Cognitive Radio defying Spectrum Management

A collection of four (short) contributions

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Abstract

This set of contributions is addressing the impact of cognitive radio on the regime of radio spectrum governance. To avoid harmful interference the current paradigm of spectrum governance uses the principle of separation. Thereby each application and user or user group is being assigned a specific part of the spectrum, using the dimensions of frequency, time and location. Cognitive radio, a special class of software defined radio's, defies this principle as a cognitive radio monitors the use of the spectrum and selects an unused part for its transmission. This capability provides a new solution in addressing the issue of spectrum scarcity. Albeit, its dynamic operating principle runs counter to the prevailing spectrum management method.

This set of four contributions first introduces the principles of cognitive radio from a technological perspective. In the second contribution the implications for avoiding harmful interference are being assessed. Here we conclude that Cognitive Radio may also resolve the so-called 'local interference problem', but it poses challenges for the regulator under the Radio and Telecommunications Terminal Directive of the European Commission. In the third contribution the implications for spectrum policy are addressed in the light of current assignments based on (exclusive) usage rights and prescribed applications. The policy changes required implies action on national, regional (in Europe: EC and CEPT) and international level (ITU). In the fourth contribution we conclude with a discussion of the field experiences obtained in Ireland with experimental licenses being awarded for the use of cognitive radio.

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Technical Challenges of Cognitive Radio-Related Systems

Przemysław Pawełczak[1]

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.

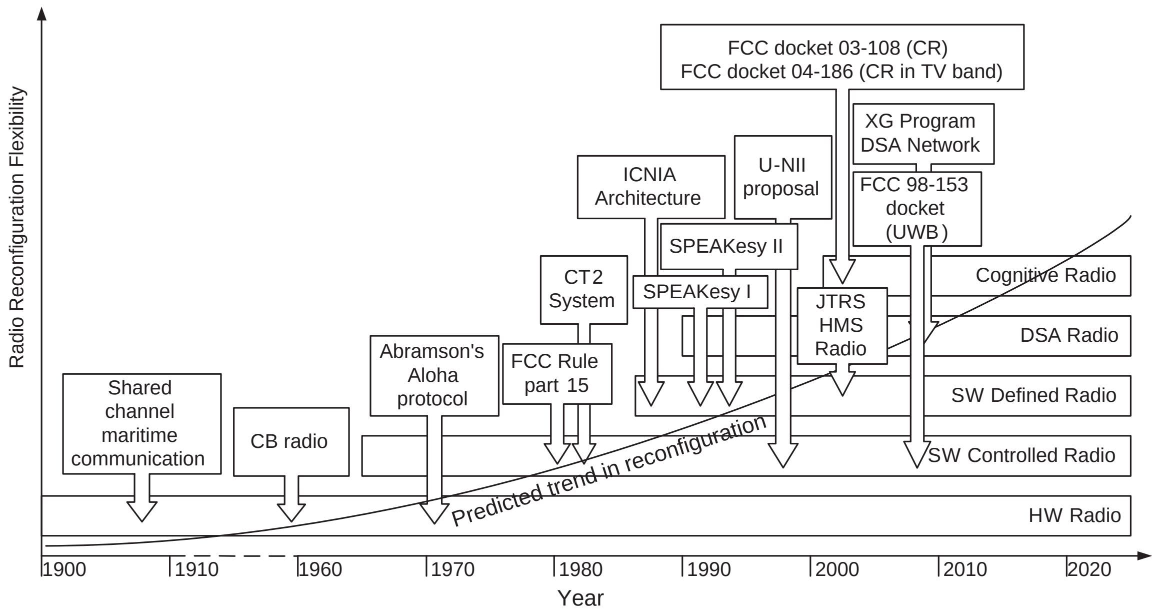

Figure 1. History of dynamic spectrum access systems and their relation to the implementation platforms, with the view on the future; HW: hardware, SW: Software.

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,

[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.

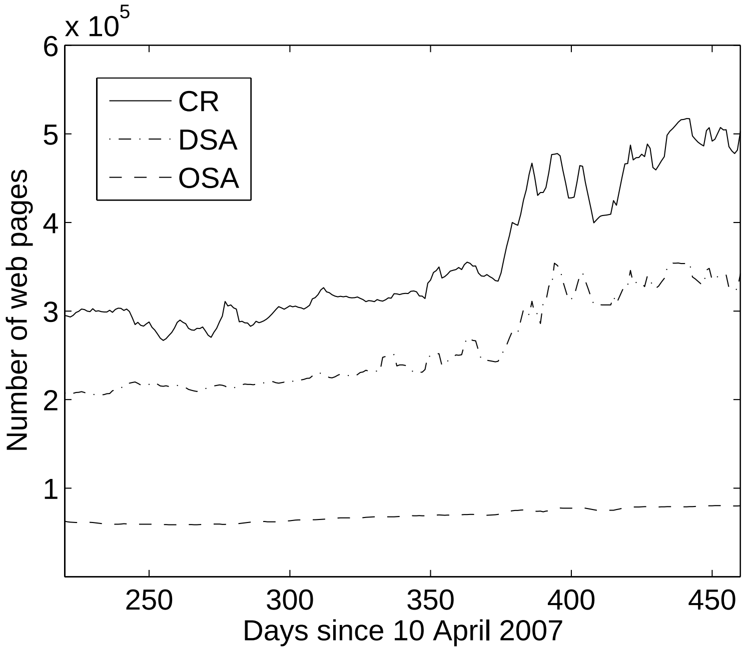

Figure 2. Statistics of the Google search engine responses for `Cognitive Radio' (CR), `Dynamic Spectrum Access' (DSA) and `Opportunistic Spectrum Access' (OSA) phrases in terms of number of WWW pages found.

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.

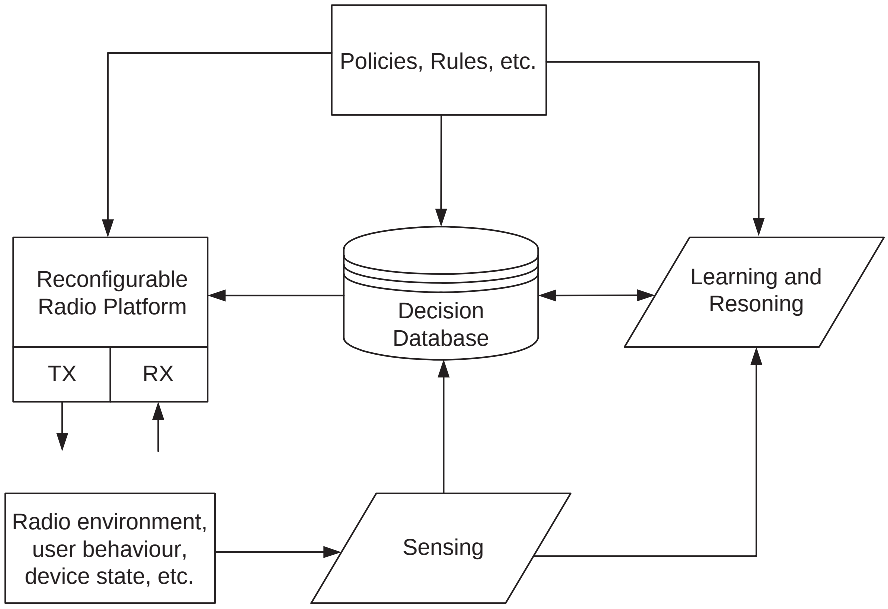

Figure 3. Components of CR node, see also [11].

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.

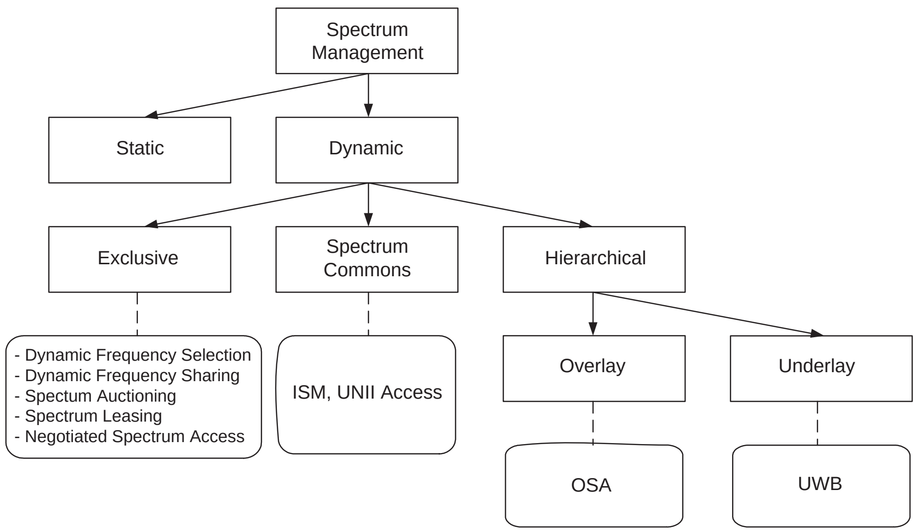

Figure 4. Modern spectrum management: Classification with the application examples (see also [17, 18]).

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

[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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Avoiding Harmful Interference – The Current Paradigm

Yvonne Veenstra and Helmut Leonhard[6]

1 Introduction

Since the early beginnings of radio-communications interference plays an important role in spectrum governance. Already in the Final Acts of the "International Radio Telegraph Convention of Berlin: 1906" we find the following: "The service of operating wireless telegraph stations should be organized, as far as possible, in a manner not to interfere with the service of other stations" [7]. One hundred years later, planning and co-ordination of radio-communications services still is based on the same principle, albeit in a somewhat different wording: "In using frequency bands for radio services, Member States shall bear in mind that radio frequencies and any associated orbits… ..are limited natural resources and that they must be used rationally, efficiently and economically…. …so that countries … …may have equitable access to those orbits and frequencies…" and "All stations, whatever their purpose, must be established and operated in such a manner as not to cause harmful interference to the radio services or communications of other Members or of recognized operating agencies…" (No's 0.3 and 0.4 Preamble Radio Regulations, 2004, ITU)[8].

Based on these principles the international 'radio-community' has developed world-wide frequency allocation charts. Member states translate these allocation charts into their own National Frequency Plans.

Based on the above mentioned principles the international Radio Regulations have been developed. A framework, consisting of rules, recommendations and procedures for the regulation of radio-communications, mostly based on technical and physical assumptions translated into technical standards and license parameters for both transmitters and receivers. What ultimately has led to some sort of device-centric approach, i.e. harmful interference is being avoided by using certified apparatus under well defined license conditions.

New technological opportunities such as Software Defined Radios and Cognitive Radios provide degrees of freedom not foreseen in the current spectrum management paradigm.[9] In this contribution we will review the potential impact of these new technologies on the current regulatory regime and the related arrangements for enforcement of the regime, and identify aspects that need to be addressed and resolved before the introduction of these new technologies can be permitted.

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[7] 1906, ITU, Geneva http://www.itu.int/ITU-R/information/promotion/100-years/documents/1906-Berlin-E.pdf

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[9] For a description and definition of SDR and CR see the contribution by Przemyslaw Pawelczak "Technical challenges of cognitive radio-related systems".

2 Avoiding Interference

With radio communications one must realize that, depending on the frequency used, radio waves can travel quite a distance and, in due course, are able to disturb other communications services. On the other hand, the radio spectrum is a scarce natural resource. So the available frequency space has to be carefully reused.

2.1 Role of the ITU

The ITU, the International Telecommunications Union, provides us with technical standards, recommendations, and procedures to solve the abovementioned problem. Together with sophisticated propagation models these recommendations and procedures are translated into predictions of coverage areas and footprints. With the tacit understanding that the quality of the so planned radio communications service has a certain predefined probability both in time and location at the boundary of the service area. The coverage area then consists of all places where the wanted signal exceeds all the unwanted contributions from interfering stations by a certain predefined protection margin.

Thus, avoiding interference seems to be a question of proper planning and coordination, and using the right equipment. In practice, this is only true for what we would call overall interference, which formally considers all the standards, recommendations, procedures, propagation models, etc. However, the real interference problem, which we would call the local interference problem, is not solved. Local interference depends on local circumstances, such as the use of electrical apparatus, the quality of the equipment, the use of other radio communication equipment in the same area, building shielding, multi-path, and other propagation effects.

Generally, the overall planning from Administrations is rather conservative. By doing so, most of the uncertainties in propagation, morphology, apparatus, etc. are smoothed out and the probability of local interference is minimized. The use of Cognitive Radio and Software Defined Radio obviates the need for this type of conservative planning, moreover, in some cases Cognitive Radio or Software Defined Radio could even solve the local interference problem.

3 Potential regulatory implications with future radio solutions

In the following we will discuss potential regulatory implications with the use of future radio equipment. In this context it is obvious that software defined radio is the greater challenge than cognitive radio; i.e. Software Defined Radio has the ability to change all its vital parameters just by downloading and installing new software or a new software release. With cognitive radio it is more or less choosing the right radio channel for communication rather than changing essential radio operating parameters. Therefore we will discuss the implications of Software Defined Radio in more detail.

3.1 Interference considerations

The ability of an Software Defined Radio to dynamically modify its operating parameters surely can help managing interference; however the potential for causing interference to other authorized radio services cannot be overlooked. Remotely programmable Software Defined Radios must have some “cognitive part” built in, so as to avoid harmful interference to other authorized services. This is a serous problem which is discussed worldwide.

The adequacy of the security requirements for SDR software is a key factor in ensuring equipment operates within its allowable parameters to avoid the emission of harmful interference. Recurring media reports of security flaws in software packages and operating systems highlight a concern that the software based security mechanisms employed in SDR could also be vulnerable. The main security issues related to SDR that have been identified include: who has the authority to control the reconfiguration of the communications equipment; protection of the reconfiguration signaling; privacy of the reconfiguration information; the correctness and availability of the information on which the reconfiguration is based; and secure download of the software required for reconfiguration and issues related to the radio emission and associated conformance requirements of radio equipment.[10]

3.2 Spectrum management

Current spectrum management techniques still provide for designating specific frequency bands for each radio service. Software Defined Radio would have the ability to completely change its behaviour: it could switch between different technologies and/or radio services. At least in Europe, under the future framework for electronic communications, service and technology neutrality are the cornerstones for innovative frequency management and use of the spectrum. The European WAPECS (Wireless Access Policy for Electronic Communications Services)[11] approach provides for proper boundary conditions for future reconfigurable radios at least for a limited set of frequency bands.

It is obvious that Software Defined Radio and Cognitive Radio will boost dynamic spectrum management and will improve spectrum efficiency. A growing number of regulatory agencies around the world believe that there is a need for a new approach to spectrum management, spectrum allocation and spectrum utilization. The new spectrum paradigm is driven, in part, by the increasingly keen competition for spectrum – a problem common to many parts of the world and to all segments of the communications industry: government, commercial wireless, public safety, etc.

The magnitude of the spectrum management task of not only comprehending all of the dynamic or temporal and spatial or geographical sharing requirements, but also anticipating changes to all of these sharing arrangements in order to code them into the devices *ex ante*, makes a strong case for devices to have the ability to have their operating parameters modifiable via software in the field. Equally important is the need to be able to change the policies that dictate the radio's behaviour. [12]

Changing policies is not straightforward. Changing the policies of spectrum management takes us decades. Policy changes become possible when an new worldview or "policy epistemology" frames the terms of debate[13]. Software Defined Radio does not fit in the present legal framework which is mainly based on "putting on

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[10] Software defined radio in the land mobile, amateur and amateur satellite services, Report M.2117, ITU, Geneva, 2007.

[11] RADIO SPECTRUM POLICY GROUP OPINION ON Wireless Access Policy for Electronic Communications Services (WAPECS), Brussels, 2005, http://rspg.ec.europa.eu/doc/documents/opinions/rspg05_102_op_wapecs.pdf

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the market", "putting into service", "free movement of goods" and corresponding institutional arrangements as "certification", "labeling", "licensing", "monitoring", and "market surveillance". The development of Software Defined Radio brings us at the principles of the legal framework.

Discussions on changes in the spectrum management framework are still going on in all regions. The remaining major issue is how to fit Software Defined Radio into the conservative legal framework.

3.3 Situation in Europe

In Europe, placing on the market and putting into service of radio apparatus is covered by the Radio and Telecommunications Terminal Directive (R&TTE)[14]. As to this directive, Member States shall ensure that apparatus is placed on the market only if it complies with the appropriate essential requirements identified in the same directive and the other relevant provisions of this Directive, when it is properly installed and maintained and used for its intended purpose.

The following essential requirements are applicable to all apparatus [covered by the R&TTE Directive]:

(1) the protection of the health and the safety of the user and any other person, including the objectives with respect to safety requirements contained in Directive 73/23/EEC [i.e. the Low Voltage Directive], but with no voltage limit applying;

(2) the protection requirements with respect to electromagnetic compatibility contained in Directive 89/336/EEC [the EMC Directive].

(3) in addition, radio equipment shall be so constructed that it effectively uses the spectrum allocated to terrestrial/space radio communication and orbital resources so as to avoid harmful interference.

Compliance with the relevant essential requirements is the corner stone for placing on the market and putting into service. The Directive provides for different procedures for the manufacturers to declare the conformity of apparatus. These procedures imply the involvement of a *notified body* during conformity assessment. Furthermore the Directive instructs the manufacturer how to make up the so called *declaration of conformity* and to affix the proper markings [i.e. the *CE mark*]. Once radio apparatus has been placed onto the [European] market, the provisions of the directive are valid for the whole European territory.

The implications for Software Defined Radio are obvious. The equipment manufacturer provides for a so called "declaration of conformity". Once the apparatus is on the market and is in use the end user is responsible for the apparatus. Changing essential equipment parameters has, or can have, an unpredictable influence on the validity of the declaration of conformity. Not only by the end user, but, with the world of viruses, spam, hacking etc. in mind even by less reliable third parties.

[14] 1999, Brussels L91/10, Official Journal EC, 7.4.1999, http://ec.europa.eu/enterprise/rtte/dir99-5.htm

4 Conclusions

From the above it can be concluded that the whole family of Cognitive Radios as technically sound concept still represents a challenge for the regulator. There are two main concerns:

- the declaration of conformity as some species of *ex ante* regulation must stay valid despite any eventually *ex post* changing of the operating parameters of the equipment,
- different approaches within different Member States due to different [local] situations might lead to problems with free circulation of Cognitive Radio.

Properly designed and programmed Cognitive Radio should overcome these difficulties and should meet the essential requirements under all circumstances. On the other hand Software Defined Radio has shown us the edge of our regulatory framework. Worldwide discussions on this theme are still ongoing. Software Defined Radio can be the facilitator to develop new institutional arrangements in spectrum governance. But, as said before, policy changes only become feasible when a new world view frames the terms of debate. The present financial crisis possibly will give raise to an new world view, even in spectrum governance.

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Does Cognitive Radio need Policy Innovation?

Peter Anker[15]

5 Introduction

The growing demand for radio frequency (RF) spectrum makes the introduction of more spectrum efficient technologies and a more efficient spectrum management regime necessary. Cognitive Radio (CR) is a promising innovative technology to improve spectrum utilization. Cognitive Radio systems not only have the potential to make more efficient use of spectrum, but also offer more versatility and flexibility, with the increased ability to adapt their operations based on external factors. Cognitive Radio systems can play an important role in achieving Dynamic Spectrum Access, and thereby a paradigm shift from a static to a dynamic spectrum management model.

Rapid progress is being made in the research on Cognitive Radio technology to facilitate Dynamic Spectrum Access. However, Dynamic Spectrum Access will require changes in spectrum management to take advantage of the possibilities for more efficient spectrum usage. This contribution focuses on the implications of Dynamic Spectrum Access on the policy dimension of spectrum management.[16]

6 Spectrum management: the current paradigm

Today, spectrum management is still based on the same principals as agreed upon in 1927. Spectrum is globally governed by the International Telecommunications Union (ITU). The Radiocommunication Sector of the ITU (ITU-R) develops and adopts the Radio Regulations, a binding international treaty, with a voluminous set of rules. The Radio Regulations are based on avoidance of radio interference through the division of spectrum in bands which are allocated to one or more services out of some 40 different radio services[17]. A wide range of regulatory, operational, and technical provisions ensure that radio services are compatible with another and harmful interference among countries is avoided. The Radio Regulations are updated in response to changes in needs and demands at World Radiocommunication Conferences (WRC), which are held every three to four years.

Individual countries adopt some or all of the allocated services of each band. Nations are allowed to differentiate from the Radio Regulations as long as no harmful interference[18] is caused to the services in other countries. Based on the allocations the

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[16] Introduction of Cognitive Radio based on Software Defined Radio will also have regulatory implications for conformancy testing and the placing of equipment on the market. This subject is dealt with in (Veenstra and Leonhard, 2008).

[17] These radio services include services such as fixed, mobile, satellite, amateur, radio navigation and radio astronomy. Most bands are shared among primary and secondary services. Primary services have priority in case of conflicts resulting in harmful interference.

[18] Harmful interference is defined as *Interference* which endangers the functioning of a *radionavigation service* or of other *safety services* or seriously degrades, obstructs, or repeatedly

national Spectrum Management Authority (SMA) assigns licenses to users. Usually a license gives an exclusive right to operate on a specific frequency in a specific location or geographic area and under specific technical conditions (power, antenna height, etc.) and other conditions such as service obligations and build-out requirements. Compliance of spectrum users with the license obligations is monitored and enforced.

Licenses are usually granted on a first come first served approach if the demand for spectrum within a particular band is considered to be far less than supply. When spectrum demand exceeds supply, the SMA has to use another mechanism to award the licenses. Increasingly, SMAs have turned to spectrum auctions, comparative hearings or “beauty contests” are occasionally used (ITU 2004).

In this model all decisions are made by the SMA. Therefore, this traditional spectrum management model is commonly referred to as Command & Control. This Command and Control model has a number of limitations: some of the portions of the spectrum are hardly used, and the method is slow in responding to changes in market and technology.

In the past, the huge inefficiencies in spectrum utilization from bureaucratic command and control were tolerable. As demand grew, advancing technology ensured that new frequency bands were available[19], and there was no need to deal with economically inefficiently used spectrum. More recently, demand has grown very rapidly and technology has delivered new services and devices to serve that demand. However, the opening up of even higher frequency bands is not going in the same pace and not all frequencies are alike[20]. This means that Spectrum Management Authorities more or less ran out of useable spectrum to identify for new services and technologies. Hence, services based on new technologies can only be introduced at the expense of existing services.

Consequently Spectrum Management Authorities all over the world are in the process of modernising their spectrum policies, and are seeking alternative spectrum management models which allow a much more efficient and flexible utilisation of the spectrum (Nekovee 2006).

Solutions have to address the lack of available (accessible) spectrum in the current static model. RF spectrum is divided into fixed and non-overlapping blocks, separated by so-called guard bands, and exclusively assigned to different services and wireless technologies, while a lot of spectrum usage is only local and limited in time.

In an economic sense, there appears to be a paradox whereby the rights to the RF spectrum are fully assigned, but a lot of RF spectrum remains unused in practice when considered on a time or geographical basis. Under the current command and control model it is very difficult to make the unused spectrum available. What is required is Dynamic Spectrum Access (DSA) and a dynamic spectrum management model that

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interrupts a *radiocommunication service* operating in accordance with Radio Regulations (ITU Radio Regulations, edition of 2004, article 1.169).

[19] In 1927 only the frequency range up to 23 MHz was allocated; in 1932 this was extended to 30 MHz, since then the upper limit was extended to 200 MHz in 1938, 10,5GHz in 1947, 40 GHz in 1959, 275 GHz in 1971 and 1000 GHz in 2000, although there are no services defined above 275 GHz.

[20] In the higher frequency range is more bandwidth (capacity) available but higher frequencies have a shorter range ceteris paribus. The ideal frequency range for e.g. mobile communications is roughly 1-3 GHz. Below this frequency range there is not enough data throughput capacity available and above this range the coverage area of the base station becomes too small.

supports it. Cognitive Radio, as a technology, is a tool to realize this goal of Dynamic Spectrum Access.

The term Cognitive Radio was first suggested by Mitola. He defines CR as a radio driven by a large store of a priori knowledge, searching out by reasoning ways to deliver the service the users want. The Cognitive Radio is reconfigurable and built on the software-defined radio (SDR) (Mitola 1999).

Nowadays, the term Cognitive Radio is mostly used in a narrower sense. Cognitive Radios have been proposed as a means to increase the efficiency of the use of already licensed spectrum. The key feature of a Cognitive Radio is its ability to recognize the unused parts of spectrum that is licensed to a primary user and adapt its communication strategy to use these parts while minimizing the interference that it generates to the primary user.

7 Dynamic Spectrum Access: what is it and what is the problem?

Dynamic Spectrum Access is based on the notion of the existence of white spots, i.e. frequencies assigned to a primary user, but, at a particular time and specific geographic location, not used by that user[21] (Haykin 2005). The objective of DSA is to provide the means to make these white spots available for secondary users. Secondary means in this context that the white spots may be used by a secondary user as long as this usage doesn't interfere with the usage of the primary user i.e. no (harmful) interference to the primary user is allowed and a primary user has priority in access to spectrum.

The basic approach of Dynamic Spectrum Access systems is to access the spectrum based on the systems own judgment of the local use of the spectrum. This is called Opportunistic Spectrum Access (OSA). The DSA system looks for white spots in the spectrum and then transmits over sections of the spectrum that are not in use. However, it has the additional complexity that it needs to keep listening for other transmitters in order to vacate a white spot when a primary user starts accessing it.

This opportunistic behavior gives rise to a problem that is known as the hidden node problem, whereby the DSA system was inadvertently not able to detect the primary usage of a frequency channel. There are different reasons for the occurrence of the hidden node problem. One of the most eminent reasons is that a primary transmitter is not detected due to 'shadowing', e.g. due to an obstruction (like a building or a mountain) in between the primary user and the DSA system. The hidden node problem makes the detection of spectrum usage by no means an easy task. In general, the sensitivity of the DSA system will have to outperform primary user receivers by a large margin (Pawelczak, 2008).

There are at least three options to overcome this hidden node problem.

One of the options is to share sensing information among different DSA systems in an area. This is known as cooperative or collaborative detection. Cooperation can improve the probability of detection and reduce the detection time and thus increase the overall agility. The drawback is the overhead needed to exchange sensing information.

A second option is to get information about the local use of a frequency band from a database. In this case the DSA system must be aware of its geographical position, e.g.

[21] Examples of white spots are the empty spaces (guard bands) between TV channels. The actual size and frequency range of the white spot will be different in different locations.

by incorporating radionavigation in the terminal; the DSA system will need to have access to the database on a regular basis and the database will have to be kept up-to-date. This option is especially suitable in cases where spectrum usage of the primary user does not change frequently, e.g. in a broadcasting band.

A third option is to use a local beacon which transmits information to DSA systems nearby. The beacon transmits information about the availability of spectrum and possibly usage conditions to the DSA systems in that area.

These solutions may lead to a need for a communication link; either between DSA systems to share sensing information or between a DSA system and a central entity to get information about usage possibilities. This communication channel is called a Cognition supporting Pilot Channel or Cognitive Pilot Channel (CPC).

There are different possibilities for the implementation of a CPC. The CPC can use a new dedicated (ideally worldwide harmonized) frequency, a specific channel of existing access technology or a combination of both.

8 Implications of Dynamic Spectrum Access on spectrum management

There are no international treaties that prohibit the use of dynamic access to spectrum in general or Cognitive Radio in particular[22]. However, there are some barriers that prevent a successful use of more dynamic forms of spectrum access. As said, in most countries the management of spectrum is based on a static approach. Spectrum is split into fixed blocks which are assigned to a specific service or technology. There are bands designated for e.g. analogue radio broadcasting, air traffic control, emergency services, television broadcasting and mobile radio. The frequencies are exclusively assigned to licensees to offer these services.

Introduction of Dynamic Spectrum Access in these exclusively designated and assigned frequency bands is only possible if these bands are opened up for other services and technologies. Since the designation of bands to specific services and the rules under which they may be used have their origin in the international framework, there is a need to adapt both the international and national regulatory framework for the management of RF spectrum.

8.1 Adapting the international regulatory framework

There is a need to enhance the regulatory framework at an international level to allow for more flexibility in the use of RF spectrum and there is a need for harmonization activities related Dynamic Spectrum Access including cooperation between DSA systems or between DSA systems and a central entity.

There are already activities started within the ITU-R that are related to these tasks. At the World Radio Conference 2007 (WRC-07) it was decided to put two related items on the agenda for the World Radio Conference in 2011.

Agenda Item 1.2 is put on the agenda for the WRC-11 to allow more flexibility in the use of spectrum:

[22] A few countries, including the United States and Ireland, have already made provision to allow the introduction of cognitive radio. See also Akalu (2008).

> *1.2 taking into account the ITU-R studies carried out in accordance with Resolution 951 (Rev.WRC-07), to take appropriate action with a view to enhancing the international regulatory framework;*

The related Resolution 951 identifies that further studies are needed in order to develop concepts and procedures for enhancing the Radio Regulations to meet the demands of current, emerging and future radio applications, while taking into account existing services and usage. The studies should take into considering that evolving and emerging radiocommunication technologies may enable sharing possibilities and may lead to more frequency-agile and interference-tolerant equipment and consequently to more flexible use of spectrum and that these evolving and emerging technologies may not require band segmentation within the traditional spectrum allocation framework.

The WRC-11 also has an agenda item (1.19) specific on Software Defined Radio and Cognitive Radio.

> *1.19 to consider regulatory measures and their relevance, in order to enable the introduction of software-defined radio and cognitive radio systems, based on the results of ITU-R studies, in accordance with Resolution 956.*

Study Group 1 (Spectrum management) of the ITU-R is responsible for the studies needed in preparation of the WRC-11. Within Working Party 1B of Study Group 1 work has started to develop definitions of Software Defined Radio and Cognitive Radio Systems, to discuss its related concepts such as the Cognition supporting Pilot Channel and a database, and to identify potential regulatory issues associated with SDR and Cognitive Radio Systems. A Correspondence Group has been set up to speed up the work.

It remains unclear what the potential changes to the Radio Regulations should be in addition to the need for more flexibility (which is tackled in agenda item 1.2). The only remaining issue that might have an impact on the Radio Regulations is the need for a globally harmonized Cognition supporting Pilot Channel. However, further studies are needed to prove the viability of Dynamic Spectrum Access based on a local beacon.

There might also be a need for involvement of regulators to create a database with local information on spectrum usage and standardization of the protocols needed to access this database. However, this task has no implications for the Radio Regulations.

The Radiocommunication Assembly prior to the WRC-07 decided to put QUESTION ITU-R 241-1/5 *Cognitive radio systems in the mobile service* on the agenda of Study Group 5 (Terrestrial services) for the forthcoming study period. The Question ITU-R 241-1/5 lists the following issues to be studied (ITU 2007):

> **1** What is the ITU definition of cognitive radio systems?
>
> **2** What are the closely related radio technologies (e.g. smart radio, reconfigurable radio, policy-defined adaptive radio and their associated control mechanisms) and their functionalities that may be a part of cognitive radio systems?
>
> **3** What key technical characteristics, requirements, performance and benefits are associated with the implementation of cognitive radio systems?
>
> **4** What are the potential applications of cognitive radio systems and their impact on spectrum management?

5 What are the operational implications (including privacy and authentication) of cognitive radio systems?

6 What are the cognitive capabilities that could facilitate coexistence with existing systems in the mobile service and in other radiocommunication services, such as broadcast, mobile satellite or fixed?

7 What spectrum-sharing techniques can be used to implement cognitive radio systems to ensure coexistence with other users?

8 How can cognitive radio systems promote the efficient use of radio resources?

Study Group 5 is expected to deliver a response to this question in the form of a Report or possibly Recommendations by the year 2010. Study Group 5 is already working on a Report on *Cognitive radio systems in the land mobile service.*

Within the European Union there are a number of activities to introduce more flexibility in the use of spectrum (WAPECS[23]) and to introduce secondary trading[24]. Both issues are included in the European Commissions proposals for the EU Telecoms Review 2007. A detailed assessment of these activities falls outside the scope of this paper.

The European Commission also mandated the European Communications Committee to perform a study on the introduction of Cognitive Radio's in the television bands. This report indicates that the feasibility of the introduction of Cognitive Radio systems has not yet been conclusively demonstrated. Since the CR technology is at a very early stage, the CEPT recommends to look further into the requirements within the European environment for CR devices to be deployed in white space spectrum in order to facilitate the further development of CR technology. The current CEPT view is that any new white space applications should be used on a non-protected non-interfering basis (CEPT 2008).

8.2 Adapting the national regulatory framework

The National Spectrum Management authority will have to adapt the national regulatory framework in order to improve the efficiency and flexibility in the use of spectrum. From a regulatory perspective there are two different models considered to improve the efficiency and flexibility, a model based on tradable property rights and a model based on open access (Faulhaber, 2006). These models need to be linked to the new technological capabilities of Cognitive Radio's and dynamic spectrum access.

Dynamic Spectrum Access in an open access regime

An open access regime is a regime in which a user can have access to spectrum without the need for a license. In this case it means that a DSA system can have access to white spots on a secondary basis without the need to have an individual license. There are only general conditions imposed to the secondary use of the band. Access to white spots

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[23] WAPECS is a framework for the provision of electronic communications services within a set of frequency bands to be identified and agreed between European Union Member States in which a range of electronic communications networks and electronic communications services may be offered on a technology and service neutral basis, provided that certain technical requirements to avoid interference are met, to ensure the effective and efficient use of the spectrum, and the authorisation conditions do not distort competition.

[24] EC Communication COM(2005)400 "A market-based approach to spectrum management in the European Union".

can be facilitated in an open access regime if strict rules are defined to keep the interference to the Primary Users at an acceptable level.

This level will have to be clearly defined by the regulator. The definition of an appropriate level is not an easy task. If the level is too restrictive the potential gains of Opportunistic Spectrum Access (OSA) are marginal, while a level that is too loose may affect the Quality of Service of the primary user. The regulator will have to cooperate with industry to set a realistic level which is based on the state of the art of technology.

No matter what interference level is defined, there will always remain a likelihood of interference, and there are no guarantees for an OSA system to have access to spectrum. This sets limitations to the use of opportunistic spectrum access and on the types of applications it can support in an open access regime. Opportunistic spectrum access is expected to be restricted to low-end applications, involving low power devices. OSA is also of interest to military users to set up ad-hoc networks without the need for central coordination.

Dynamic Spectrum Access in a market based approach

A market based approach to RF spectrum management is based on the introduction of property rights. This approach is characterized by three elements, adapted from (Baumol and Robyn 2006):

1. Well-defined exclusive rights to the use of spectrum;
2. A market-type mechanism such as an auction for an initial allocation of spectrum rights;
3. A secondary market in which these rights can be sold or leased.

In this case the SMA will have to assume the responsibility to set well defined usage rights in the market, with as few usage restrictions as possible.

A number of countries already introduced the possibility of secondary trading. However, in most cases there is an approval mechanism from the authorities before trading may take place. These kind of barriers make instant trading impossible and, hence, will have to be removed to exploit the full potential of Dynamic Spectrum Access.

A market based approach is expected to provide the possibility for active coordination between the primary user and the secondary (cognitive) user about the likelihood of interference, and on guarantees about access to spectrum. If the barriers to instant trading are removed, the opportunity to buy and sell rights to access spectrum can be based on the actual demand for spectrum. This creates the opportunity to use DSA systems for higher valued services, such as mobile telephony, and for a spot market to be introduced. A spot market is a perfect means to acquire and sell rights to spectrum access based on the actual demand at any given moment in time.

Information about the actual ownership of RF spectrum rights will have to be readily available to facilitate trading. The SMA is ideally positioned to perform the task to keep record of these ownership rights to the use of spectrum. Inclusion of monitoring information about the actual usage of spectrum by the primary users can further facilitate trading by giving more insights in the possibilities for secondary usage.

If the spectrum market is introduced in a region, e.g., the European Union, trading can also be used to ease the problem of cross-border coordination. Nowadays the use of spectrum in border areas is based on an equal split of the use of spectrum between neighbouring countries through the definition of preferential rights. However, there is no relationship with the actual demand for spectrum at either side of the border. If instant trading is allowed the usage rights can be tuned to the actual demand.

9 First applications

Digital Enhanced Cordless Telecommunications (DECT) can be regarded as a first implementation of spectrum sensing. A DECT telephone selects a frequency channel based on sensing of the channels available for DECT. However, DECT uses an exclusively assigned frequency band; sensing is only used to determine the best available channel within the band.

The first application that senses the available channels to detect and avoid other users is Unlicensed Radio LAN in the 5 GHz band. The Radio LAN uses a subset of OSA, which is called Dynamic Channel Selection (DFS). DFS is used to prevent a device from accessing a specific frequency channel if it is in use by a primary user, notably radar systems. The difference between OSA and DFS is that DFS is not used to seek spectrum access, but to prevent spectrum access if co-channel interference might occur. Close cooperation between regulators and industry was needed to define and standardize DFS in such a way that it can detect all different radar systems that are active in the bands involved.

The first application of Cognitive Radio is foreseen in the “white spots” of the TV-bands based on opportunistic spectrum access. The Federal Communications Commission (FCC) of the USA has already published a notice of proposed rulemaking to permit unlicensed opportunistic access to white spaces in the TV bands (FCC 2004). In response to this notice the IEEE has created a working group (IEEE 802.22) which aims to develop a standard based on opportunistic spectrum access of the television bands to provide fixed wireless broadband access in rural and remote areas.

10 Conclusions

Today’s spectrum management is still based on the same principles as set out at the time of the crystal radio. This results in highly ineffective use of spectrum. New innovative technologies, such as Cognitive Radio systems offer a huge potential to increase spectrum efficiency thereby facilitating Dynamic Spectrum Access. To make Dynamic Spectrum Access possible RF spectrum regulations will need to be adapted. A prerequisite for DSA is the need for more flexibility in the use of RF spectrum.

The Spectrum Management Authority and the industry will have to work in close cooperation to realize the goal of Dynamic Spectrum Access. One of the fields of cooperation is to define the requirements for spectrum sensing and the associated interference limits to primary users.

A too narrow focus an open access regime to realise Dynamic Spectrum Access will limit the possibilities for new emerging technologies, e.g., Cognitive Radio. A market based approach can be a good addition to reach the goal of more efficient spectrum usage whereby access to spectrum is based on actual demand.

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Spectrum Management and Cognitive Radio in Ireland

Rajen Akalu[25]

1 Introduction

Engineers have historically understood channel capacity in terms of bandwidth and the operation of Shannon's Law which provides a formula for the maximum error-free transport capacity on a communications link.

Software-defined radio (SDR) allows the adoption of new communication technologies by means of simple software upgrades, rather than replacing expensive hardware. These upgrades can be accomplished by direct wireless download. This reduces the cost of upgrading and allows immediate compatibility to be achieved among devices used by different agencies and organizations.

This has the possibility of more flexibly managing spectrum by time, frequency, space, power and coding of the transmitted wave form.

Cognitive radios (CR) are subset of SDRs. They are controlled by powerful microprocessors which have been programmed to analyze a number of the radio channel parameters. They have the ability to adapt the modulation technique, output power and frequency used to the results of the analysis performed. They provide the possibility of being re-programmed dynamically to accommodate different regulatory structures by adjusting frequencies, bandwidth, and directionality. This allows more effective use of expensive to replicate hardware and infrastructure.

Unfortunately the benefits of replacing policy-based spectrum management with device-centric spectrum management can be realized only when *all* devices in a frequency band are cognitive such that they can negotiate with each other. For this reason there is a continued need to co-ordinate with legacy systems in order to mitigate interference. (Lansford, 2004).

In the case of cognitive radio there is a need for national and international regulatory bodies to appreciate the emerging mechanisms for configuration management of this type. This will involve the monitoring of software/hardware network configurations and terminal control (e.g. automatic shutdown in the case of incorrectly configured equipment).

The extent of external control and where this control should be situated will not be straightforward given the many vested interests ranging from operators, users, national governments, handset manufacturers and software providers. There is therefore a clear imperative for extensive collaboration in these matters.

This paper discusses the approach taken by the Commission for Communications Regulation, Ireland (ComReg) to licensing SDR applications. The adoption of a new licensing regime for radio service and technology trials is discussed. One of the key features of the scheme is that it allows innovative new wireless services to be offered to

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the public on a trial basis. This will allow new service concepts to be tested in a realistic environment at an early stage of development, ensuring that subsequent commercial offerings are properly tailored to meet the needs of users.

2 Developments in cognitive Radio

Cognitive Radio, like artificial intelligence has no agreed upon definition. The lack of concensus on what CR is and is not or whether we should discuss instead cognitive networks or systems is the source of considerable regulatory confusion. For the purpose of this paper it is defined as “a transceiver that is aware, adaptive, and capable or learning from experience” (Le et al. 2007, p. 1037).

Mitola describes six processes which together allow a cognitive system to ‘employ model based reasoning to achieve a specified level of competence in radio-related domains’. This is also an useful analytical point of departure. (Mitola, 1999)

These processes are:

1. Observing the outside world.
2. Orientation of the system.
3. Planning one or more courses of action.
4. Deciding upon a course of action.
5. Acting to influence the operation of the system.
6. Learning from experience.

The possibility of a software and hardware architecture that is aware, adaptive and capable of learning holds much promise for solving the technical problems of cross-layer optimization, spectrum access and interoperability.

The faciliation of access is (or should be) the goal of spectrum management assuming that the mutually harmful relations between users can be mimised. It is the discussion of how this is to best accomplished that the regulatory *Real Politik* of radio spectrum decision-making begins to emerge. This is because of the continued need to co-ordinate with legacy systems.

So leaving aside government use of spectrum for the moment, the regulatory problem is how to stimulate users in the commercial context with exclusive rights holders of radio frequencies to adopt spectrum-efficient radio technologies, when it is not in their economic interest to do so. This is to be done while providing the appropriate incentive to private firms to invest in costly R&D as well as infrastructure roll out.

Traditionally, this has been accomplished through spectrum licences. As cognitive radios are expected to operate at frequencies that were originally licensed to incumbent radio services, in addition to available frequencies in unlicensed bands, understanding how radio licences have operated historically are a key aspect to reform. The next section deals with how individual licences operate within the Irish regulatory framework for spectrum management.

3 Irish regulatory framework for spectrum management

One of the Commission for Communications Regulation's (ComReg's) functions pursuant to the *Communications Act 2002* is the compliance of radio equipment.[26] This is achieved in large part through the issuance of radio licences. Operators in possession of a 'wireless telegraphy apparatus' are required to obtain an authorized licence[27] unless the apparatus in question is subject to an exemption order.[28] In this latter case the apparatus is 'licence-exempt' and need only adhere to specified order conditions.[29]

The licensing framework as established by the 1926 Act largely focused on apparatus and individual rights of use. Technical restrictions were specified assuming a certain application or technology. The technical limitations of these devices were subsequently specified in the licence conditions.[30] In this context it was relatively straightforward to predict and detect interference however this also created an institutional framework that was less responsive to technological development.

There was widespread agreement in response to a recent consultation conducted by ComReg that the focus of regulatory attention in this area should shift from the use radio equipment to spectrum usage.[31] This would *inter alia* better take into account the increased availability and diversity of radio communications equipment.

A licensing framework based on technologies deployed within a given band rather than the licensed use of particular equipment would facilitate the delivery of electronic communications services, since operators would have greater flexibility with respect to the technology they could deploy within their awarded band.[32]

Achieving this end would seem to involve not restricting licensees to specific technologies or applications as a condition of their licenses. Since interference concerns remain as pressing as ever, the licensee would still be subject to usage constraints. But the objective would be to confine the licensee to specified emissions that could be radiated within the licensees awarded band. Assuming these conditions were met the licensee would be free to deploy any technology or service.

In this regard, the view taken by ComReg is that "appropriate provision should be made for spectrum use rather that maintaining the Wireless Telegraphy (WT) licencing framework of licensing apparatus."[33]

The position taken in this regard would suggest that a transition to a new spectrum licensing regime could only be accomplished by departing significantly from the 1926

[26] s. 10 (e) Commmunications Act 2002.

[27] s. 3(1) *Wireless Telegraphy Act 1926.*

[28] *Ibid* s. 3(6)(a).

[29] Regulation 9(2) Electronic Communities (Electronic Communications Networks and Services) (Authorization) Regulations 2003 S.I No. 306 of 2003.

[30] s. 6 Wireless Telegraphy Act 1926.

[31] ComReg (2003) Response to Consultation "Future of Electronic Communications Networks and Services – Rights of Use for Radio Frequencies," Doc. 03/39.

[32] *Ibid.*

[33] *Ibid* at p.10.

Act. An overhaul of the WT Act 1926 has been on the agenda of the Department Communications Energy and Natural Resources (DCENR) since 2001.[34]

3.1 Ireland and the EU

In the context of spectrum management no country, even Ireland, is an island. All EU member states have *inter alia*, made commitments to the development of an internal market that facilitates the free movement of goods and services with the objective of developing trans-European networks.[35] But as all member states have developed their own governance (and thus licencing) regimes there is a strong need to streamline this process.

One of the chief ways of achieving this type of uniformity amongst the licencing regimes of the various member states is through adherence to the principle of technological and service neutrality. As the success of any given future technology or service cannot be known in advance, the approach taken in the EU regulatory framework to facilitate technological development has been to create a regulatory environment that is 'technology neutral.' This term implies that regulations must neither impose nor discriminate in favour of the use of a particular type of technology.[36]

Although service neutrality is not defined in the *Framework Directive* this refers to the taking of proportionate steps to promote specific services where this is justified.[37]

However, while seeking to introduce flexibility of any kind into the licencing regime, there are the technical assumptions associated with interference constraints and spectrum efficiency. The assumptions made in the decision making process invariably reflect judgements concerning technologies that are going to be deployed within that band. The main objective of member states in this context is seen as ensuring a coherent authorization regime, in spite of differences in applications and spectrum conditions of use.

3.2 Difficulties in seeking to implement 'technology neutral' radio licenses - harmonization or flexibility?

EU policy proposals on technology neutrality are somewhat confusing in that they seem to further both a flexible licensing regime at the EU level and harmonization at the same time.[38] This is due to the fact that what is to be agreed upon by EU member states with respect to the identified bands is not stated explicitly.

Clarity in this regard is afforded by recalling the distinction that exists between the technical and non-technical management of radio spectrum. Technical management within the EU includes harmonization and allocation. This should reflect general policy

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[34] DEMNR "Wireless Telegraphy Act" *available at* http://www.DEMNR.gov.ie/Communications/Business+and+Technology/WT+Act/WT+Act.htm

[35] For discussion see R. Akalu, "EU spectrum reform and the Wireless Access Policy for Electronic Communications Services (WAPECS) concept" *info* VOL. 8(6) 2006, pp. 31-50.

[36] Directive 2002/21/EC of the European Parliament and of the Council of 7 March 2002 on a common regulatory framework for electronic communications networks and services. Recital 18.

[37] *Ibid.* The example of a specific service that would not necessarily be subject to service neutrality is digital television.

[38] See Radio Spectrum Policy Group (2005) Opinion on Wireless Access Policy for Electronic Communications Services (WAPECS) RSPG05-102final, *available online* at http://rspg.groups.eu.int/doc/documents/meeting/rspg8/rspg_05_102.pdf.

principles identified at the Community level. Non-technical management refers to the spectrum licensing procedures and award processes[39] which take place at the national level.

In the context of spectrum management in the technical sense, harmonization relates primarily to *de jure* harmonization – i.e. mandatory measures facilitating the co-existence of different radio equipment or networks within a given band. *De jure* harmonization measures promote economies of scale by granting investment certainty and facilitating interoperability. This type of harmonization in relation to the deployment of pan-EU services would require a *Directive* or *Decision* as such a measure could not be imposed unilaterally by any one member state.[40]

De facto harmonization in contrast, occurs where industry participants adopt similar technology uses in a given frequency band in response to market forces or commercial imperative without such use being imposed by regulators.

The concept of flexibility in the context of non-technical spectrum management can be understood as "increasing the ability of the spectrum regulatory framework to facilitate and adapt, in a timely manner, to user requirements and technological innovation by reducing constraints on the use of spectrum and barriers to access spectrum."[41]

Increasing user access to spectrum and reducing regulatory constraint relates primarily to licencing procedures and award processes. A necessary implication of the departure from the 'command and control' model is that the relaxation of regulatory conditions entails a diminution of administrative discretion since the process involves the granting of increased rights to licencees who will in turn seek to exercise these new rights fully.

As all stakeholders seek to maximize the degree of flexibility with respect to spectrum currently held or sought, they will tend to use the term flexibility to support contradictory objectives.[42]

3.3 Spectrum Trading and spectrum markets

It is important to understand technological neutrality in the context of spectrum trading and the greater use of market process to assign spectrum usage rights.

For primary assignment of spectrum it is commonly asserted that spectrum auctions provide a "mechanism for the regulator to ensure that any newly released spectrum into the market is acquired by those who value it the most."[43]

This 'mechanistic' approach to spectrum assignment is however premised on a model of 'rational' bidders operating in a perfectly competitive market. In order to understand how spectrum auctions can be best used in spectrum management, it is necessary to

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[39]Decision No 676/2002/EC of 7 March 2002 on a regulatory framework for radio spectrum policy in the European Community (Radio Spectrum Decision).Recital 11.

[40] For example Council Directive 87/372/EEC of 25 June 1987 on the frequency bands to be reserved for the coordinated introduction of public pan-European cellular digital land-based mobile communications in the Community.

[41] Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT) ECC Report 80 p. 19.

[42] *Ibid.*

[43] See M. Cave *et. al.* Essentials of Modern Spectrum Management, Cambridge University Press: 2007. p. 41.

explore conceptual underpinnings of the above proposition so as avoid speaking at cross-purposes. Such discussion can ultimately serve to facilitate the effectiveness of auctions.

A first order consideration is to define clearly what actually is meant by 'value' in relation to spectrum. The term value has no objective measure; it therefore has little intrinsic operational relevance. From the standpoint of spectrum management, value is simply a word, what matters is the meaning ascribed to it. When value is discussed in relation to an auction, what is really being discussed is price. How much money will the auction raise?

The tacit assumption is that revenue generated from the auction correlates to social value. Generally speaking, the efficacy of a spectrum auction turns on the extent to which this correlation is valid.

Spectrum auctions (which can be understood as a proxy for the market) relies heavily on the provision of spectrum trading. Since auctions only approximate market outcomes, trading is viewed as a means through which the market inefficiencies (arising from the auction), may be 'corrected'.

Allowing users to trade spectrum is a means through which a user that is willing to pay more to obtain spectrum held by another is able to acquire this. Market exchanges however require clearly defined property rights. Without this the costs associated with making the transaction become prohibitive as neither the buyer nor the seller can adequately describe the subject matter of the transaction.

If the spectrum use rights are fixed, subject to contiguous separation which is generally agreed upon by all users and are perpetual (viz. akin to real property markets), then spectrum trading will work well.

In Ireland at the present, licence transfers between undertakings requires regulatory consent. Trading refers to the transfer of spectrum without prior consent of the regulator in a secondary market. Taken together, the introduction of spectrum trading and liberalization in the form of licence flexibility is expected to increase the need for spectrum monitoring.[44]

This is because with less regulatory oversight and more flexibility given to licencees with respect to the technology they deploy, the exercise of their licence and whether they are able to transfer their licence to subsequent users without regulatory consent, the likelihood of unexpected interference scenarios would become greater.

The thinking here is that such conflicts are to be resolved by the courts. But it should be remembered that courts deal with *ex post* inter-party conflict rather than intra-party radio network planning (the province of regulatory agencies). It is also likely that court procedures will be used strategically to frustrate and delay market entry.

4 Wireless Test and Trial Licensing

We return to how to better facilitate cognitive radio given the above constraints. One such initiative within Ireland has been the Wireless Test and Trial Licencing scheme.[45] This licence allows the licensee the testing or trialing innovative wireless services

[44] ECC Report 80 *supra* n. 9 at p. 7.

[45] Wireless Telegraphy (Research and Development) Licence S.I. 113 of 2005.

within Ireland at specified locations . It may also be issued to licence a new wireless service which does not fit within an existing licensing category.

Distinction is made between 'testing' and 'trialling' radio technologies within the scheme. A Wireless Test Licence allows the licensee to carry out research and development using radio spectrum which may involve the testing, development, evaluation, improvement and/or advancement of new and novel wireless applications. This licence does not allow the licensee to provide services to third parties or involve members of the public.

A Wireless Trial Licence by contrast does allow the licensee to carry out trials of novel or innovative radio services involving members of the public or other third parties, for the purpose of testing applications and apparatus.

5 Trial results to date

This paper focuses on the innovative work by the Centre for Telecommunications Value Chain Research.[46] In 2007 CTVR was awarded a test licence for use at the DySPAN 2007 conference. The licence authorised the research and development of software-based reconfigurable radios in two 25MHz bands, centred at 2.080 GHz and 2.350 GHz respectively, in a number of locations across Ireland.

The CTVR software-based reconfigurable radio platform has 3 principal elements:

1. A novel reconfigurable software radio architecture (IRIS)
2. An experimental handheld baseband-to-RF hardware module
3. A novel wideband antenna

The researchers have shown using the license, that the platform can be populated with information, components, algorithms, methods, logic and intelligence as desired. Ireland's geographical location allows making unused spectrum available for such purposes easier than would otherwise be the case.[47]

Using the bands licensed under the test licence the group has been able to create, and repeat, experiments which can evaluate the performance of highly complex algorithms.[48] The network architecture seeks to establish the rules for technical co-existence (i.e. the ability of two or more nodes/entities to share a common frequency band) by exploiting whitespace (viz. unused spectrum at any particular point of observation). The imperative for greater utilization of the spectrum was highlighted by occupancy measurements performed in Dublin 2007 that no more than 13.6% of the

[46] The Centre for Telecommunications Value-chain Research is a multi-institutional, multi-disciplinary research centre head-quartered at Trinity College, Dublin. The centre includes University College Cork, University College Dublin, NUI Maynooth, University of Limerick, Tyndall Institute, Dublin Institute of Technology and Dublin City University. Industrial partners include Bell Labs Ireland, Xilinx and EADS.

[47] This was a key observation as part of the Irish development strategy advanced in 2005. See FORFAS (2005) "Wireless an area of opportunity for Ireland."

[48] See Nolan, K. *et al.* "Dynamic Spectrum Access and Coexistence Experiences Involving Two Independently Developed Cognitive Radio Testbeds" in Proceedings of the IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN'07), 22-25 April 2007, Dublin, pp: 270 -275.

spectrum opportunities (in frequency and in time) are utilized in Dublin during a high use period when measured from an elevated location.[49]

The researchers have also described 'cyclostationary signatures' which can be intentionally embedded in a digital communications signal, detected through cyclostationary analysis and used as a unique identifier.[50] This enables transmitter and receiver technology to overcome a number of the challenges associated with network coordination in emerging cognitive radio applications and spectrum sharing regimes. The research output of the group is both impressive and considerable. With such a wealth of data and results, one would expect to see regulatory agencies radically transforming the licensing regimes in order to allow the citizenry to avail of this novel and technically superior system. Alas this is not the case. The next section discusses regulatory reform proposals that seek to facilitate cognitive radio.

6 Regulatory reform proposals to facilitate cognitive radio

Much of the debates concerning reform of regulatory rules to facilitate CR turn on the Hardin's exposition of the 'tragedy of the commons.' (Hardin, 1968). The fundamental problem he notes lies in the fact that "[f]reedom in a commons brings ruin to all" (Hardin 1968, p. 1244). As has been noted since not *all* devices are cognitive the problem how to manage cognitive and non-cognitive radio technologies remains and thus regulatory intervention of one kind or another will be warranted.

CR presents itself as a technical solution. Hardin defines a technical solution "as one that requires a change only in the techniques of the natural sciences, demanding little or nothing in the way of change in human values or ideas of morality" (Hardin 1968, p. 1243). Hardin concludes that the population problem has no technical solution; it requires a 'fundamental extension of morality.' Hardin's seminal paper was applied to the problem of overpopulation. However his remarks are of great relevance the class of problems into which the management of spectrum falls.

Since it is mathematically impossible to maximize two dependent variables at the same time, the possibility of a technology solution (CR or otherwise) that will satisfy all users simultaneously is unlikely to materialize. The decision to favour one solution to the commons problems will invariably involve a choice of some kind or another. This can be buried within technical protocols or market mechanisms, depending on the proponents' level of technical understanding of wireless technologies. A brief survey of two reform proposals that seek to facilitate CR-like technologies will be illustrative.

In discussing spectrum auctions, Eli Noam outlines a proposal for what he terms 'open spectrum access' (Noam 1998). At present physically, no device exists for spectrum brokerage yet. This has not stopped engineering researchers from attempting from envisioning this architecture from a technical perspective, e.g. DIMSUMNet architecture of Bell Labs (Buddhikot, 2005).

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[49] Erpek, T. and Steadman, K., "Spectrum Occupancy Measurements: Dublin, Ireland, Collected On April 16-18, 2007" available online at http://www.sharedspectrum.com/measurements/download/Ireland_Spectrum_Occupancy_Measurements_v2.pdf

[50] See Sutton, P. *et al.* "Cyclostationary Signatures in Practical Cognitive Radio Applications" IEEE Journal on Selected Areas of Communications, VOL. 26(1) 2008.

Essentially Noam calls for an open access system where access fees (set by clearing houses and based on network congestion) would be required by spectrum users. Noam seeks to transcend both licence-exempt and property rights models of spectrum with this approach.

Weiss and Jondral table the concept of ‘spectrum pooling.’ (Weiss and Jondral, 2004) For them, spectral efficiency will be enhanced by overlaying a new mobile radio system on an existing one without requiring any changes to the actual licensed system. The idea is similar to Noam’s but here, the licence holder obtains a rent for use of spectrum during idle periods. They assert “once the technical obstacles are overcome and the feasibility of spectrum pooling is proven, politics cannot refuse this idea.” (Weiss and Jondral, 2004, p. 8)

They conclude that “a lot of work remains to be done in this field, but one thing is sure: the better the technical concept, the greater the potential acceptance of legislators, regulators and future customers.”(Weiss and Jondral, 2004, p. 14)

Quite why Western Judeo-Christian culture has developed such an extraordinary obsession with technology is examined by Noble in his *Religion of Technology* where he addresses the question. He argues that, at its core, technology embodies a tenet of religious millenarianism promising the transcendence of mortal life. (Noble 1997). But to Weiss and Jondral’s point, the lack of reform of the *Wireless Telegraphy Act* 1926 is evidence enough of the proposition that established regulatory practices die very hard indeed.

There’s nothing wrong with the above proposals, but what is important to appreciate is that spectrum management is and will remain fundamentally about choice. These choices, just or unjust will take place in the context of regulatory decision making. Human choices that cannot be rendered unbiased by reference to technologies or markets.

Perhaps what is needed is not so much pursuit of a panacea, but willingness to meaningfully engage with the fundamental problem to find a workable solution. This returns us to the regulatory process and how decisions are made within it. Hardin argues that “[w]e must find ways to legitimate the needed authority of both the custodians and the corrective feed-backs” (Hardin 1968, p.1246).

Operators may rail (sometimes with good reason) against decisions of regulatory agencies, but some entity has to make decisions for better or worse, the relevant question is whether they have the powers and competence to do so.

This will involve providing greater clarity on the extent to which government should intervene in providing an efficient infrastructure to foster growth and competitiveness in the communications sector. Imperfection and injustice is generally preferable to chaos. The challenge is not so much how to change, but when to allow it and with what consequence.

Regulators need to better engage those affected by regulatory decisions in their assessment of whether changes in market structure in specific radio sectors for example are required to better appropriate returns to the economy as a whole. This will involve greater independence, commitment to longer-term social goals and choices that will invariably harm the interests of certain users. Historically this has always been the way forward; it’s just always difficult to accept.

7 Conclusion

The management of spectrum presents a dilemma with no optimal solution – science, technology and even markets all have significant drawbacks. What is important to appreciate is that they all depend on governance institutions to allow them to operate.

In many cases (and Ireland is no exception), reform of the regulatory structure is the last thing considered. Probably with good reason as it is perhaps easier to negotiate the laws of physics than it is to reason with an incumbent.

Regulatory reform proposals tend to mirror technical solutions, which while impressive can never please everyone, all the time. Regulatory decision making in the final analysis involves choice. Markets and technologies are paths taken, not end-points. It is the process that determines these questions that requires our greatest attention. Or as Hardin would say, what is required is no less than a 'fundamental extension in morality'.

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