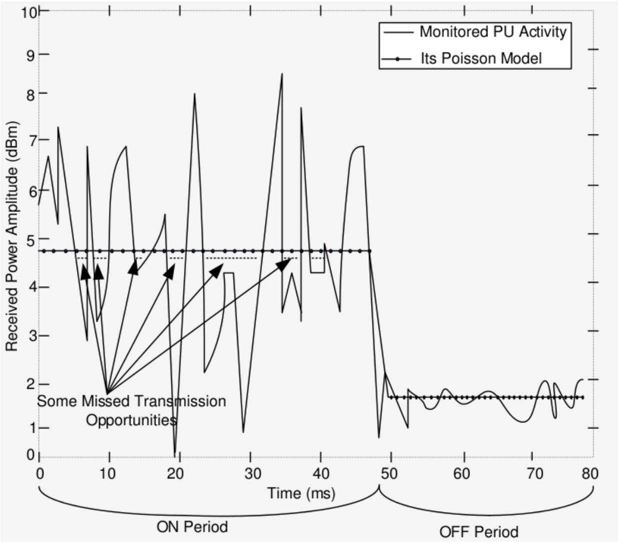

Fig. 6: Missed Opportunities in Poisson Model [52]

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2) *PU Modelling Based on Statistics*

A simple method for learning and classifying traffic patterns on primary channels is proposed in [29]. The authors consider a primary network that consists of multiple channels with independent traffic patterns. The method starts by collecting spectrum usage information (through spectrum sensing) and stores this information in the channel database (in binary format). If the channel is free, the channel state (CS) flag is set to 0, and CS is set to 1 if the channel is occupied. Once the spectrum information is stored, the traffic patterns of each channel are classified as either stochastic or deterministic. The channel classification algorithm used is based on the periodicity, where an edge detection method is used for period search. The average separation of the raising edges and the standard deviation of the separations (of the edge) are used to determine whether the traffic is deterministic or stochastic. After classifying traffic type, the idle time prediction method is selected. To predict the PU idle time, the CS information (stored in the channel database) is used. If CS = 0, the idle time prediction is set to 1. If CS = 1, the idle time prediction is set to 0. Secondary transmission will continue on channels with longer idle time, and once the PU appears on this channel, the SU will switch to the channel with the longest expected remaining idle time. Fig 7 summarizes the model as proposed

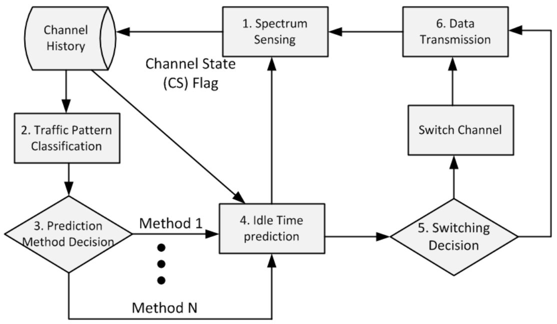

Fig. 7: Prediction System Model [29]

in [29].

Acharya *et al.* [57] proposed a predictive model based on long-term and short-term usage statistics of TV channels. In this model, the usability characteristics of a channel are based on TV channel statistics and are later used for selection of a channel for opportunistic transmission. The model uses a threshold mechanism to filter out channels with frequent and heavy appearance of PUs.

In [58], a multivariate time series approach is used to learn the PU characteristics and then predict the future occupancy of neighbouring channels. In order to reduce the complexity and storage requirements, a binary scheme is used; where 0 represents empty and 1 represents occupied channels.

3) PU Modelling Based on Measured Data

Riihijarvi *et al.* [59] proposed a technique to characterize and model the spectrum for DSA with spatial statistics and random fields using measured data. The proposed techniques were implemented using data obtained through spectrum measurements. First, they perform spectrum characterization by treating spectrum measurement results as a realization of some unknown random field Z. In this case, random fields are considered as extensions of the theory of stochastic processes from one-dimensional time to multi-dimensional space. Different metrics suitable for characterizing second-order stochastic spatial structure of the primary spectrum are derived using *Moran's I* [60] and *Geary's C* [61] statistics. These are two statistics commonly used to measure the degree of spatial correlation for spatial data whose covariance structure is defined by neighbourhoods.

Moran's I statistics is defined as:

$$I = \frac{n}{S_0} . \frac{\sum\sum W_{ij}(Z_i - \bar{Z})(Z_j - \bar{Z})}{\sum(Z_i - \bar{Z})^2} \tag{3}$$

where n is the sample size, W_{ij} is a matrix of weights (where $W_{ij} = 1$ if site i, j are neighbours, otherwise $W_{ij} = 0$). $S_0 = \sum\sum W_{ij} =$ twice the number of neighbours, Z_i indicates the continuous response at site i, and finally $\bar{Z}$ denotes the usual estimate for the mean of Z. The value of Moran's I lies between -1 and +1, where former indicating strong negative autocorrelation and latter strong positive autocorrelation. See [59] for Geary's C statistics representation. The above spatial statistics models were tested on distributed spectrum occupancy measurements of frequency bands used by popular wireless services such as Wi-Fi, TV and cellular networks. However, it was found that Geary's C requires sufficient amount of data to ensure that existing similarity patterns are not missed when the investigated bands are only rarely (i.e. in less busy locations/times).

A time-varying statistical model for spectrum occupancy using actual wireless frequency measurements is proposed in [62]. Using statistical characteristics extracted from actual RF measurements, first-order and second-order parameters are employed in a statistical spectrum occupancy model based on a combination of different probability density functions.

4) Other PU Modelling Techniques

Canberk *et al.* [52] developed a real-time based PU activity model for CRNs using first-difference filter clustering and correlation. In this difference model, the PU signal samples are first collected over a pre-determined duration, then the observed PU signals are clustered together if they are greater than a threshold. The authors developed a *PU activity monitoring module* which is implemented within each SU to monitor the spectrum bands and then samples the PU activity. In simple terms, this module is responsible for local spectrum sensing by testing the well known H_1 and H_0 hypotheses [2], where H_1 indicates that the PU has an activity in the spectrum band and H_0 indicates that there is no PU activity in the spectrum band. This PU activity monitoring module stores samples of the monitored PU activities into a vector, q, of size p as [52]:

$$q = [q(1), q(2), \cdots, q(m), \cdots, q(p)] \in \Re^p, \tag{4}$$

where m is the sampling index and p is the total number of PU monitored activity samples. This model claims to produce accurate PU estimation and higher throughput than the Poisson model.

C. Open Research Issues in Spectrum Characterization

1. *Secondary user activity modelling*

Most of the available literature focuses on the modelling of PU activities and neglects the modelling of SU behaviour. With the anticipated growth in the number of CRNs, it is important to devise reliable models for SU behaviour and characteristics.

2. *Heterogeneous Users Activity Database*

Spectrum characterization involves reliable modelling of PU activities. It has been suggested in [14] that a database can be used to store all the knowledge of the PU radio frequency environments. A major challenge is to create a reliable and secure database to store both the PUs and SUs activity models.

In summary, spectrum characterization allows CRNs to be aware of their operating RF environment and to intelligently determine the ongoing PU activities in a licensed spectrum. Using the learning ability of the CR, the history of the spectrum usage information can be used for predicting the future profile of the spectrum. In this section, we have discussed the key issues in RF environment characterization and PU activity modelling. Table I summarises the PU activity modelling techniques (with advantages and disadvantages) discussed in this paper. We have also discussed some open research issues for spectrum characterization in CRNs. In the next section, we discuss spectrum selection as another key function of spectrum decision.

TABLE I: Primary User Activity Modelling: Summary

Modelling Technique	**Advantages**	**Disadvantages**
Poisson Modelling	Widely used and easy to model traffic	Fails to capture short-term temporal variations; does not consider correlations and similarities within data
Statistics Modelling	Predicts future PU idle time based on history and learning	High probability of SU collision with PUs
Measured Data Modelling	Uses real measured data	Low computational complexity

V. SPECTRUM SELECTION IN CRNS

Once spectrum holes are characterized, the next major step is to select the best available spectrum suitable for the user's specific QoS requirements. In CRAHNs, the set of channels available for each node is not static. Due to dynamically changing topologies and varying RF propagation characteristics, spectrum selection techniques in CRAHNs should be closely coupled with routing protocols (commonly called joint route and spectrum selection). In this section, we discuss related work on addressing the spectrum selection problem in centralized and distributed CRNs. We conclude the section with some key open research challenges.

A. Spectrum Selection in Centralized CRNs

A typical centralized CRN is the IEEE 802.22 WRAN standard, which specifies a fixed point-to-multipoint topology. The cognitive function of IEEE 802.22 is in dynamic channel management [19]. Spectrum availability in IEEE 802.22 depends on whether a TV channel is occupied by incumbent users or not. Each TV channel occupies a frequency bandwidth of 6 to 8 MHz, depending on the country of operation. For example, in South Africa, each TV channel occupies a bandwidth of 8 MHz. Besides TV services, wireless microphones are also incumbent users on TV channels. These wireless microphones occupy very narrow bandwidths (in the range of 200 kHz) of the TV channel. It is important for a CRN operating on TVWS to support variable channel widths when selecting specific channels for different services or applications. The advantages of variable channel widths are discussed in [63], where it is shown that decreasing the channel width increases the communication range. This is mainly due to improved SNR (i.e. higher SNR for narrower widths) and resilience to delay spread. The delay spread resilience is shown in [63] for an OFDM network, "where the guard interval increases by a factor of two each time the channel width is halved". The mixture of TV and wireless microphone users within the TVWS makes it important for a BS to also consider narrow bandwidth incumbent users when performing spectrum selection.

Spectrum selection in centralized networks normally lies at the BS or AP. In TVWS based networks (such as IEEE 802.22), the biggest spectrum selection challenge is the fragmentation of the available frequency. This fragmentation varies from one channel to several channels, depending on the density of the TV stations. In [64], a spectrum assignment algorithm for managing variable channel width is proposed. This algorithm, called signal interpretation before Fourier transform, uses SDR to perform time-domain analysis of the raw signal in order to determine the available channel width. A moving average over a sliding window of the signal amplitude value is computed for accurate detection of the beginning and end of packet transmission.

In [65], a non-cooperative game theoretic framework is proposed to evaluate spectrum management functionalities in CRNs, with a particular focus on spectrum selection. In this framework, the spectrum selection process is modelled as a non-cooperative game among SUs who can opportunistically select the best spectrum opportunity. Two different cost functions that include the number of interferers, the bandwidth and the expected holding time are considered. The first cost function is defined as a linear combination of the three factors: interference, bandwidth and holding time. The second cost function considers the product of these three defined parameters.

A policy-based spectrum selection architecture for centralized CRNs is proposed in [66]. Three different pre-defined policies for spectrum selection are presented: weighted selection, sequential selection, and combined selection. In weighted selection, weights are given to each selection criterion within the BS and the best channels are selected based on the sum of weighted values. In sequential selection method, the policy manager provides the channel selection order and the channel selection procedure continues until there are no more channels (i.e. identified vacant channels) left. And finally, the combined selection method uses both the weighted and sequential methods. Several criteria are used for the BS to make the proper spectrum or channel selection. This includes coverage area, number of supported nodes, average SNR, and channel occupancy history.

B. Spectrum Selection in Distributed CRNs

In distributed multi-hop CRNs, such as CRAHNs, the entire communication session consists of multiple hops with rapidly changing channel properties and switching from one channel to another (heterogeneous spectrum availability). This imposes new challenges for designing optimal routing protocols. In order to address spectrum selection in multi-hop CRNs, a joint spectrum and route selection design approach is preferred [15], [16], [35], [67]–[71]. In joint spectrum and route selection design, lower layer (such as MAC layer) knowledge of the wireless medium is shared with the network layer [16] in order to make an intelligent decision. In this subsection we review related joint spectrum and route selection in multi-hop CRNs.

Routing in traditional multi-hop wireless networks is a well known and well studied problem. The emergence of multi-hop

CRNs brings new challenges to routing which call for new cognitive routing approaches with novel metrics that capture spectrum availability and PU activities [68]. If we decouple the route and spectrum selection, each of these tasks will be distributed to the network and MAC layers, respectively. Although it offers an apparently simple solution to managing spectrum in multi-hop networks, decoupling route and spectrum selection suffers from poor prediction of link quality and also fails to address end-to-end optimization, which is important for multi-hop transmission [69]. A comparative study between two design methods, (1) decoupled route and spectrum selection, and (2) joint route and spectrum selection, is presented in [69]. The authors note that joint route and spectrum selection design allows each SU node to select the packet route, the channel to be used by each link on the route, and a time schedule of the channel usage [69]. In this paper we focus more on the joint route and spectrum selection method due to its relevance to our theme, and readers are referred to [69] for the decoupled route and spectrum selection method.

A joint routing and spectrum selection protocol which computes paths from a source to a destination by considering the PU activities and the path availability is proposed in [68]. This protocol exploits the parallel transmission capability of CR nodes and calculates the link capacity on every channel dynamically. In [70], a probability based routing metric is presented. This metric relies on the probability distribution (which is assumed to be a log-normal distribution) of the PUs to SUs interference at the SU node over a given channel. The path selection algorithm is initiated by the source node whenever an application requests a route to a destination. The source node acquires information about other nodes through link state advertisements over the control channel.

Ju and Evans [16] introduced a scalable cognitive routing protocol (SCRP) for mobile ad-hoc networks which employs an intelligent flooding protocol to save on routing overhead. This is achieved by allowing nodes to selectively flood route request (RREQ) packets along predicted strong links and over predicted preferred frequencies or channels. Unlike traditional on-demand routing protocols, SCRP makes use of neural network machine learning methods to make the CR nodes aware of history.

One of the challenges in joint spectrum and route selection is re-routing and switching to other available channels or links once the PU appears. To address the problem of SU link disconnections, Shih *et al.* [15] proposed a route robustness approach for path selection in multi-hop CRNs. This is done by guaranteeing a basic level of robustness for a set of routes, and then selecting some routes from this set and determining the spectrum to be allocated on each link. In [35], a joint interaction between on-demand routing and spectrum scheduling is proposed where an analytical model is used to describe the scheduling-based channel assignment progress. This model reduces the inter-flow interference and frequent channel switching delay. A distributed algorithm that jointly solves the routing, spectrum assignment, scheduling and power allocation in multi-hop CRNs is proposed in [71]. Through this method, each SU node makes real-time decisions on spectrum and power allocation based on locally collected information. Thus, SU nodes can adjust their transmission power, in order to maximize link capacity, based on the assigned spectrum band.

C. Open Research Issues in Spectrum Selection

1. *Cooperative Spectrum Selection*

Cooperation has been at the forefront of research in CRNs due to its advantages over non-cooperative approaches. A good example is in cooperative spectrum sensing, where neighbouring SUs share their sensing information with the aim of exploiting spatial diversity. A challenge in cooperative spectrum selection is on how to combine information from cooperating users while addressing the transmission or cooperation overhead.

2. *Spectrum Selection in Heterogeneous Traffic Networks*

In a given CRN, the SUs may have heterogeneous QoS requirements. The available spectrum may exhibit fluctuating and variable spectrum qualities. In heterogeneous traffic networks, a challenge is to select appropriate bands to satisfy the heterogeneous QoS requirements of each SU.

3. *Frequency Switching Delay along Multiple Hops*

In multi-hop CRNs, each intermediate SU node receives packets on one frequency channel, switches its transceiver to a different frequency channel, and then transmits the packets to the next node. The time a packet takes to reach its destination, after traversing multiple nodes, results in a cumulative channel switching delay. There is therefore a need to develop cognitive routing protocols which minimize the cumulative delay along the entire path.

In this section, we have discussed the importance of spectrum selection in CRNs for distributed and centralized network topologies. In centralized topologies, spectrum selection decision is made by the central node such as the BS or AP. The situation is more complex in multi-hop CRNs, which calls for a joint spectrum and route selection approach. Although joint spectrum and route selection design offers improved accuracy and reliability, it comes with additional complexity and communication overhead. Table II briefly summarizes selection techniques discussed in this paper. We concluded the section by listing some open research issues for spectrum selection in CRNs. For additional open research issues in multi-hop CRNs, readers are referred to [72].

VI. RECONFIGURATION IN CRNS

In traditional wireless networks, the radio terminals are statically configured to operate over pre-defined frequency channels with pre-defined transceiver parameters and characteristics. Although such systems may employ adaptive techniques to adjust various transmission parameters such as transmission power, and modulation and coding schemes, their hardware-based architecture limits their flexibility to adapt to the external environment. However, heterogeneous spectrum availability and DSA requires systems that are far more flexible. CRs offer such flexibility and are able to rapidly adapt their transceiver parameters (such as channel width,

TABLE II: Spectrum Selection Solutions: Summary

Selection Technique	Advantages	Disadvantages
Centralized selection (e.g. IEEE 802.22)	Controlled at the BS or AP and standard based.	Single point of failure and fragmentation of channels.
Joint routing and spectrum selection	Efficient spectrum usage; good end-to-end performance.	Computational complexity; communication overhead; and re-routing due to channel switching.
Decoupled routing and spectrum selection	Simple to implement since it uses existing solutions.	Unreliable route selection due to spectrum fluctuation; poor end-to-end performance; and requires multi-radios.

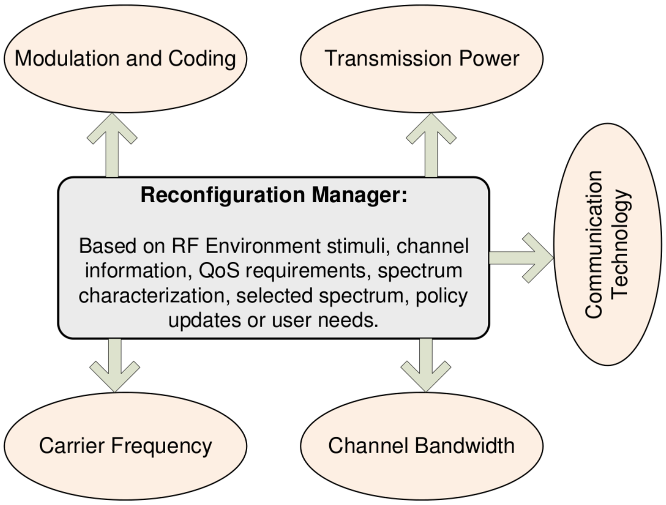

Fig. 8: A CR Reconfiguration Manager

centre frequency, transmission power, modulation and coding) based on the external RF environment, policy updates, QoS requirements, selected spectrum, channel characteristics and the needs of the users. This is illustrated in Fig. 8. This flexibility is easily realised by implementing CRs using SDRs [27].

The CR reconfiguration task requires a clear understanding of how the communication parameters interact within the different protocol layers. Based on our spectrum decision framework (see Fig. 2), reconfiguration of parameters occurs after the spectrum of choice has been characterized and selected. In this section, we first discuss reconfigurable parameters in a CR, and then present some related work on CR reconfiguration in both centralized and distributed CRNs. We also discuss energy efficiency in CRNs because it affects the reconfigurable radio parameters. We conclude this section with open research issues.

A. Reconfigurable Parameters

In this subsection, we study radio parameters that are commonly reconfigured in CRNs in order to adapt and satisfy the QoS requirements and regulatory policies. We limit our discussion to the parameters depicted in the reconfiguration manager in Fig. 8.

1) ***Modulation and Coding Schemes***

A CR should reconfigure the modulation and coding schemes to adapt to changing user requirements and channel conditions [2]. An adaptive transmission scheme based on a simplified transmission scenario and environment for CRNs is proposed in [73]. Based on the interference temperature model, the proposed scheme adaptively selects the modulation order that provides the maximum throughput for the SUs in the given channels.

2) ***Transmission Power***

Power control is used to manage and adjust the transmitted power of wireless nodes in order to achieve objectives such as reducing co-channel interference, managing data quality, maximizing network capacity and minimizing energy usage [74]. An effective CR power control scheme must be a trade-off between the protection of PUs from harmful interference and the support of SUs' QoS, as long as the interference constraint is not violated [75]. Unlike conventional radios, a CR adapts its transmission parameters based on the environment that it operates in. The transmission power of a SU affects the communication range and also how often the SU sees spectrum opportunities. If a SU wants to transmit at high power levels, it must wait for the opportunity to do so (meaning it should wait until there is an available channel that allows higher power secondary transmission). In CRAHNs scenarios, if a SU chooses to use low power for transmission, it may have to rely on multi-hop relaying, whereby each hop has to wait for its own opportunities to transmit [76].

3) ***Operating Frequency***

Operating frequency is another key reconfigurable parameter in CRNs. It is the capability of a CR to dynamically reconfigure the CR's centre frequency in response to changes in the RF environment. In [77], a predictive model is proposed to dynamically select the correct configurations, including the operating frequency. This prediction model must be updated continuously to ensure real-time prediction of the correct system configuration to achieve a specified goal based on a set of possible system configurations, environmental conditions, and an expressed demand.

4) ***Channel Bandwidth***

Channel bandwidth refers to the width of the spectrum over which a CR transceiver spread its signals. A CR can communicate on either narrower or wider bandwidths, depending on the environment and application. It is crucial for a CR to support variable channel width adaptation in order to operate in heterogeneous networks (i.e. using different wireless technologies). A good example of channel width adaptation is where a Wi-Fi node adapts its channel width to communicate in 5, 10, 20 and 40 MHz channels in order to operate on both 2.4 GHz and TVWS frequencies. Channel bandwidth adaptation can also be useful in rural areas where low throughput links can be tolerated in exchange for increased range and reduced power. This channel width adaptation forms part of reconfiguration capability in CRNs.

5) *Communication Technology*

The reconfigurable capability of the CR should also allow interoperability among different communication systems (such as cellular GSM, LTE, Wi-Fi, WiMAX, etc.). For instance, a CR can operate under different radio access technologies (RATs) without the need to manually set it. This makes CRNs heterogeneous wireless networks since they are composed of various types of communication technologies and networks.

B. Parameter Reconfiguration in CRNs

The centralized CRN, such as a cellular network, can dynamically configure its transceiver with the appropriate RATs and the RF spectrum to adapt to environmental requirements and conditions. Reconfiguration may affect all or most layers of the protocol stack, with the PHY, MAC and Logical Link Control (LLC) and network layers being the most affected. At the PHY and MAC layers, there may be hardware components, such as transceivers, that dynamically change the RATs they operate and the spectrum they use, in order to improve capacity and QoS levels [78]. In this subsection, we look at related work on CR reconfiguration for both centralized and distributed CRNs.

In [79], a heuristic-based two-phase resource allocation scheme is proposed to address the problem of channel and power allocation for SUs in a cellular CRN. This scheme starts by allocating channels and power to the CR BSs to maximize their total coverage area while maintaining the interference constraints for PUs. From there, each BS allocates the channels among the CRs within its cell in order to maximize the total number of CRs served under a particular cell.

Chandra *et al.* [63] made a case for adapting channel widths in Wi-Fi based networks. Properties of different channel widths were studied using measurements from controlled environments. The impact of channel width is characterized based on flow throughput, communication range and power consumption. The results of their experiments approach the theoretical Shannon capacity, for example when the channel width was doubled from 5 to 10 MHz in a certain scenario, the throughout increased by a factor approaching two (1.89 to be precise). They also found that narrower channels are more energy efficient and resilient to multi-path delay spread.

In order to gain a clearer understanding of the impact of CR reconfiguration, the design of experiments (DOE) method is used in [77] to determine how the radio settings affect the CRN performance. DOE is a set of tools and methods for determining cause and effect relationships within a system or process. The authors used the DOE method to determine how parameters at the PHY, data link, network and application layers interact during the reconfiguration.

Kaur *et al.* [80] used fuzzy logic to implement a queuing based adaptive bandwidth allocation scheme in centralized CRNs. (Fuzzy logic is a superset of Boolean logic that has been extended to handle the concept of partial truth.) This scheme assists the channel distributor to decide the quantity of bandwidth that can be allocated to the SUs at any given time. A hierarchy-based strategy is used to optimize the amount of bandwidth allocated to the SUs depending on the arrival rate of both the PUs and SUs. It is the capability of the scheme to decide on the quantity of bandwidth to be allocated to the SUs, which enables it to reconfigure the SU parameters.

Reference [22] presents a mobile network based functional architecture for the management and control of reconfigurable radio systems. This architecture includes dynamic self-organizing, planning, management, dynamic spectrum management and joint resource management across heterogeneous access technologies.

Kim *et al.* [81] proposed a joint admission control and power allocation scheme for CRAHNs. The proposed scheme allows the SUs to estimate the interference limits at the PU's receiving points depending on the traffic load of the primary network. The authors developed models to analyse the outage probability for SU QoS constraints and the violation probability for PU interference constraints. They use these analytical models to develop a joint admission control and rate/power allocation method subject to QoS and minimum rate requirements, as well as maximum transmit power and fairness constraints for SUs.

A survey of CR as an application of artificial intelligence (AI) with a specific focus on reconfiguration is presented in [82]. In this paper, a cognitive engine (CE) is defined as an intelligent agent responsible for the management of the cognition tasks in a CR. In this context, the term ”intelligent” refers to behaviour that is consistent with a specified goal. Using AI, a CE is implemented as an independent entity interacting with the radio transceiver in order to make the decision on how to reconfigure the radio parameters. While current research on CR focuses mainly on DSA, we expect to see the application of AI techniques in CRs to extend beyond DSA to other application areas in the future.

C. Energy Efficiency

In CRNs, energy is consumed during different spectrum management activities such as spectrum sensing and data reporting [14]. When designing spectrum decision schemes, it is important to consider energy efficient techniques to ensure that less energy is consumed during these cognitive activities. A challenge in CRNs is to strike a balance between the conflicting goals of minimizing the interference to the PU and not compromising the QoS of the SUs [76], [83], [84]. To address this problem, it has been suggested in [83] that the transmit power be adapted based on the reliability of the sensed information. A CR enables us not only to adjust coding, modulation and transmission power, but also to learn and adjust electronic component (such as power amplifier) characteristics in order to minimize energy consumption [85]. Energy consumption is application dependent; therefore there is a need for different energy efficiency models to address the heterogeneous QoS and applications supported by a CRN.

In [85], an energy optimization framework for delay insensitive QoS requirements in CRNs is proposed. This framework enables learning of the radio component characteristics (such as power amplifier efficiency) to adjust radio parameters in order to minimize energy consumption. Based on the CR reconfiguration framework proposed in [85], an intelligent choice of configuration can lead to lower power and energy consumption. In medium- and long-range wireless communications, the power amplifier (PA) usually dominates the system power and energy consumption [85]. Using the CR's reconfiguration capability, it has been shown that energy savings of up to 75% can be achieved compared to conventional systems [85].

A joint optimization solution between the MAC and the PHY layers to maximize energy efficiency is proposed in [84]. This paper investigates energy-efficient transmission duration design and power allocation where a SU selects the available spectrum for data transmission. The link adaptation scheme proposed in [86] balances circuit power consumption and transmission power to achieve the maximum energy efficiency, which is defined as the number of bits transmitted per Joule of energy. The paper demonstrates that energy efficiency can be improved by increasing channel power gain, bandwidth, and by reducing circuit power consumption, which are reconfigurable parameters.

TABLE III: Parameter Reconfiguration Solutions: Summary

Radio Parameters	**Existing Techniques**	**Comments**
Modulation and Coding	Adaptive transmission scheme [73].	For centralized CRNs and based on interference temperature.
Transmission Power	Joint admission control and power allocation scheme [81].	For CRAHNs and SUs estimates the interference limits at the PUs receiver.
Operating Frequency	Predictive model to dynamically select the correct operating frequency in [77].	Requires continuous update to ensure real-time prediction
Channel Bandwidth	Queuing based adaptive bandwidth allocation scheme [80].	Assists the channel distributor to decide the quantity of bandwidth for SUs in centralized networks.
Communication Technology	Mobile network based reconfigurable radio systems in [22].	Allows CR to operate under different radio access technologies and includes dynamic self-organizing.

D. Open Research Issues in CR Reconfiguration

1. ***Practical Implementation***

Most research on parameter reconfiguration in CRNs has been based on computer simulation and mathematical analysis. However, these investigation techniques do not adequately capture all of the technical issues associated with parameter reconfiguration. In order to achieve more realistic and accurate results, it is crucial to build and experiment on more practical implementations of parameter reconfiguration techniques in CRNs.

2. ***Energy Efficiency***

In energy constrained scenarios, such as rural areas in Africa or mobile networks, it is important to consider energy efficient approaches during the reconfiguration of the CR parameters. While some aspects of energy efficiency have been explored in existing work, it is still an open challenge to investigate energy efficiency in the context of spectrum decision.

In summary, this section discussed the reconfigurability of CRs in order to satisfy the user's needs. We began by presenting common reconfigurable parameters and then discussed related work in CR reconfiguration. Table III provides a summary of the solutions discussed in this section. We also discussed energy efficiency issues affecting CRNs reconfiguration. We concluded this section by listing open research issues.

VII. SPECTRUM DECISION IN COGNITIVE RADIO PLATFORMS

In addition to the research efforts presented in the previous sections, there is ongoing work on the development of CR platforms to prototype and implement various techniques on CRNs. A ten year (1999-2009) study of hardware platforms and testbeds related to CR concepts is presented in [87]. There are various software radios and RF hardware available for the implementation of CR platforms. For a detailed comparison of different CR platforms see [88], where five different platforms are discussed and compared: the Universal Software Radio Peripheral (USRP) hardware [89] and GNU Radio software [90] platform; the Wireless Open Access Research Platform (WARP); the OpenAirInterface.org platform; the Winlab Network Centric Cognitive Radio Hardware Platform (WiNC2R); and the COgnitive Based Radio (COBRA) platform. The next subsections focus on the practical implementation of spectrum decision in CR platforms. Specifically, spectrum selection and CR reconfiguration are covered, but not spectrum characterization. This is because there is little or no work reported in the literature on the practical implementation of spectrum characterization in CR platforms. We conclude this section with open research issues.

A. Spectrum Selection Implementations

In [30], a channel capacity estimation engine that determines the available capacity of the routes in a CRN is proposed. This engine uses a scheduling aware routing algorithm to choose the best route from all the possible routes by simultaneously considering interference, MAC interactions and estimated capacity.

The GNU Radio based platform is used in [91] for the demonstration of sequence detection algorithms for dynamic spectrum access networks. Channel-sequencing algorithms are normally used to determine the order of multiple non-overlapping channels in which the SU should look for opportunities. A sequence detection algorithm is used for performing spectrum sensing whereby PU's access pattern is exploited using Markov memory modelling techniques. The transition information in the PU channel access is then used for improving spectrum selection in centralized CRNs. In [92], an intelligent SDR platform with CR capabilities [93] is used for the development of context-aware transmission adaptation and channel selection in OFDM-based CRNs using outdoor links (as opposed to indoor or in-lab links). This work also includes the implementation of spectrum decision functions for long-range rural connectivity provisioning.

B. CR Reconfiguration Implementations

Mandke *et al.* [94] developed a CR test-bed called Hydra using GNU Radio software and USRP hardware. The authors used Hydra to perform opportunistic link level rate-adaptation, which demonstrates the reconfiguration capability of a CR. In [95], an implementation of OFDM based systems in a GNU Radio framework is proposed. This platform features a run-time dynamic reconfiguration of radio parameters such as total transmit power, allocated rate and power over sub-channels.

In [96], a dynamic reconfigurable platform based on early access partial reconfiguration (EAPR) is proposed. EAPR is a partial reconfiguration method proposed by Xilinx to enhancement timing performance and simplify the process of building a partial reconfiguration design. This method allows rapid switching of the configuration of radio parameters from one implementation to another without changing the hardware.

In [97], a hardware platform known as Kognitiv networking over white spaces (KNOWS) is proposed for utilizing the TVWS in a Wi-Fi like network. The platform implements the reconfigurable radio using a commercial off-the-shelf (COTS) IEEE 802.11g card to generate the OFDM signals at 2.4 GHz. A wide band frequency synthesizer is used to convert the received signals to the TVWS band. To control the reconfigurable radio, the interface to the MAC layer is a list of register values that specifies the operating frequency, bandwidth, and the transmission power level. The nodes can reconfigure their operating frequency from 400 to 928 MHz in 0.5 MHz steps, as well as the channel bandwidth to 5, 10, 20, and 40 MHz. The threshold for packet reception in the TV band is -85 dBm. The time overhead for adjusting the radio parameters (e.g. frequency, bandwidth, and power level) is less than 100 μs.

C. Open Research Issues in CR Platforms

Over the past decade we have witnessed growing research on CR with interesting theoretical and simulation results published. However, we have seen slower progress on practical hardware and system development for CR technology [87]. This may be associated with different research challenges, three of which are of them are discussed in this subsection.

1. *Spectrum Characterization Implementation*

The available literature on spectrum decision implementation focuses on spectrum selection and CR reconfiguration. However, to the best of our knowledge, no practical implementations of spectrum characterization on CR platforms have been reported. Therefore, the practical implementation of spectrum characterization in CR platforms remains an open research question that still needs to be addressed.

2. *A Complete Functional CR Platform*

The majority of CR platforms reported in the literature focus mainly on demonstrating a single aspect of CR (such as spectrum sensing, spectrum selection, or CR reconfiguration) separately. As the field matures, practical test-beds and field trials of the complete dynamic spectrum management framework (1) are needed. In order to achieve this, there is a need to develop and build an integrated CR platform capable of performing all CR functions with an interface to a dynamic geo-location database. More specifically, we would expect to see the practical implementation of integrated spectrum decision incorporating spectrum characterization, spectrum selection and CR reconfiguration.

3. *Large-Scale CRN Deployment*

Available CR platforms are typically based on a few SDR nodes for research and development purposes. However, there are no existing large-scale outdoor platforms that can be used to study different factors (such as multipath, path loss, the hidden node problem, etc.) affecting CRNs operating as secondary networks within a licensed radio environment. This would be particularly useful in rural and sparsely populated areas. There is therefore a need to develop large-scale CRN platforms to enable real-life CR deployments in the future.

In summary, there are numerous SDR platforms developed to implement and prototype CR functions. GNU Radio software and USRP hardware-based platforms are common because they are cost effective and widely deployed with a large support community. However, the majority of these platforms focus on the implementation of spectrum sensing rather than spectrum decision. In this section, we discussed related work on the implementation of spectrum decision functions on practical CR platforms; and also listed open research issues that still require attention. The next section looks at future developments in CRNs.

VIII. FUTURE DEVELOPMENTS IN CRNS

Although the CR area is relatively new, it has grown rapidly in just under a decade. Due to the fact that CRs solve a global pressing need (i.e. how to more efficiently manage scarce and precious RF spectrum), it has received considerable attention from regulatory bodies, standardization bodies, governments, academia and industry around the world. Over the past decade, research on CRs has resulted in thousands of publications in international peer-reviewed journals, magazines, and conference proceedings. Today, almost every call for papers to technical conferences includes at least one topic in CR and spectrum management or efficiency. This growth is expected to continue for at least the next five to ten years and beyond.

This paper covered spectrum decision, one of the key components of CR technology. The open research challenges identified in this paper are focused only on achieving spectrum decision in CRNs. However, looking at CR more broadly as an enabling technology for efficient spectrum management, the future looks bright. This is particularly so with all the ongoing world-wide research and regulatory efforts collectively aimed at making a CR a reality. We now list some of the potential future developments in CRs as an enabling technology for DSA:

- We foresee future developments in CR technology being potentially one of the most influential scientific and engineering endeavours of the 21st century. As indicated in [98], software or computer-based thinking will be the driving force.
- The success of CRs may see it being considered as a key technology in fifth generation (5G) wireless networks.
- Spectrum regulatory agencies across the world will have to face a fundamental paradigm shift in the way they manage the spectrum. In future, network operators may also have a role in regulating their own RF spectrum with the option of leasing to third parties (through the so-called secondary spectrum markets). The beginning of such spectrum reforms are already being witnessed in some countries through spectrum auctions.
- New forms of businesses to facilitate spectrum trade and intermediation promise to dominate in the future. A potential example is the dynamic frequency broker (DFB) system proposed in [99]. DFB acts as a local computerized frequency coordination authority and keeps a complete database of frequency assignments within an area as well as an updated terrain propagation path loss model of its area. It then assigns frequencies on a temporary basis based upon transmitted signal power, spectral density, receive and transmit antenna properties and the required received signal to interference level.
- The integration of AI techniques into CRNs as discussed in [82].

For spectrum decision specifically, we see the following as the potential future developments:

- We are likely going to witness widespread usage of game theoretic approaches as a mathematical tool for addressing spectrum decision and selection problems. This will enable CRs to make autonomous, independent and rational strategic decisions [100] on the available spectrum bands.
- The need for accurate PU characterisation calls for knowledge based on-line databases. Unlike proposed spectrum brokerage business systems, such as in [99], PU activity databases may be controlled by primary network operators, and may only be accessible by CRN operators who are willing to operate as secondary networks.
- Although CR promises efficient utilization of the RF spectrum, it is challenged with network switching delay. This spectrum switching delay includes times for the spectrum decision process in the base station, signalling for establishing new channels, and RF front-end reconfiguration [26]. It is during this switching time that the transmission of the SU is temporarily disconnected which may be detrimental to delay-sensitive applications.
- Interference management and resource allocation is another important topic to consider when dealing with spectrum decision algorithms in CRNs. So, future spectrum decision algorithms should answer this question: How can the SUs transmit simultaneously with the PUs while keeping the interference level of the SUs within an acceptable range [101]?
- Various security issues related to spectrum decision will have to be addressed. For example, how to ensure that only authorised users are permitted to use secondary CRNs and allowed access to sensitive spectrum decision information such as PU and SU activity models.

Finally, more research and development efforts should aim at addressing other relatively unexplored areas of CR-based spectrum management such as spectrum sharing and spectrum mobility. However, the existing research challenges on spectrum sensing and spectrum decision have not been exhausted and doubtless new ones will continue to emerge in the future. These challenges are sure to occupy researchers for some years to come.

IX. CONCLUSION

Spectrum decision in CRNs is crucial to ensure that appropriate available spectrum bands are selected to satisfy the heterogeneous QoS requirements of the SUs. In this paper, we presented the main functions related to spectrum decision in CRNs based on an extensive study of the existing literature. We explored spectrum decision based on its three key functions: spectrum characterization, spectrum selection and CR reconfiguration. We identified a number of open research issues related to key functions of spectrum decision. We also reviewed various ongoing research work on practical implementations of spectrum decision in CR platforms.

It is worth mentioning that in CRNs, the spectrum decision capability relies on effective spectrum sensing and reliable or accurate data on primary network characteristics (e.g. from geo-location spectrum databases). To realize all of CR's promised capabilities, especially on spectrum decision, the open research issues raised in this paper still need to be addressed. We hope that this paper will be a useful reference point for new and existing researchers in the area of spectrum decision in CRNs, and thus contribute towards the realization of fully functional spectrum aware CRNs.

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