Cognitive Radio: Technology Survey and Future Research Directions

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***Abstract*— Currently, the radio spectrum is statically allocated and divided between licensed and unlicensed frequencies. Due to this inflexible regulatory policy, some frequency bands are growing in scarcity, while large portions of the entire radio spectrum remain unused independently of time and location. Cognitive Radio is a recent network paradigm that enables a more flexible and efficient usage of the radio spectrum. Basically, it aims to allow wireless devices to opportunistically access portions of the entire radio spectrum without causing any harmful interference to licensed users. This document provides a brief description of this research area. Emphasis is put on Cognitive Radio genesis, issues that must be addressed, related technologies, standardization efforts, state of the art and future research directions in the field, according to the vision of the authors.**

Keywords-Cognitive Radio; Dynamic Spectrum Access; Medium Access Control; MAC; Learning

I. Introduction

This document aims to provide a brief description of the current state of development of the Cognitive Radio (CR) area, focusing on layer-2 and upper layer related issues, as well as a discussion about future research directions. The genesis and principles of CR are first introduced in the current section.

The radio spectrum is divided into licensed and unlicensed frequencies. The licensed spectrum is for the exclusive use of designated users. For instance, it includes the UHF/VHF TV frequency bands. The unlicensed spectrum can be freely accessed by any user, following certain rules (e.g., not exceeding a defined limit for transmission power). It includes, for instance, the ISM (Industrial, Scientific and Medical) and U-NII (Unlicensed National Information Infrastructure) frequency bands. ISM is shared by technologies such as IEEE 802.11 for wireless local area networks (WLANs), Bluetooth (IEEE 802.15.1) for wireless personal area networks (WPANs), ZigBee (built upon IEEE 802.15.4, which specifies the physical layer and media access control for low-rate WPAN) for low-cost and low-power wireless communications, and cordless phones. Therefore, these technologies, which operate and coexist in the same frequency bands, must compete with each other for the same limited spectrum resources.

While the unlicensed spectrum bands are becoming more crowded, especially ISM in densely populated areas, a report from Federal Communication Community (FCC) concluded that many licensed frequency bands are often underutilized, creating temporally available spectrum opportunities that are variable in time and space [1]. For instance, measurements taken between January 2004 and August 2005 by the company Shared Spectrum Company (SSC), show that on the average only 5.2% of the spectrum between 30 MHz and 3 GHz is in use at six different locations in the United States of America. The highest value was 13.1% at New York City and the lowest was 1% at the National Radio Astronomy Observatory (Socorro, New Mexico). These measurements clearly show that large portions of the licensed spectrum remain unused by licensed users, also designated as primary or incumbent users, independently of time and space. According to Tsagkaris, Katidiotis and Demestichas [30], this underutilization of the radio spectrum is explained by the aforementioned static assignment policies, and also by an often criticized governments' overregulation. It can be noted that, currently, the improvement of spectrum regulation is being debated in many countries in order to alleviate an already diagnosed artificial spectrum scarcity.

Cognitive Radio (CR) has emerged as one of the keys that can help addressing the aforementioned inefficient usage of the radio spectrum. It exploits unused licensed radio frequencies, often designated as spectrum holes or white spaces. CR aims to enable secondary users to autonomously access spectrum holes in the entire spectrum to increase performance, as long as they do not harmfully interfere with primary users. Basically, at a given time and location, CR aims to avoid the existence of portions of the spectrum going underutilized while others are crowded with many devices competing for the same channels. Therefore, the two main concerns of this recent networking paradigm are increasing the performance which is delivered to secondary users and protecting primary users from any harmful interference.

CR devices perform a kind of operation that is often designated as Dynamic Spectrum Access (DSA), Opportunistic Spectrum Allocation (OSA), Spectrum Allocation Access or Spectrum Agile Radio. A CR is a reconfigurable radio (Software Defined Radio - SDR) that is able to intelligently adapt its spectrum usage to the changing radio frequency environment and according to some predefined objectives, leading to the selection of the best operating frequency band and transmission parameters. CR issues can span all the layers of the communication protocol stack, but its basics are mostly limited to the physical (PHY) and medium access control (MAC) layers.

CR is still in its early stages of development and has recently brought intensive research on techniques that aim to provide a more flexible spectrum paradigm to be used in future wireless networks. According to Beltrán, Gutiérrez and Melús [35], CR will also contribute to the shift in business models and market structure that the wireless telecommunications area is about to witness. They refer CR as one of the new technologies that, in combination with dynamic pricing and spectrum allocation schemes, will offer alternatives to locked-in contractual relationships between provider and customer. Therefore, CR is considered a key enabler for the transition to a more competitive telecommunication landscape, where new operators will collectively and seamlessly provide customers with more flexible and dynamic spectrum arrangements.

The remainder sections are organized as follows. In section II, a description of the CR technology is presented, namely the related architectural approaches, issues, and standardization efforts. As CR issues are mostly related to the MAC sub-layer, section III summarizes the main features of several existing CR MAC proposals. Section IV briefly refers the implications of CR on the network and transport layer protocols. Section V describes the relevance of learning based on past experience in CR scenarios. Section VI discusses future research directions. Finally, conclusions are presented in section VII.

II. COGNITIVE RADIO TECHNOLOGY

This section describes the CR technology, focusing on architectural approaches, main issues, and standardization efforts.

A. *Objectives of CR*

CR aims an efficient utilization of the overall radio spectrum, avoiding crowded unlicensed channels while large portions of the licensed frequencies remain vacant at the same time and location. The main functionalities required for CR management are spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility. This because CR users must: (1) determine the spectrum holes (spectrum sensing); (2) select the best spectrum opportunities to meet the user communication requirements (spectrum decision); (3) coordinate access to the selected channels with CR neighbours (spectrum sharing); (4) switch to the selected opportunities (spectrum mobility); (5) maintain seamless communication during spectrum handovers; and (6) avoid any harmful interference to primary users. These self-configuration and self-optimization capabilities must include learning based on past experience, reasoning and dynamic adaptation of transmission parameters.

The status of a wireless channel can change due to several reasons in CR, such as node mobility, operating frequency, neighbour interference, transmission power and primary user appearance. When a CR device senses an opportunity that is more interesting than the working channel, it should proactively switch to it through an appropriate reconfiguration. However, specific requirements of some applications (e.g., multimedia streams) should be considered when deciding to execute a spectrum handover operation. In the users' perspective, spectrum handovers should be seamless, i.e., transparent.

B. *CR architectural approaches*

The architecture of CR networks can either be centralized or distributed. Spectrum allocation and access are controlled by a central entity in the centralized approach (e.g., a base station in an infrastructure-based network) and by CR users in the distributed approach. Akyildiz, Lee and Chowdhury [29] designate centralized CR networks as infrastructure-based CR networks and distributed CR networks as CR ad-hoc networks. In distributed CR networks, the secondary users need to incorporate all the CR-related capabilities, and spectrum allocation can either be achieved cooperatively (i.e., through the exchange of control and sensing information between neighbours) or non-cooperatively.

C. *Main CR issues*

The last two subsections have described the main objectives of the CR technology and the two possible architectural approaches that can be applied to CR networks. This section goes further in terms of details. It describes the main issues that must be addressed by CR in order to meet its objectives.

1) *Self-coexistence*

One of the most important and specific issue of CR is to avoid secondary users to harmfully interfere with primary users. However, self-coexistence is difficult to achieve in CR scenarios because well-defined cellular architectures and frequency allocations are not provided, primary users have non deterministic activities, and neighbouring secondary users compete for the same spectrum holes. According to Mody et al. [11], coexistence does not require the use of cognitive techniques, but the latter can be used to facilitate the former.

Overlay and underlay are two possible spectrum access techniques. With the underlay approach, secondary users are constrained to keep transmission power below the noise floor of primary users (i.e., the Interference Temperature as defined by the FCC [2]). Therefore, transmissions of secondary users are perceived as noise by the licensed users and spectrum handovers are not an issue. This can be achieved through spreading the transmitted signal over a wide frequency band, which enables a short range high data rate to be achieved with very low transmission power [8]. UWB (Ultra Wide Band) is such a technique.

With the overlay approach, which requires dynamic spectrum access and has received much more attention from the research community, a node accesses the network using a portion of the spectrum that is not being used by primary users. Therefore, restrictions are imposed on when and where secondary users can transmit, and not on transmission power. In this case, service interruption losses can be caused by the appearance of primary users and must be addressed. The overlay approach requires appropriate and accurate sensing and signalling mechanisms to cope with primary user activity in CR scenarios. Sensing and signalling are described in the next two sections. In the remaining of this document, CR implicitly and exclusively designates the overlay approach.

2) Accurate Sensing

Sensing aims to determine if a channel is idle or busy in terms of primary user activity. Furthermore, it can be considered a sampling process, and is related to the PHY and MAC protocol layers.

Concerning the PHY layer, hree groups of primary user detection techniques can be considered: (1) transmitter detection; (2) primary receiver detection, which is only feasible for the detection of TV receivers; and (3) interference temperature management, which is difficult to achieve [5][29]. Most of the current research effort focuses on the transmitter detection technique, which can be based on three different schemes: (1) matched filter detection; (2) energy detection; and (3) feature detection [5][29]. Energy detection is the easiest scheme to implement.

Usually, the access to the spectrum is achieved through a "sense-before-transmit" approach (see Fig. 1), i.e., a channel is sensed before any transmission. In order to minimize interference to primary users, secondary users can be limited to send just one packet in one "sense-before-transmit" round. Cooperative MAC protocols, which enable secondary users to share sensing information with each other, are required for an efficient and accurate detection of primary user activity. A cooperative sensing approach helps to solve the hidden primary user problem, i.e., when a channel that has been sensed available at source location experiences primary activity at the receiver side and vice-versa (see Fig. 2). Therefore, it addresses problems such as the adverse effects of noise uncertainty, multi-path fading and shadowing [5][29], which are main factors that degrade the efficiency of primary user detection in wireless networks. However, cooperation introduces traffic overhead that must be considered in resource-constrained networks.

Centralized, distributed and external sensing are possible approaches for cooperative sensing. In centralized sensing, a central unit (e.g., a base station or an access point) collects sensing information from CR devices, processes this input for decision making and broadcasts the output to the CR devices and/or other central units in the network. The IEEE 802.22 standard (see section D) and DSAP [7] are such examples. In distributed sensing, CR users share information among each other but they take their own decisions about the spectrum bands they can access. In external sensing, an external agent performs the sensing (e.g., through a dedicated network of spectrum sensing units) and broadcasts the channel occupancy information to the CR users.

3) Signalling

It follows from the previous discussion that CR scenarios require the exchange of control information between CR devices for spectrum sensing and sharing. Most CR MAC protocols use a common control channel (CCC), which facilitates signalling and also neighbour discovery in CR ad-hoc networks. CCCs can have hardware requirements for simultaneous operation on multiple channels, must enable the secondary users to continuously operate without any disruption, and can be dedicated. A CCC is easy to deploy, enables efficient broadcasting and allows distributed sensing. However, it is a potential bottleneck for network performance and scalability, as data channels remain underutilized while secondary users contend for the CCC, and is also prone to jamming attacks by malicious users. Possible candidates for CCC deployment are: (1) licensed spectrum; (2) unlicensed spectrum (e.g., ISM); and (3) UWB.

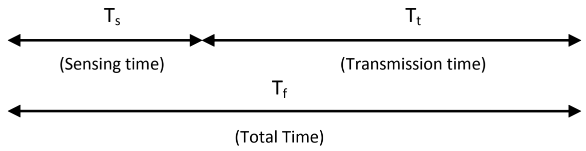

Figure 1. The "Sense-before-transmit" approach.

4) Optimized spectrum decision

In CR scenarios, secondary users are expected to dynamically choose the best available channels and transmission parameters. For instance, CR MAC protocols should be able to determine the order spectrum bands must be searched for minimizing time and energy that are needed to find a spectrum opportunity [28]. However, spectrum decision is still unexplored despite being a core issue in CR [2], and requires learning techniques that enable decision making even when accurate real-time information is not available. Niyato and Hossain [4] enumerate several techniques and methods that can be applied by the CR engine (see Fig. 3) for learning and decision making in CR (e.g., evolutionary computation, fuzzy logic, Markov decision process, pricing theory, and reinforcement learning). The CR engine includes a knowledge base, a reasoning engine and a learning engine [41]. The learning engine is responsible for manipulating the knowledge, based on experience, and its outcomes are intended to be accessed in the future by the reasoning engine for decision making. Therefore, at any time, decisions are generated based on the information that is defined in the knowledge base and on observation.

5) Seamless spectrum handover

Seamless transition with minimum quality degradation is a fundamental goal for any spectrum handover scheme. When QoS (Quality of Service) is a concern, no associated latency should be noticed by users, which may require upper layers of the protocol stack to be involved in the process. For instance, if estimation for spectrum handover latency is known in advance, an application that plays video streams from the network can buffer enough data before handover starts, and deliver it while the process takes place. According to Akyildiz et al. [2], there are many open research topics to be investigated in spectrum handover.

6) Cross-layer design

While spectrum sensing is restricted only to the PHY and MAC layers, spectrum management (e.g., spectrum handover, decision making and scheduling) can be related to all upper layers, which makes interaction and coordination between the different layers of the protocol stack necessary. Hence, to get better performance, the strict layer-based approach is often violated in wireless networks, namely through cross-layer interactions (see Fig. 3). For instance, in the proposal of Jia and Zhang [13], routing is computed by a cross-layer entity and the results are given to the network layer that just constructs the routing table.

7) Energy Efficiency

The aforementioned issues must be addressed by mechanisms that are energy efficient, i.e., have limited communication and resource requirements, since most of the devices are battery powered. The number of sensed channels must also be minimized through appropriate prioritization mechanisms as sensing is one of the main sources of energy and time consumption in CR scenarios. It can also be referred that cooperative sensing can indirectly address the energy efficiency problem as it enables the utilization of simpler CR devices with no or limited sensing capabilities (e.g., the IEEE 802.22 standard [17]). However, the overhead traffic required for cooperation can have a significant impact on network performance.

D. Standards

IEEE 802.22 [17] and SCC41 [11] are the today primary CR standard efforts and are briefly described in this section.

The IEEE 802.22 standard [17] is the first effort for achieving a CR international standard. It defines CR techniques that are specifically targeted to enable unlicensed devices to exploit television white spaces in the VHF and UHF bands (54-862 MHz) in a non-interfering basis for the deployment of Wireless Regional Area Networks (WRAN). Primary users include devices such as wireless microphones that can come on and off dynamically and are difficult to detect because they use low levels of transmission power and low bandwidths. IEEE 802.22 adopted a centralized single-hop model (each mobile device is associated with a base station (BS) and is not suitable for multi-hop networks (i.e., where users take help of neighbours for forwarding data to the destination when it is not one hop away). In IEEE 802.22, wide coverage is provided by several base stations.

The IEEE SCC41 (Standards Coordinating Committee 41), formerly known as IEEE P1900, addresses the area of Dynamic Spectrum Access Networks (DySPAN) and aims to develop standards for next generation radio and advanced spectrum management. There are several working groups that address specific issues such as interference and coexistence (P1900.2), architecture and interfaces for DySPAN in white space frequency bands (P1900.4a), distributed decision making (P1900.4.1), policy language (P1900.5) and spectrum sensing (P1900.6).

III. COGNITIVE RADIO MAC PROTOCOLS

The main functions in CR scenarios are spectrum sensing, spectrum access and spectrum sharing, which are mainly performed at the physical and link layers. Therefore CR MAC protocols are required and have been proposed in the literature. According to Cormio and Chowdhury [28], there are three main approaches for spectrum access in CR scenarios: (1) random access protocols (i.e., CSMA/CA - Carrier Sense Multiple Access with Collision Avoidance - like access for data and control traffic); (2) time-slotted protocols (i.e., synchronized time slots for control and data); and (3) hybrid protocols (i.e., partially time-slotted and partially random access).

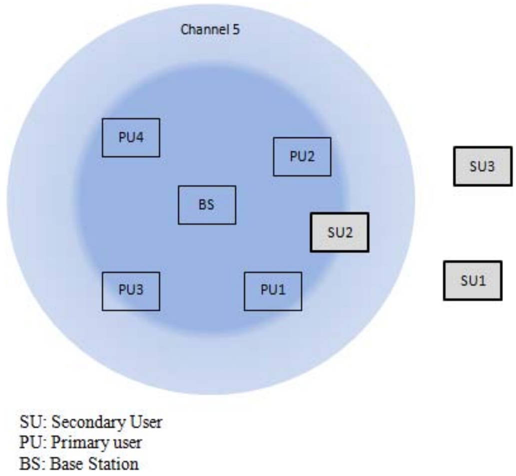

Figure 2. The hidden primary user problem.

From the sample of CR MAC proposals that is summarised in Table I, it can be concluded that most current proposals: (1) target ad-hoc network structures; (2) are random-based in terms of spectrum access; (3) require a dedicated common control channel; (4) require at least two radios/transceivers, being one of them dedicated to the common control channel, which is a waste of spectrum; (5) do not include any mechanism for achieving a balanced usage of spectrum opportunities; (6) are not QoS-aware; (7) do not address channel aggregation; (8) do not expect the existence of backup channels; (9) are not designed for energy efficiency; and (10) do not cope with false alarms and missed detections which are due to the imperfect nature of detectors. From these proposals, it can also be concluded that avoiding the common control channel requires synchronisation and time slotted approaches, which are more complex to design and implement, especially in ad-hoc networks [34]. Finally, it must be highlighted that mechanisms that explicitly address seamless spectrum handovers and optimized spectrum selection (e.g., through prediction), two core issues of the CR area, are not effectively addressed in most proposals.

IV. UPPER LAYER PROTOCOLS

The main operations in CR scenarios, i.e., spectrum sensing, spectrum sharing, and spectrum access are mostly related to the PHY and MAC layers. However, CR capabilities can influence the performance of any upper protocol layer and, when QoS is a concern, observation, learning and decision making must also be performed at the network, transport and application layers [4]. For instance, Issariyakul et al. [6] study the performance issues of the transport layer in overlay CR networks, and Akyildiz, Lee and Chowdhury [29] discuss several key challenges, concerning performance and open research issues, which are faced at the network and transport layers in Cognitive Radio Ad-Hoc Networks (CRAHNs).

According to Akyildiz, Lee and Chowdhury [29], in CRAHN, connectivity is also spectrum-dependent, which means that a disconnection can also be caused by a primary user appearance or a spectrum handover, even without mobility. Therefore, the type of disconnection must be indentified and appropriately addressed through innovative approaches [29]. The main differences with traditional routing protocols are that CR-based routing protocols must take into account the activity of primary users and its consequences (e.g., service interruption losses) to determine the best routes.

In CR networks, a secondary user is not able to forward packets during sensing. Therefore, sensing must also be considered at the transport layer in order to avoid excessive retransmissions and packet losses on the paths with any node in sensing state, especially in multi-hop distributed networks, and, consequently, the interaction between MAC and transport entities is necessary. Globally, the transport protocols need to be spectrum-aware in CR scenarios and, therefore, require new algorithms (e.g., for congestion window scaling in TCP) [29]. Akyildiz, Lee and Chowdhury [29] describe a TCP-based protocol for CRAHNs, which they refer to be the first work aiming to address the transport layer challenges in CRAHNs.

V. LEARNING BASED ON PAST EXPERIENCE

Spectrum decision can be performed reactively, as a consequence of an unexpected link failure, or proactively, i.e., through anticipation. Therefore, learning based on past experience is a core issue in CR scenarios, as it essentially enables characterizing the channels in terms of primary user activity and, consequently, the existence proactive decision schemes. Some of the benefits of proactive spectrum decision are: (1) a decrease of time and energy spent to find an idle channel before any transmission, as channels can be prioritized according to their probabilities of availability; (2) a decrease in the number of spectrum handovers and service interruption losses, because channels can be prioritized according to their expected durations of availability; (3) a decrease in terms of interference to primary users, as primary user appearance can be probabilistically determined during transmission.

In CR scenarios, primary user traffic is modelled as a binary sequence of alternating busy (ON) and idle (OFF) states with variable durations. Therefore, the main concern in CR scenarios is predicting the durations of the present and following periods, in an alternated sequence of ON and OFF states, or the probability of availability of a channel, based on past experience and observation. Akyildiz, Lee and Chowdhury [29] briefly describe the main characteristics of some proposals about primary user activity modelling and refer that some of them are not feasible in real scenarios. They also conclude that more practical models must be developed.

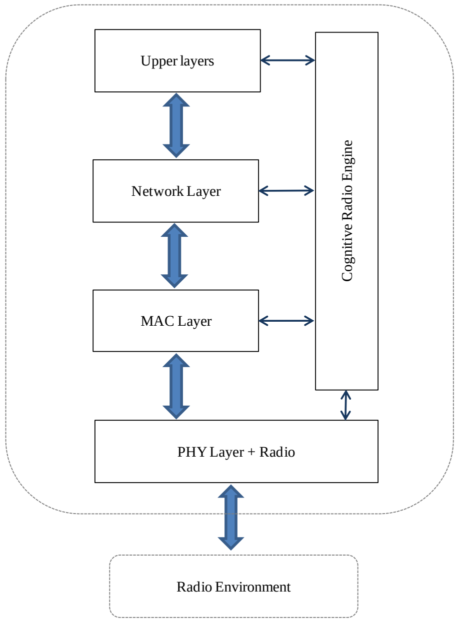

Figure 3. Generic Cognitive Radio Architecture.

TABLE I. CR MAC CHARACTERISTICS

Proposal		Network Architecture	Spectrum Access	Number of Radios/ Transceivers	Control Channel
Ghaboosi, Latva-aho, and Xiao	[3]	Mesh	Random	2	Yes
Niyato and Hossain	[4]	Mesh	Random	1	-
Hamdaoui and Shin	[9]	Ad-hoc	Hybrid	1	Yes
Kondareddy and Agrawal	[10]	Ad-hoc	Hybrid	2	-
Jia and Zhang	[13]	Ad-hoc	Random	2	Yes
Pawelczak et al.	[14]	Ad-hoc	Random	1 or 2	Yes
Joe and Son	[18]	Ad-hoc	Random	Multiple	Yes
Nan, Hyon, and Yoo	[19]	Ad-hoc	Hybrid	2	Yes
Su and Zhang	[20]	Ad-hoc	Time-slotted	2	Yes
Le and Hossain	[21]	-	Time-slotted	1	Yes
Hsu, Weit, and Kuo	[22]	Ad-hoc	Random	2	Yes
Ma, Han, and Shen	[23]	Ad-hoc	Random	3	Yes
Choi, Patel, and Venkatesan	[24]	Ad-hoc	Random	2	Yes
Zhao et al.	[34]	Ad-hoc	Hybrid	1	-
Hsieh et al.	[37]	Infrastructure	TDMA	2	Yes
Zhang, Fitzek, and Iversen	[38]	Infrastructure	Random	1 (CR devices) Multiple (Access Points)	-
Ghaboosi et al.	[39]	Ad-hoc	Random	2	Yes
Timmers et al.	[40]	Ad-hoc	Random	2	Yes

In the literature, several Machine Learning algorithms are considered to be adequate for proactive spectrum selection in CR scenarios, such as: (1) semi-Markov processes; (2) hidden Markov models; (3) Bayesian network; (4) neural networks; and (5) genetic algorithms. According to Clancy and Stuntebeck [32], the application of Machine Learning to CR Networks can be defined as follows: "CR users should be able to remember lessons learned from the past and act quickly in the future". It is important to select the techniques taking into account the constraints that are inherent to CR scenarios (e.g., real-time operations and limited capacity in terms of processing, memory and energy).

A few proposals exist in the literature concerning proactive-based approaches for CR scenarios, such as the works of Jiang, Grace and Liu [27], Kim and Shin [33], Höyhtyä, Pollin and Mämmelä [31], Tsagkaris, Katidiotis and Demestichas [30], and Zhao, Tong and Swami [34].

VI. FUTURE RESEARCH DIRECTIONS

Based on the previous sections, which briefly surveyed the CR area, some conclusions will now be drawn about the future research directions that must be pursued in order to turn CR into a mature area.

A. Seamless spectrum handovers

Seamless spectrum handovers are a major requirement in CR scenarios, as any lack of QoS assurance for secondary users is undesirable, especially for some classes of data traffic (e.g., multimedia streams and real-time traffic). Spectrum handovers also affect link state parameters and, therefore, can be wrongly perceived as network instability (e.g., congestion or link errors) by protocols in upper layers (e.g., transport and routing protocols). According to Akyildiz et al. [2], there are many open research topics to be investigated concerning spectrum handovers, and Sherman et al. [16] state that the type of the information to be accessed, QoS and security requirements for data streams should be considered in CR scenarios.

B. Proactive spectrum selection and interference avoidance

Intelligent decision mechanisms are expected for taking optimized spectrum access and sharing decisions. The main goals are delivering the maximum performance to secondary users and avoiding harmful interference to primary systems, which are expected to be unaware of the dynamic spectrum access according to the orthodox vision of the CR paradigm. In this context, the applicability and feasibility of learning based on past experience and observation, and intelligent decision making algorithms, which are capabilities of the CR engine (see Fig. 3), are often considered a core CR issue and were discussed in section V. This approach includes knowledge from other areas, such as reinforcement learning, i.e., learning by interaction with the environment, where different actions are tried and outcomes are observed without any trained example.

However, it can be concluded from the CR MAC proposals which have been referred in section III that optimized spectrum selection is still an unexplored issue. All the analyzed CR MAC proposals assume that secondary users dynamically choose the best available channel for transmission, which is effectively one of the CR principles. However, they do not specify how, i.e., according to which criteria and metrics, and through which mechanisms, or only propose simple mechanisms that are not accurately justified and evaluated. The only exceptions are POMDP [34] and the work of Jiang, Grace and Liu [27]. Other proposals concerning proactive spectrum selection and, more concretely, traffic modelling and prediction in CR scenarios do exist (see section V), but were not integrated with CR MAC protocols. Therefore, their practicality was not properly evaluated. CR networks include inherent challenges that must be taken into account to get useful and practical results. For instance, decisions must be taken on the fly (i.e., CR has real time requirements. Evaluating and validating the traffic modelling mechanisms using real measurements, which is not a common practice, is also another important issue that must be addressed in order to draw more convincing conclusions.

Proactive spectrum selection is definitively a main CR issue which needs further developments and must be considered a priority in terms of research.

C. Interdependency between the propagation characteristics of radio signals and the frequency band in usage

The interdependency between the propagation characteristics of radio signals (e.g., path loss) and the frequency band in usage (see Section II.C) should also be investigated in terms of its applicability to CR scenarios (e.g., avoidance of spectrum outages, tuning of the area of coverage). None of the CR MAC protocols that have been referred in section III addresses this issue. However, there are some proposals in the literature that consider the propagation characteristics of the frequency in usage, such as the work of Jo, Choi, and Cho [12], which presents a seamless spectrum handover algorithm that targets CR networks with a multi-cell infrastructure architecture.

D. Alternatives to the common channel

It has been outlined in previous sections that most of the existing CR proposals are based on a common control channel which is used for coordination and efficient spectrum sensing. However, this approach can saturate and, therefore, limit the scalability and overall performance of the network. Common control channels are also prone to jamming attacks. Therefore, more efficient and robust alternatives must be investigated. Cormio and Chowdhury [36] refer several related works that aim to set up and maintain reliable CCCs, while addressing several inherent challenges, such as saturation, robustness to primary user activity, jamming attacks, and limited control coverage. They also highlight several drawbacks concerning these works, and propose AMRCC (Adaptive Multiple Rendezvous Control Channel), a CCC design for CR ad-hoc networks based on frequency hopping

It is definitively a research priority to design scalable and robust CR MAC protocols, especially for distributed architectures.

E. Energy efficiency

Energy efficiency is a major concern in wireless communications as it enables to preserve battery life. In CR scenarios, spectrum sensing is one of the main sources of energy and time consumption, but also one of its key components. The lower the number of channels that are scanned the lower the power that is consumed and the time that is spent. However, scanning the entire spectrum and arbitrarily selecting the channels to sense, two common approaches in CR MAC proposals, are not appropriate to reduce the average number of channels that must be sensed prior a successful access. In fact, among the CR MAC proposals that were referred in previous sections, only the work of Jiang, Grace and Liu [27] explicitly aims to reduce the need for spectrum sensing. It uses a reinforcement learning-based approach which enables CR devices to use their prior learning experiences instead of sensing.

F. Validation of CR protocols

Most CR proposals referred in section III where validated through simulation or analytically, which is not totally convincing in many situations. Prototyping is another approach, but usually requires more resources that are not always available. Hence, the existence of alternative solutions is highly desirable.

In this context, GNU Radio/USRP-based experimental platforms are becoming popular in the wireless research community and are suitable for small-scale proof-of-concept of wireless proposals [13][25]. The USRP (Universal Software Radio Peripheral) hardware connects to a general purpose computer using the Universal Serial Bus (USB), and GNU Radio is an open source toolkit for building software radios. For large-scale experiencing, other solutions exist, such as ORBIT (Open Access Research Testbed for Next-Generation Wireless Networks) [26], which is a radio grid testbed that consists of an indoor radio grid emulator for controlled experimentation and an outdoor field trial network for end-user evaluations in real-world settings.

VII. CONCLUSIONS

In this document, the CR area, which is still in its infancy and aims to enable an efficient utilization of the radio spectrum, has been briefly described under different perspectives, putting the emphasis on layer-2 issues, learning based on past experience, and implications on upper layer protocols. The main objective was to provide the readers a global vision of CR concerning its principles, present state of development, and possible future directions. It was shown that several challenging issues still need further investigation, making CR an open research area, such as: (1) seamless spectrum handovers; (2) proactive spectrum selection; (3) interference avoidance; (4) energy efficiency; and (5) alternatives to the common control channel. Integrating practical learning capabilities with CR MAC protocols is also a core challenge in CR, as it enables to effectively address several of the aforementioned issues. Besides these issues, which are directly connected to the MAC sub-layer, other domains must also be considered, such as business models to support CR, regulation issues, and how upper layers can take advantage of CR to optimize their operations (e.g., routing).

It can be concluded that CR is, without any doubt, in the critical path to the wireless networks of the future. However, a significant amount of work remains to be done.

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