Technical Challenges of Cognitive Radio-Related Systems

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1 Introduction[2]

We are observing recently a huge interest in the Cognitive Radio-related wireless communications, both from the research and policy and regulation community. From the moment of publishing seminal paper by Mitola on Cognitive Radio [1], 19 books and 15 special issues of various journals have been published, together with 33 organized conferences and workshops dedicated to Cognitive Radio [2]. This is still a very fresh and fascinating research topic, therefore many technical research questions still need to be answered. In this paper we will focus on some of the technical difficulties involved in the deployment of Cognitive Radio in the real-life scenario. This paper will also describe what is actually meant by Cognitive Radio and what are the technical challenges associated with this concept.

1.1 Infinite Capacity, Infinite Possibilities

Martin Cooper, former corporate director of Research and Development for Motorola, and by many considered the father of the mobile phone, once stated that the number of wireless voice or data transmissions that can be conducted over a given area in all of the useful radio spectrum doubles every two and a half years[3]. Thus at the time this article was written theoretical number of possible wireless connections at the spot where Guglielmo Marconi performed his first spark gap transmission in 1895 raised from 1 to an astonishing 4.04×10^{13}.

But, for example, when one looks closely at the proliferation and utilization of Wi-Fi Access Points (APs) in crowded city areas, no much space is left for the Cooper's law. To give a sharp example, one of the Ofcom studies (United Kingdom's communications market regulator) showed that the average maximum number of APs that can be accommodated per square kilometer, such that reasonable Quality of Service (QoS) can be experienced by individuals, is 25.79, assuming that no other devices, e.g., Bluetooth and microwave ovens, radiate at a given frequency [3]. In a contrast to that, rough estimates of Wi-Fi proliferation in central London, performed by British futurist Peter Cochrane, revealed a stunning number of 200 APs/km^2!

1.2 Cooper's Law: Theory versus Reality

WLAN 2.4 and 5 GHz bands are overpopulated since their capacity is too small for a far too high number of interested parties. But even if WLAN network administrators would like to direct *ad hoc* some of the traffic to different bands to reduce the congestion, they are forbidden to do so since it would violate local spectrum licensing

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[2] This paper draws upon ongoing PhD research by the author. Aspect that are discussed in this paper have appeared in an earlier version in the IEEE DySPAN 2005 conference proceedings, and will appear in part in a book chapter in "Defining Cognitive Radio", edited by A. Wyglinski, M. Nekovee, and Y.T. Hou, to be published by Elsevier in 2010.

[3] Although we are not aware of any written document stating this observation, the Internet legend credits this law to Cooper.

laws. Even more interesting, with a closer look at any recent spectrum utilization measurement one will notice a huge asymmetry in spectrum utilization. That is, while popular spectrum bands, like WLAN are highly congested in certain geographical areas, majority of spectrum bands, although assigned to different systems, are practically silent. Under-utilization is especially visible in the licensed bands, i.e., bands for which one must acquire a license, potentially from a spectrum regulator, before any usage. Pagers, analogue television and telephony, although slowly disappearing in the annals of telecommunication history, still have a reserved place in spectrum charts, which no one except these licensees can use. Therefore, indeed WLAN users would benefit from a temporal spectrum translation, while this would cause no interference to anyone, since there would be no one to interfere with!

Thus the problem lies not in a Copper's law but in archaic spectrum licensing and management. Such static spectrum assignment, applied to radio frequencies for almost a century, leads to a so called *quasi-scarcity of the spectrum*. It would be thus logical to allow unlicensed users to exploit dynamically (opportunistically) licensed frequencies when they are free (to minimize interference) at a specific place and time. Theoretically, such approach would increase overall frequency reuse and would boost the throughput for applications that opportunistically use the empty frequencies. This way of spectrum access will be called throughout this paper Opportunistic Spectrum Access (OSA).

There have been many successful attempts in the past to liberalize spectrum access this way. Before going further with the introduction, let us briefly discuss the history of non-conservative approach to spectrum management.

2 A Brief History of Elastic Spectrum Management

Dynamic and opportunistic spectrum sharing is not a novel idea and is probably as old as radio communication itself. Looking at a history of radio regulation (especially in the United States) we can find many examples of attempts to liberalize spectrum market. Here by liberalization we mean maintaining a set of radio channels and assigning them on demand basis. Such maintenance would be completely distributed (using specific ”radio layer management protocols") or supported by a spectrum regulator.

One of the first communication systems with shared radio resources, developed in early 1920s, was maritime communication, see Fig. 1. There 2.182 kHz band was used as emergency and control channel on which all ships could listen whether someone is willing to communicate, by broadcasting working carrier identifier for further communication.

After the World War II, around 1960 USA's Federal Communications Commission (FCC) allowed using shared channels in land mobile communication, where one trunking channel could be used by many parties. With hardware extensions, like tone-coded squelch or Listen Before Talk (LBT), and the fact that most transmitted messages were short, shared channel communication became very efficient. In the mid 1970s FCC allowed to share channels at 27 MHz band (so called Civil Band (CB)) at first come first served (FCFS) basis. The only restriction that users of CB bands had to adhere to were maximum transmits power limits.

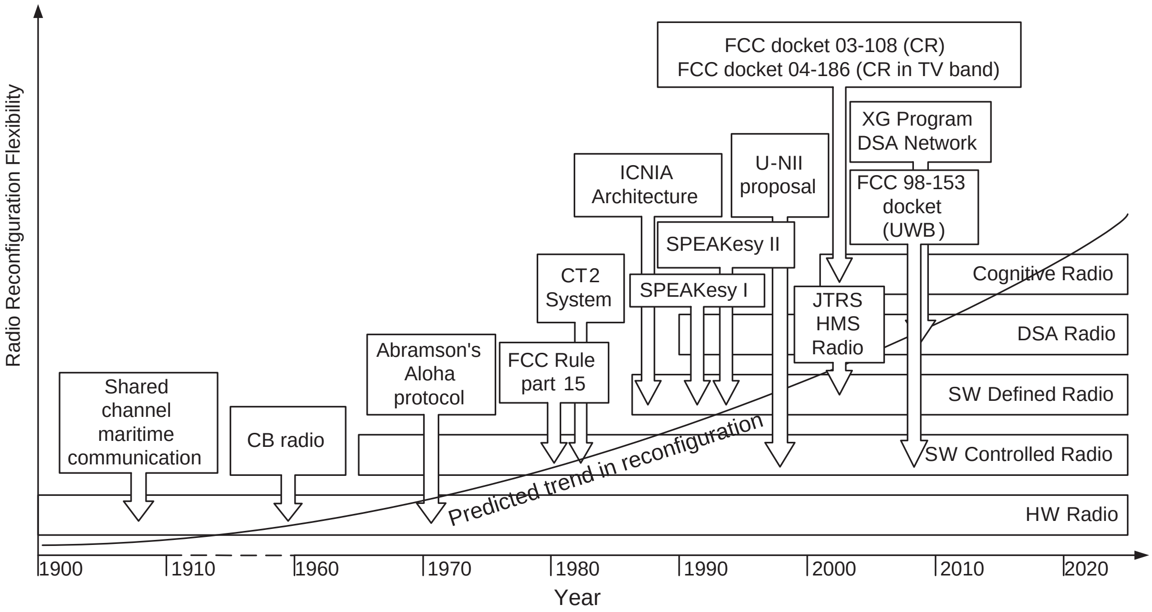

Figure 1. History of dynamic spectrum access systems and their relation to the implementation platforms, with the view on the future; HW: hardware, SW: Software.

With the advent of wireless data communication more flexible ways of spectrum management were possible. Abramson's Aloha protocol, presented in 1970, was a solution to use radio channels for wireless data communication, without any centralized coordinating entity. The ideas of random access were later extended to Packet Radio Networks. This, indirectly, gave a path to a FCC Rule part 15, which described the ways of coexistence of low power wireless devices in Industrial, Scientific and Medical (ISM) band. Adopted in 1985, it initially described the methods for wireless devices using spread spectrum as a communication technique. Later part 15 Rule was changed to specify any modulation technique that met required power limits, was wide enough and did not contain ``strong spectral lines''. No Etiquette nor LBT protocols were defined in FCC Rule. Its huge success was later legitimized by FCC acceptance of Apple Corp. proposal in 1995, to allow everyone use 5 GHz band (called Unlicensed-National Information Infrastructure (U-NII)) without any prior allowance. Currently, U-NII is used with success for wireless packet-based communication.

British Cordless Telephone Second Generation (CT2) system standardized in the mid 1980s, was another example of successful distributed channel management technique. 40 MHz band divided in 40 channels was managed by a Base Station (BS) that could monitor the level of interference on all channels and choose one that possessed minimum interference. CT2 systems were very popular in Hong Kong and Singapore.

In George Gilder's article ``Auctioning the Airwaves'' published in Forbes on April 11, 1994, author envisioned the future in which ``the wireless systems (...) will offer bandwidth on demand and send packets wherever there is room''. In parallel, Eli Noam from University of Columbia proposed in 1995 an ``Open Spectrum Access'' paradigm [4] in which interested parties would pay for bandwidth whenever demand occurs. Although both proposals addressed no technical issues and were mainly aiming at packet data communication, it was a sign for radio regulators that real steps in liberalizing spectrum market should be done, i.e., it was clearly visible that it might be better to promote licensed parties that share their non-utilized resources. Therefore, in 2002 FCC issued 98-153 docket, permitting many users to transmit on single channel, using low power communication based on Ultra Wide Band (UWB) communication.

Recently released FCC docket 03-122 revisited rule 15, allowing wireless data users to share channels with radar systems on a LBT basis. Finally FCC realized that Cognitive Radio (CR) techniques are the future substrate that stimulate full growth of ``open spectrum'' (see FCC docket 03-108 on CR techniques and FCC docket 04-186 on CR in TV spectrum).

We note that some probes of radio channel liberalization were not so spectacular, mainly due to non-flexible rules of operation given by the regulator. Examples of such systems were Radio Common Carrier (RCC) issued in mid 1970s, 800 MHz channel Air Ground Telephone Service (AGTS) from 1990s, Unlicensed Personal Communications Service (UPCS) and Large Scale Low-Earth Orbit Satellite System (called ``Big'' LEOS) with shared Code Division Multiple Channels (CDMA) (early 1990s). First, RCC could operate only when multiple service providers decided in how to share common channels, which was not so financially attractive due to competition between all interested parties. Second, AGTS was not popular due to many rules of operation that FCC provided. Third, UPCS specification by FCC also included many restrictions to the operation of potential systems. Moreover it had to share channels with microwave point to point links and often space separation was necessary between different UPCS devices. Finally, ``Big'' LEOS failure was mainly due to financial problems of service providers, because of licensing fees.

Brief illustration of the above discussion is given in Fig. 1. More information on historical developments in dynamic spectrum management can be found in [5]. Now, given the knowledge on the past in flexible spectrum management we obviously need to look at the future.

3 A Futurist Dream of OSA

In the late 1990's, in parallel to what has been happening over the last 100 years in radio spectrum management, community of researchers, visionaries, futurists and alike started to think about combining flexible spectrum access concepts with intelligent radio hardware platforms and smart networks. In this framework, emerging paradigms of dynamic spectrum access were related to cognitive communications[4]. The computation abilities of current electronic devices as well as recent developments in computer science and artificial intelligence allowed researchers to start thinking of introducing the cognition into the wireless networks and devices. This functionality would allow wireless systems in general to become more flexible, inferring from the environment the required actions and adapt the internal parameters to fulfill the needs of the user best. These cognitive devices would *per se* also allow to harvest the radio spectrum more optimally, allowing more users to communicate efficiently, without additional needs for licensing.

The idea of CR, as it is called in the literature, started to attract lots of attention. Since the introduction of this concept formally in 1999 by Mitola and Maguire Jr.[6] a massive amount of literature has been published on that topic. In nine years more than 35 conference and workshops that focused solely on CR have been organized and approximately 20 scientific journals special issues on CR have been published. Looking at the results of our simple investigation based on Internet webpage crawling, see Fig. 2,

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[4] The term *cognition* is a popular topic in psychological and social sciences which relates to information processing, understanding and making sense of the observations.

we can conclude that CR, as well inter-related with CR Dynamic Spectrum Access (DSA) and OSA, become increasingly popular.

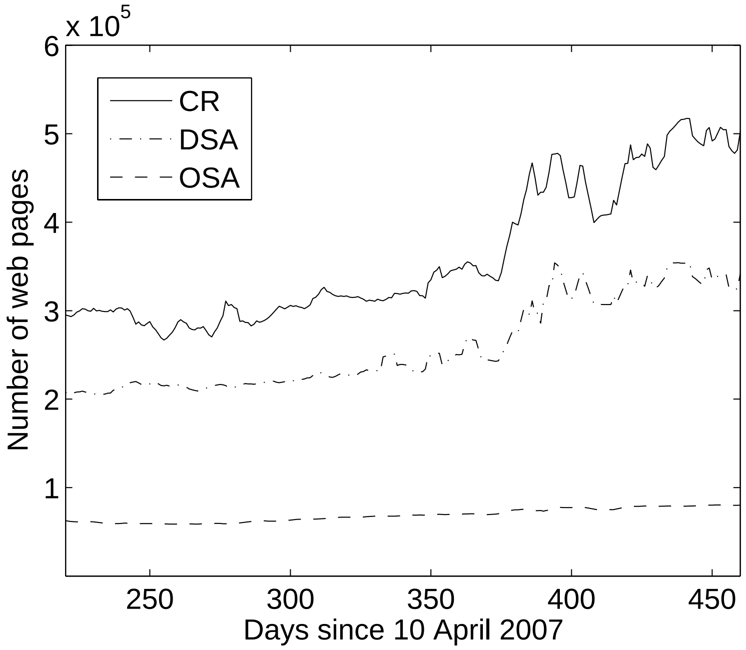

Figure 2. Statistics of the Google search engine responses for `Cognitive Radio' (CR), `Dynamic Spectrum Access' (DSA) and `Opportunistic Spectrum Access' (OSA) phrases in terms of number of WWW pages found.

Moreover, recent research papers outline the possibility of extending the principle of cognition to entire heterogeneous networks, thus defining the concept of Cognitive Networks (CN) [7] The aim of CNs is to self-adapt to changing requirements from users' applications in order to provide QoS and self-management capability. Such networking paradigm is based on the availability of Software Adaptable Network elements, driven and configured by a cognitive process. Cognitive process is a decision making engine which decisions are based on current network conditions and involving adaptation and learning techniques. Growing interest on this research topic is demonstrated by IEEE Communications Society Technical Sub Committee on Cognitive Networks (http://www.eecs.ucf.edu/tccn/).

3.1 Advantages and Applications of OSA

Since OSA and related concepts are radio access techniques, they can be applied to any communication system or network that suffers from spectrum shortage. It becomes attractive since it does not need any specially designed modulation technique, coding, etc. What OSA does is it reuses spectrum which has been detected as vacant, using any already existing communication technology. We can think of any currently existing network that can be upgraded with OSA functionality. Ad Hoc, sensor and cellular are the ones that might benefit from additional spectrum capacity that OSA can offer. Operation specific networks can also benefit from the introduction of OSA.

Also, OSA attractiveness has been recognized by ETSI, and has been considered as one of the candidates for future radio interface of 4G networks. The potential for OSA has been also found by IEEE. Its newest standard specifying protocols for future Regional Access Networks (RANs), called IEEE 802.22, aims at the design of a new radio interface that would work in the so called *white spaces*, i.e., places in radio spectrum vacated by analog television signal. Yet another initiative of the IEEE is a standard related to reconfigurable heterogeneous radio interfaces, called IEEE 1900.4.

3.2 Essential Concepts Related to OSA

Unfortunately, during the course of research on OSA, there has been a lot of ambiguity in naming certain concepts. First, we note that different modern approaches of spectrum management are commonly mistaken with CR.

3.3 Ambiguity in CR Definitions

Historically, CR was first described in [6, 8, 9] as a decision making layer at which ``wireless personal digital assistants and the related networks were sufficiently computationally intelligent about radio resources, and related computer-to-computer communications, to detect user needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs". It was a vision of an intelligent wireless ``black-box" with which user travels. Wherever the user goes, the CR device would adapt to new environment allowing the user to be always connected [6].

We need to note, that Mitola was not only the creator of CR notion, but also he coined the term SDR, see for example [8] He thought of CR as a natural extension of SDR, where software allowed to flexibly alter transmission and reception parameters, to all layers of communication stack. Also, he was the first one to think of including intelligence *ergo* cognition to the whole radio setup.

Six years after Mitola's first article on CR, Simon Haykin in his invited article to IEEE Journal on Selected Areas in Communications [10], recapitulated the idea of CR. He defined CR as ``inclusive of SDR, [idea] to promote efficient use of spectrum by exploiting the existence of spectrum holes", or ``intelligent wireless communication system (...) that adapt(s) to statistical variations in the input stimuli with two primary objectives in mind: highly reliable communication (...); [and] efficient utilization of radio spectrum." Thus he reduced CR to spectrum utilization-oriented device. His whole article focuses on signal processing techniques that could be helpful in managing particularly the second goal, i.e., efficient utilization of radio spectrum. Not only he defined his own CR, but also altered the basic cognitive cycle proposed by Mitola [8]. This paper was the first major paper that gave totally different definition of CR, and at the same time introduced terminology confusion. Interestingly, according to Google Scholar, as of 30 September 2008, original Mitola's paper on CR [8] was cited 404 times, while Haykin's paper [10] was cited 669 times.

Yet another notion of CR can be found in Information Theory (IT) community. There, CR can be reduced to analysis of capacity and throughput of Tx-Rx pair 1 (in that context called Secondary users) with Tx-Rx pair 2 (called Primary users) that interferes with pair 1. In this context a notion of *cognitive channel* is presented, i.e., a channel in which secondary pair of nodes possesses some kind of side information on what actually interferer is transmitting. It is clearly seen that cognition in IT context is far different from the cognition of Mitola.

The cognitive functionality may be spread across the layers of the communication architecture, resulting in coordination amongst the layers for an efficient use of available spectrum. Fig. 3 explains the basic functional blocks of such CR node. Specifically, apart from a reconfigurable radio, a CR node has various other components. The sensing and policies block (if available) are extensively used in deciding the availability of spectrum. These blocks also help to drive the learning and reasoning functions. The decision database along with the input from the sensing and policies block drives learning. The end result is that the radio is configured based on input from different layers of the communication stack as well as from the environment inputs.

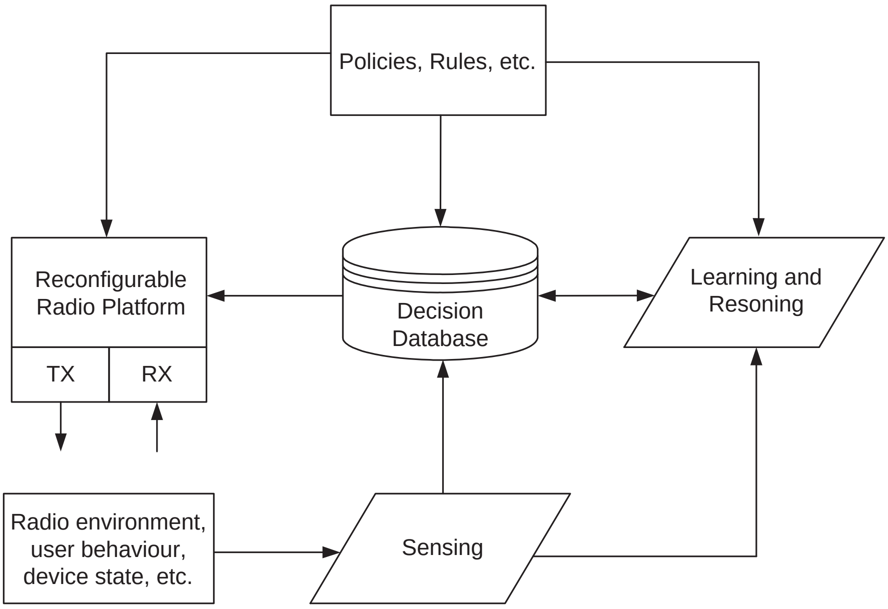

Figure 3. Components of CR node, see also [11].

Interestingly the SDR Forum explains CR as “a radio that has, in some sense, 1) awareness of changes in its environment and 2) in response to these changes adapts its operating characteristics in some way to improve its performance or to minimize a loss in performance".

In contrast to the above mentioned definitions, FCC describes CR as wireless node or network able to negotiate cooperatively with other users to enable more efficient utilization of radio resources, see FCC Docket 03-108 and 03-186 for more detail description. CR would be able to identify portion of unused spectrum and utilize it for communication purposes. Thus, FCC approach is a simplified form of Mitola and Maguire's vision where only radio spectrum conditions are considered while taking decision about future transmission and reception parameters. In this paper, whenever we refer to CR, we take FCC's view of the CR and proceed with this understanding. Yet another definition ambiguity comes from the CR implementation. Categories and classes of different future adaptive radio devices are listed in Table 1.

Type of Radio	Platform	Reconfiguration	Intelligence
Hardware	HW	Minimal	None
Software	HW/SW	Automatic	Minimal
Adaptive	HW/SW	Automatic/Predefined	Minimal/None
Reconfigurable	HW/SW	Manual/Predefined	Minimal/None
Policy-based	HW/SW	Manual (database)/Automatic	Minimal/None
Cognitive	HW/SW	Full	Artificial/Machine Learning
Intelligent	HW/SW	Full	Machine Learning/Prediction

Table 1. Classification of Adaptable Radio Devices; HW: Hardware, SW: Software

This simplistic comparison tries to show the differences between them, since some confusion still subsists in CR community on how to classify different devices and systems. Please note that in Fig. 1 different milestones in spectrum management flexibility have been mapped into different hardware platforms. The more flexible the given system is, the more flexible the hardware platform becomes. Certain milestones that we have to note in developing software based radio platforms are SpeakEasy [12], Joint Tactical Radio System [13], DARPA XG Program radios [14] and Integrated communications, navigation, identification avionics (ICNIA) [15]. We can predict semi-exponential growth in hardware flexibility in the coming years.

We also remark that other names are used in the literature to define CR systems, for instance, Dynamic Spectrum Access (DSA), Spectrum Agile Radio (SAR) or OSA. However, we feel that intelligent spectrum management is a logical component of CR but not its synonym. We refer to IEEE P1900.1 standard [16] for further discussion. We will elaborate more on this below.

4 Modern Spectrum Management Approaches

OSA belongs to a class of modern spectrum management techniques that are often vaguely defined [11, 17, 18]. To clear the ambiguity in terminology let us briefly introduce our classification in Fig. 4.

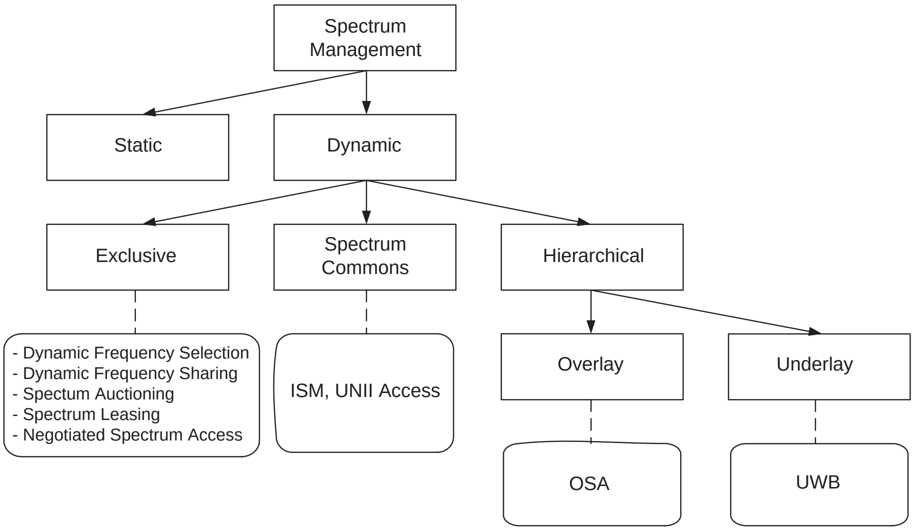

Figure 4. Modern spectrum management: Classification with the application examples (see also [17, 18]).

We consider three essential models: *Exclusive Spectrum Management* (ESM), the *Spectrum Commons* (SC) sharing model, and *Hierarchical Spectrum Management* (HSM). The ESM model still gives exclusive channel use to each user or provider, but differs from a static assignment in the sense that the channels are allocated dynamically among possible licensees. The process of exclusive channel access is usually governed by radio regulation bodies. The differences between ESM approaches, specified in Fig. 4, depend on the economic model that varies from country to country. In the SC model, different users compete for the assigned frequencies on equal terms. The HSM model gives Primary (Licensed) Users (PUs) more rights to use the spectrum then other Secondary (Unlicensed) Users (SUs). We can distinguish two HSM approaches. In *Overlay* HSM, only one user/system can use a frequency band at particular space and time, and the SUs have to back off when a PU is present. However, when no PU is present, the SU can opportunistically use the frequency band, so this technique is also referred to as OSA. In *Underlay* HSM, a SU can transmit in an already occupied band if this transmission does not increase the interference to the PU above a given threshold. A further classification of Overlay HSM (not shown in Fig 4) involves *Symmetric Coexistence* (when both SU and PU networks adapt) and *Asymmetric Coexistence* (when only the SU network adapts, obeying the PU requirements). Clearly, OSA is the most flexible spectrum management technique. Furthermore, Asymmetric OSA allows achieving maximal spectrum use without significantly altering the current spectrum regulation market.

5 Research Challenges

Due to the amount of published papers and the interdisciplinary nature of the topic, it is not possible to provide an exhaustive analysis of all research works available on OSA communications. The purpose of this section is therefore to briefly describe issues which are yet open and current under debate in the framework of research on OSA and CR networks.

5.1 Computation-related Problems

Decision Process

As CR and Cognitive (Radio) Networks (C(R)Ns)[5] are driven by a decision process, a relevant research issue related to *where* and *how* the decision, e.g., on spectrum availability, should be taken. The first question is directly related to whether the cognitive process should be implemented in a centralized or distributed fashion. This aspect is more critical for CNs, where intelligence is more likely to be distributed, but also CRs, as decision-making could be influenced by collaboration with other devices. The second issue is related to the choice of the decision algorithm. It represents a challenging topic, since although several optimization schemes based on learning are available in the literature, like neural networks, genetic algorithms, ant-colony optimization, etc., they need further analysis and customization to fulfill the system requirements.

Learning Process

More complex cognitive functionalities are related to enabling a devices or a networks to learn from past decisions to improve their behavior. The design of the learning algorithm represents by itself a challenge, and measurements which should be employed by learning open new issues related to which measurements to use and how to perform them.

Interaction with all Layers of Protocol Stack

While the aspect of inter-protocol interaction is *per definitionem* included in the concept of CN as means to support user and applications requirement, no relevant and comprehensive analysis is available to address the performance and, in general, the behavior of applications and networks based on CR and CN technology.

5.2 Architecture-related Problems

Implementation

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[5] Cognitive Radio Network (CRN) is a a network capable of establishing links between its CR Nodes to establish connectivity, and to adjust its connectivity to adapt to changes in environment, topology, operating conditions, or user needs.

While general block diagrams and functional blocks of CR are being identified, an open issue is represented by the hardware and software architecture to support CR and related designs. Indeed, in the case of a single CR device this problem is closely related to research on Software Defined Radio (SDR). However, in a wider scenario including cooperation among several devices and across different network and higher levels of adaptation, architectural issues represent a complex challenge as they include mainly the definition of architectures for Software Adaptable Networks [7], but also compliance and inter-operability with ISO/OSI or TCP/IP protocol stacks, standardization of transparent signaling structures.

Equipment Test Procedures and Certification

Equipment that is capable of using new technologies that enable underlay or overlay OSA will have to go through the multiple tests. It is not only the interference that these devices can cause to its surroundings but also the `intelligence' that these devices have to sense the surroundings need to be quantified. This is a very hard problem since this measures indirectly the intelligence that is built into these devices.

Devices with potential CR capability bring new challenges also for the certification process. To prove that a radio device will always remain within operational boundaries is more difficult compared to traditional radios. Future hardware vendors must know the design methodologies and testing procedures to affirm that their devices will not interfere with any PU of a given frequency channel. Many technical studies are involved such as hazard analysis, listing potential causes for out of compliance transmission, and description of previous behavior-based certification efforts. In fact, its most important task is to standardize the dependability of a radio system vis-a-vis quantifying the level of trust one has.

Different levels of trust can be defined for a particular spectrum based on its primary user. As an example, if a CR radio uses frequencies assigned for avionics, it must have a high level of confidence in its capabilities to detect the activities of the primary users.

5.3 Physical Layer-related Problems

Accurate and Secure PU detection

Every OSA network or device needs to detect which part of the spectrum are vacant. The so called spectrum sensing should be performed such that it will result in high confidence in spectrum occupancy decision. Also, the spectral sensing protocols must guarantee that even a malicious adversary cannot trick the secondary users into using a non-vacant channel and interfere with a PU. One of the primary goals of OSA networks is to identify spectrum holes and to make these available to traditionally spectrum starved applications, without requiring the PU to reprogram their hardware and functionality. In other words, it is essential for the SUs to detect the presence of a PU and evacuate immediately if there is a PU active in a band. However noise and propagation conditions make spectrum sensing a very difficult task.

5.4 Protocol-related Problems

Inter-operability

With the ability to switch between various bands of frequencies to achieve higher spectrum usage, the OSA devices will not be confined to one frequency band. Thus many technologies will be using multiple frequency bands. In such a scenario, the question is how to maximize the spectrum usage with these devices co-existing and cooperating or collaborating with each other. The different networks and the users should use the available free spectrum in an efficient and fair fashion.

5.5 Signaling

It represents a key research issue as both CRs and CRNs need to configure lower level parameters or networking devices, respectively, and therefore the underlying infrastructure needs to provide software reconfiguration and programming, thus requiring SDR or SAN [7] technology. The requirement for programmable devices leads to two main challenges.

First, because of the limitations of the layering principle, in order to provide efficient operation, programmable devices should offer cross-layer interfaces suitable for adaptation and optimization. Specific signaling architectures are needed in order to enable internal or network-wide exchange of information and commands between cognitive devices or among distributed devices constituting a single cognitive entity.

Second, while the debate on cross-layering has already gained maturity even with conflicting ideas [19] it is worthwhile to address signaling architecture as a relevant point to support cross-layer or in general optimization solutions. Indeed, several signaling architectures are available which can be classified on the basis of the different types of interaction among protocol at different layers inter-layer signaling, or network-wide signaling [20].

5.6 Security

Most of the work has been concentrated on denial-of-service (DoS) attacks that will affect the design of authentication protocols. Although it is essential to build on these initial forays to develop secure protocols for spectrum access by the SUs, it also important to consider other aspects of security like authorization. First, CRNs inherently assume that PUs and SUs are distinguishable. Authenticating PU and SU is especially important since they have unequal privileges. Although, this may be fairly straightforward for centralized architectures by making the SUs sign using a centralized authority, this is harder to achieve in a distributed secondary network where a centralized authority cannot always be implemented. Second, in the context of CNs, there is an unique authorization requirement called conditional authorization. It is conditional because the SUs are authorized to transmit in licensed bands only as long as they do not interfere with PU communications in that band. As it is difficult to pinpoint exactly which of the secondary users is responsible for harmful interference to the PU transmission, this type of authorization is hard to enforce and even more so in a distributed setting. Hence conditional authorization poses a unique challenge in OSA. So far several researchers have begun working on security implications for CRNs [21, 22, 23], however this area is still in its infancy.

5.7 Medium Access Control

Although IEEE 802.22 standard working group is already developing the MAC Protocol for Wireless Regional Access Networks, other MAC designs have not been made into standards. Particularly distributed MAC for ad hoc networks operating in the opportunistic spectrum access manner are not well covered. In the standardization domain IEEE 802.11 group covers some of the topics of intelligent spectrum management (e.g., IEEE 802.11k), but those are limited to the operation in the unlicensed bands.

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