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Required regulative actions to introduce cognitive radio

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ABSTRACT OF THE
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This thesis provides guidance for regulatory measures which enable the introduction of cognitive radio in the near future. These measures should be globally harmonised in order to allow the same principles and rules to be used with cognitive radio systems (CRS) around the world.

Regulatory measures rely on the capabilities of CRS to detect and monitor spectrum in order to avoid existing usage. Based on this information CRS may operate, however, it should not cause harmful interference to existing usage. Regulation should take into account these requirements of shared use.

There are a number of questions related to regulatory measures for the introduction of cognitive radio systems. These questions require comprehensive studies and field tests to verify proper functionality.

In 2007 the radio communication conference of ITU (WRC-07) approved an agenda item for the conference of 2012 where the regulatory measures to introduce software defined radio and cognitive radio should be studied. The introduction of the CRS relies heavily on the results of WRC-12.

Keywords: cognitive radio systems, software defined radio,
spectrum management

AALTO-YLIOPISTO	DIPLOMITYÖN
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Tässä diplomityössä esitetään taajuushallinnollisia toimia, jotka mahdollistavat kognitiivisen radion käyttöönoton lähitulevaisuudessa. Taajuushallinnollisten toimien tulee olla mahdollisimman kattavia siten, että samanlaisia radiolaitteita voidaan käyttää samanlaisilla periaatteilla ja säännöillä maailmanlaajuisesti.

Taajuushallinnolliset toimet ovat riippuvaisia kognitiivisen radion kyvyistä havaita ja väistää taajuusalueella olevat signaalit sekä sen jälkeen toimia aiheuttamatta haitallisia häiriöitä nykyiselle käytölle. Nämä yhteiskäytön vaatimukset tulee ottaa huomioon sääntelyssä.

Taajuushallinnolliset toimet yksinään eivät mahdollista kognitiivisen radion käyttöönottoa, sillä monet tässä työssä esitetyt tekniikat vaativat lisää tutkimustyötä toiminnallisuuden todentamiseksi. Osa näistä tekniikoista on edelleen periaatetasolla. Kognitiivisen radion testauskäyttö todellisessa radioympäristössä tulee sallia, jotta tutkimustulokset ja taajuushallinnollisilla toimilla asetettujen käyttörajoitusten soveltuvuus voidaan varmistaa.

Vuonna 2007 kansainvälisen televiestintäliiton (ITU) radiokonferenssissa (WRC-07) hyväksyttiin vuoden 2012 konferenssille asiakohta, jossa ohjelmistoradion ja kognitiivisen radion käytöönoton vaatimia hallinnollisia toimia tulee tutkia. Lähitulevaisuudessa suurimman vaikutuksen kognitiivisen radion käytölle antaa vuoden 2012 radiokonferenssin tulos.

Avainsanat: kognitiivinen radio, ohjelmistoradio, taajuushallinta

Preface

This Master's thesis has been done in the Finnish Communications Regulatory Authority (FICORA) during the preparatory work for the World Radio Conference 2012. This preparatory work has included many useful meetings, thus providing a lot of good material for the thesis (almost too much).

I want to thank my instructor Mrs. Margit Huhtala for fruitful co-operation, guidance and a very supportive attitude during my studies and especially with this thesis. Without her, my work would not be finalized ever!

I also want to thank all my colleagues at the Finnish Communications Regulatory Authority (Radio Frequencies) for their positive and supportive attitude towards my efforts to achieve a Master's degree over the past ten years. Thanks to colleagues Mr Pekka Ojanen and Mr Kodo Zhu from the Nokia Corporation and Mrs Eiman Mohyeldin from Nokia Siemens Networks GmbH & Co. KG., we have had many visionary and practical discussions during the Groundhog Day's in Geneva. A special thank to Mr Ari Mujunen for reviewing this text endlessly, and to Mr William Martin for his proofreading of the final draft of the thesis manuscript.

I would also like to thank Mr Riku Jäntti (Prof.) for his guidance and supervising this thesis.

Otaniemi, 6th of April 2010

Jan M. Engelberg

Contents

Abbreviations

ATSC	Advanced Television Systems Committee
AWGN	Additive White Gaussian Noise
CEPT	European Conference of Postal and Telecommunications Administrations
CPG	Conference Preparatory Group
CPM	Conference Preparatory Meeting
CRS	Cognitive Radio Systems
DD	Digital Dividend
DTT	Digital Terrestrial Television
DVB	Digital Video Broadcasting
DVB-T2	Digital Video Broadcasting - Terrestrial 2
ECC	Electronic Communications Committee of CEPT
ECS	Electronic Communications Services
EIRP	Equivalent Isotropically Radiated Power
ETSI	European Telecommunications Standards Institute
FICORA	Finnish Communications Regulatory Authority
FSS	Fixed Satellite Service
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronic Engineers
ITU	International Telecommunications Union
ITS	Intelligent Transportation System
ITU-R	International Telecommunications Union - Radiocommunication Sector
MIFR	Master International Frequency Register
NRA	National Regulatory Authority
NTSC	National Television System Committee
PMR	Professional Mobile Radio
RAS	Radio Astronomy Service
RAT	Radio Access Technology
RLAN	Radio Local Area Network
RR	Radio Regulations
RCC	Regional Commonwealth in the field of Communications
SDR	Software Defined Radio
SNR	Signal-to-noise ratio
TV	Television
UHF	Ultra High Frequency (300 to 3000 MHz; 1 to 10 cm)
VHF	Very High Frequency (30 to 300 MHz; 10 cm to 1 m)
WLAN	Wireless Local Area Network
WRC	World Radiocommunication Conference
WRC-07	World Radiocommunication Conference 2007
WRC-12	World Radiocommunication Conference 2012

1 Introduction

This thesis provides guidance for regulatory measures which will enable introduction of cognitive radio in the near future. These measures should be globally harmonised in order to allow the same principles and rules to be used with cognitive radio systems (CRS) around the world. This will enable economies of scale in the manufacturing of radio devices with cognitive capabilities; making a new technology evolution possible as a way to respond to spectrum scarcity due to the foreseen increase of data traffic.

1.1 Objectives

The main objectives of this thesis are to identify the necessary regulatory actions to introduce cognitive radio, and to propose future actions that will be needed in order to fulfil these regulatory requirements.

Regulatory actions, in this thesis, are actions to be performed by regulatory bodies: National Regulatory Authorities (NRAs), regional telecommunication organisations (e.g. European Conference on Postal and Telecommunications (CEPT) in Europe) and the Radiocommunication Sector of the International Telecommunication Union (ITU-R).

Regulatory requirements are meant to provide guidance for researchers and vendors, since they do not necessarily have a deep understanding of radio regulation and its mechanisms. The main misunderstanding is that innovative and advanced technology alone is sufficient to justify access to spectrum and everything happens quickly and smoothly, which is usually not the case due to existing usage.

1.2 Methodology

This thesis describes principles on how national, regional and international regulation work and how they are interrelated. There are number of cognitive techniques which are introduced in this thesis, all of which may require independent regulatory approaches and, when combining these techniques, even a new approach may be needed. There are also some estimates of how mature these cognitive techniques are from the regulatory point of view. Through these steps, the required regulatory actions are identified; and, when needed, future work and actions are proposed.

In this thesis the sharing and coexistence issue has been examined between mobile/fixed service using cognitive radio capabilities and broadcasting service in the VHF and UHF bands.

1.3 Organisation of the thesis

In Section 2 this Master's thesis explains how access to spectrum has been regulated. A brief introduction to Cognitive Radio and Software Defined Radio is included in

Section 3. The Section 4 describes the main techniques which are needed for the introduction and implementation of Cognitive Radio Systems. This section also introduces regulatory problems related to cognitive capabilities. Section 5 is an overview of the international and national spectrum management framework, here regulative measures are analysed. Finally, in Sections 6 and 7, the conclusion and future work that needs to be done are expressed.

2 Access to spectrum

The radio spectrum has been recognised as a scarce natural resource, thus the use of it has been regulated nationally and internationally for years as described in Section 5. As such, more efficient and flexible use of the radio spectrum has been one of the goals for the international regulatory environment. One way to use the spectrum more efficiently is to promote the use and development of advanced radio technologies.

Spectrum utilisation measurement campaigns have indicated that parts of the spectrum are not used efficiently geographically or timely (see Figure 1). These unused parts of the spectrum can be used when a radio has capabilities to get information from its surrounding radio spectrum, and, based on this information, a radio can start using this spatially and timely unused spectrum. Advanced radio systems could make these kinds of decisions quickly and independently, and by this increasing the overall and the efficient use of the spectrum.

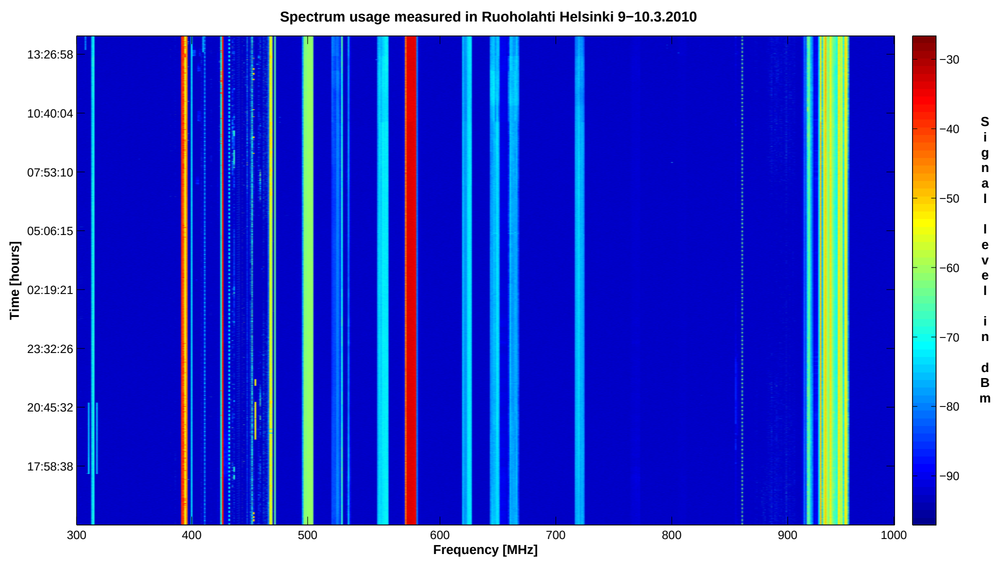


Figure 1: Spectrum occupancy measurement in Ruoholahti, Helsinki.

This measurement was made on 8th to 9th of March 2010 in the FICORA monitoring station at Ruoholahti, Helsinki. A 24 hour period measurement with a frequency range from 300 MHz to 1000 MHz was done with a Rohde & Schwarz ESPI receiver. Measurement parameters were:

- Centre frequency 650.000 MHz,
- Span 700.000 MHz,
- Resolution bandwidth 30 kHz,

- Video bandwidth 30 kHz,
- Measurement rate 0.2 per second,
- Start time 8.3.2010 at 15:10:08 and stopped on 9.3.2010 at 14:19:08.

The intention of the measurement was not to obtain accurate signal levels in dBm, but rather to have an overview on how spectrum is being used in this location. From Figure 1 it can be seen clearly that there is quite a lot of unused spectrum, even in the Helsinki city centre area. However, more accurate and rigorous measurements are needed before declaring any part of the measured spectrum as unused. The purpose of this measurement example is only to indicate current spectrum usage and thus cannot be used as a basis for the identification of unused spectrum. A more detailed analysis of this measurement is contained in Appendix B.

Traditionally, access to the spectrum has been granted via standard procedures defined in the Radio Regulations by the ITU Radiocommunication Sector (ITU-R), through national legislation or a combination of both. In Radio Regulations the different types of use are defined as radiocommunication services (and radio astronomy service) for which frequencies are allocated on a band by band basis. Most bands are allocated to multiple services, i.e. usage is shared between services. Based on the class of priorities, the allocations are also divided into two categories: primary and secondary allocations.

The only forum where spectrum allocations (Article 5 of RR [6]) can be altered, updated or deleted is in the World Radio Conference (WRC). WRCs are held every three or four years and the time between conferences is called the "study period". During the study period, various ITU-R study groups make necessary studies to fulfil the needs of the next conference. These studies are usually technical studies that make possible inter-service sharing between radiocommunication services.

Radiocommunication services can be divided further: terrestrial and space radiocommunication. There are a number of radiocommunication services defined by ITU-R, e.g. fixed service, fixed satellite-service, mobile service, broadcasting service etc.

An additional usage category has been introduced at the national and regional levels. In Europe, this usage is called licence-exempt usage or general licence. In these frequency bands all users have equal rights: when stations are using such a frequency assignment, they shall not cause harmful interference to a station, and shall not claim protection from harmful interference caused by a station operating in accordance with the provisions of the Radio Regulations. In other words, licence-exempt stations are operated on a non-protected and non-interference basis. One other type of licence-exempt usage is when the frequency band has been allocated to a specific service, for instance a fixed service and the use of frequencies are controlled by frequency assignments to individual stations of this service. In addition to this, the same band could be used for licence-exempt devices provided that they do not cause harmful interfere to primary service and cannot get any protection from the

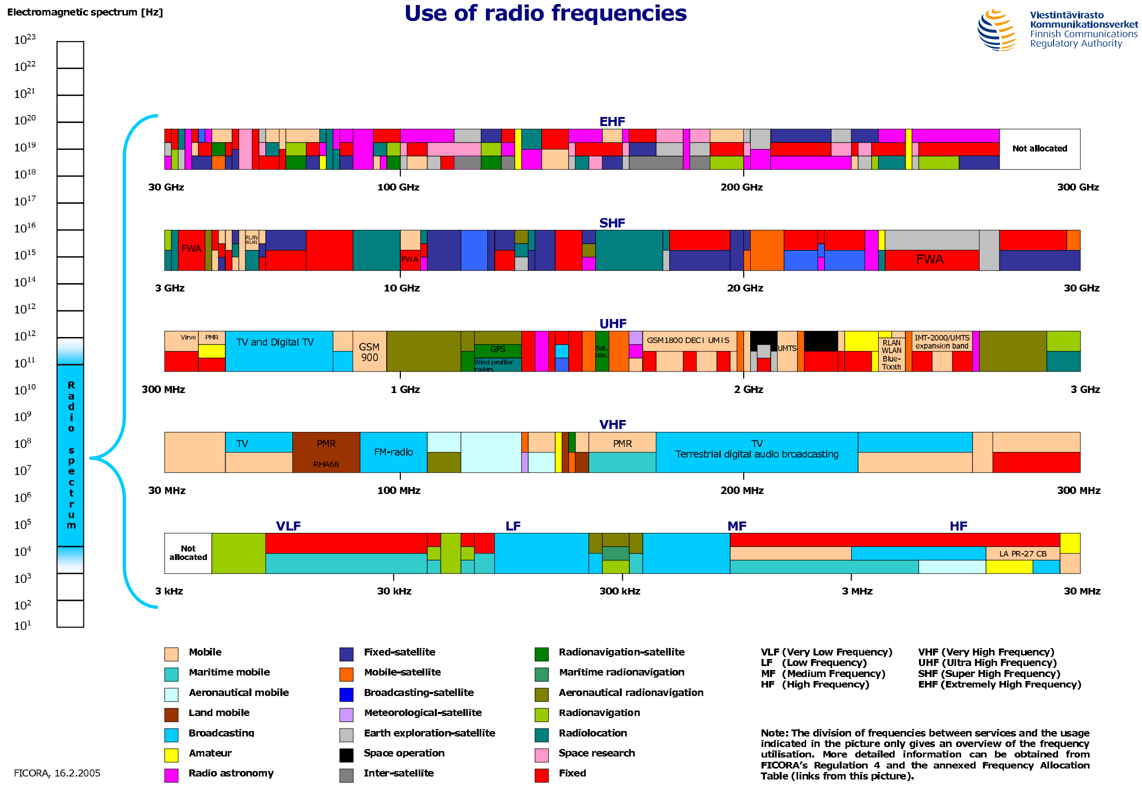


Figure 2: Use of frequencies in Finland according to allocations in RR [12].

primary service. An example is ultra-wideband automotive radars in the 22 GHz frequency band.

National regulatory authorities (NRAs) control spectrum usage by adopting international or regional spectrum allocations into national regulation. When a portion of the spectrum has been internationally allocated to a radiocommunication service, an individual country can decide the use of spectrum according to the national demands by authorising the use of a specific frequency or radio channel. The overall picture of spectrum allocations in Finland is shown in Figure 2.

It should be noted that the radio astronomy service (RAS) is protected through footnote 5.149 in the Radio Regulations [6]. This footnote lists all frequency bands used by the RAS and requires that administrations take all practical steps to protect the radio astronomy service from harmful interference. However, the RAS is itself using cognitive techniques to identify unused parts of the spectrum in frequency bands used by active radio transmitters. The power levels that are being measured by the RAS are very low, therefore the identification of unused spectrum requires careful decision making, otherwise measurements are polluted by transmitted signals.

2.1 Unused spectrum — under-utilised spectrum

Temporally and/or geographically under-utilised frequency bands could be considered as unused spectrum. This kind of spectrum exists in many frequency bands, when the whole band or parts of it are under-utilised. Typical and well known applications which under-utilise the spectrum usage are, for example, television (TV) in the UHF band, the fixed satellite service (FSS) in many bands such as the C-band (3400–4200 MHz) and many radar applications. These allocations are highlighted due to the following reasons:

- TV — In many countries, the switch-over from analogue to digital TV broadcasting has left parts of the spectrum unused in many geographical locations.
- FSS — Typical FSS satellite frequency assignments cover the whole band based on the frequency allocation according to ITU Radio Regulations. However, in many cases a single earth station is using only a marginal amount of spectrum (e.g. satellite transponders cover 3600–4200 MHz and a receiving earth station is using bandwidth from 4 kHz to 72 MHz.
- Radiolocation Service (Radars) - The situation is comparable to FSS usage, since the allocations for this service have wide frequency bands, for instance, 2700–3400 MHz. All radar sub-bands cannot be considered for the CRS, because radars in fixed carrier frequency usually operate in a safety-related service. The case is slightly different with frequency hopping radars and some parts of the bands may be available for cognitive radio if it has enough immunity against pulsed interference.

However, the usage patterns of these applications cannot be generalised based on the application itself. A case by case analysis is still needed, however the harmonised approach should be implemented in order to allow shared use of the frequency bands used by the applications mentioned above. This harmonised approach needs to be recognised by all stakeholders due to the scarce nature of the radio spectrum.

It should be noted that some (most) licence holders consider that unused spectrum does not mean that it should be open to everyone. They consider that they have higher rights despite the fact that they are not using all the assigned spectrum in every location all the time (in some cases this is not even required).

However, the national administrations usually have a totally different view on this issue. Administrations may issue additional licensing conditions to promote the efficient and timely use of the spectrum. For example, this has been done in Finland for over 10 years in Fixed Wireless Access licensing where every licence holder has to start operations within a year counted from the date when the licence was issued. If they had failed to start operation, FICORA could have revoked the licence or could have started the cancelling procedure.

In some cases, this debate is highly political and not a technical one. In these cases a government policy promotes some radiocommunication services over others or has to do so. One good example is the switch from analogue to digital terrestrial TV which is also known as the Digital Dividend (DD). After DD some of the TV spectrum could be allocated to land mobile service, however the broadcasting community opposes this kind of action due the requirements for the future high definition terrestrial TV systems using technologies like DVB-T2.

2.1.1 An example of unused spectrum — White Space

The term *"white space"* has been used for a couple of years when referring to the unused parts of the licensed radio spectrum[1]. Also this term has a number of varying definitions that are used around the world. However, there are situations when the licensed spectrum is unused intentionally. This does not mean directly that it could be considered as white space. This is due to the fact that licensing procedures keep parts, or a whole band, unused for some time before a new service or application starts its operation. In such cases, a given NRA has cleared some spectrum before the licensing process starts, for example, before a spectrum auction, and it will remain unused until the winning bidders start their network roll-out. This period of time varies a lot and could be quite short (weeks) or very long (several months to even years), thus it might not be feasible at all to use such white space, at least within a service that will use the whole assigned band with numerous transceivers (e.g. public mobile networks).

White spaces could be used in countries with large geographical areas with a relatively low number of transmitters in a given licensed system. These systems are traditionally based on high power transmitters with large protection zones, such as TV transmitters in the VHF and UHF bands. Another possibility is to use white spaces in the frequency bands where only a small portion of the assigned frequency band is used by the systems, for example the fixed satellite-service (FSS).

United States

In United States this term is used in conjunction with the broadcasting (TV) use in the VHF and UHF bands. The Federal Communications Commission (FCC) uses the following terminology [4]:

> *. . . to allow unlicensed radio transmitters to operate in the broadcast television spectrum at locations where that spectrum is not being used by licensed service (this unused TV spectrum is often labelled as "white space").*

The use of white spaces in United States is possible when radio devices use CRS capabilities, for instance, sensing and/or geolocation; fulfil technical requirements

[1] It should be noted that unallocated spectrum and unused frequency bands are not considered white space.

and pass equipment certification requirements as defined in Appendix B of the FCC Second Report and Order 08-260 [4].

At the moment, the FCC has been sued over its plan to allow the use of licence-exempt devices to access parts of the television spectrum (white spaces) by The National Association of Broadcasters (NAB) and the Association for Maximum Service Television (MSTV). They want to change the FCC's decision and prevent the use of white spaces in the broadcasting TV bands. This lawsuit was filed in the U.S. Court of Appeals for the District of Columbia Circuit on February 27, 2009.

Europe

In Europe the current definition according to the CEPT Report 24 [18] is the following:

> *"White Space" is a label indicating a part of the spectrum, which is available for a radiocommunication application (service, system) at a given time in a given geographical area on a non-interfering / non-protected basis with regard to other services with a higher priority on a national basis.*

This definition is used in the work of the Electronic Communications Committee of CEPT (ECC) and its subordinate bodies. However, in Europe the use of the term is not restricted to the UHF bands, although the Project Team 43 of the Spectrum Engineerign Working Group is specifically working on technical and operational requirements for the operation of cognitive radio systems in the "white spaces" of the frequency band 470–790 MHz.

2.1.2 Regulatory problems related to the use of unused spectrum

The main regulatory problem lies in the licence conditions of the radio licences already granted. In many countries the parts of the spectrum have been assigned through auction processes amounting to billions of US dollars, therefore the auction winners are eligible to have reasonable expectations to have some revenue for their investments. In many auctions the rights to use the spectrum has also been granted for many years, for instance, 20 years with the possibility of re-selling the spectrum or parts of it. In these cases, it is quite hard for an administrative body to introduce any additional burden on licence holders.

In addition to licence conditions, some regulation is needed if these conditions, or rights of use, need to be changed during the licence period. In Finland, this is embedded in the national telecommunications legislation. It is stated in the Radio Act [19] that

> *"During the validity period of a radio licence, the Finnish Communications Regulatory Authority may amend the licence conditions without the consent of the licence holder if this is essential because of a change in the confirmed utilization plan for a radio frequency, because of regulations on frequencies or because of international treaty obligations, or if it is justified for the prevention or removal of interference in radiocommunications or on the basis of the radio frequency bands primary purpose of use. Licence conditions may also be amended if this is essential because of a change in the economic or technical operating prerequisites of a telecommunications operator engaged in the market or if it stems from the arrival of a new telecommunications operator on the market or other similar need to reorganize radio frequency usage arising from a change in market circumstances. (11/2007)."*

The Finnish approach has been used for years and auctions are not favoured since they do not necessarily respond to the demands on the end-users/citizens and often do not take into account the overall national situation (a similar problem can often be seen in the European Commission telecommunication regulation). Moreover, the Finnish radiocommunications environment is already a very competitive market, therefore it is almost impossible to enter the market as a green field operator, i.e. without the needed infrastructure resources (relatively large country geographically with very low population density with high requirements for quality of service).

2.2 Coexistence and sharing

One key element in spectrum use is the coexistence and sharing of the spectrum. Sharing/coexistence means that the radio systems share some of the resources (spectrum and/or time) in a certain geographical area in a way which makes it possible to operate both systems without causing harmful interference to each other. This kind of usage is based on the classifications of systems into two categories: primary and secondary and these terms have a specific meaning in the ITU-R language. Similar language has been adopted by the regional and national regulatory bodies.

As stated from the Radio Regulations Edition of 2008 [6]:

> *Stations of a secondary service:*
>
> *a) shall not cause harmful interference to stations of primary services to which frequencies are already assigned or to which frequencies may be assigned at a later date;*
>
> *b) cannot claim protection from harmful interference from stations of a primary service to which frequencies are already assigned or may be assigned at a later date;*

c) *can claim protection, however, from harmful interference from stations of the same or other secondary service(s) to which frequencies may be assigned at a later date.*

The main purpose of sharing/coexistence is to allow other usage, which shall not cause interference or otherwise influence the performance of other systems. By allowing other use, the flexibility and overall spectrum efficiency improves.

Sharing/coexistence between radio systems is possible if the negative impact of one radio system on the performance of other radio system is minimised. This is usually done by minimising the interference, however other ways can also be used to protect the performance of other system.

There are two main types of sharing/coexistence:

- between existing systems and a CRS, i.e. primary users vs. secondary users[2];
- between cognitive radio technologies.

The first type of sharing/coexistence is the case when a CRS identifies an unused part of spectrum and shares this spectrum with existing systems, for example, the band is allocated for the fixed service and assignments are for radio links, the band is shared with UWB devices (land mobile service). The idea is that a CRS can use this part of spectrum if the performance of existing system(s) is not decreased by the CRS in any way.

The other type means that all cognitive radio technologies share the same part of spectrum with the same rights. This case is similar and also comparable to the behaviour of licence-exempt devices in ad-hoc networks.

2.3 Efficient access to spectrum

This chapter described how access to the spectrum is done in a regulatory manner. There are differences between countries on which aspects are promoted and which are not. Some countries support a technology and service neutral approach on all bands and some have more traditional regulatory measures in place. These two approaches, nevertheless, have the same goal – flexible, efficient and interference free spectrum use, however the final result remains to be seen.

[2]This kind of terminology is not used in the regulatory regime. In regulatory terms a primary user can be a station/assignment of primary service or secondary service.

3 Introduction of Software Defined Radio and Cognitive Radio

This chapter provides descriptions and definitions for software defined radio and cognitive radio from scientific literature. The relevant definitions for this thesis have been defined by the ITU Radiocommunication Sector (ITU-R).

3.1 Software Defined Radio (SDR)

The term Software defined radio (SDR) was invented in 1991 by Joseph Mitola III, although similar ideas have been discussed and considered in the defence sector since the 1970s. Software Defined Radio is a wireless device the parameters and behaviour of which can be altered or reconfigured with software. At the moment, SDR still is a radio partly implemented in analogue components and partly by software controlled electronics that control various operational functions. Software in this context can be digitally implemented in logic or as code inside the microprocessor.

Basically, SDR refers to reconfigurability of the radio interface by software. This reconfiguration can be done either over the air or by other means. One of the main function of SDR is that it is one enabler of Cognitive Radio (CR) [3].

In 2007, ITU-R developed a Report ITU-R M.2117 — Software defined radio in the land mobile, amateur and amateur satellite services. In this report SDR was defined as:

> *Software Defined Radio (SDR):* A radio in which the RF operating parameters including, but not limited to, frequency range, modulation type, or output power can be set or altered by software, and/or the technique by which this is achieved (see Recommendation ITU-R M.1797).
>
> Note 1 — Excludes changes to operating parameters which occur during the normal pre-installed and predetermined operation of radio according to a system specification or standard.
>
> Note 2 — SDR is an implementation technique applicable to many radio technologies and standards.
>
> Note 3 — Within the mobile service, SDR techniques are applicable to both transmitters and receivers.

During the preparation of the World Radiocommunication Conference 2012, the ITU-R Working Party 1B developed a Report ITU-R SM.2152 — Definitions of Software Defined Radio (SDR) and Cognitive Radio System (CRS). This report was conducted since the above mentioned definition was considered to be too service specific, especially the third note. This latest definition was approved by the ITU-R Study Group 1 in September 2009:

Software Define Radio (SDR): A radio transmitter and/or receiver employing a technology that allows the RF operating parameters including, but not limited to, frequency range, modulation type, or output power to be set or altered by software, excluding changes to operating parameters which occur during the normal pre-installed and predetermined operation of a radio according to a system specification or standard.

The research and early stage usage of SDR has been initiated in the context of military communications [26], this has also been the case with other advanced communications developments such as the development and use of radio communication systems using spread spectrum modulation techniques.

3.2 Cognitive Radio (CR) and Cognitive Radio Systems (CRS)

The term cognitive radio (CR) was first introduced by Joseph Mitola III and Gerald Q. Maguire, Jr. in 1999 [1]. In this article an ideal cognitive radio is a device which is capable of cognitive actions during a cognition cycle. This cognitive cycle has six phases: "Observe, Orient, Plan, Learn, Decide, Act", see Figure 3.

The definition has evolved since that time, and all those working in this field seem to have their *own* definition and interpretation of cognitive radio.

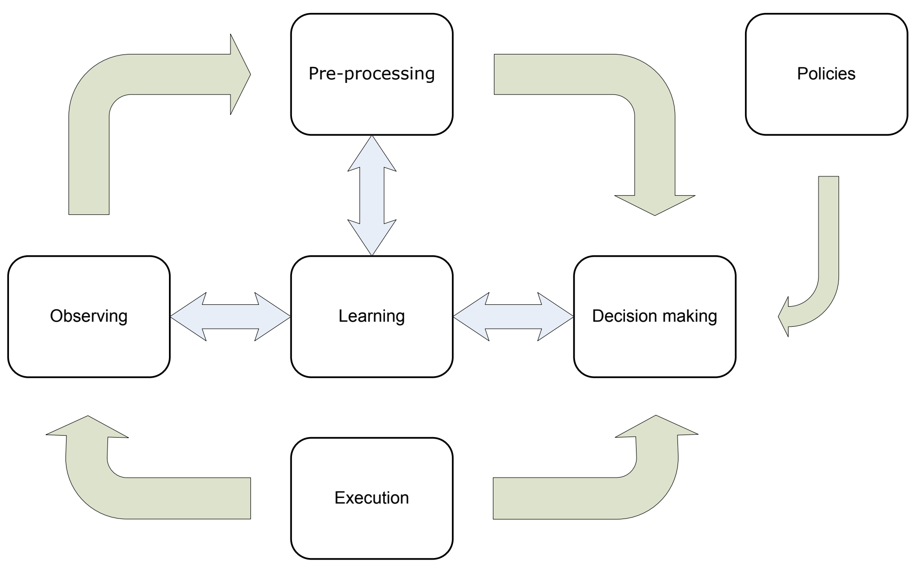


Figure 3: Basic cognitive cycle [11].

The latest definition for a CRS was approved by the ITU-R Study Group 1 in September 2009 and it can be found in the Report ITU-R SM.2152:

> *Cognitive Radio Systems (CRS):* A radio system employing technology that allows the system: to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.

3.3 Relationship between SDR and CRS

This section introduces the technical approaches and differences between the Software Defined Radio and Cognitive Radio Systems.

Software Defined Radios are capable of reconfiguring themselves and they provide the following features [20]:

- Radio interface adapts to accommodate variations of new radio interface standards,
- Incorporation of new emerging applications and services,
- Incorporation of software technology updates,
- Exploitation of flexible heterogeneous services of radio networks.

It should be noted that SDR is already in use, and has been already in use for a number of years.

The CRS can be considered as a SDR, at least its reconfigurability functions, however higher level functions, especially learning, makes it a totally different technique.

Therefore, these two techniques should not be mixed in any way. This was also one of the main reasons for the ITU-R to develop Report ITU-R SM.2152, which has two clearly separate definitions, one for SDR and the other for CRS.

3.4 Conclusion

Based on the differences between SDR and CRS, one should understand that SDR can be deployed without CRS and CRS without SDR, however some features of CRS can be deployed more easily using SDR.

The following chapter provides detailed information about various CRS capabilities and how these fit into the regulatory environment.

4 Different CRS capabilities, methods and techniques

The cognitive capabilities of a radio often refer to the opportunistic access to the unused spectrum. One of the key elements is the identification of these geographically and timely the unused parts of spectrum.

Cognitive radio systems have the capability to share the spectrum which is already used by other users. This is possible through the three key functions, actions and activities of CRS to:

1. obtain knowledge of its radio environment and location,
2. make a decision based on the obtained information and
3. act based on the decision (both autonomously and dynamically).

Obtaining the knowledge of the radio environment and own location is the starting point of the cognitive process of the radio. This capability can be performed through the implementation of specific features such as sensing, positioning and introduction of a cognitive pilot channel (CPC).

It is also necessary to have information on the spectrum rules and restrictions of the usage, which apply to the current location and frequency band under action. These rules can be very complex in nature since they depend on the type of licence designation and the sharing conditions in the band. The following sharing conditions are typically used by spectrum managers/authorities around the world: frequency sharing, time sharing, geographical sharing and any combination of these.

To fully benefit from the gathered information, the CRS has to be able to adjust its performance dynamically in order to protect incumbent users of the spectrum. These kinds of dynamic actions include the change of radio access technology and/or operating frequency. This could be performed by having features like: frequency agility (transmitters and receivers are able to change their operating frequency), transmit power control, adaptive antennas, adaptive modulation and coding, and the ability to learn.

It should be noted that to guarantee the protection of existing users, the CRS may have several capabilities utilised simultaneously, however not a complete set of cognitive capabilities is required for accessing the unused or shared spectrum. These capabilities can also be service and/or frequency band specific. Therefore, these requirements could vary based on the incumbent use of the specific frequency band.

4.1 Pre-cognitive techniques

There have been a number of radio systems that have employed pre-cognitive techniques in the past. Military communications have used adaptive systems for years.

Such a radiocommunication system can change its radio parameters based on the channel quality. Furthermore, newer radiocommunication equipment which uses techniques such as Dynamic Frequency Selection (DFS)[3] and a Detect and Avoid (DAA)[4] mechanism can be considered as pre-cognitive radio systems.

These systems sense the environment and change their radio parameters based on the received information. The changeable parameters are predetermined, thus radio users cannot arbitrarily change the behaviour of the radio equipment. Predetermined parameters are defined during the sharing studies, which are done before the introduction of these devices into the market either at a regional level (e.g. CEPT in Europe) followed by the ITU study groups (e.g. the use of RLAN in 5 GHz bands). These sharing studies provide necessary information to standardisation organisations to create and maintain standards that fulfil the regulatory requirements, thus making manufacturing of the devices possible. Standardisation bodies and manufacturers usually take part in sharing studies as one group of stakeholders [14].

The remainder of the chapter deals with various methods and techniques that can be utilised by a CRS, however the purpose is not to create an exhaustive list of all possible cognitive technologies.

4.2 Techniques for obtaining knowledge

One of the main functions of a CRS is its capability to obtain the knowledge of the surrounding environment. In this context, the environment covers many aspects related to subsequent behaviour of CRS, for example, the knowledge of the operational and geographical environment, the regulatory regime, the internal state of a CRS and to the monitored usage patterns and user's needs and any changes in the environment.

Cognitive radio systems (CRS) can use various techniques to obtain knowledge, such techniques include:

1. Spectrum sensing by performing a spectrum scan;
2. Geolocation — Global Positioning System (GPS) or other positioning systems;
3. Listening to control channel (e.g. the Cognition supporting Pilot Channel);
4. Access to data base (wireless or fixed connection);
5. Receiving information from other elements of the CRS.

[3]Dynamic Frequency Selection (DFS) detects interference from other systems and avoids co-channel operation with these systems, notably radar systems. It also provides on aggregate a uniform loading of the spectrum across all devices.

[4]Detect and Avoid (DAA) mechanisms detect the signals of other radio systems and decrease the transmit power of the Ultra Wide Band device until it does not cause interference to other systems.

Any combination of these techniques could also be one approach.

In this section the main techniques are defined based on the relevant scientific literature.

4.2.1 Sensing

The simplest method to obtain knowledge is based on sensing. A lot of studies are assuming that CRS devices monitor licensed transmission and transmit only when they receive no licensed transmission.

To use spectrum sensing to identify unused spectrum, it might be necessary to identify the type of transmission which needs to be sensed. Therefore, the initial stage of a CRS could be band specific, providing a set of signals which need to be identified before accessing the spectrum. The basic idea is that sensing produces detailed information of the radio environment. Based on these received signal levels, the unused parts of the spectrum can be recognised and can be used by the CRS.

There are different sensing techniques under evaluation and the main research interest focuses on various detection methods. Such methods are, amongst others, matched filtering, energy detection and cyclostationary detection [21]. There are known problems with sensing at low SNR. This so called "SNR wall" could cause uncertainties (errors in the noise power estimation) that vary with the degree of knowledge of the primary signal and the detection method used [28]. These methods differ in the levels of complexity and ability in detection of signals at different levels and of classifying these signals. The choice of the method depends on the sensing requirements (signal level) and the additional complexity of the environment.

Other problem with the sensing is the shadow fading problem, which can result in the hidden node problem. This situation occurs when a signal transmitted by the user/station of primary/secondary service (e.g. TV transmitter) is not received by a CRS due to the shadowing effect of terrain or other obstacles. In this case the CRS will obtain false information and starts co-channel transmission, which causes harmful interference to the TV receivers in the vicinity of the CRS. This so called hidden node problem could be solved by combining sensing information from multiple cognitive radio devices, however, this combined information needs to be processed in a centralised manner [31]. This distributed sensing is still under study, therefore relying only on sensing may not be a reliable method for obtaining the knowledge of environment at the initial stage of CRS introduction.

UHF band 470–698 MHz

As an example of sensing, the UHF frequency band 470–698 MHz is considered here in more detail. The values in this example are based on the FCC requirements [4].

Sensing of transmitted signals is based on the received power of signal in CRS devices. Incumbent, protected services in this band are digital TV and wireless

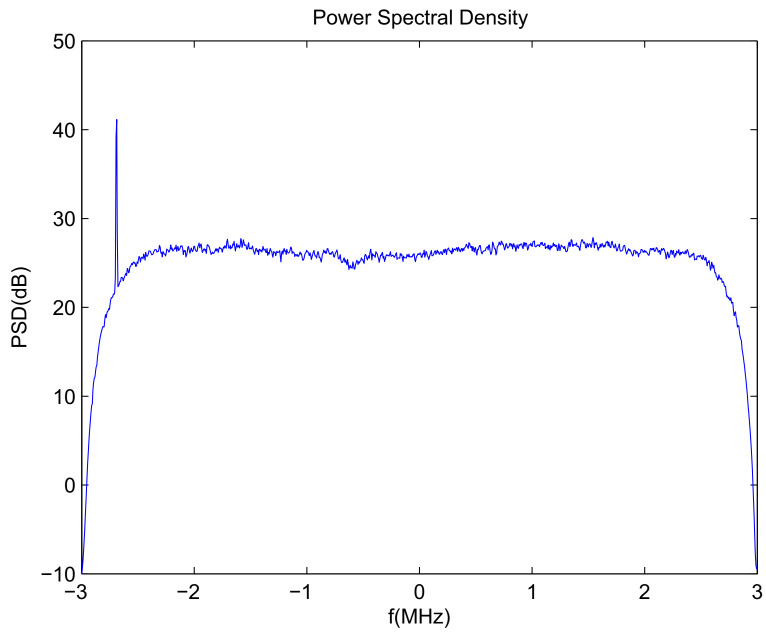


Figure 4: Received PSD of typical ATSC signal [15].

microphones. Usually the sensing level (threshold level) is defined by the most sensitive system, in this case digital TV. Based on the transmitter parameters and receiver requirements of the TV or set-top boxes the required sensing level is -114 dBm, received with a 0 dBi antenna in a CRS device. This level is far below the noise floor of a typical receiver, since the thermal noise is -106.2 dBm in 6 MHz bandwidth used by the ATSC system, and with a noise figure of 6 dB.

To detect a signal level of -114 dBm requires that even lower levels can be actually detected, for instance, -116 dBm, since some margin is required for the effects of additive white Gaussian noise (AWGN) and multipath fading due to mobility. The received power level of -116 dBm provides a requirement for a signal-to-noise radio (SNR) of -22 dB [27]. To build such a receiver, however, is quite challenging [9]. One solution to this detection problem can be seen in the power spectral density (PSD) of a typical ATSC signal, as can be seen in Figure 4. Sensing could be tuned to measure only this narrow pilot carrier. The exact location of pilot carrier in frequency is known from the equipment standard [29]. It is easy to see the pilot carrier in the lower edge of the TV channel. Note that the x-axis is normalised, but the y-axis is not.

Another problem is that co-channel[5] usage based on the power levels detected by a CRS device can cause harmful interference. This kind of interference scenario occurs when a given CRS device senses no DTT signals and, based on this knowledge, decides to start transmitting its own signal with a predefined equivalent isotropically

[5]When frequency separation is zero. Refers to the use of the same radio frequency channel by two or more emissions.

radiated power (EIRP) level. If this predefined EIRP for the CRS is too high, interference may occur in the DTT coverage area. This is demonstrated in Figure 5.

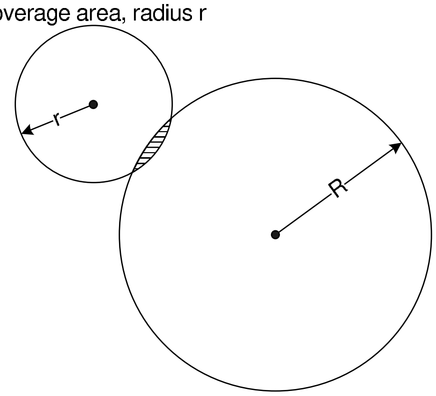


Figure 5: Co-channel interference overlap.

In real life, the edge of the coverage area is usually non-uniform, thus making this scenario even more difficult to predict. It is not possible for the CRS to have knowledge where the DTT coverage area edge lies based on the sensed DTT emission, therefore CRS EIRP levels need careful evaluation. Although, the fact that TV receivers are using directional antennas gives additional room for this estimation. Actually, the antenna directivity in the edge of the coverage area is usually quite high, it therefore provides some additional protection for TV signal reception. It will be necessary to do simulations with various EIRP levels of CRS and confirm the results with field tests. At least the following obstacles may make sensing potentially unreliable:

1. The technical characteristics of the DTT transmitter (EIRP and antenna height) cannot be sensed.
2. Radio propagation characteristics between the DTT transmitter, victim DTT receiver and the CRS device cannot be derived through sensing.
3. DTT signal power at the edge of coverage area varies in different countries, therefore this information needs to be provided to the CRS by other means than sensing.
4. Sensing uncertainties with low SNR.
5. Hidden node problem.

For these reasons, CRS devices relying only on sensing capability cannot be considered reliable to protect licensed use, unless the obstacles listed above are resolved.

Similar problems can occur in every frequency band where sharing is based on the protection levels defined by sharing studies.

Therefore, one conclusion is that additional information from the licensed transmitters needs to be conveyed to CRS devices in order to guarantee interference-free operation.

4.2.2 Geolocation database

The second method for a CRS to obtain knowledge of its environment is to have a database which contains information on the existing use and regulations. When using the database to provide necessary frequency usage information to the CRS, the location of the CRS is needed, and this concept is usually called a geolocation database. This section describes existing requirements and rules for geolocation databases.

At the moment, there are only two nations who have established some kind of regulation for geolocation databases: the United States and the United Kingdom. They both have similar concerns for the usability of geolocation databases.

Current requirements for geolocation databases have focused on the TV broadcasting bands, 470–790 MHz (band edges used in Europe). The transmitters in this band have similar technical parameters throughout Europe. The band is allocated for broadcasting and, in many countries, mainly for digital terrestrial television (DTT). Geolocation is a possible solution for avoiding DTT transmissions, since transmitter characteristics (location, frequency, power level, etc.) are more or less stable (at least changes happen very infrequently). The countrywide databases are probably quite easy to establish and maintain, since the technical characteristics of stations are well known and the coverage area calculations of each transmitter are available.

A more complicated situation occurs when the unused TV channel is used by radio microphones the locations of which are not known with the same level of accuracy as the DTT. These wireless microphones are used in theatres, rock concerts and fairs; some of the usage could be very temporal in nature. The technical characteristics of microphones are also quite similar, thus, in principle, the required data can be entered into the database without problems. However, the temporal usage requires more actions for the database operator/maintenance and causes more frequent actions between the database and CRS. Some kind of data quality information (e.g. time labels or validity time of data) is needed. This information could be used to define how often the CRS needs to have database access. The microphone issue could be solved by allocating a few unused TV channels for wireless microphones. Another solution could be to allocate another (totally new) spectrum for microphones, but this does not solve the problem of the existing microphones.

The use of a geolocation database is possible if the following issues are solved:

1. Location accuracy;

2. Ownership of database;
3. Transmitter parameters or aid for decision making;
4. Accessing the database;
5. Structure of the database.

These are also under study in the CEPT Spectrum Engineering Project Team 43 (SE43).

Introduction of Geolocation in UHF band 470–698 MHz

So far the only requirements for geolocation have been introduced by the FCC in [4], where protection of the digital TV (ATSC) service is provided by using geolocation with database access. In this thesis only the protection of digital TV is considered, since Digital Dividend is an ongoing issue throughout the world. In Europe, Ofcom UK made a consultation on "Digital Dividend: Geolocation for Cognitive Access" [17], it was closed on the 9th of February 2010. Unfortunately the result of this consultation has not yet been published.

Usually the protection of TV service is done by defining the protection contour around an individual TV transmitter. This contour is done by using the propagation curves provided by the ITU [10]. For example, the FCC defines this protection curve using the propagation model where the field strength of -41 dBμV/m is received in 50% of locations and 90% of the time.

In the FCC rules [4], both fixed and personal/portable devices are covered. The FCC requires that both device classes[6] are directly connected to an incumbent TV database via Internet. This database provides essential information to determine possible operating channels. Sensing is used to confirm that these channels are unused. This TV database should contain at least the following information:

- transmitter coordinates (long/lat),
- effective radiated power (ERP),
- horizontal antenna pattern (required only for directional antennas),
- channel number,
- station call sign.

So far only Google Inc. has made a proposal to provide a database management solution for TV band devices [16].

[6] There are two types of portable devices in this FCC rule: Mode I and Mode II, however this requirement is only for Mode II devices. Mode I is a client, it is not able to initiate a network. Mode II devices are masters and are able to determine the available channels in the area.

4.2.3 Cognitive Pilot Channel (CPC)

A Cognitive pilot Channel can be a way to convey the necessary information to let CRS devices obtain knowledge of the status of the radio spectrum through a common pilot channel. The beacon should transmit various kinds of information on existing usage. The following parameters are from a preliminary list defined by IEEE 802.22.1 [22]: the location of the originator of beacon frame, occupied TV channels, security related status of beacon frame, parameter #1 (frame number, priority level, antenna characteristics, etc.), parameter #2 (TV channel width, cease transmission, time parity, ...), parameter #3 (antenna locations, etc.). It could make the scanning process simpler and faster for terminals that are not aware of the existing spectrum usage. The CPC may lie inside the target band (in-band) or outside of the intended band (out-band), however in this case the location of the CPC should be internationally agreed.

Researchers have recognised these two forms of CPC and either of them needs to be able to transfer information in both directions (down-link and up-link capability).

- In-band CPC can be considered as a logical channel within the radio environment, where numerous Radio Access Technologies (RATs) are used at the same time in a given location, and where specific channels are used by existing technologies.
- Out-band CPC, a radio channel outside the frequency band used by RATs. It uses either a new radio interface or legacy systems with a suitable set of characteristics [14].

The main technical issue with a CPC is the location and signal characteristics of the CPC itself. In addition to this, the use of a CPC raises a number of regulatory issues, for example, management of the frequency information and regulatory environment which need to be carefully studied and solved.

4.2.4 Issues with obtaining knowledge

Sensing, the geolocation database and the CPC are the main techniques that a CRS can use to obtain knowledge of its radio environment.

There are many technical challenges and uncertainties with sensing. The FCC requires that sensing is implemented in all TV band CRS equipment. The sensing should work on: digital ATSC, analogue National Television System Committee (NTSC) and for wireless microphone systems (e.g. Electronic News Gathering). The sensing needs to be possible down to a -114 dBm level as was described earlier. For ATSC, the measured bandwidth is averaged over 6 MHz, for NTSC over 100 kHz and over 200 kHz for wireless microphones. The FCC is also considering sensing only devices with very low output power (50 mW).

The performance and requirements for geolocation database are key elements which need to be solved. For example, the FCC requirements [4] for a database contain the following elements:

- Geolocation and access to the database: It should be used by fixed and portable Mode II devices; geolocation accuracy needs to be ± 50 metres; location can be provided by GPS or by other means which guarantees the location of CRS.
- Database for TV bands: Lists available TV channels in the vicinity of a TV station location; has register identities of TV stations and their location; gives information on other protected channels and their locations (e.g. RAS use in 608–614 MHz band).
- CRS equipment information: FCC ID, serial number, locations, point of contact, etc.

The FCC will finally certify and approve the official database. It could be possible that there will be more than one designated database administrator who will manage their own databases. The Database cost could be covered by some kind of administrative fee for users.

The FCC rules also require that fixed devices have to connect to the database when installed and after that on a daily basis. If a fixed CRS device does not have an Internet connection it may communicate via another connected device to the database. The most important rule is that they have to stop operation if the used channels are no longer available.

For portable Mode II devices the rule is similar, they also have to connect to the database before starting operation in a new location and also on a daily basis.

The main problem with a CPC is that it may need dedicated frequency assignment to broadcast parameters to the CRS. The use of a dedicated assignment needs harmonisation efforts from standardisation bodies, since it is vital that the exact location in frequency of the CPC beacon is generally used through the region. Otherwise the regulation and devices will become more and more complex to implement. The FCC rules do not provide any requirement or guidance for the CPC.

The rest of this chapter tries to answer how the obtained knowledge is used in a CRS, both before transmitting and after transmission has started.

4.3 Techniques for decision making and adjustment

To fully benefit from the obtained knowledge, the CRS needs to be able to make decisions and adjust its operational parameters according to the received knowledge. This process can be considered cyclic or continuous. It is essential that this decision making does not need user actions, i.e. changes should be performed autonomously in a way that it has no impact on user experience (service).

The change of operational parameters could be based on the predefined policies and regulation or online information, for instance, from an approved database. It could also be a combination of these. Operational parameters can be changed rapidly in order to respond to, for example, user requirements (Quality of Service), a changing radio propagation environment or even to its own state changes such as low battery charge.

Decisions must be made autonomously and also based on learned knowledge. The decision-making procedure needs to take into account different CRS scenarios, since different mechanisms could be needed for different deployment scenarios. The following deployment scenarios are under study:

- Ad-hoc type, indoor device-to-device communications;
- Public mobile network type (outdoor cellular);
- Wireless Local Area Network type indoor/outdoor deployment;
- Other deployment scenarios.

Each of these scenarios may need specific regulation as shown in the FCC rule and order [4].

4.4 Learning

Learning is a feature of a CRS that makes it totally different from SDR. Learning process helps CRS to improve its performance using stored data from previous actions and their results (e.g. quick response to user demands based on the stored usage patterns). The CRS needs to analyse its actions through the performance and optimise the transmitting parameters accordingly. The goal is to improve overall capacity and performance of the system/network. Analysis is based on the stored information of the obtained knowledge from the environment which is changing through the actions of the CRS and radio-related elements. It is necessary that this data is accurate and provides responses to actions in a way that analysis can be performed from this data. Learning provides additional information for decision making and its own performance adjustments. This cycle may also improve the learning feature of the CRS.

The learning may use machine learning algorithms and models. A lot of research effort has also been put on the “game theory”, “policy engines” and heuristic algorithms. These are still under research for management of CRS [25].

4.5 Toolbox Approach - Data fusion

A toolbox approach combines various cognitive techniques in the equipment. Some of these techniques could be mandatory, some not. It is up to each manufacturer to decide which techniques are used, however, the mandatory ones define the minimum set of capabilities.

The decision above needs to be defined case by case and it is based on the obtained knowledge from each environment. This includes also existing policies and all other relevant issues.

In this case, data obtained by different cognitive capabilities needs to be analysed. This requires careful algorithm planning, since this data from various methods provide different protection criteria on the same incumbent user. A CRS needs to be able to decide which source is the most reliable and thus be used as a basis of analysis. The simplest way is to use the geolocation database and just check with sensing that there are no signals in the air. This becomes more complex when sensing is done collectively by a number of CRS devices.

4.6 Conclusion

In this chapter the most popular cognitive capabilities were covered. Some technical problems which needs to be solved before the introduction of CRS is possible were highlighted.

4.6.1 Concerns about sensing

Sensing is perhaps the simplest method to obtain knowledge, therefore the use of it raises a number of questions that need answers. These questions are:

- How to be certain that there are no receivers which need to be protected in the vicinity of a CRS in a certain location?
- Sensing accuracy due to technical implementation, especially antenna characteristics of a CRS.
- How to improve sensing accuracy with low SNR when noise lecels are uncertain?
- How to avoid hidden node problems when various obstacles can block signals and disturb sensing?

Answers should be provided by research institutes, standardisation organisations and other stakeholders. Simulations, calculations and other results should be demonstrated and verified in real-life field tests. The regulatory work of the CEPT is still ongoing, the work of project team SE42 should be finalised before the end of 2010. A new correspondence group has been established under the Frequency Management Working Group and it tries to find other possible frequency bands which can be used by cognitive radio systems. This group has just started its work and therefore the first results will be available early next year.

4.6.2 Sensing versus geolocation with database access

It is also necessary to compare different techniques used to obtain knowledge. Due to the nature of these techniques, a comparison is only useful between sensing and the geolocation database[7].

The Federal Communication Commission (FCC) issued a report and order [4], where a regulation for cognitive radio systems was defined for the first time in history. This regulation contains elements which are needed in order to introduce cognitive radio systems into the unused TV spectrum, i.e. TV *white space*. The FCC has also made some field tests with prototype CRS equipment with capabilities such as sensing and geolocation with database access. Based on these field tests, the protection of the TV broadcasting service requires both spectrum sensing and geolocation with database access.

These tests showed that a comparison of different types of CRS capabilities is not straightforward, since the protection criteria for sensing and geolocation database are not defined in a similar way. A similar test needs to be done also in Europe, since the signal characteristics of ATSC and DVB-T (and DVB-T2) are different. European systems are OFDM-based, and the American ATSC system characteristics were described earlier in this chapter.

[7] One could see that geolocation database and CPC are very similar techniques, thus comparison is needed only with one or other, here the comparison is made against the geolocation database.

5 International regulatory framework

There are many players in the world of spectrum management and each of them has a different role and ability to influence the use of the radio spectrum. In Figure 6 the players and their relationships are presented. This figure reflects the current situation in European Union member states, such as Finland.

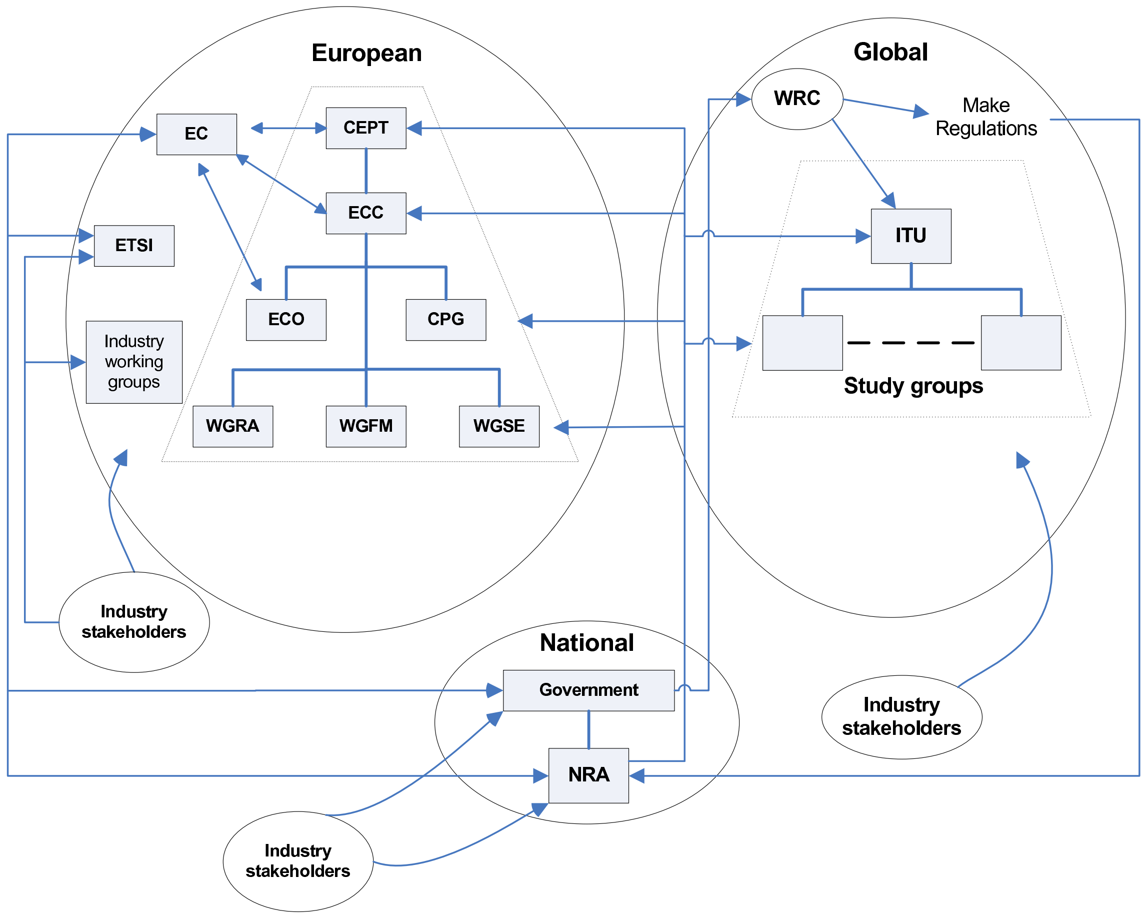
The relationship between players is very complicated, since everyone has to act on various levels and forums. This has resulted in a complex spectrum management situation, especially nowadays when industry is seeking economies of scale through global markets. It is essential that mass market products can be used unchanged all around the world. For that purpose, worldwide harmonisation of spectrum use is preferred. In the early days, National Regulatory Authorities (NRAs) could allow the use of spectrum by technical innovations such as Nordic Mobile Phone in Nordic countries (Finland, Norway and Sweden) by multilateral agreements. Today, however, this kind of national flexibility is partly lost in the European Union.

One main goal of the international regulatory framework is to keep up with the pace of technical evolution and user requirements. Therefore, it is getting more and more important to introduce and allow flexibility in spectrum management. This is needed for a timely response to a rapidly changing technological environment and demands palaced upon it. This is usually done by adopting a technology neutral position when allocating frequency bands to radiocommunication services. One example is the introduction of International Mobile Telecommunication-2000 (IMT-2000) in the RR, where IMT-2000 refers to various technologies: EDGE, UMTS, CDMA2000 and DECT. This can be considered as a technology neutral approach. Some players do not think that this is flexible enough, therefore new methods to promote the efficient use of spectrum are being studied. One method to respond is the introduction of Cognitive Radio Systems, which can utilize unused spectrum and the already occupied spectrum more efficiently, thus improving overall spectrum usage.

5.1 National level

As an example, in Finland, spectrum allocations and associated regulations are based on the Radio Act [19]. Spectrum authorities such as the Finnish Communications Regulatory Authority (FICORA) have established the national spectrum regulation which includes some or all allocated services of each band from the international Radio Regulations (RR). National regulation can deviate from the ITU RR as long as this use does not cause harmful interference[8] to neighbouring countries.

[8] *Harmful interference*: Interference which endangers the functionality of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with Radio Regulations (CS). There are two additional type of interferences in the RR: *permissible interference:* Observed or predicted interference which



CPG	(WRC) Conference Preparatory Group
ECO	European Communications Office
NRA	National Regulatory Authorities
WGFM	Working Group Frequency Management
WGRA	Working Group Regulatory Affairs
WGSE	Working Group Spectrum Engineering
WRC	World Radio Conference

Industry Stakeholders include companies, consultants, industry groups and international agencies.

Figure 6: International regulatory framework inter-relationship, based on [7].

Within these allocations, National Regulatory Authorities (NRAs) assign licences to users. A licence guarantees efficient, appropriate and sufficiently interference-free use of radio frequencies. A licence (radio licence) must be acquired for the possession and use of a radio transmitter. There are classes of equipment which can be used without a licence. The use of these kinds of collective frequencies is called, for example, licence-exempt use, unlicenced use or a general licence. Variations in terms are mainly due to differences in national regulatory frameworks. Use of licenced bands requires a licence, otherwise it is illegal.

According to article 4.4 of the ITU Radio Regulation [6], the National Administrations are already able to authorise the use of cognitive radio systems in their countries. Through the authorisation process new applications can start the use of a frequency band when the requirements are met for neither causing harmful interference to existing users and their stations nor demanding more protection than the primary user.

5.1.1 Spectrum regulation in Finland

This chapter describes how spectrum regulation is organised in Finland by introducing the key organisations and their responsibilities.

Background

There are two responsible organisations for spectrum management in Finland, the Ministry of Transport and Communications (MINTC) and the Finnish Communications Regulatory Authority (FICORA).

The MINTC makes decisions on the overall frequency policies and the role of FICORA is to act based on these policies, i.e. manage the use of frequencies, issue licences and control the use of radio frequencies in Finland. The main goal is to guarantee that all users can have access to the radio spectrum, and that this spectrum is interference free or that the interference level is acceptable. The other important goal of FICORA is to be able to recognise and fulfil the needs of future systems in a way that technically and economically feasible radio frequencies can be assigned — taking into account the present radio systems and their frequency usage.

The rights to use frequencies is done through the licensing procedure which can be divided into two categories: a) licensed use and b) unlicensed use (licence-exempt

complies with quantitative interference and sharing criteria contained in the RR or in the ITU-R Recommendations or in a special agreement as provided for the RR; *accepted interference:* Interference at a higher level than that defined as permissible interference and which has been agreed upon between two or more administrations without prejudice to other administrations. The last two are used in the coordination of frequency assignments between administrations.

use). Every single radio transmitter that is not exempt from licensing needs a radio licence. Receivers do not need a radio licence (e.g. TV and radio receivers).

In addition to spectrum management and licensing, FICORA takes part in international spectrum harmonisation and standardisation work in many organisations and on many forums (e.g. ETSI, IEEE, CEPT, ITU). The aim of this work is to harmonise the use of frequencies in order to receive economies of scale in the manufacturing of radio equipment, however it should be noted that the need for some radio systems is critical despite the relatively marginal use of those (e.g. emergency transmitters). FICORA also does technical steering and supervises the use of radio equipment. Part of this work is to remove and solve interference situations caused by transmitter and device failures or illegal use of transmitters (use against conditions of a licence or without a licence).

Frequency planning tools

National administration have a number of spectrum management tools. In Finland, the following tools are in use:

- Frequency assignment database (update and various search functions)
- Interference calculation tools
- Digital map based planning tools
- Frequency allocation database
- Frequency planning tools for Fixed Radio Links and Satellites
- Frequency planning tools for Radio and Television Broadcasting
- Data transfer tool for cellular networks

The frequency assignment database is the main register of FICORA. It contains antenna sites (mast locations) and assigned frequencies, coordinated frequency assignments and also coordination plans with the neighbouring countries. The frequency database is linked to the licensing database, i.e. when FICORA issues radio licences, the frequency information comes from the frequency database and the licensing information comes from the licensing database. The information is combined in the licensing database and the outcome is a printout which has all the information from both databases. Data can be searched with different kinds of searches, for example, frequency, city, mast code, licence number, customer number etc. The result of the search is visible on the screen.

There are three different interference calculation software systems in use: the first one is an in-house built interference calculation software for land mobile networks and fixed radio links below 1 GHz. The remaining two commercial planning software

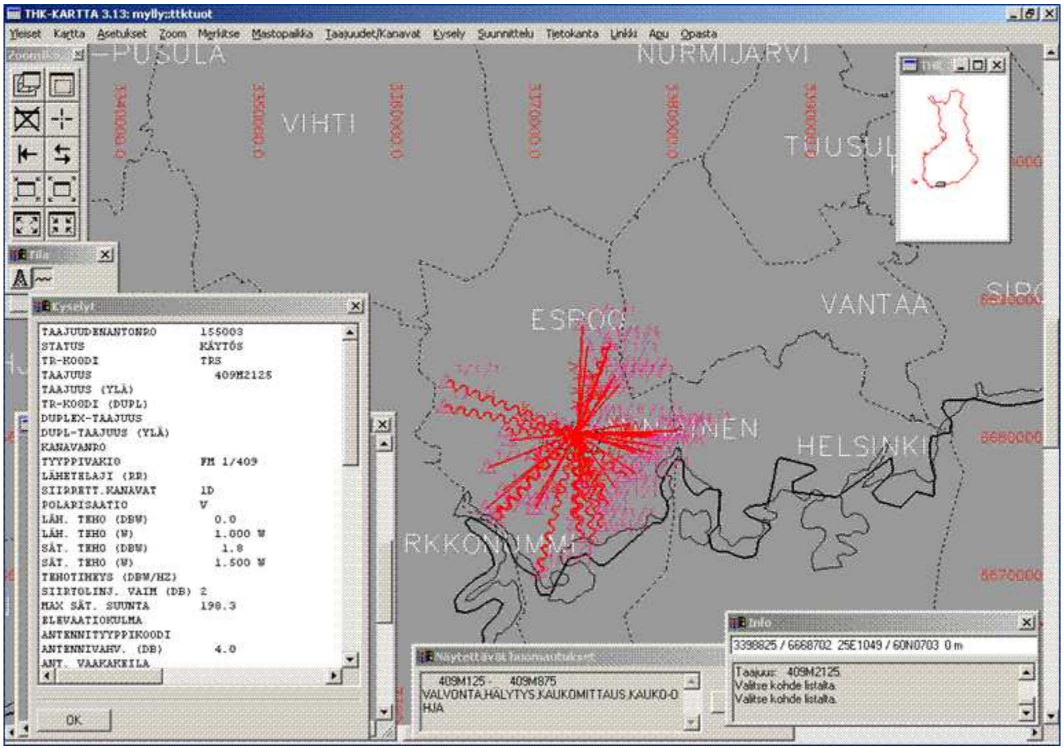


Figure 7: A sample view of the graphic map display.

systems have been acquired from LS Telecom Ag: “CHIRplus_broadcasting” for broadcasting service and “MultiLink” for fixed radio links. These planning tools are used for planning new stations and for changing the characteristics of existing ones. These interference calculation tools are also connected to the frequency assignment database.

The digital map software is used for planning and searching for frequency assignments. It is possible to create terrain profiles with this mapping tool. FICORA has a lot of different type of maps which can be used with this software.

The frequency allocation database is used for maintaining the national table of frequency allocations, similar to the Article 5 of Radio Regulations. Software for data transfers from cellular networks is an application which automates database entries to the frequency assignment database. This is possible by using a predefined data format.

Licensed use

According to the Act on Radio Frequencies and Telecommunications Equipment (1015/2001) [19], the use and possession of a radio transmitter needs a licence (radio licence). The licence defines the exact technical parameters that have to be used, for instance, the maximum transmitter power, the antenna location and height and other parameters which could have an impact on the level of interference around the transmitter location. Besides the technical conditions, there are additional usage conditions in a licence. For example, in the border areas in order to avoid harmful interference the requirement is that the use of frequencies has been agreed with the neighbouring countries.

There are a little less than 60 000 issued licences with around 55 000 licence holders in Finland. In these licences over 1 280 000 individual frequency assignments have been registered in the FICORA frequency assignment database. Every year FICORA issues around 4 500 new licences and the number of changes to existing licences is almost 1400 annually.

These licences cover all levels of society, including, for example, private/personal mobile networks below 1 GHz (PMR), various telematic systems used in transportation systems (ITS), municipal engineering (e.g. water distribution systems), remote control systems of industry, personal paging systems, programme making and special events (concerts, sporting events, etc.), maritime and aeronautical radio systems, fixed radio links, and so on.

Some radio systems providing a network service in Finland also need a licence (concession) issued by the Council of State[9]. Such systems are transmitters of a broadcasting system (digital TV) and public mobile communications systems (GMS, UMTS, and future systems). These are defined in Section 4 of the Communications Market Act (393/2003) [30]. As a special "pre-agreed" case, the Ministry of Transport and Communications will however issue a licence (concession) for an operator who already operates a Fixed Wireless Access network and wishes to start operating an Electrical Communication Service network in the 3 500 MHz band.

Unlicensed use / licence-exempt use of frequencies

The target set by spectrum regulation for unlicensed use is to provide guidance to industry to develop and manufacture equipment in a way that their technical parameters cause very little interference or can accommodate some level of interference without much degradation of performance. In these licence-exempt frequency bands, similar regulation is used through the region, for instance, in Europe the same harmonised standards developed by the European Telecommunications Standards Institute (ETSI) are used for manufacturing radio equipment.

Usually these licence-exempt devices have a low-power transmitter and the number of devices in a certain geographical area can be high or even very high. Such devices are: mobile terminals (mobile phones and USB/PCMCIA data cards), wireless broadband data systems (WLAN/RLAN), garage door openers at 433 MHz, radio controlled models, etc. More information on licence-exempt use of radio equipment can be found in Regulation FICORA M15 [32].

[9] A radio licence from FICORA is also needed.

5.2 Regional level

Regional organisations such as the CEPT (The European Conference of Postal and Telecommunications Administrations) and the CITEL (The Inter-American Telecommunication Commission) have a key role in the preparation of WRCs. Individual administrations contribute to the work of these organisations. In Europe, the CEPT has established a group specially working towards WRC. This Conference Preparatory Group (CPG) is responsible for all WRC agenda items. Its main goal is to develop the common European view on all agenda items which are known as ECPs (European Common Proposals). The ITU is a specialist agency of the United Nation and has 191 Member States and more than 700 Sector Members and Associates (private companies, non-governmental organisations and other entities). All nations have one vote in the meetings, therefore ECPs are a very powerful tool with 48 votes instead of an individual country vote.

There can be three kinds of allocations in the Radio Regulations (RR):

- Global — Allocation covers all three radio Regions.
- Regional — Region 1, Region 2, Region 3 or any combination of these as shown in Appendix A.
- Country — National allocations are listed in the footnotes of the RR.

Within the scope of spectrum harmonisation, the main goal is to achieve a global allocation in the RR. This harmonised approach also supports economies of scale and mass market production.

5.3 ITU — the global body

The mission of the ITU Radiocommunication Sector (ITU-R) is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including those using satellite orbits, as well as to carry out studies and approve recommendations on radiocommunications. The primary objective is to promote efficient, appropriate and sufficiently interference-free use of radio frequencies. The ITU maintains the Master International Frequency Register (MIFR) in which notified stations and/or radio systems are registered in order to get international protection and also for coordination purposes by ITU member states.

The use of radio frequencies is done through the Radio Regulations (RR) and Regional Agreements. These can be updated only in the World and Regional Radiocommunication Conferences. The performance and quality issues of radiocommunication systems are defined in the recommendations. These regulations and recommendations bind NRAs, thus national implementation/deployments should be made according to these conditions [13].

5.4 Summary

The required regulatory actions, which are needed to introduce cognitive radio depend heavily on the existing use of the radio spectrum. In some cases, no regulatory actions are needed and in some cases it is impossible to introduce a CRS in certain frequency bands used for safety services and applications.

6 Regulatory measures

In many cases CRS technology implies dynamic spectrum access, i.e. a system is capable of adapting its operation and access to the spectrum by obtaining knowledge of its radio environment. These systems provide a possibility to have flexible and efficient spectrum management and the use of the spectrum in all dimensions (frequency, time, location and code) [23]. However, a CRS could also be used by any radiocommunication service itself, therefore CRS can be used to improve and make spectrum use of these services more efficient and flexible. In this case there should not be any need for regulatory measures, i.e. a CRS is employed within a service through the technical evolution of the radio equipment it uses.

This chapter summarises the regulatory measures that are needed for the introduction of CRS technology.

6.1 National

According to the Article 4.4 of the ITU-R Radio Regulations [6], it is up to each administration to decide what kind of use can be allowed via different licensing regimes (licenced or unlicenced), although this Article contains some restrictions on which it can be used.

The first countries which have allowed the use of CRS or which make statements of the use are: the United States, the United Kingdom, and Finland.

The United States has published a detailed regulation how CRS techniques are supposed to be used in the broadcasting band 470–698 MHz [4]. The United Kingdom also published a statement with a regulatory framework for the introduction of CRS in the 470–790 MHz band (TV band in Europe) [17]. Finland has also made regulatory changes which allow testing of CRS in the 470–790 MHz band [24].

A common approach should be the goal, therefore harmonised rules should be applied through the region or globally.

In the author's opinion, the National Regulatory Authorities should have spectrum regulation rules which promote the efficient use of spectrum, for example, by putting the deadlines for network roll-out, by setting population and geographical coverage requirements, by establishing quality of service policies, etc. These kind of licence conditions give guidance to licence holders and promote efficient and meaningful use of the radio spectrum.

6.2 International

The member states of the ITU are focusing their work on the forthcoming WRC-12 conference. The agenda item 1.19 of the next World Radiocommunication Conference (WRC-12) should consider regulatory measures to introduce Cognitive Radio

Systems. In this process a number of options are being developed in order to fulfil the requirements of this agenda item. The responsible group for CRS issues is the ITU-R Working Party 1B which should finalise its work by June 2010.

The following methods have been recognised to fulfil this agenda item in WRC-12:

a No regulatory measures needed for a SDR (NOC).

b No regulatory measures needed for a CRS (NOC).

c CRS studies to continue within the Study Groups (ITU-R Resolution or WRC Resolution + No Change to Articles of RR).

d Propose changes to the RR (change proposal to RR) in WRC-12 or future WCR.

As listed above, there are several methods to fulfil agenda item 1.19 of WRC-12, however some of these do not address directly the challenges of the introduction of CRS technology. This is mainly due to the reason that some member states are of the view that the only regulatory measures are text changes in the Articles of Radio Regulations. Therefore their position is no change in the RR. On the other hand, some administrations are of the opinion that more actions are needed already in this WRC, i.e. a certainty that studies to introduce cognitive radio systms shall continue in the ITU-R study groups. These studies should focus on sharing issues, i.e. sharing between services and within a service.

At this stage some of the methods are not feasible options due to unfinished studies related to the method itself. Any method proposing changes to RR in 2012 seems not to be realistic, since any possible change in the articles of RR (e.g. change of allocation, footnotes etc.) should be agreed during a preparation phase before July 2010.

Therefore, the work at the ITU level should focus on the specific requirements for further studies and the introduction of regulatory measures in the future WRCs, if needed. The key element here is the recognition of the spectrum sharing possibilities in the bands where sharing was considered not to be feasible without cognitive capabilities of a radio.

After successful introduction of CRS, the ITU-R radiocommunication services should consider themselves how to make most of the allocated spectrum. CRS technology could be one potential way to make the most of it, i.e. technical evolution introduces cognitive radio systems in various radiocommunication services. This evolution is foreseen if cognitive radio systems are capable of responding to all concerns raised by the incumbent spectrum users as any new technology always needs some time to prove its benefits over older technologies.

6.3 Actions required

There are many technical and operational uncertainties before any of the cognitive capabilities can be considered reliable. Research and development work should focus on solving these open issues. These should be solved technically and proven via field tests and trials. Based on the results, the preliminary view how to introduce CRS may also be affected, this should be taken in to account in the Conference Preparatory Meeting in February 2011 and, of course, at the WRC-12 conference in 2012.

National regulatory authorities should promote field tests and pilot networks on various frequency bands in order to get real information about cognitive capabilities (pros and cons). Regulatory requirements could be adjusted based on the results, although results in many cases could be insufficient and more work is still needed.

7 Conclusion

The future work depends heavily on the result of WRC-12. The final goal is to have efficient regulation that allows the use of Cognitive Radio Systems in the bands where sharing between radiocommunication services was not feasible without cognitive capabilities embedded in the radio equipment or systems.

Governments should endorse the development and use of advanced radiocommunication technologies (such as the CRS) that use spectrum more efficiently and enhance flexibility.

This Master's thesis describes widely-used spectrum management methods and how these methods can accommodate rapid technical evolution of techniques and applications. Most of the Radio Regulation was developed before personal radio and mass market mobile communications equipment was introduced.

There are other agenda items in WRC-12 which deal with the changing environment of radiocommunications. This work should also be taken into account when CRS regulation is being developed, since traditional radiocommunication service definitions may need to be revised due to convergence.

This Master's thesis could be used as a guide to which actions are needed in different regulatory levels during the WRC-12 preparatory work.

With regard to spectrum management, the right timing together with sufficient spectrum management actions and regulatory activities are of vital importance in order to respond to the ever-increasing demand for the technically feasible and interference-free spectrum.

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A Regions in the Radio Regulations

The world has been divided into three Regions for frequency allocations, see the map in Figure A.1.

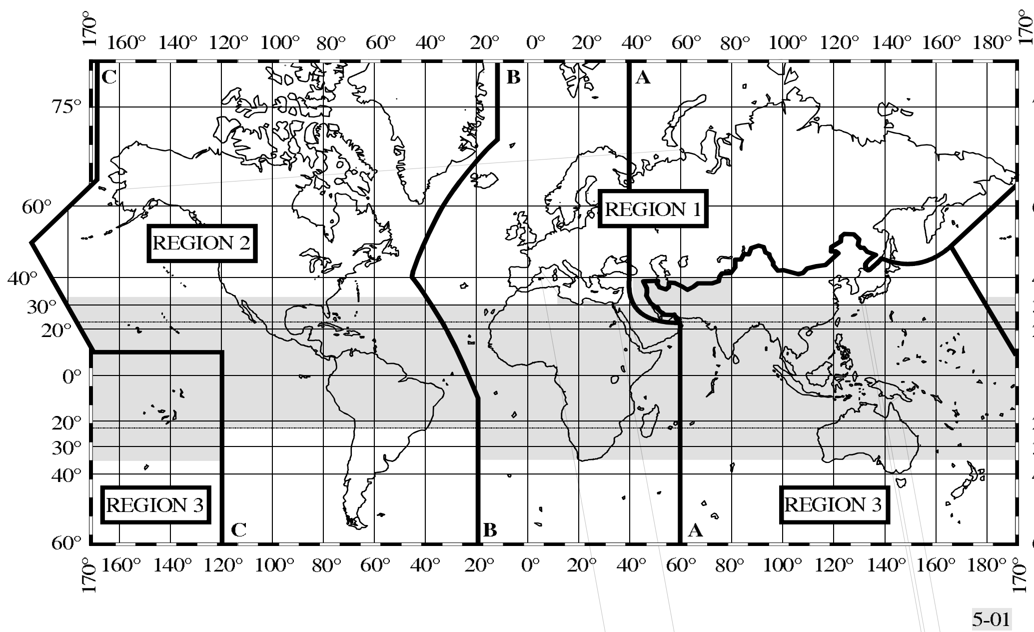

Figure A.1: Three Regions of the world for frequency allocations [6].

In general terms: Region 1 includes countries from Africa, Europe and RCC[10]; Region 2 all the countries from American continent and Region 3 countries from Asia and the Pacific area.

[10]RCC – Regional Commonwealth in the field of Communications.

B Spectrum occupancy measurement in Ruoholahti, Helsinki

This measurement was made on 8th to 9th of March 2010 in the FICORA monitoring station at Ruoholahti, Helsinki. A 24 hour period measurement with a frequency range from 300 MHz to 1000 MHz was done with a Rohde & Schwarz ESPI receiver, data was collected with Rohde & Schwarz "Romes" measurement software. Post processing of data for the figure was done with Matlab software.

Measurement parameters were:

- Centre frequency 650.000 MHz,
- Span 700.000 MHz,
- Resolution bandwidth 30 kHz,
- Video bandwidth 30 kHz,
- Measurement rate 0.2 per second,
- Start time 8.3.2010 at 15:10:08 and
- Stopped on 9.3.2010 at 14:19:08.

This measurement was limited to 300 MHz–1000 MHz due to the tuning range of the rooftop antenna.

In Figure B.1 existing use can be clearly seen, at least the following signals can be recognized:

- Blue line at approximately 313 MHz: Sound program transmission, fixed radio links and mobile transmitters for one-way sound program transmission.
- Strong signals just below 400 MHz are used by the base stations of the national Emergency services network (395.0125–399.8875 MHz).
- Base stations of private TETRA network can be seen in the band 424.0125–426.3375 MHz.
- Several Professional Mobile Radio (PMR) networks can be seen between 400–470 MHz.
- The yellowish line at approx. 470 MHz is used by radio microphones/reporter communications.
- The next eight signals are signals from digital TV transmitters. The red line is from a DVB-H transmitter, located in Salmisaari.

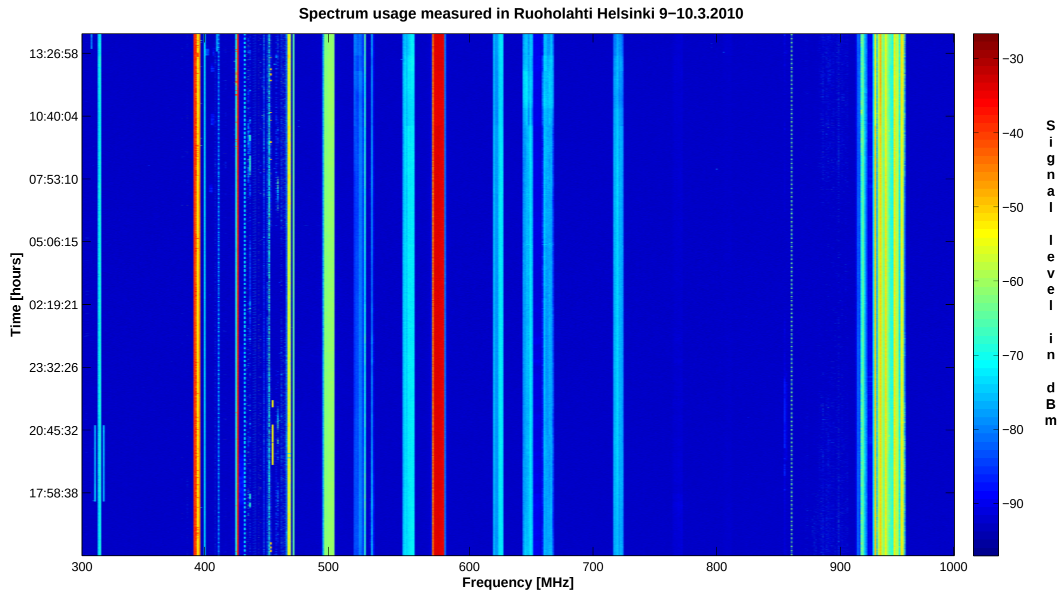

Figure B.1: Spectrum occupancy measurement in Ruoholahti, Helsinki.

- Thin “white” line around 863 MHz is used by wireless audio applications and radio microphones.
- Last signals are from GSM base stations, starting from 921 MHz (GSM for railways) up to 960 MHz.

In general, signals from mobile stations of the above mentioned systems cannot be seen in Figure B.1 due to the bursty nature of signals from mobile terminals. Also the resolution of this figure is insufficient to highlight signals from mobile terminals.