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The impact of dynamic access technologies on radio spectrum management

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The impact of dynamic access technologies on radio spectrum management

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Executive summary

The demand for spectrum is increasing particularly due to the accelerating growth in wireless data traffic generated by smart phones, tablets and other internet access devices. Most of prime spectrum is already licensed. The licensed spectrum is underutilized and used inefficiently, i.e. spectrum sits idle at any given time and location. Dynamic Spectrum Access (DSA) is proposed as a solution to provide access to the temporarily unused spectrum commonly known as white spaces to improve spectrum utilization, increase spectrum efficiency and reduce spectrum scarcity. The aim of this research is to investigate potential impact of DSA technologies on spectrum management. To fulfill this aim the study focuses on three subjects namely: 1) The potential benefits and challenges of DSA technologies on spectrum from a technical point of view 2) The international and national spectrum regulatory and standardization developments in DSA technologies and their impact on spectrum management 3) The market effects on the take up and the ultimate success of DSA technologies from a spectrum management point of view. The study focuses on cognitive radio systems (CRS), since they are the most advanced DSA technology and have received a lot of interest from national regulatory authorities (NRA), academics and industry players.

First, the study explores the technical aspects of CRS and their effects on spectrum management. The study concludes that the main potential benefits of CRS are increased spectrum efficiency, better spectrum utilization and flexible spectrum access. Other benefits relate to the regulatory function of spectrum management. These benefits include less regulatory work as most work will be done in standardization through technical protocols and use of the geo-location database to manage spectrum dynamically. The main challenge is interference associated with spectrum sensing, certification of CR equipment and security threats in CRS networks.

Second, the study reviews the current regulatory and standardization developments of CRS and its effects on spectrum management. The study concludes that the regulatory and standardizations activities underway worldwide particularly in the US and the UK on television white spaces (TVWS) will provide confidence to the industry players to deploy CRS commercially. This will also encourage other countries that have adopted a “wait and see” approach to embark on a regulatory process for the introduction of CRS. The successful introduction of CRS in TVWS may lead to further implementation in other spectrum bands. Third, the study explores market aspects of CRS in the wireless communications industry to determine the take up and the success of CRS from a spectrum management point of view. The study concludes that CRS have a potential to lower entry barriers and increase entry in the wireless communications industry that is currently low. It is expected commercial massive

deployments of CRS will come at a slower pace as it will take a step by step approach due to uncertainties associated the current state of the technology, business cases and policies.

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1. Introduction

Radio frequency spectrum affects many aspects of society. It provides access to a range of services such as national security, public safety, and scientific, military and commercial services. But successful transmission or communications is only possible if users are safeguarded from interference by other users. For this reason governments regulate the use of spectrum. The wireless industry plays an important role in the economy. Management of radio frequency spectrum is fundamental to the future growth of the wireless industry. In Europe it is estimated that the total volume of services which depend on radio spectrum availability is worth at least €200 billion annually [1].

Radio frequency spectrum is a limited resource that has become increasingly in demand in the last two decades due to the introduction of many competing radio-communication products and services. The demand for spectrum is increasing particularly due to exponential growth of wireless data traffic generated through smart phones, tablets and other portable internet access devices. The growing demand for spectrum has led to a review of spectrum management.

Historically, spectrum has been licensed using the command and control management. The spectrum management debates argue that command and control approach lacks the flexibility to respond to new spectrum dependent developments and associated technologies. Accordingly, there is a trend to reform spectrum management that is moving away from the command and control method. The market based methods were introduced in the late 1980s to license spectrum and have been implemented by several countries. Another method is open access which allows access to spectrum to all potential users. The open access method gets rid of exclusive licensing. One implementation is 'licence-exempt bands'[1] for Wi-Fi and DECT cordless telephony; for instance. A more advanced way of open access is possible with dynamic spectrum access (DSA) technologies, which allows much more flexible use of this scarce resource. Considering that a lot of spectrum currently sits idle at any given time and location; DSA has the potential to improve spectrum utilization, increase efficiency in spectrum use and reduce spectrum scarcity by even a much higher degree than just the licence-exempt bands. DSA requires new technologies such as Cognitive Radio (CR).

1.1 Research justification

Increasing demand for spectrum requires alternative ways of managing spectrum that are responsive to technological and economic changes while taking into consideration the public sector needs of spectrum [2]. DSA technology including cognitive radio technology have a

[1] Also known as Industrial, Scientific and Medical (ISM) bands.

potential to offer a solution to the increasing demand of spectrum through spectrum sharing without increasing the risk of interference to existing users or other users. DSA and cognitive radio will have an impact on spectrum management; however the extent of the impact is not clear. In order to investigate the impact of DSA on spectrum management it is essential to understand the interplay between technical, market and policy aspects of DSA. So this thesis explores these aspects so as to determine the potential impact of DSA on spectrum management.

1.1.1 Scientific Relevance

The study contributes to the academic literature on radio spectrum management reforms. The current research on DSA and CR technologies mainly focuses on technical aspects of DSA technologies and spectrum management, whereas there are other aspects of the former that will also have an impact on the latter. These include (international and national) spectrum policy developments and market developments. Therefore it is essential to examine the interplay between the technical, policy and markets aspects of DSA technology as they will all determine its impact on spectrum management. The scientific relevance of this thesis is to close that gap by conducting a multidisciplinary study that assesses the potential impact of DSA technologies on spectrum management.

1.1.2 Social Relevance

The study also contributes to the on-going policy debates on radio spectrum management reforms. The reforms on the management of the radio spectrum resource have a potential to promote or hamper innovation in radio communication technologies. Introduction of new technologies such as DSA in the wireless communications industry may result in greater competition which will in turn benefit consumers. The benefits include choice from a wide range of services and lower prices. The social relevance of the study is to investigate how to realize optimal benefits from dynamic spectrum access technologies from a spectrum management point of view.

1.2 Research questions and objectives

The main objective of this thesis is to investigate the potential impact of DSA technologies on spectrum management, and thereby:

- To provide knowledge about the benefits and challenges of DSA technologies in spectrum management from a technical point of view.
- To examine how the current and new policy developments will determine the impact of DSA technologies on spectrum management.

- To examine the effects of the wireless communications market developments on the take-up and the success of DSA technologies from a spectrum management point of view.

The main research question is:
What is the potential impact of dynamic spectrum access technologies on spectrum management?
A number of sub-research questions provide answers to this question. The study consists of three parts. The first part answers sub-research question 1, the second part answers sub-research question 2 and the third part answers sub-research question 3.

Sub-research questions:

1. *What are the benefits and challenges of dynamic spectrum access technologies relevant to spectrum management from a technical point of view?*
2. *To what extent will the current and new policy developments (international and national) determine the impact of dynamic spectrum access technologies on spectrum management?*
3. *How will the market developments affect the take-up and ultimately the success of dynamic spectrum access technologies from a spectrum management point of view?*

1.3 Scope of the research

The research questions are comprehensive, so the scope of the study is narrowed down. First, spectrum management is a broad topic. The study focuses on spectrum licensing. However, some elements of spectrum allocation are included in the study as allocations and assignments are interrelated. Second, there is a wide range of dynamic access technologies; so the study focuses on cognitive radio technology. This is because cognitive radio is the key enabling technology for DSA and also the most advanced DSA technology.

Third, chapter 3 of the study analyses the market aspects of cognitive radio in the wireless communications industry. This analysis focuses on the mobile communications industry and wireless data services (Wi-Fi). The reason for this is that the demand for spectrum is quite high in this industry due to accelerating growth in the wireless data traffic generated on smart phones, tablets and other portable internet access devices.

1.4 Methodology

The study uses an exploratory qualitative research method as the quantitative method is inappropriate to analyse future developments in the wireless communications industry. Exploratory research is appropriate for this study since there is relatively little knowledge about the impact of DSA technologies on spectrum management. For data collection; triangulation of data sources is used in order to explore the topic under study from multiple perspectives [3]. Data was collected from scientific articles, policy documents, market reports and on-going studies in FP7 research projects[2]. The scientific articles were selected based on a two-step process. First, the key words were used (spectrum management, dynamic spectrum access and cognitive radio) to retrieve relevant articles from the University library online searching tool and Google scholar search engine. Second, the snowball method was used to search relevant articles by examining the references of the retrieved articles. Data was also collected from semi-structured interviews. The interviews involve open ended questions to elicit views and opinions from experts on DSA technologies and spectrum management. The interviewees were selected based on their expertise on DSA technologies and spectrum management, with some assistance from colleagues from Agentschap Telecoms and my supervisors.

The first question focuses on the technical aspects of DSA technologies. This question is answered using data collected from scientific articles on spectrum management methods and DSA technologies in particular CR collected from IEEE journals, Information and Economic Policy, Wireless Personal Communications, American Economic Review. Other data sources are used such as ITU, CEPT and FCC. Furthermore, interviews were conducted to determine the technical aspects of DSA and their impact on spectrum management. Open ended questions were asked, for example*: How to deal with risk of interference from cognitive radio systems?* A list of interviewees is provided in Appendix A and the questions in Appendix B (Part A).

The second question focuses on the current and new spectrum policy developments (international and national). Regulatory and standardization activities at the following international organizations are reviewed. ITU, IEEE, CEPT, European Commission and ETSI. Accordingly, relevant regulatory and standardization documents were collected from these organizations. At the national level regulatory activities from Australia, the US and the UK are reviewed. Therefore, relevant regulatory documents were collected from NRAs of these countries. These countries were selected based on being in the forefront regarding spectrum reforms and also on the availability of relevant policy information.

The third question focuses on market developments relating to cognitive radio systems in the wireless communications industry. Porters five forces model is used to analyse the industry. This question is answered using data collected from scientific journals mainly from IEEE, conference papers and market study reports. Furthermore, interviews were conducted to determine impact of cognitive radio in the industry and on spectrum management. Open ended

[2] European Union FP7 targeted research project on secondary spectrum access.

questions were asked, for example: *How will cognitive radio systems open up new business opportunities and threats in the wireless communications market*? A list of interviewees is provided in Appendix A and the questions in Appendix B (Part B).

1.5 Thesis outline

The thesis consists of five chapters. In line with the considerations of this chapter, the remainder of the thesis is structured as follows. Chapter 2 explores the technical aspects of dynamic spectrum access through cognitive radio and its effects on spectrum management. This chapter focuses on the benefits and challenges of DSA technologies. Chapter 3 reviews the current (international and national) regulatory and standardization developments of dynamic spectrum access through cognitive radio and its effects on spectrum management. Chapter 4 explores market developments relating to cognitive radio systems in the wireless communications industry and their impact on spectrum management. Chapter 5 draws conclusions, reflects on the limitations of the study and make recommendations for future research.

2. Spectrum management and dynamic access technologies

This chapter answers sub-research question 1 of the thesis.

1. *What are the benefits and challenges of dynamic spectrum access technologies relevant to spectrum management from a technical point of view?*

The chapter explores the technical aspects of dynamic spectrum access (DSA) through cognitive radio (CR) and its effects on spectrum management. This is relevant to the main research question because in order to understand the potential impact of CR on spectrum management, it is essential to understand the formers' benefits and challenges relevant to the latter. The chapter is structured as follows. The first section provides some background information on the liberalization of the telecommunications industry. The second section discusses spectrum management and the three commonly used spectrum management methods (command and control method, market based method and open access or commons approach). The third section discusses three DSA technologies (DECT, Ultra wide band and cognitive radio) with a focus on cognitive radio. The fourth section discusses enabling techniques for cognitive radio (spectrum sensing, geo-location database and beacon). The fifth and the sixth sections explore technical benefits and challenges of CR, respectively. Interviews were conducted to identify the benefits and challenges of CR, refer to chapter 1. The seventh section concludes the chapter.

2.1 Liberalization of the Telecommunications industry

In this section liberalization of the telecommunications industry is discussed below to provide a historic background of telecommunications regulation in order to put spectrum management into a broader telecommunications context. The section focuses on the European telecommunications industry.

Historically, around the world telecommunications services were provided by state owned natural monopolies. In most countries these state owned monopolies were part of a government department responsible for Post, Telephone and Telegraph (PTT) or Ministry of Posts and Telecommunications (MPT). The PTTs were typically responsible for providing telecommunications services and regulating the industry at the same time.

Liberalization of the European telecommunication sector started in 1987 with the exception of UK, which liberalized its telecommunications market in 1981 [4]. Prior to this, the competition law did not apply to the telecommunications sector. Scholars cite some developments that led to this process. Industrial policy kick started this process given that its view was that the European telecommunications sector was going to lose out to US firms [4] [5]. The US had liberalized its telecommunications market earlier and the American companies were reaping the benefits. Another significant event that contributed to the process was the ruling of the Court in British Telecom case of 1985, in which the court ruled against British Telecom [5]. The court ruling was that telecommunications was a regular economic activity in terms of the Treaty and as such the competition law was applicable to the telecommunications sector [6]. Consequently, in 1987 the Commission published a green paper on telecommunications for public comment [7]. Private actors including the round table for European Industrialists, users groups and the UK supported the Commission green paper on liberalization of the telecommunication sector [4]. In 1988 the Commission, issued the terminals directive [8]. The terminals directive provided for the end of monopoly in the provision of terminal equipment and the establishment of type approval bodies independent of the network operators [4]. In 1990 the Commission issued a controversial directive for the liberalization of the telecommunication service market [4]. This directive proposed for the liberalization of all services expect basic voice and telex [9]. Parallel to the service directive formulation process, the Commission issued another directive, the open network provision directive (ONP) [10]. The ONP directive dealt with the establishment of the internal market for telecommunications services through the implementation of open network provision. In its mission to completely liberalize the telecommunications service market, the Commission called for a review of the service directive in 1992 [4]. The purpose of this review was to liberalize voice telephony. Subsequent to a long process, a Council resolution [11] on full liberalization of all services including voice telephony was passed in 1993 [4].

In spite of the progress in liberalizing the service market, the Commission together with some private actors were not pleased with the fact that there were still monopolies in the telecommunication infrastructure market [4]. With the exception of the UK, the PTTs maintained their monopoly of the infrastructure as a result they controlled access to the network by potential competitors [4]. The Commission set out its plan to liberalize the infrastructure market in a series of green papers [4]. The green papers and the subsequent directives were issued on the following: satellite communications [12], mobile communications and personal communications [13], liberalization of telecommunications infrastructure and cable television [14]. Subsequently, another directive on complete infrastructure liberalization was issued in 1996. This directive spelt out the regulatory framework for the new open competition regime, which included interconnection, licensing and provision of universal access [15]. Since then, a number of directives had been issued to amend the directives discussed above. Spectrum management in the European Union is based on the electronic communications regulatory framework [16] and the radio spectrum decision [17] that was established to develop the radio spectrum policy.

2.2 Spectrum management

Radiocommunications took off subsequent to the discovery of the laws of electromagnetism in the late 19th century defined by Maxwell's equations and experiments by Alexander Popov and Guglielmo Marconi transmitting radio signals [18]. Since then various systems transmitted using any spectrum band that was suitable for them and this resulted in interference as the radiocommunications services and applications grew. Consequently, in 1906 the first International Radiotelegraph Conference (IRC) was convened in Berlin to establish a framework to manage spectrum at an international level [18]. In order to avoid interference and to meet the static demand of spectrum, a multi-level static approach was established. Technical regulations to control interference were viewed as key to managing spectrum.

Under the multi-level approach, spectrum management takes place at two levels namely allocation and assignment or licensing. Allocation refers to allocating one or more radio services to a spectrum band while assignment refers to authorizing use of spectrum by a user with specified conditions. Under the static approach spectrum is split into fixed blocks that are allocated to specific services or technology and frequencies are exclusively licensed to licensees. The first regulations established at the IRC have since been expanded and revised by radio communications conferences and are known as the Radio Regulations (RR). The ITU Radio RR are issued consequent to a World Radiocommunications Conference (WRC) to harmonize frequency bands with radiocommunication services. Harmonization can also take place at the regional level as well. For example harmonization in Europe takes place at the CEPT and at the European Union level. At the national level, spectrum licensing is done by a NRA or a relevant Ministry depending on the laws of a country.

The competing goals for spectrum management can be classified into three categories [2].

1. Economic efficiency: to ensure that spectrum is allocated to users and uses that derive highest value, with minimal transaction costs and entry barriers, while responsive and flexible to changes in the market and technology

2. Technical efficiency: to ensure intensive use of spectrum and compliance with interference limits while promoting introduction and development of spectrum saving technologies.

3. To safeguard the interests of spectrum use for public service while ensuring that spectrum use is in line with government policy and international and regional obligations.

Based on these goals, the increase in spectrum demand requires alternative ways of spectrum management that are responsive to technological and economic changes while taking into consideration the public sector needs of spectrum.

2.2.1 Spectrum management methods

The section below discusses three spectrum management methods that are mainly discussed in literature and are also widely used around the world.

Spectrum management is still based on the same principles that were established a century ago namely: mainly to prevent interference and to meet the static demand, hence the static spectrum management. However, static spectrum management is challenged due to the high dynamic demand of spectrum management and the advent of DSA technologies which allow spectrum sharing while protecting users from interference. There is growing body of research on spectrum management [19] [20] [21] [22] [23] [24]. This research is mainly focused on the three models, namely command and control i.e. the old one, and the recent ones: property rights and open access or commons. These methods "differ in how they define rules for spectrum access and use; management of a certain band; exclusion of others from that band; and alienation, that is the right to sell or lease spectrum to others" [19].

The sub-section below discusses the three commonly used spectrum management methods namely: command and control, market based methods and open access or commons approach. There are also hybrids of these three methods that are discussed in [21] [24]. For the purpose of this thesis, the three commonly used methods will be discussed.

2.2.1.1 Command and control method

Under the command and control method, spectrum is assigned to users using administrative methods as the need arises. Command and control is a restrictive method whereby a NRA prescribes who may use the spectrum and under what conditions. The NRA grants exclusive use of the spectrum to the users. The NRA decides on the technical conditions such as the type of service and technology and technical parameters and also on the spectrum fees and lastly on any other issue they deem relevant such as roll-out obligations. Spectrum is typically assigned to users on a first come first served basis and beauty contest is used in cases where there is more than one applicant for a specific band. Under the beauty contest the NRA sets out criteria in which to evaluate the applications. The applicants are required to furnish information as set out by the evaluation criteria. The best applicant in terms of the evaluation criteria is issued a spectrum licence. This method was introduced during the establishment of spectrum regulation in the early 1900s. The main principle behind this method is to prevent interference and to meet the static demand of spectrum, as the demand was static when the method was established.

Command and control has advantages and disadvantages. The main advantage is that it minimizes the risk of interference between services. However, exclusive licensing leads to inefficient use of spectrum as spectrum stays idle most of the time and it can lead to spectrum hoarding since it does not provide incentives to licensees to maximize the value of spectrum holdings [21]. It could also stifle innovation due slow spectrum reallocations to new systems and to the restrictive technical licence terms and conditions. As it is based on static spectrum management, it cannot cope with the current high and dynamic demand of spectrum. In some spectrum bands, spectrum access is more of a significant challenge than scarcity of spectrum, to a greater extent command and control approach limits the ability of potential spectrum users to obtain such access [25]. There are also disadvantages of this method based on the implementation process. In practice this methods is vulnerable to long delays, subjective judgments by the NRA and misallocations of spectrum due to political pressures i.e. government picking the "winners". [25] recommends that command and control should be used only in cases where prescribing spectrum use is necessary to accomplish important public interest objectives and to adhere to treaty obligations.

2.2.1.2 Market based methods

Under the market based methods, a spectrum user is granted exclusive use through auctions and is allowed to transfer these rights in secondary markets. The principle behind this method is that markets are more efficient in assigning spectrum to its social value maximizing uses than NRAs as markets handle better demand and supply information and allocation and assignment mismatches [21]. Market based licensing was first coined by [20] but has only been implemented since the late 1980s. This method has advantages and disadvantages. Proponents of this method argue it can solve three challenges of spectrum management at the same time in that market forces drive allocation, assignment and dynamic adjustment [19]. This method is transparent, less prone to manipulations, place a market value to spectrum and have a shorter licensing period and offers flexible use rights that are governed primarily to minimize the risk of interference [19]. They also argue that trading spectrum rights would move spectrum from lower value to higher value uses and users until the cost of spectrum to any buyer is equal to its value of some next best user [22].

This method has weakness. There is a risk for spectrum users to hoard spectrum in cases where the potential buyer could offer competitive services. In an ideal situation, a spectrum user would make the spectrum available if it incurs positive opportunity costs but this is unlikely since the spectrum user will only make spectrum available if there is a positive difference between opportunity costs and lost profits [19]. There are also weaknesses attributed to the implementation process. For example an auction design determines the success of an auction [26]. European spectrum auctions received some criticism in particular the Dutch auctions. [27] contends that the outcome of the Dutch 1800MHz auction was not efficient due to the auction design and that the proceeds could have been higher. For the 3G Dutch auctions there are arguments that the auction design was wrong in the sense that the number of licences was equal to the number of incumbents which led to new entrants teaming up with incumbents losing the opportunity to increase competition [28][23][29]. [25] recommends that this method should be applied to most spectrum, particularly in bands where scarcity is relatively high and transaction costs associated with market based negotiation are relatively low.

2.2.1.3 Open access or commons approach

For the purpose of this study "commons" and "open access" are used interchangeably. Under this method, spectrum is openly accessible to all potential users on condition that they adhere to the rules or etiquettes that manage the risk of interference. The rules are typically developed by a NRA and they require adherence to technical standards and transmitted power limits.

This method eliminates the need to rely on the market parties or the government to allocate spectrum resources. It is based on the principle that the spectrum resource is a public commons [30]. Open access was introduced in the 1990s in the ISM bands (900 MHz, 2.4GHz and 5GHz) which were initially used by industrial, scientific and medical purposes (ISM).

Furthermore, proponents of this method argue that it has low barriers to entry, high certainty about access to the band, low lead times from innovation to market, provides for less demand on the licensed spectrum, and encourages creativity through sharing and diversity [21]. Under this method the administration costs of the NRA are lower compared to the other two methods. Proponents of this method also argue that empirical evidence of common property arrangements concludes that there is a strong positive impact between the specific assignment of property and disposition rights in common resources and the efficiency of their use [19]. The main criticism of this method is congestion and interference often referred to as the "tragedy of the commons". Weaknesses also include the following, that it would be difficult to clear the band for reallocation, the users have no legal right to complain about the interference and lower quality of service.

In practice, open access method particularly Wi-Fi resulted in a lot of innovation and entrepreneurship [21]. [25] recommends that open access method should be used in cases where scarcity is low and when government wants to promote efficiency and innovation.

2.2.2 Comparison of the three methods

This section provides a comparative summary of the three methods in table 2.1

Table 2.1 Comparison of the three spectrum management methods

	C&C method	Market based method	Open access method
Licensing/assignment	First come first served, beauty contest	Auctions and secondary markets (Trading)	Adherence to the rules/etiquette
Exclusivity	Exclusive use	Exclusive use	Non-exclusive
Principle behind the methods	Prevents interference and meets static demand	Markets allocate spectrum more efficiently	Spectrum is a public commons
First implementation	Has been used since early 1900s (since inception of spectrum regulation)	Has been used since late 1980s	Has been used since the 1990s
Risk of interference	Low	Low	High
Spectrum efficiency	Inefficient spectrum use	Less efficient spectrum use	Efficient spectrum use
Effect on innovation	Stifle innovation	Promotes innovation	Promotes innovation
Flexibility in spectrum use	Low flexibility	High flexibility	High flexibility
Advantages	Low risk of interference	Transparent, shorter licensing period, low risk to hoard spectrum	Efficient spectrum use
Barriers to entry	High barriers of entry	High barriers of entry	Low barriers of entry
Implementation process	Vulnerable to long delays and misallocations, high risk to hoard	Bad auction design-inefficient outcome	Results in innovation and entrepreneurship
Where and when appropriate to use	When necessary for public interest purposes	In band where scarcity is high	Where scarcity is low to promote efficiency and innovation

2.3 Dynamic spectrum access technologies

Dynamic Spectrum access is defined as "technique by which a radio system dynamically adapts to select operating spectrum to use available (in local time-frequency space) spectrum holes with limited use rights" by IEEE 1900.1 [31] DSA makes spectrum sharing possible between users of spectrum by reducing the risk of interference. Furthermore, DSA enables spectrum sharing not only in the frequency dimension but also in geographic location and time dimensions. A spectrum user that operates a DSA technology is often referred to as a secondary user (SU) and an existing user typically licensed is often referred to as a primary user (PU). Most studies in literature focus on DSA as sharing between PUs and SUs. However sharing using DSA can take place among users as equals. For example in unlicensed spectrum bands, open access or commons model spectrum, spectrum is shared among users without any of the users given priority over the others. There are three DSA models namely interweave, underlay and overlay [32] [33] [34]. The paragraphs below provide a brief overview of these models based on these sources.

First, the interweave model is also referred to as opportunistic spectrum access since the secondary user (SU) is allowed to use the spectrum only when the primary user (PU) is not active on the band. This is based on the principle that the best solution for sharing is to completely avoid interference by allowing SU to transmit only when the channel is not occupied by the PU. This technique requires the SU to have knowledge of the activity information of the PU. The SU periodically monitors the band to detect occupancy in different parts of the band and opportunistically transmit in the spectrum holes without causing interference to the PU.

Second, the underlay model allows for concurrent transmissions of the PU and SU under the condition that the interference generated by SUs is below a certain threshold that is acceptable to the PUs. This technique is based on the assumption that the SU has knowledge of the interference caused by its transmitter to the receivers of the PUs and also based on the assumption that PUs transmit all the time. There are two methods used to keep the interference below the threshold. The first method is that the SU spreads its transmitting power over a wide range of spectrum such that the interference to the PU's narrow band is below the threshold. The UWB technology employs this model primarily for short range communications. The second method is referred to as the interference temperature. Under this method the SUs are allowed to transmit with a higher power under the condition that the total interference from all SUs is below a certain threshold. However, measuring the total interference to the PUs and imposing the interference constraint on the SU becomes a challenge.

Third, the overlay is the most recent; it is similar to the underlay model in that it allows the SU to access the spectrum when the PU is active on the band, however the difference is that instead of imposing the interference constraint to the SUs, the SUs maintains the PUs performance without degradation. This technique is based on the assumption that the SU has knowledge of the PUs codebooks and messages. The SU can obtain this information if the PU employs a uniform standard communication based on publicized codebooks or the former can periodically broadcast their codebooks. The SU can use this information to cancel the interference using channel coding, dirty paper coding and network coding or the SU can assign some of its power for its own communication and the remainder of the power to assist the PU transmissions. This is done in order to make sure that the performance of the PU remains unchanged.

The DSA technologies consist of a wide range of radio systems including Ultra Wide Band, DECT and Wi-Fi, WiMAX and the most advanced: cognitive radio. The section below discusses the three DSA technologies namely: DECT, UWB and Cognitive radio.

2.3.1 DECT

Digital Enhanced Cordless Telecommunications (DECT) is a standard designed to provide access to any type of telecommunications network offering a number of applications and services [35]. A wide range of DECT applications includes PSTN and ISDN access, wireless PABX, GSM access, wireless local loop and cordless terminal mobility (CTM). DECT falls under dynamic spectrum access technologies and can be regarded as a preliminary implementation of spectrum sensing as it is required to scan the local radio environment periodically to receive RF strength on idle channels and select the most optimal channel to set up a communication link. DECT can be regarded as interweave even though it uses an exclusively licensed band so sensing is employed to determine the best available channel within the band. DECT utilizes real time dynamic channel selection process to provide high utilization of spectrum [36]. The real time dynamic channel selection in DECT systems makes it possible for coexistence of uncoordinated private and public systems on designated frequency bands. A DECT device has access to all the common access channels and when a connection is required, it selects a channel that is the least interfered at the specific time and location. As a result of this there is no need for traditional frequency planning and the installations are simple. There is also no requirement to split the frequencies between different services and users and this leads to efficient use of spectrum. The benefits of DECT are that it combines efficient spectrum utilization and a long range fixed wireless local loop with mobility.

2.3.2 Ultra wide band

Ultra wide band (UWB) is an underlay technology which transmits large amounts of data over a wide frequency spectrum using short pulse, low powered signals [37]. The FCC first report and order defines UWB device as a device that emits signals with a fractional bandwidth greater than 0.2 or a bandwidth of at least 500 MHz at all times of transmission [38]. The underlay method is employed by UWB technology for primarily short range communications. The SU transmits power that spreads over a wide range of spectrum in order to ensure that the interference to the narrow band of the PU is below the threshold. As a result the FCC defined UWB devices in terms of compliance with emissions limits in order to make them coexist with legacy systems, rather than specifying techniques related to the generation and detection of RF energy [39]. The FCC prescribed the power limits, and frequency ranges within which the UWB devices are obliged to operate. UWB is an old technology that has been used by military however its use in communications for commercial applications in relatively new [37]. This is made possible by recent advancements in spread spectrum.

UWB has a number of benefits. It is a spectrum sharing technology that shares spectrum with existing users of the spectrum to ensure spectrum efficiency. When the UWB is implemented such that is does not cause harmful interference to existing users of the spectrum, it increases spectrum efficiency by using spectrum that has already been utilized. Another advantage of UWB is increased flexibility in spectrum use. A number of parameters make it possible to design a radio that can be used to optimize system performance as a function of required data, power, QoS and user performance [40]. The same device can be designed to offer services for numerous applications with different requirements without the need for additional software. UWB offers high speed data rates over very short range distances.

Even though UWB offers a number of opportunities for wireless communications, it faces some challenges which have contributed to a slow implementation. The main challenge surrounding the implementation of UWB technology is possible interference to existing users since its devices occupy a wide range of spectrum [41]. Another challenge is that UWB requires a complex signal processing to recover data from the noisy environment as it is a carrier less system [37]. This is because narrow band and other carrier less signals in the vicinity have a potential to interfere with carrier less transmission and reception.

UWB offers a wide range of applications including wireless communications, vehicular radar systems, medical systems, surveillance systems and radar systems. Wireless communications include wireless home networking high density use in office buildings high speed WPAN/ WBAN, wireless telemetry and telemedicine [40]. Applying ad hoc networking concepts between the nodes of a WBAN/WPAN network further increases spectrum efficiency [42], 2003). UWB is an alternative to other WLAN such as Bluetooth and Wi-Fi as it offers high speed data transfer rates of 100 Mbps up to 1Gbit/s over short distances [41].

2.3.3 Cognitive radio

Cognitive radio (CR) is the most advanced DSA technology. Software defined radio (SDR) is a key enabling technology for CR. Both “software defined radio” and “cognitive radio’’ and were coined by Mitola III in 1991 and 1998, respectively [43]. There are a number of definitions for SDR. IEEE 1900.1 defines SDR as a "Radio in which some or all of the physical layer functions are software defined". SDR is a multiband radio that supports multiple air interfaces and protocols and reconfigurable through software. CR typically utilizes SDR but it is not a requirement, the former can be implemented without using the latter. Cognitive Radio means a radio with cognitive abilities that interacts with its environment with a cognitive cycle for a response: to observe, orient, plan, learn, decide and act [43]. The ITU defines cognitive radio “as 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” [44].

The main characteristics of CR are cognitive capability and reconfigurability [45] [46] [47]. First, the cognitive capability is realized through real time interaction with the radio environment to identify spectrum holes for transmission opportunities so as to share spectrum with other users without causing interference to the existing user. Cognitive ability consists of four functionalities namely spectrum sensing, spectrum analysis, spectrum decision and spectrum mobility [45]. Spectrum sensing determines available channels and detects presence of existing users when SUs operate in the band by estimating interference levels. Spectrum analysis estimates the channel state information and predicts channel capacity for transmission. Spectrum decision selects the appropriate spectrum in terms of the spectrum characteristics and user requirements. When the band in use becomes unavailable, the spectrum mobility function takes over to provide seamless transmission.

Second, reconfigurability refers to selecting and reconfiguring the best spectrum band and the most appropriate operating parameters. A CR can be programmed to transmit and receive on different frequencies with different access technologies supported by its hardware design [45]. The reconfigurable parameters in CR include operating frequency, modulation, and transmission power and communication technology.

2.3.4 Comparison of the DSA technologies

The table 2.2 makes a comparison between the three DSA technologies; DECT, Ultra wide band and Cognitive radio.

Table 2.2 Comparison of DECT, UWB and cognitive radio technologies

	DECT	Ultra Wide Band	Cognitive Radio
DSA approach	Interweave	Underlay	Interweave
Principle behind	Dynamic channel allocation	Transmits concurrently with the existing users/PUs	Transmits in the spectrum holes.
Enabling technology	Multi carrier TDMA technology with TDD	Spread spectrum	Software defined radio
Techniques	Employs spectrum sensing	SU transmits wide bandwidth with very low power below a certain threshold,	Spectrum sensing, geo-location database and beaconing
Advantages	Dynamic channel selection, no need for traditional frequency planning	Transmits wide bandwidth over short distances	Transmits in white spaces without causing interference to PUs.
Spectrum efficiency	Spectrum efficient through dynamic channel selection	Spectrum efficient through concurrent transmission with existing users.	Spectrum efficient through using spectrum holes
Applications	Telephony applications with some mobility	High speed data over short distances	DSA applications

2.4 Enabling techniques for cognitive radio

The section below discusses the three enabling techniques for CR namely: spectrum sensing, geo-location database and beaconing. This is essential in order to understand the technical aspects of CR that affect spectrum management.

The real time interaction of CR with radio environment is made possible by CR enabling techniques. These techniques make it possible for CR devices to determine when and where it is safe to transmit in the frequency band without causing interference to the existing user or PU. There are three CR enabling techniques that are often discussed in literature, namely: spectrum sensing, geo-location database and beaconing. The main function of these technologies is to detect the presence or absence of existing users or PUs and determine which channels are available for use by SUs. These techniques provide CR with information and the ability to detect and react to changes in spectrum use. Successful operation of CR relies on the cognitive ability to obtain this information.

2.4.1 Spectrum sensing

Spectrum sensing refers to a process of detecting spectrum holes and uses them in an opportunistic manner without causing interference to PUs. Spectrum sensing entails signal detection, spectrum availability detection, spectrum opportunity detection and spectrum access [48]. Signal detection means detecting the existence or absence of a signal in a spectrum band. Spectrum availability detection decides whether there is spectrum available for use by secondary users, while spectrum opportunity detection extends spectrum availability detection to encompass secondary users and services requirements. Spectrum sensing can also be classified as transmitter detection methods, receiver detection methods and cooperative methods [48]. The three sensing methods will are discussed below.

2.4.1.1 Transmitter detection method

Transmitter detection assumes that the PU is transmitting information to the primary receiver when the spectrum sensing takes place [48]. Transmitter based detection methods include energy detection, matched filter detection, cyclostationary feature detection, eigen value detection; waveform sensing and radio identification based sensing [48]. The first three methods which are often discussed in literature are briefly discussed below.

First, under the energy detection, the received signal energy is assessed and compared with the predetermined threshold [48]. The SU is assumed to be active on the band if the received signal energy exceeds the threshold or else the spectrum is assumed to be idle. Energy detection does not require the SU to have knowledge about the signal of the PU [47] [45]. Energy detection has low computational complexities and as such it is easy to implement. However, it has shortcomings including that it cannot distinguish between noise and signal, the decision threshold is subject to variation with the SNR, it can only operate with accurate knowledge of the noise and it is not effective for wideband signals.

Second, the matched filter technique requires prior knowledge of the PU transmission, for example modulation type and order, pulse shaping and also requirements of high power consumption and perfect synchronization [45]. The main advantage of matched filter is that it can achieve a high processing gain within a short time. However, its weakness is the requirement for prior knowledge of the PU transmission information.

Third, the cyclostationary feature detection technique is able to distinguish between noise and signal. This technique is based on the cyclostationary feature present in many wireless communications signals i.e. the statistical properties of the transmitted signal vary over time [48]. This method detects PU transmissions by exploiting the cyclostationarity features of the received signal. However, its disadvantage is the requirement for prior knowledge of specific transmitted signal and parameters and high computational complexity.

2.4.1.2 Receiver detection methods

Under the receiver detection sensing, the SUs rely on the fact that when the PU is in a receiving mode it is not passive, as such it produces leakage of electromagnetic waves [48]. The SU detects the leakage power while the PU is receiving. Receiver detection is based on energy detection technique. The receiver detection methods has advantages over transmitter detection methods in that the former have the ability to locate the PU, the exact primary band in use and the high probability to find spectrum holes in high density of primary receivers. However, its shortcomings include the price of the architecture, the near-far problem and that it requires a highly sensitive energy detector.

2.4.1.3 Cooperative methods

When spectrum sensing is carried out by a single SU, such SU may experience a hidden node problem due to fading and shadowing. The hidden node problem occurs when a SU is within the protection area of a PU but fails to detect the presence of the PU [49]. Figure 2.1 shows hidden node problem.

Therefore, sensing information from multiple SUs is essential for more accurate detection, commonly known as cooperative detection [46]. In literature, cooperative sensing is recommended as a solution to fading shadowing and the hidden node problem [32] [46] [45]. Cooperative detection relies on information exchange between the SUs. Cooperative detection is implemented in two ways; centralized mode (partial cooperative) and decentralized mode (total cooperation detection) [32] [48]. Under the centralized mode the SUs detect the channel independently or with some help from local operation with nearby SUs and the information are sent to fusion center to decide on channel availability. Under decentralized mode, the SUs detect the channel and exchange the information among each other to reduce the detection time and to increase their agility. Each SU makes its own decision on the availability of the channel. This approach can increase the throughput of the SUs and limit the interference to the PUs at the same time. However, Cooperative sensing has shortcomings such as developing efficient information algorithm and increased complexity.

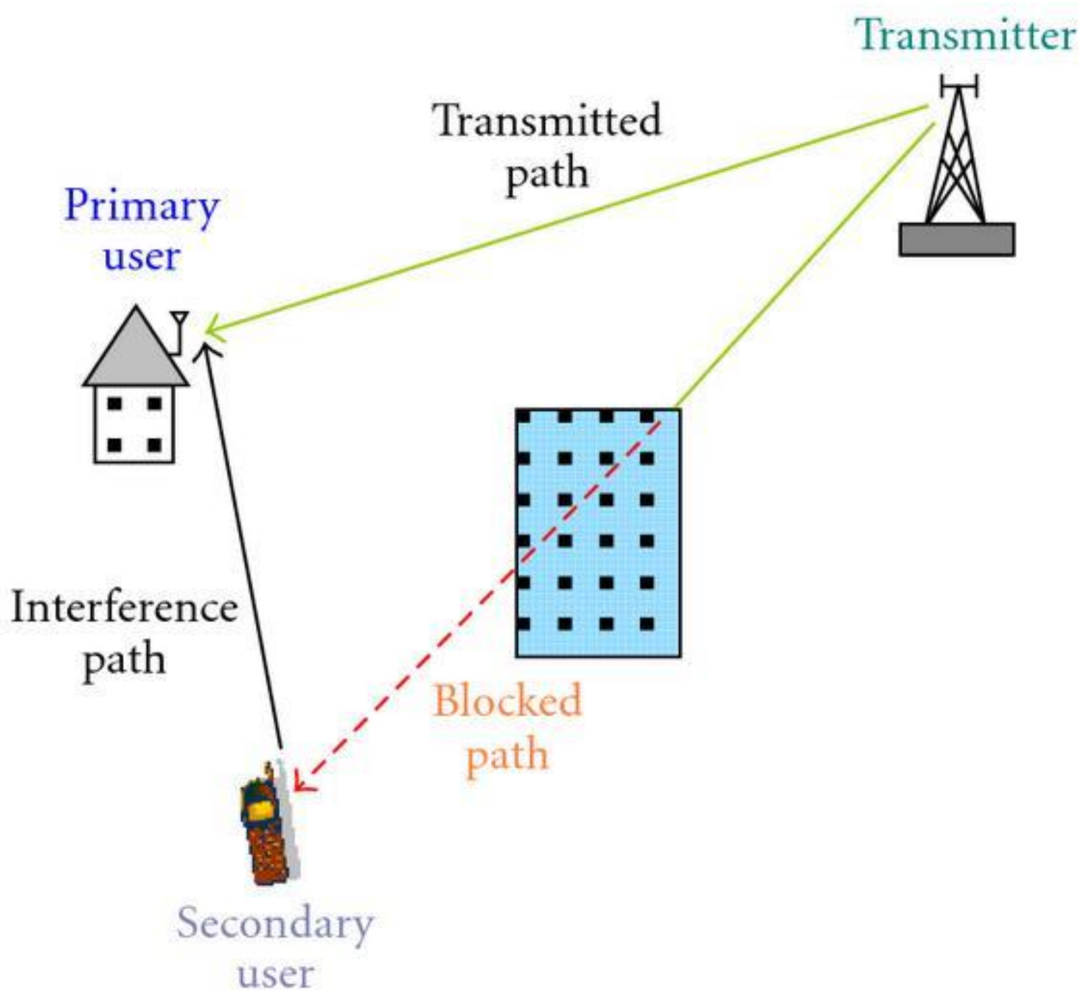

Figure 2.1 Hidden node problem [Source: [50]]

2.4.2 Geo-location database

Due to the challenges posed by spectrum sensing, CR implementation is focused on geo-location database. Under the geo-location database approach the PUs and SUs are equipped with location estimation and or sensing device that estimates their location e.g. GPS [51]. PUs provide their spectrum and location information to the central database. The central database broadcasts information about channel availability together with the location information of the PUs. The SUs verify their location by comparing it with the location of licensed users in order to obtain information about channel availability they can use locally. SUs send their spectrum requests with location information to the cognitive base station. The cognitive base station assigns channels to the SUs and broadcast the geo-location database, so that other SUs can see that the channel is occupied by a SU. When the PU or the SU stops transmitting on the channel, the channel is made available to other users. The PUs can use the channels reserved by a SU if there are no channels available [52]. However, if there are free channels available the PUs will use those instead of forcing the SU to vacate the band.

Geo-location database is the most debated recently and the most preferred approach by regulators for the implementation of CR in Television White Spaces (TVWS) [53]. For example, ECC report 159 has chosen geo-location database over spectrum sensing for the deployment of white space devices in DTV, PMSE, radio astronomy and aeronautical radionavigation services in the 470 -790 MHz band [54]. This report concludes that spectrum sensing is not reliable enough to avoid possible interference to licensed services bands in the said band. Similarly, the FCC requires white space devices to use geo-location database.

Even though geo-location database is the preferred method for the near future, there are still open issues associated with this method including decisions on the entity to build and maintain the database, reliable accurate location information for indoor users and a need for additional connection for devices so that they can access the database prior to any transmission in the DTV bands [53]. Some of these shortcomings can be addressed, for example inaccurate location information can be addressed with advanced technologies such as A-GPS and indoor GPS or use more advanced reliable cognitive positioning systems [51].

2.4.3 Beacon

Beacons are signals that can be used to show that particular channels are occupied by existing users or are vacant. A beacon is part of an existing user or PUs protocol and gives information about its spectrum occupancy [53]. Under the beacon method SUs can only transmit on the channel if they receive a beacon identifying that particular channel is vacant. A beacon can either broadcast permission for CR devices to access the band or broadcast denials of spectrum access for CR devices. A single beacon approach with either grant or denial approach can be less reliable [52]. So, a dual approach is proposed to improve reliability, where both grant and denial beacons are used to improve reliability. In this case if the grant beacon is detected and no denial beacon is detected, the SU is allowed to use the spectrum, whereas if grant and denial beacons are detected from different PUs simultaneously the SU is prohibited from utilizing the spectrum. The benefits of the beacon method is that it increases the chances of detection at lower threshold values and that the detected information is aggregated and constantly accessible using a permanent channel [54] [53]. However, the use of a permanent channel requires a dedicated channel to be found and reserved to transmit and receive information. This method requires a beacon system to be deployed and its complexity increases the costs of network deployment.

2.5 Benefits of cognitive radio on spectrum management

This section discusses technical benefits of CR from a spectrum management point of view.

2.5.1 Flexibility in spectrum use

Flexibility means allowing users to have maximum autonomy to determine the highest valued use of their spectrum, subject only to the rules that are necessary to afford reasonable access by other spectrum users and to limit interference between multiple spectrum users [25]. Flexibility can be implemented under any of the licensing methods in the following areas [25]:

- Spectrum use-spectrum users should be afforded maximum possible flexibility to decide how to use spectrum, for example whether to provide commercial services or for private use on condition that they adhere to applicable general parameters
- Technology-spectrum users should be allowed to use technology that is best suited to their proposed use or service
- Usage rights-efficient secondary market rules should be set up to facilitate the transfer of spectrum rights from one party to another.

Furthermore, a study on increased flexibility and liberalization in European spectrum management concluded that there are potential benefits to be realized from more flexibility spectrum use [55]. The study suggests that, evidence from countries that have implemented more flexible spectrum management, predominantly from South America suggests that flexibility in spectrum management leads to more competitive markets and lower consumer prices. The study also suggests that technology and service neutrality is most appropriate in spectrum management as interference can still be controllable under flexible systems. Flexibility in spectrum management can be implemented in many ways, in order to increase spectrum efficiency. For example by, spectrum property rights, spectrum commons or open access and dynamic spectrum access.

Additionally, according to [56] “flexible spectrum management refers to a set of new and dynamic procedures and techniques for obtaining and transferring spectrum usage rights and dynamically changing the specific use of frequencies”. Therefore DSA has a potential to promote flexibility in spectrum management in that it allows for such dynamic procedures and techniques to grant and transfer spectrum usage rights and change the specific use of frequency band. Furthermore [41] conducted a study on the impact DSA technologies in spectrum management and he concluded that these technologies will result in increased spectrum efficiency, better frequency utilization and flexible access to spectrum. The interviewees agree with [41] that DSA through cognitive radio will improve utilization of spectrum, increase spectrum efficiency and allow flexible access to spectrum. Interviewees also argue that DSA will bring new opportunities for new spectrum users and applications. Some interviewees state DSA will improve flexible use of spectrum not only in terms of technical parameters but also in terms of time and geographic space. As frequency planning will be done in terms of frequency, time and geographic space.

2.5.2 Better spectrum utilization and increased spectrum efficiency

The FCC spectrum policy task force report (SPTF) concluded that spectrum access is a more significant problem than physical scarcity in many spectrum bands [25]. The report also concluded that preliminary data and observations suggests that many segments of the spectrum are not utilized for a significant periods of time and that use of these white spaces can be increased significantly. Given that, increased spectrum sharing through DSA technologies including the CR provide access to idle spectrum while protecting the rights of existing users.

CR can also be used to share spectrum between government and private users. For example military spectrum and spectrum for emergency services sits idle most of the time making it ideal for sharing using CR. In case of an emergency the CR system could easily vacate the band for use by the existing users.

As stated in section 2.3 spectrum sharing can be implemented based on the arrangement that consists of sharing among equals or sharing PUs and SUs. The former case is equivalent to commons or open access model. Spectrum is shared among users and no user is given priority. This model leads to increased spectrum efficiency compared to exclusive licensing with many spectrum holes. Open access has a high risk of interference. As a result, this band is typically used for services that do not require high quality of service. The use of cognitive radio in these bands could significantly reduce the risk of interference and improve the quality of service.

Sharing between PUs and SUs is the most practical when the former have been granted exclusive rights. As discussed in section 2.3, in this approach SUs are allowed to share spectrum using interweave, underlay and overlay models. Opportunistic access can be implemented using CR combined with spectrum sensing, beaconing or geo-location database; to determine when it is safe to transmit without causing harmful interference to the PUs. Opportunistic access for implementation in the television white spaces (TVWS) is debated a lot in literature and in policy circles and has gained support from regulators and industry as the preferred band for CR implementation.[3] As mentioned in section 2.5.1, interviewees agree that CR has a

[3] Refer to Chapter 3

potential to improve spectrum utilization and increase spectrum efficiency as it allows opportunistic access to spectrum.

2.5.3 Other benefits of cognitive radio on spectrum management

Apart from technical benefits CR also has benefits associated with the role of the NRA in managing spectrum. CR can reduce the policy burden of spectrum management. As the users can share spectrum the demand for issuing licences may be reduced [57]. CR can also benefit spectrum management for example, the geo-location database does not only provide a solution to protect PUs from interference in TVWS but can also be used by a NRA as a tool to manage spectrum dynamically [58]. Some interviewees state that use of CR will result in less work for NRAs because once the initial frequency planning has been done not only in terms of frequency space but also in terms of time and geographic space. The frequency plan will not require regular reviews as is the case with static frequency planning because the reviews will be done to a greater extent by reviewing standards through technical protocols, instead of regular frequency planning reviews. DSA could create a new role for the NRA or a third party known as the spectrum broker. The role of the broker includes controlling the basic etiquette, manage interference, solve disputes between primary and secondary users and negotiate spectrum trading deals [59].

2.6 Challenges of cognitive radio on spectrum management

This section discusses technical challenges of CR namely: interference, certification and security issues.

2.6.1 Interference issues

Some of the challenges of CR are related to spectrum sensing, as discussed in section 2.4.1. Inaccuracy in spectrum sensing can lead to interference i.e. a SU interfering with a PU. This may happen due to fading, noise uncertainty, and aggregate interference uncertainty [60]. This challenge can be overcome by making CR more sensitive so that it can tell the difference between a white space and a faded PU signal. This can also be overcome by cooperative spectrum sensing. However, cooperative sensing has its drawbacks such as increased decision making time, security concerns from malicious SUs that can intentional mislead the final decision by reporting incorrect data, concerns about newness of the data due to exchange delay and complex control and coordination.

Another challenge of spectrum sensing is aggregate interference uncertainty. This happens when an unknown number and locations of CR operate on the same band [60]. The aggregate interference may be harmful to the PU even though the latter is out of any interference range of the SU. According to [60] this can be addressed by the following. First, high sensitive detectors that can detect PUs located beyond the interference range. Second, using energy detection where local SUs detect each other and avoiding occupying the same band at the same. Third, using system coordination whereby, SUs negotiate access and manage aggregate interference through a cognitive channel control (CCC) at increased implementation cost.

The interviewees agree that interference is a key technical challenge of cognitive radio and spectrum sensing is a case in point. This can be improved by the ongoing research in spectrum sensing. The interviewees suggest that in the early implementation stages most reliable techniques such as database methods should be used in combination with sensing or sensing can be used in less critical systems until the current challenges of the latter have been solved. The interviewees indicate that not all bands can be used for CR, for example bands used for safety of life services and passive service will find it difficult to cope with the risk of interference. One interviewee mentions that there could be situations where a CR does not want to vacant the band while another one tries to access the band. This leads to a collision which can be solved by politeness protocols, where the devices can start talking to each other and predator protocols are also needed to discourage the predatory behavior. So the interviewee suggests that with regard to the cognitive functionality of CR a balanced approach should be developed between politeness and predatory behavior protocols.

2.6.2 Security and certification issues

The capability of the CR to change its transmission parameters in response to changes in the radio environment makes it vulnerable to security threats. Security threats can be intentional for example a deliberate attack or unintentional due to internal failure or malfunctioning. [61] classifies these threats into two categories namely: threats that are common to both CR and conventional wireless communications and threats that are specific to CR. Even though security threats are possible in conventional wireless systems, their implementation and impact on CR systems is specific. For the purpose of this study, security threats specific to CR are discussed. Specific CR threats include masquerading, jamming, saturation of the CCC, malicious alteration, unauthorized use of spectrum bands and internal failure of the CR node. The paragraphs below briefly discuss CR security threats based on [61].

Cooperative CR networks are more vulnerable to these attacks as these networks assume that the nodes are altruistic and make logical decisions to optimize spectrum use. In masquerading, a malicious node provides false information for spectrum sensing or spectrum sharing. For example a malicious source can mimic characteristics of a PU in a specific frequency band, to make the SU avoid using the band as the latter detects the presence of the former. Jamming attacks can be implemented across multiple channels using a single malicious node to cause degradation of the network, to perform a denial of service (DoS) attack on a node and to learn

about the behavior of the network so as to implement more threats. For example a jamming attack can make the CR network to choose a specific frequency band for the CCC so that another malicious node can implement eavesdropping of cognitive messages. CCC is used to distribute cognitive messages in the CR network. Saturation of the CCC is implemented by sending a large number of cognitive messages to the CCC to deny its service to the CR network. Malicious alteration can be implemented by altering cognitive messages exchanged in the CR, or by altering the behavior of a CR node in order to support other threats. Unauthorized use of spectrum occurs when a malicious node uses spectrum bands without authorization to gain more traffic bandwidth or traffic capacity or a malicious node can emit power in unauthorized spectrum bands to cause degradation of service to PUs. Internal failure of a CR node occurs due to the failure of a CR node resulting in a variety of impacts depending on the type of failure. For example the CR node can stop functioning with other CR nodes or it can transmit in the wrong frequency band.
[61] does not only identify the security threats to CR but also proposes a number of solutions to address such threats. For example a jamming attack in a specific frequency band could be avoided by frequency hopping. However, this comes with a tradeoff of increased complexity of the CR network as the CR nodes should be informed of the change in frequency bands. Unauthorized use of spectrum can be mitigated by distributing spectrum monitoring across the CR users to detect malicious nodes. An administrative method is required to shut down the malicious node once it has been detected. Malicious alteration and masquerading can be mitigated by protection techniques based on trust or reputation such as signal analysis or authentication of CR nodes. Internal failure of a CR node can be avoided by implementing data fusion process of collaborative spectrum sensing, in which a reputation score is allocated to each terminal based on how consistent its local report is with the final decision. Eavesdropping can be avoided by applying protection of confidentiality while saturation of CCC can be mitigated by robustness and protection of system integrity.

Furthermore, CR devices bring about new challenges for the certification process as it is difficult to prove that the device will remain within the operational boundaries considering that they are capable of reconfiguring themselves. Certification of devices is done in order to ensure that a radio device adheres to interference and safety regulations. The certification process is done using evaluation and certification criteria in terms of regulations, standards and industry specifications that has to be adapted to handle complex CR [61]. Certification of CR is complex due to complexity of the technology and different stakeholders that can be involved in the certification process. The risk of interference and safety of CR devices depends on the behavior of complex software systems to a greater extent than the conventional radios [62]. As a result, this requires new certification mechanisms that strike the balance between mitigating the risks and cost of certification. [62] proposes solutions to the certification process of CR devices. This can be done by categorizing frequency bands in terms of risks associated. For example frequency bands that are assigned to safety of life services are high risk; as such a higher level of assurance should be required for devices that are capable of transmitting in those bands. Another mechanism that can be used for certification of CR devices is device operational duration or limited duration certification lease. Devices can be authorized to operate for a short period of time and renew the certification once the old one expires. The benefit of this method is that if the certification was granted by mistake i.e. not detecting design mistakes during the certification process or if the device causes interference its operation can be withdrawn within a known period of time. Once the device has gained more trust from the regulatory body, the permission period can be extended. One interviewee suggests that equipment vendors are concerned about reconfigurable devices as this provides an opportunity to other parties other than them to reconfigure the devices. Another interviewee suggests that in order to solve this problem, certification procedures should be used and that reconfigurability protocols should not be open to the user.

2.7 Conclusion

As stated at the beginning of this chapter, this section answers sub-research question:

1. *What are the benefits and challenges of dynamic spectrum access technologies relevant to spectrum management from a technical point of view?*

The main benefits of DSA through cognitive radio discussed above are increased spectrum efficiency, better spectrum utilization and flexible spectrum access. As it has been argued that spectrum utilization is very low and that spectrum sits idle at any given time and geographic location, so spectrum sharing through cognitive radio gives access to this idle spectrum while protecting existing users from interference. In this way cognitive radio will improve spectrum utilization and increase spectrum efficiency. In licensed bands, the licensed users can be protected by using one of the CR enabling techniques to determine when and where it is safe for a CR device to transmit in a particular band. CR can be used in licence exempt bands as well to significantly reduce the risk of interference and improve quality of service.

Cognitive radio will increase flexibility in that it allows easy access to spectrum and also allows dynamic transfer of spectrum usage rights. CR will also provide flexibility by allowing change in spectrum use in terms of technology and applications. Flexible use of spectrum will improve because spectrum will be managed dynamically not only in terms of frequency space but also in time and geographic space.

There are also other potential benefits relating to the regulatory function of spectrum management in the long term. DSA has potential benefits for NRAs, for example the geo-location database can be used to manage spectrum dynamically apart from using it for TVWS. CR could lead to less regular reviews of regulations. As most regulatory work will be done in standardization through technical protocols instead of regular reviews of regulations by the NRAs. CR could also create a new role for NRAs or a third party known as the spectrum broker.

The main challenges of CR are interference, security and certification issues. Even though CR promises to increase spectrum efficiency and improve utilization there are still some issues concerning interference. Interference issues are mainly associated with spectrum sensing. Currently sensing is viewed as the least reliable technique for determining white spaces due to fading, noise uncertainty, aggregate interference and hidden node problem. The interviewees argue that these challenges can be improved by the on-going research on spectrum sensing. In the meantime, CR can be implemented using the database method in combination with spectrum sensing until a solution to the latter has been found. Interviewees also argue that CR cannot be implemented in all spectrum bands, as some services are critical and vulnerable to interference such as safety of life services and passive services. The interviewees suggest that a balanced approach between politeness and predatory protocols should be adopted to prevent predatory behaviour by CR.

The other challenge is security and certification issues. CR capabilities of changing its transmission parameters due to changes in the radio environment make it vulnerable to security threats. Cooperative networks become more vulnerable to these threats due to the altruistic manner of their operations. These threats can be addressed in a number of ways but have trade-offs such as; increased complexity of the CR networks and increase in cost of Cr equipment. The reconfigurability capability of CR brings about certification issues since the behaviour of a CR device can be altered even after certification. As a result, new certification mechanisms that strike the balance between mitigating the risks and cost of certification are required. This can be done by categorizing bands according to risks associated with them and by implementing a device operational duration or limited duration certification lease. There are also suggestions that reconfiguarability protocols should not be open to the user in order to avoid reconfiguring by parties other than the manufactures. As CR technology development advances, its benefits and challenges on spectrum management may change. Therefore further investigations in this regard are required.

3. International and national spectrum management policy developments in respect of cognitive radio

This chapter answers sub-research question 2 of the thesis.

2. *To what extent will the current and new policy developments (international and national) determine the impact of dynamic spectrum technologies on spectrum management?*

The chapter reviews the current regulatory and standardization developments of dynamic spectrum access (DSA) through cognitive radio (CR) and its effects on spectrum management. This is relevant to the main research question because the potential impact of CR on spectrum management will be determined by the standards and regulations that govern its operation. The chapter focuses on the international and national developments. For each of these levels, firstly spectrum management is discussed briefly in order to put regulatory and standardization developments on CR into a broader spectrum management context, and secondly standardization and regulatory activities are reviewed. The chapter is structured as follows. The first section of explores regulatory implications for the introduction of cognitive radio within spectrum management methods discussed in chapter 2. The second section reviews CR activities in the ITU. The third section reviews CR activities in Europe (ETSI, CEPT and EC). The fourth section reviews CR standardization activities in IEEE. The fifth section makes a conclusion on the regulatory and standardization activities on CR at the international level. The sixth section makes a country comparison of regulatory developments on CR in the US, the UK and Australia. As stated in chapter 1, these countries were selected because they are in the forefront regarding spectrum reforms and their relevant regulatory information is available. The seventh section concludes on the chapter.

3.1 Regulatory implications for the introduction of cognitive radio

This section analyses regulatory requirements for CR implementation within spectrum management methods discussed in chapter 2.

Introduction of CR depends on the degree they are allowed to operate by the regulations, which are often linked to availability of technical standards. In order to realize the benefits of CR, regulations and standards should be developed at international and national level. These regulations should define the rules for the operation of CR. International standardization and harmonization is required for interoperability and economies of scale of CR. As a result, international organizations such as the ITU, IEEE, ETSI, CEPT and the EU are involved in CR standardization and regulatory initiatives.

CR can be introduced with varying degrees of regulatory implications under the three spectrum management methods (command and control method, market based methods and open access method) discussed in Chapter 2. First, under the command and control, CR can be implemented in two scenarios. In the first scenario a licensee can use CR within their own spectrum. No regulatory changes are required if the licensee operates according to the licence conditions. In the second scenario a RNA can allow secondary use through secondary licensing or licence exemption. This case requires changes to the regulations, which define the rules for the operation of CR in order to minimize the risk of interference to the licensed users.

Second, under the market based method, CR can be introduced in three scenarios. In the first scenario a licensee can use CR within their own spectrum. No regulatory changes are required if the licensee operates according to the licence conditions. In the second scenario the licensee can lease unused spectrum for CR use. In this case regulatory changes are not required as long as the lessee adheres to the licence conditions. In the third scenario a RNA can allow secondary use through secondary licensing or licence exemption. This case requires changes to the regulations, which define the rules for the operation of CR in order to minimize the risk of interference to the licensed users.

Third, under open access method, CR can be used by the users of the spectrum in licence exempt bands. No regulatory changes are required as long as the users comply with the rules or etiquettes that apply to licence exempt bands.

3.2 Spectrum management in the ITU

This section reviews CR activities in the ITU.

The RR divide the world into three regions. Region 1 covers Europe, Africa, Middle East and former Soviet Union including Siberia, Region 2 covers North and South America, and Region 3 covers Asia and Australia. The RR contain the ITU allocations. There is a wide range of space and terrestrial services namely, mobile, fixed, broadcasting, maritime, and aeronautical. Service allocations to a frequency band can be primary or secondary. A secondary service is not allowed to cause harmful interference to primary services and to claim harmful interference from primary services. These allocations harmonize frequency bands with radio services on a global basis and in cases where this cannot be done; harmonization is done at the regional (ITU regions) level. Countries can deviate from the ITU allocation in their table of frequency allocation on condition that they do not cause interference to and or claim interference from the ITU service allocations in other countries [63].

3.2.1 CR activities in ITU-R

WRC-07 adopted an agenda item 1.19 calling for WRC-12 to consider regulatory measures for the introduction of SDR and CRS. WRC-12 agenda item 1.19 is "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 (WRC-07)" [64]. Resolution 956 was adopted by WRC-07 and resolves to invite ITU-R to study if there is a need for regulatory measures related to the application of CRS and SDR. In line with this agenda item, ITU-R developed the definitions of CRS and SDR in Report S.M.2152 [44][4]. The definitions assist in the execution of the studies in that they provide a common understanding of the terms and facilitate their use in ongoing ITU-R work in unambiguous way. The agenda item deals with SDR and CRS, however the study focuses on CRS. On this agenda item, the WRC-12 decided that there was no need for a change to the RR since CRS is not a radiocommunication services but a technology that can be implemented in systems of any radiocommunication service and have to comply with the RR. The conference adopted Recommendation COM6/1 taking into consideration that the Radio Assembly (RA-12) adopted Resolution ITU-R 58 which calls for further studies on the implementation and use of CRS [65]. Recommendation COM6/1 is intended to facilitate the deployment and use of CRs particularly in border areas.

The ITU-R studies acknowledge that CR technologies may offer significant benefits to spectrum management by providing increased spectral efficiency and mitigate the problem of congestion. However, their concern is the protection of existing services from potential interference from services using CRS. The ITU-R is currently developing a report on CRS in the land mobile service (LMS.CRS) above 30MHz and excluding IMT [66]. International Mobile Telecommunications (IMT) is the ITU-R terminology for mobile systems that provide access to a wide range of services communications including advanced mobile services supported by mobile and fixed networks that are increasingly packet based. This report presents the applications and analysis of technical and operational characteristics of CRS. The analysis includes the potential benefits and challenges of the technical and operational elements together with existing and emerging applications using cognitive technologies and capabilities. The report also deals with the descriptions of applications of CR and possible deployment scenarios from a technical perspective namely:

- Use of CRS technology to guide reconfiguration of connections between terminals and multiple radio systems
- Use of CRS technology by an operator of radiocommunication systems to improve the management of its assigned spectrum resources
- Use of CRS technology as an enabler of cooperative spectrum access
- Use of CRS technology as an enabler of opportunistic spectrum access

The ITU-R also identified CR enabling techniques:

[4] Refer to section 2.3.3.

- Spectrum sensing capability including collaborative and cooperative sensing
- Geo-location
- Access to information on spectrum usage and regulatory requirements through the use of a database, logical or physical CCC
- Capabilities to adjust operational parameters based on obtained knowledge

The ITU-R suggests that these capabilities in particular the database technique do not only have the potential to provide increased efficient use of spectrum but also offer more versatility and flexibility through the ability to adapt their operations.

3.3 Spectrum management in Europe

The first part of this section provides some background on spectrum management in Europe in general and second part reviews the allocation of the digital dividend. The third part reviews CR activities in the European Commission (the Commission). The fourth part reviews CR activities in CEPT. The last part reviews CR activities in ETSI.

Different organizations play specific roles in spectrum management in Europe. European Conference of Postal and Telecommunications Administrations (CEPT) perform regulatory work and represent the international cooperation process between European countries. The European Commission develops policy and represents the integration process between 27 member states. European Telecommunications Standards Institute (ETSI) develops ICT standards within Europe.

3.3.1 The role of the European Commission in spectrum management

The role of the Commission in spectrum management has always been minimal; however it is expanding its role particularly in the area harmonization, flexibility and sharing across Europe. The objective of the Commission spectrum policy is to support the internal market for wireless services and to promote innovation in electronic communications and other sectors. The Commission spectrum management is based upon the electronic communications regulatory framework [16] and the radio spectrum decision that was established to develop the Commission radio spectrum policy [17]. The objective of this decision is to coordinate policy approaches and encourage harmonization to support the internal market. The decision sets up principles and procedures on how to develop and implement the policy. Subsequently, two bodies were established to develop and support radio spectrum policy. The Radio Spectrum Policy Group (RSPG) was established to advise the Commission on high level spectrum policy matters including harmonization and spectrum licensing [67]. The Radio Spectrum Committee (RSC) develops technical implementation measures for the Commission. The current regulatory framework supports service and technology neutrality and allows for exclusive rights to spectrum and spectrum trading. This supports a move away from the command and control method.

Historically, the Commission has focused on the harmonization of services within frequency bands, but recently there are initiatives aimed at introducing more flexibility in spectrum use and spectrum sharing. The Commission is working on spectrum sharing approaches including collective use of spectrum.

Under the current regulatory framework, member states are allowed to set out the conditions of use of spectrum to be adhered to by radio equipment. The conditions can be harmonized at a European level through a Commission spectrum decision that is obligatory to EU member states or by implementing an ECC decision or a recommendation. On the other hand, if the obligatory harmonized guidance is not available member states can develop their regulatory arrangements.

3.3.2 The digital dividend

Entrenched in the Commission spectrum policy is the allocation of the digital dividend in Europe. The digital dividend is the band 790 to 862 MHz, 72 MHz of spectrum ("800 MHz band") is spectrum that is freed up in the switchover from analogue to digital terrestrial television transmissions. The digital dividend has many potential uses namely: DTT, broadcast mobile TV, commercial broadband services both to fixed locations and to mobile devices, wireless broadband services for public protection and disaster relief (PPDR), services ancillary to broadcasting and programme making (SAB/SAP), cognitive technologies and innovation reserve [68]. When making policy decisions about the allocation of the digital dividend, the Commission takes into consideration the following: firstly, policy decisions have an impact on the neighbouring States; hence there will be a need for frequency coordination. Secondly, harmonizing the allocations will have a positive impact on economies of scale in equipment. Thirdly, roaming is important for wireless broadband and mobile TV [55][68].

The policy objectives of the Commission in respect of spectrum include harmonizing technical arrangements, promoting effective and efficient use of spectrum, preventing harmful interference, avoiding competition distortions, maximizing spectrum flexibility and ensuring health protection [69]. Given that this band is optimal for coverage of large areas due to its propagation characteristics, this band is suitable for coverage and access of wireless broadband in rural areas. In line with other policy objectives namely, broadband access for all in the digital agenda for Europe, the Commission made the following decisions. Mandates the freeing of this band by 1 January 2012 to ensure access to broadband communications by 2013. For the long term additional digital dividend should be envisaged below 790 MHz. Coverage obligations should be attached to the spectrum rights as terms and conditions of the licence since 800 MHz band covers large areas [70]. The Commission mandates the Member States to use the CEPT preferred frequency arrangements or alternative arrangements as described in CEPT report 31 and CEPT report 29 for cross border coordination.

3.3.3 CR activities in the European Commission

The RSPG first report on cognitive radio issued in 2010 was aimed at informing policy makers in Europe about the discussions on the impact and challenges of such technologies on spectrum management. The report explains definitions of concepts and terminology used, provides CR enabling technologies, provides possible implementation scenarios of CR in the different methods of spectrum management and their regulatory impact, highlights differences between US and EU in terms of the framework for white spaces and identifies issues that require further attention. The report adopts the ITU-R definitions of SDR and CR. The report discusses CR enabling techniques namely: spectrum sensing, cognitive pilot channel (CPC), and geo-location database. The report concludes that sensing may not be sufficient to protect primary users, therefore a case by case approach is required and this may require a combination of the techniques. For the database, the report recommends that European standardized protocols or languages to access and format data within the database should be harmonized. For the CPC, it recommends further studies on the form of the CPC and the frequency to be used by the CPC.

Furthermore, pertaining to possible scenarios CR can be implemented by collective use spectrum approach (CUS) and individually licensed spectrum if the rights of use are traded or leased using vertical sharing and horizontal sharing. RSPG defines CUS as “collective use of spectrum allows an underdetermined number of independent users and /or devices to access spectrum in the same range of frequencies at the same time and in a particular geographical area under a well-defined set of conditions” [71]. Under the CUS, vertical sharing where CR devices share spectrum with the existing users, is opportunistic spectrum access. For example in the case of TVWS. In this case the NRA designate frequency to implement opportunistic access and set up appropriate technical conditions as it is the case with the TVWS. On the other hand, horizontal sharing in CUS refers to a case where a dedicated band identified by the NRA has usage restrictions to ensure compatibility with existing users. For example, this sharing can be used in ad hoc networks. In this case the NRA identifies the band for CUS and sets up usage restrictions to ensure that devices have same rights and equal chance to access spectrum. Under the use of CR where the rights of spectrum use could be tradable or leased, in vertical sharing the licensed spectrum user could allow secondary use of spectrum in specific times and locations when it is not used. No regulatory intervention is required in this model, apart from adhering to tradable or leased rights and flexible licence conditions. While with horizontal sharing, licensees form a pool of spectrum that can be used by all of them. In this case, the NRA defines the minimum technical conditions for the pool of spectrum.

Subsequently, in 2011 RSPG published an opinion on cognitive technologies aimed at creating sufficient confidence in existing spectrum users and industry players to develop CR technologies by addressing the prospects of the implementation of CR technologies and identifying any need for coordination at the EU level. The RSPG considered the following: regulatory implications of CR under the current EU framework, the three enabling technologies of CR namely: sensing, CPC and database and made the following recommendations. Measures for the implementation of CR should be left to the member states under the condition that coordination matters are addressed for each band concerned. Accreditation of the database and provision of information to database managers and incumbents should be dealt with nationally. ETSI should be requested to study ways to secure access and exchange of information from database to CR devices.

3.3.4 CR activities in CEPT

A lot of work is done in electronic communication committee (ECC) with regard to TVWS. In 2008 CEPT issued report 24 [72] on technical considerations regarding harmonization options for the digital dividend which, provides a preliminary assessment of the feasibility of implementing CR in white spaces. This report provides a definition of white spaces identifies possible deployment scenarios and formulate key assumptions so as to conduct first sharing studies. White space refers to "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". Specifically, white space in the UHF band refers to 8 MHz segments of spectrum between active stations in a given area and in a given time.

The deployment scenarios can comprise licensed and licence exempt applications. The report does not have conclusions on the feasibility of cognitive sharing schemes for white space device (WSD) and recommends that any use of white spaces applications should be on non-protected non-interfering basis. The report recommends that further studies should be conducted in this regard.

Consequently, in 2011 CEPT SE43 produced ECC report 159 [54] that provides the technical and operational requirements for the possible operation of CR in the white spaces in 470-790 MHz band so as to ensure the protection of incumbent services. The studies consider sensing, geo-location and beacon (to a lesser extent) techniques for the protection of broadcasting services, PMSE services, Radio astronomy; aeronautical radionavigation services (ARNS) and mobile/fixed services. Regarding the ARNS and mobile or fixed services, the studies conclude that there is a need for further studies. This is because additional information would be required for the deployment consideration of such services in order to conduct an appropriate analysis, and the methodologies used for such analysis are not fully developed. In respect of the rest of the services, the studies conclude that sensing would not provide sufficient protection from interference. Accordingly, the studies recommend the use of geo-location to ensure protection of these services. The report provides the requirements and principles for the operation of WSD employing the geo-location approach. It identifies the type of information that should be communicated by the WSD and the geo-location database. The report also provides direction on a general methodology for input/output translation procedure between the WSD and geo-location database. The report also provides a general methodology to assess the amount of spectrum potentially available for use by WSD. Lastly, the report identifies the following issues that require further studies. Areas related to WSD characteristics, technical considerations on the protection of broadcasting services and PMSE, regulatory consideration on the protection of PMSE, protection of ARNS, protection of fixed and mobile services, requirements for geo-location database technique and assessment of spectrum potentially available for WSD.

3.3.5 CR activities in ETSI

In ETSI the standardization of CR is performed by the Reconfigurable Radio Systems Technical Committee (TC RRS). RRS is a generic term for radio systems encompassing software defined and or cognitive systems. The work of TC RRS is complementary to that of IEEE SCC41 and IEEE 802[5] and it is focused on the CR/SDR standards dealing with the specific needs of the European Regulatory Framework and CR/SDR for TV white spaces adjusted to the digital TV signals characteristics in Europe [73]. The work in this committee is carried out by four working groups (WG). Technical Report TR 102 838 [74] summarizes the feasibility studies conducted by the working groups.

3.3.5.1 WG1: System aspects studies

WG1 deals with RRS systems aspects and focuses on formulating an overall technical framework that maps various topics being studied in other working groups. It also identifies subjects for standardization and covers possible regulatory impacts of the RRS technologies [75].

The studies identify objectives and requirements of CR. The objectives include increased efficient use of spectrum, enhancing user experience, optimization of the mobile operator network and a longer term goal i.e. the shift from static to dynamic spectrum management and access. The studies also identify four spectrum use scenarios for CR namely: dedicated spectrum (licensed band) for short term, shared spectrum (licence-exempt bands) for short term, secondary usage in dedicated bands with primary users for medium term and spectrum dedicated for CR use for long term. Additionally, WG1 identifies a number of CR enabling

[5] Refer to section 3.4.

technologies. These include spectrum sensing, pre-cognitive radio technologies CPC, geo-location, primary protection database and reconfigurable base station management.

Furthermore, the studies develop CR systems concepts with centralized and decentralized approaches. The centralized approach is operator driven and for wide area use, in this case the central-network management system (C-NMS) collects traffic and spectrum usage information from composite wireless network (CWN) and allocates traffic to different radio networks in the CWN. On the other hand, the decentralized approach is aimed for local adhoc mesh networks through collaboration between autonomous mobile devices and networks. Such collaboration is enabled by cognitive control network.

3.3.5.2 WG2: Reconfigurable radio equipment studies

WG2 deals with network architectures for reconfigurable radio systems focusing on SDR as enabling technology supporting the CR functionalities introduced in WG 3 and by enabling the operational requirements.

The studies focus on identification of potential SDR standardization axes for both mobile devices (MD) and reconfigurable base stations (RBS). Regarding MD, the studies propose that technical specifications for these three interfaces (multi-radio access interface, unified radio application interface and reconfigurable RF application interface) should be developed and also for the SDR reference architecture specification for MD and radio programming model and interface specification for MD. Pertaining to RBS, the studies recommend that standardization should work on maintenance optimization, fast and cost efficient network deployment, flexible network operation regarding technology migration and spectrum reuse and fast network planning.

3.3.5.3 WG3: Cognitive network management studies

WG3 work is divided into two items namely: functional architecture (FA) and cognitive pilot channel (CPC). The WG developed two technical reports for the FA [76] and the CPC [77]. The first item deals with the requirements for the improvement of spectrum and radio resources in RRS and proposes FA as a generic architecture. The second item deals with the main concepts and possible implementation options for the CPC so as to improve utilization of spectrum and radio resources in RRS. CPC is defined as a channel that conveys the elements of necessary information facilitating the operations of CR and was initially proposed to facilitate the collaboration between networks and terminals in heterogeneous radio environment [73].

Regarding the FA, the studies identify main modules that are included in the FA namely; dynamic spectrum management, dynamic self-organizing network planning and management, joint radio resource management for multi standard radio resource management and configuration control module for execution of the reconfigurations. The studies make recommendation for the development of technical specifications for the FA.

In respect of the CPC, two deployment options have been developed namely: out of band CPC and in band CPC. The out of band CPC is conceived as a radio channel outside radio access technology (RAT) while the in band CPC employs transmission mechanism within the technologies of the heterogeneous radio environment. The studies conclude that further technical research activities for CPC.

3.3.5.4 WG4: Public safety studies

WG4 deals with the application of RRS to public safety area in two work items: user requirements and system aspects. It employs user requirements as inputs for the definition of the system aspects. WG4 identifies possible drivers for the application of RSS in public safety domain and concludes that the cognitive network management system (CNMS) is one of the main areas to be investigated and defines models of CNMS that could be applied to public safety. With regard to interoperability the studies recommend that the definition of interfaces at the network infrastructure level and some areas of security should be considered for standardization. Security areas include the definition and interfaces to ensure security of cognitive radio networks and data protection in adhoc and mesh RSS networks.

3.4 CR activities in IEEE

This section reviews CR activities in IEEE. The review is quite technical due to the technical nature of the standards.

The IEEE 1900 Standards committee was established in 2005 to develop standards related to the next generation radio systems and advanced spectrum management [78]. In 2007, this committee was reorganized to encompass all IEEE standards and named Standards Coordinating Committee (SCC41) on dynamic spectrum access networks (DySPAN). In 2010, the SCC41 was renamed IEEE DySPAN-SC. The work of this committee includes new techniques and methods of dynamic spectrum access radio systems with a focus on improved use of spectrum and the management of radio interference. The working groups under this committee deal with various standards for different aspects of CR.

The WG 1900. 1 formulates standard definitions and concepts for DSA relating to emerging wireless networks, system functionality, and spectrum management amendment. This WG creates a framework for developing standards in other WG within the DySPAN-SC. WG 1900.2 develops technical guidelines for analysing the potential for coexistence or in contrast interference between radio systems operating in the same frequency band or between different frequency bands. WG 1900.4 works on the architectural and functional definitions of the terminals and the network and the exchange of information between them. WG1900.4 works on two projects. 1900.4a amends 1900.4 to include architecture and interfaces for dynamic spectrum access networks in white space frequency bands. 1900.4.1 develops standards for interfaces and protocols enabling distributed decision making for optimized radio resource usage in heterogeneous wireless networks.

WG1900.5 defines a vendor-independent set of policy-based control architectures and corresponding policy language requirements for managing the functionality and behavior of dynamic spectrum access networks. This standard also defines the relationship of policy language and architecture to the needs of at least the following stakeholders: the regulator, the operator, the user, and the network equipment manufacturer. Follow on work on 1900.5.1 and 1900.5a is in progress. 1900.5.1 defines a vendor-independent policy language for managing the functionality and behavior of dynamic spectrum access networks based on the language requirements defined in the 1900.5 standard. 1900.5a amends 1900.5 by defining the interface description between policy architecture components. WG1900.6 defines the logical interface and supporting data structures used for the information exchange between spectrum sensors and their clients in radiocommunication systems. Subsequently, WG 1900.6 is working on a new standard, 1900.6a that amends 1900.6 to provide specifications to allow integrating 1900.6 based distributed sensing systems into existing and future dynamic spectrum access radio communication systems. WG 1900.7 specifies a radio interface including media access control (MAC) and physical (PHY) layers of white space DSA radio systems supporting fixed and mobile operation in white spaces without causing interference to existing users. The purpose of this standard is to enable the development of interoperable, cost effective, multi-vendor white space DSA radio systems in white spaces on a non-interfering basis to existing users. Recently the ad hoc group on DSA in vehicular environments was created within the DySPAN-SC to identify the direction and the requirement of DSA for Vehicular Communications.

Other relevant standards for CR are developed within the IEEE 802 LAN/MAN standards committee [79]. WG802.22 on wireless regional area networks specifies the air interface, including MAC and PHY layers, of point to multipoint wireless regional networks with professional fixed and portable terminals operating in UHF/VHF broadcast band between 54 MHz and 862 MHz. The aim of this standard is to enable use of CR in white spaces to facilitate broadband access particularly is sparsely populated rural areas on a non-interference basis to existing users. WG 802.11 is working on 802.11af standard that defines modifications to 802.11 MAC and PHY in order to meet the legal requirements for channel access and coexistence in white spaces. WG 802.16 is working on 802.16h standard that specifies policies and MAC enhancements to enable coexistence between licence exempt systems based on 802.16 standard and to facilitate coexistence of such systems with primary users.

3.5 Conclusion on regulatory and standardization activities at the international level

The sections above reviewed regulatory and standardization activities around the world at the international level. The review was done in the following organizations: ITU, IEEE, CEPT, ETSI and European Commission. There are similarities in terms of the CR activities in ITU-R, CEPT and the EU. The main concern is the protection of existing services from potential interference from services using CR. Accordingly the regulatory instruments focus on protection of existing services. Therefore, they consider the following enabling techniques for CR in varying degrees. Geo-location database, spectrum sensing, beacon and CPC/CCC. While paying more attention to geo-location and spectrum sensing, they recommend that the latter is least reliable and therefore may not provide sufficient protection to existing users. Consequently, they recommend the use of geo-location database as the most mature and reliable to ensure protection of existing services in the short term. The regulatory instruments also consider implementation scenarios of CR and their operational and regulatory implications.

With regard to standardization activities, IEEE and ETSI were reviewed. IEEE works on standards relating to CR, different committees deal with different aspects of CR. IEEE DySPAN standards committee works on new techniques and methods of DSA systems focusing on improved spectrum management and interference management. IEEE 802 LAN/MAN standards committee works on the use of TVWS by CR to provide broadband services. ETSI works on the standardization aspects of CR and its work is complementary to that of IEEE focusing on CR/SDR standards with European specific needs.

3.6 Country comparison of regulatory developments on CR

This section firstly reviews CR regulatory activities in the US, the UK and Australia. Secondly, it makes a comparison between the CR regulations of these countries.

3.6.1 Spectrum management in the US

Regulation of radio communications began in the US in 1912 [20]. Since then until the early 1990s, the US managed spectrum using the command and control method. In 1993, legislation was amended to allow the FCC to license spectrum through competitive bidding [25]. Furthermore, in 1997 legislation was passed that provides for the FCC to allocate spectrum in a way that provides flexibility in use. Until the 1990s spectrum policy at the FCC has been developed using an adhoc approach on a band-by-band basis and service-by-service basis [25]. General spectrum management review on a compressive basis took place in the 1990s. The first review was in 1989 by the NTIA, which investigated the fundamental spectrum objectives and led to the introduction of competitive bidding in 1993 [25]. In 1999 and 2000, the FCC engaged in public consultation on spectrum management and developed a number of policy statements

“Principles for reallocation of spectrum to encourage the development of technologies for the new millennium” focusing on spectrum management and “principles for promoting efficient use of spectrum by encouraging the development of secondary markets”, respectively [25]. In 2002, SPTF was established to assist the FCC in identifying and evaluating changes in spectrum policy that would result in increased public benefits obtained from spectrum use. The SPTF report [25] made a number of recommendations including that the FCC should allow for maximum feasible flexibility of spectrum use by both licensed and unlicensed used, and that the FCC should provide incentives for efficient use of spectrum.

3.6.1.1 Rulemaking on cognitive radio in the US

The US rulemaking regarding CR was initiated by the spectrum task report in 2002 [25]. This the report recommended among other things that the FCC should facilitate flexible, efficient and reliable spectrum use through opportunistic or dynamic access by using CR and consider additional spectrum for unlicensed devices through opportunistic spectrum use of existing bands by using CR in white spaces. Consequently, the first report and order and further notice of proposed rulemaking was published in 2006 [80]. The FCC allowed the operation of fixed unlicensed devices in vacant TV channels with the exclusion of TV channel 37 and 52 to 69; under the condition that they will not cause interference to TV and other existing services. The FCC prohibited the operation of personal/portable devices on TV channels 14 to 20 that are used by public safety services. However, the FCC did not adopt final technical rules for the operation of such devices in this notice.

Subsequently, in 2008 the technical rules to allow the operation of unlicensed devices in TV white spaces were adopted in the second report and order and memorandum opinion and order [81]. In this notice, the FCC adopted the following rules. The FCC provides for the operation of both fixed and personal/portable devices in the TV white spaces on unlicensed basis in channel 2 to 36 and 36 to 51 in the UHF and VHF bands. Fixed devices must use a geo-location database access and spectrum sensing to determine a list of available channels for their use. Fixed devices are required to sense at -114 dBm level. Fixed devices are allowed to operate up to 1 Watts transmitter output power and with an antenna gain to achieve 4W EIRP. Personal/portable devices are allowed to operate in two modes. In mode II, a device determines the available channels using its own geo-location access capabilities. In Mode I, a device is under the control of fixed or a personal/portable device operating in Mode II as it does not have the capabilities to determine available channels. Personal portable devices are allowed to operate up to 100mW EIRP and up to 40mW in cases where they operate on adjacent TV channels or other licensed services. The database will be created and administered by third parties selected by the FCC through a public process. All devices should undergo equipment certification process by the FCC laboratory.

In 2010, the FCC adopted a second memorandum opinion and order (MO&O) which updated the rules in the second report and order and memorandum opinion and order [82]. The greater part of the rules was upheld but the FCC made the following changes. The rules eliminate the requirement that devices must also sense to detect the signal of TV stations and wireless microphones in addition to the use of geo-location database. As a result, certain rules were amended to reflect that geo-location database is the only method for determining channel availability. For example Model 1 devices are required to verify channel availability and model 11 devices are required to monitor its location every minute except on sleep mode. The rules modify the previous rules governing measurement of adjacent channels. The rules require that communication between devices and geo-location database and between databases is secure. The rules also require that all information that is required to be in the databases be publicly available.

In 2012, the FCC made further changes to the rules in the third memorandum opinion and order [83]. The FCC was of the opinion that these changes will result in decreased operating costs for fixed devices and allow them to provide greater coverage therefore increasing availability of wireless broadband services in rural and underserved areas with a minimal risk of interference to incumbent services. The FCC made the following amendments. The rules for adjacent channel emissions are modified to specify fixed values, instead of varying the limit relative to the in-band power. The rules also slightly increase the maximum permissible PSD for each category of devices to 0.4dB. Table 3.1 shows these limits.

Table 3.1 FCC revised PSD and adjacent channel emission limits [Source: [83].

Type of TV bands device	Power limit (6 MHz)	PSD limit (100 kHz)	Adjacent channel limit (100 kHz)
Fixed	30 dBm (1 Watt)	12.6 dBm	-42.8dBm
Personal/portable (adj. channel)	16 dBm (40 mW)	-1.4 dBm	-56.8 dBm
Sensing only	17 dBm (50 mW)	-0.4 dBm	-55.8 dBm
All other personal/portable	20 dBm (100 mW)	2.6 dBm	-52.8 dBm

The FCC believed that the adoption of the rules on use of CR in TVWS would allow them to learn a lot about the potential for the unlicensed devices to cause interference to the licensed users and how to avoid that interference in the future. Accordingly, the FCC made a decision to review the rules within two years based on the types of devices on the market, the extent of their implementation, technical developments and interference problems that may have arisen.

3.6.2 Spectrum management in the UK

Similar to many countries, historically the UK has managed radio spectrum using the command and control method. While Ofcom acknowledges that this approach has been successful in the past, they realize that it is no longer appropriate due to the economic and technical developments that have led to an increasing demand for spectrum. The review of spectrum management in the UK was initiated by Cave report on the review of radio spectrum management [2]. This report made a number of recommendations relating to changes to spectrum management. The main recommendation was for the UK to move to market based approach spectrum management which includes auctions with trading and liberalisation. This began with the introduction of administrative incentive pricing that incentivizes increased efficiency in spectrum use by reflecting the economic value in the spectrum fees. In 2000 auctions were introduced in the UK to assign spectrum. The new approach of spectrum management in the UK is implemented through spectrum trading, spectrum liberalization and release of unused spectrum and allowing maximum flexibility in spectrum use. One of the spectrum policy objectives is to allow, wherever possible spectrum to be managed through the market, using trading and liberalization unless it is justified for public policy reasons to take a different approach.

3.6.2.1 Rulemaking on cognitive radio in the UK

The rule making on CR in the UK was initiated by the launch of Digital Dividend Review (DDR) in 2005 [84]. The DDR considered how to make the digital dividend available for new uses. Subsequently, the DDR statement was issued, which considered the use of interleaved spectrum by licence exempt devices. The statement proposed to allow licence exempt use of interleaved spectrum by cognitive devices as long as they do not cause interference to licensed users including Digital Terrestrial Television (DTT) and Programme Makers and Special Events (PMSE) services. Ofcom believed that applications by such devices are likely to encourage innovation and competition and benefit consumers and citizens. In February 2009, Ofcom published a consultation document on licence exempting cognitive access devices using interleaved spectrum [85]. The consultation dealt with the technical, operational and practical issues regarding the implementation of the cognitive radio devices. It considered three techniques of cognitive access: sensing, geo-location database and beacon. These techniques were assessed against three criteria that are consistent with the DDR objectives i.e. the risk of interference to licensed use, the efficiency of spectrum use and the practicality of introduction. The consultation concluded that the deployment of beacons in the medium term was unlikely due to the practical difficulties associated with them and that beacons do not have compelling advantages over the other two techniques. Therefore, there was no need to continue with the regulatory work to enable them. Pertaining to sensing and geo-location database, Ofcom concluded that they are inclined to enable both and will allow the stakeholders to decide on which technique they prefer as they both have advantages and disadvantages.

In July 2009, Ofcom issued a subsequent statement on licence-exempt cognitive devices using interleaved spectrum [86]. The statement further concluded that in the short to medium term, geo-location database should be implemented and promised to investigate further the speed at which the database can be updated and whether sensing would also be required in addition to geo-location. However, Ofcom acknowledged that they would prefer not to require sensing in addition to geo-location only if there is a strong need for it, as there are currently challenges in implementing the former. Ofcom further concluded that they would allow sensing alone as well as geo-location and modified the parameters for sensing to be more stringent than the levels set out in the consultation, i.e. 6 dB lower. Nevertheless, Ofcom noted that they would not make regulations for sensing only devices in the near future as the implementation of such devices is likely many years away. Table 3.2 sets out parameters for sensing and geo-location database proposed by Ofcom.

Table 3.2 Key parameters for sensing and geo-location proposed by Ofcom [Source: [86]

Cognitive parameter	Sensing (value)	Geo-location (value)
Transmit power	4 dBm (adjacent channels) to 17 dBm	As specified by the database
Transmit power control	Required	Required
Bandwidth	Unlimited	Unlimited
Out of band performance	<-46 dBm	<-46dBm
Time between sensing	<1 second	-
Sensitivity assuming a 0dBi antenna	-120 dBm in 8 MHz channel -126 dBm in 200 kHz (wireless microphones)	-
Location accuracy	-	100m

In November 2010, Ofcom issued a discussion document on using geo-location to enable licence exempt access to the interleaved spectrum [87]. The discussion document made the following conclusions.

The term “cognitive devices” was changed to “white space devices” due to the fact that when a database is used the device does not display cognitive behavior but simply responds to the information received from the database and that the term WSD is used in the US. There are two types of WDSs. The classification is similar to that of the US i.e. Mode I and Mode II but different terminology:

1) Master devices that contact a database to obtain a set of available frequencies in their area and
2) Slave devices that obtain the relevant information from master devices but do not contact databases themselves.

- Ofcom would set out the high level parameters that they would expect to see transferred to and from the database while letting the industry and standard bodies determine the detailed protocols.
- There should be flexibility with regard to the number and form (open or closed) of database. Nonetheless, each database will have to be registered and there must be a system to verify its correctness.
- As a result, there should be an agreed process whereby all database owners can download the parameters of licensed operations from single databases probable owned by the PMSE band manager and the broadcasters.
- The conclusion is that translation from transmitter location to frequency availability should be required within the database and not in the device. This decision might be reviewed in the future.
- Issuing a time validity stamp on frequency updates is a better solution than setting a minimum update time. Two hourly updates might initially be the default.
- Database providers are in liberty to use push technology if they so wish, that will not be incorporated into any regulations at this point.
- Further discussions are required with licensees and other stakeholders so as to set the parameter values used in propagation modeling.
- Bodies apart from Ofcom can host any databases under the condition that they are appropriately regulated.
- The issue about how can any costs associated with the database be met will not be addressed immediately and might be revisited as the market structure becomes clearer.

Ofcom made further conclusions after holding a workshop with the stakeholders on licence exemption and Ofcom directory for geo-location databases:

The white space devices would be licence exempt. For Ofcom to manage the database, the devices would initially consult Ofcom list of database and choose from this list its preferred database. The devices would contact the preferred database and provide as a minimum its location, the accuracy of that location (unless better than 100m), height above the ground if mounted on a mast. The database would reply within 10 seconds with an information set that includes the start and end frequencies for available bands, associated maximum power levels, a time validity for the information and any requirement for sensing to be used in addition. The database providers should update their algorithms within a period of one week.

Subsequently, in September 2011, Ofcom made the following conclusions in the statement entitled implementing geo-location [88]. Exempting WSDs from licensing requires a statutory instrument (SI) which provides the necessary legal framework for their operation, due to the fact that in the UK any device that emits radio signals must either have a licence or be exempted from licensing. Ofcom also concluded to further work on the following:

- Consult on and subsequently publish a SI exempting WSDs from licensing
- Work with the industry to enable information about licensed services in the interleaved spectrum to be made available to a database
- Spell out requirements for geo-location databases and providers that wish to be accredited listed on the Ofcom website

Ofcom decided to be proactive and went ahead with the implementation of WSDs and the development of geo-location database regulations despite that there are currently no European harmonized standards. Ofcom acknowledges that harmonization and standardization work in Europe is not at an advanced stage currently and that once the European standards are complete they will supersede the relevant national regulations. Ofcom aims to assist advancement of the European standards for WSDs in a timely manner consistent with the UK objectives as they believe that a harmonized approach is desirable.

3.6.3 Spectrum management in Australia

According to [89] Australia has been leading spectrum management liberalization for nearly two decades due to its geographical isolation and its commitment to management reforms. Australia has used administrative pricing which sets the prices to encourage efficient use of spectrum since the 1980s [90]. Spectrum trading and technology neutrality was introduced in Australia in the late 1990s through the Radiocommunications Act 1992 (the Act) [91]. The Australian Communications and Media Authority (ACMA) manages radio spectrum according the objects of the Act. One of the objects of the Act is to ensure efficient allocation and use of spectrum for the benefits of the public and provide a responsive and a flexible approach to meeting the needs of the spectrum users. In 2009, ACMA set out the following principles for spectrum management [92].

- Allocate spectrum to the highest value use
- Enable and encourage spectrum to move to its highest value use
- To the extent possible, promote both certainty and flexibility

- Balance the cost of interference and the benefits of greater spectrum utilization

Parallel to issuing the principles, ACMA also released a five year spectrum outlook 2009-2014 that outlines the spectrum requirements of key services over the next five years [93]. Since then ACMA has been issuing the five year spectrum outlooks annually.

3.6.3.1 CR activities in Australia

Even though Australia has been in the forefront of spectrum management reforms, it is lagging behind the UK and US in terms of regulatory activities regarding the implementation of CR. This might be due to ACMA view that third party agreements allow for the introduction of DSA technologies in principle without changes to the Australian regulatory arrangements and that a number of DSA scenarios in spectrum licensed bands are already possible under the current regulatory arrangements including: spectrum trading, spectrum leasing and third party agreements [94]. ACMA provides scenarios for licensees to authorize DSA to operate in the licensed bands. For example, a licensee could consider real time trading, leasing or selling white spaces to secondary users for the operation of DSA technologies. Another scenario is spectrum pooling, whereby licensees could cooperate to pool their underutilized spectrum to create greater spectrum capacity and sell it to third parties or to each other. The agreements between the licensees and the third parties or secondary users should be in line with the conditions of the spectrum licence. Nonetheless, ACMA acknowledges that there have been a limited number of trades or third party agreements among companies. ACMA is of the view that the introduction of DSA may increase industry keenness to consider third party authorization of spectrum on a real time basis. However, ACMA realizes that these scenarios assume the use of similar technologies by multiple users and that regulatory and technical challenges arise when heterogeneous technologies share spectrum in a dynamic coordinated manner.

Furthermore, ACMA is of the view that DSA technologies can be accommodated by the current class licensing regime under the condition that they do not cause interference to other services. A class licence is issued to permit any person to operate specified devices for a certain purpose as long as such person adheres to the conditions of the licence [91]. The conditions of the licence can include the frequency band and other technical requirements, compliance to standards and location of operation. A class licence is similar to licence exempt or open access method. However, ACMA cannot issue a new class licence in a spectrum licence band even if it was in agreement with all licensees in the band as the section 138 Radiocommunications Act 1992 prohibits the issuing of a class licence authorizing the operation of radiocommunication devices in a part of the spectrum that is designated for spectrum licences. As such, this requires amendment to the law to allow ACMA to consider the inclusion of class licenses in spectrum licence bands such as the use of TVWS in broadcasting bands. Accordingly, section 138 of the Radiocommunications Act was amended in 2011 to allow ACMA to issue a class licence in part of the spectrum designated for spectrum licences under the under the following conditions:

Issuing the class license will not cause interference to the services of spectrum licensees, issuing the class licence would be in the public interest and that the ACMA must consult all licensees that may be affected by the proposed class licence.

In its spectrum outlook (2011-2015) ACMA undertook to work on arrangements to address spectrum management issues related to DSA technologies and to be mindful of these technologies when developing technical frameworks for new and expiring spectrum licences. ACMA also pointed out its intention to issue a discussion paper in this regard in 2011 [95]. However, to our knowledge ACMA has not yet released a discussion paper on this issue. In the subsequent spectrum outlook (2012-2016) ACMA reiterates that regulatory arrangements associated with DSA/CR will be subject to further work and that it is mindful of such technologies when designing technical framework for new and expiring spectrum licences.

In addition, in the initial consultation on the future arrangements for 900MHz band published in May 2011, ACMA is considering a review to facilitate the introduction of new technologies including CR in the 900 MHz band [96]. ACMA seeks comments on any regulatory measures that should be put in place in order to facilitate the implementation of CR in the 900 MHz band. ACMA published the future spectrum requirements for mobile broadband –towards 2020 in parallel with the 900 MHz consultation. In this document ACMA also seeks comments on how it could include new technologies that have a potential to provide greater frequency efficiency and utilization, such as CR in the current and new regulatory arrangements. Nonetheless, ACMA has not yet started with a regulatory process that specifically deals with technical and regulatory requirements for the introduction of CR. It is not clear as to why ACMA has not yet started the process. It is not clear if the reluctance of ACMA to start the regulatory process in this regard is due to the reluctance of the spectrum licensees to allow secondary access, as [89] argues that spectrum licensees in Australia are reluctant to permit secondary access.

3.6.4 Country comparison of CR regulations

There are similarities and difference between CR regulatory activates of the countries discussed above. The US and the UK have both have embarked on a rulemaking process to allow the operation of CR in the TVWS. The US was the first country to start the process and the UK followed. Australia has not really started with the rulemaking process specifically for cognitive radio devices. This may be due to ACMA's view that some DSA scenarios are possible in the current regulatory arrangements. The ACMA has expressed in several documents; its intention to work on regulatory arrangements associated with DSA/CR. However, it is not clear at the moment as to when they will start the process.

Regarding the US and the UK there are similarities and differences in terms of the regulations. Regulations in the UK and the US allow the operation of CR in TVWS on a licence-exempt basis.

For the identification of white spaces, the regulations permit the use of geo-location database and sensing. Some of the differences are attributable to the regional differences as the US and the UK belong to different ITU-R regions. The differences also emanate from differences in the principal legislations and relevant regulations that govern management of radio frequency. For example the channel plan spacing for television transmission in the UK and the US is 8MHz and 6MHz respectively. The technical standards for DTT are different, the US standard is ATSC and the UK standard is DVB-T. As a result CR devices operating in the white spaces in the US should be able to detect very low DTT signals. Another difference between the two countries is the availability of TV white spaces. The US has a number of TVWS available due to its "cable and satellite TV centric" [71]. There are also differences regarding equipment certification. The US requires type approval of equipment by the FCC while in the UK there is no such requirement instead the R&TTE directive mandates the manufacturer to certify equipment. Table 3.3 highlights the differences between the US and the UK in terms of the white space devices regulations. Australia is not included in this table because it has not yet started with the regulatory process regarding CR devices.

Table 3.3 Comparison of the US and the UK CR regulations

	US	UK
Frequency bands	WSD operate in 54-72 MHz, 76-88 MHz, 174-216 MHz, and 470-698 MHz	WSDs operate in 470-550 MHz and 614-790 MHz
WSDs classification	Fixed and personal/portable devices	Master and slave devices
Technique for determining TVWS	Fixed devices use geo-location or spectrum sensing	Geo-location and sensing only allowed
Technique for determining TVWS	Portable devices operate in Mode II (access database itself) and Mode I (controlled by a fixed device or Portable operating in Mode II)	Master devices access database/sensing itself and slave device controlled by master device
Certification rules	All devices should be type approved by FCC	All devices should comply with R&TTE Directive
Sensing only devices	Require additional tests	No additional tests required
Sensing time	Every minute	Every second
Transmit power-non	100mW	50 mW

adjacent channels		
Transmit power-adjacent channels	40mW	2.5mW
Geo-location accuracy	50m	100m
Certification of database	FCC certifies the database and designate administrators	Database operated by OFCOM and other regulated bodies

3.7 Conclusion

As stated at the beginning of this chapter, this section answers sub-research question 2.

2. *To what extent will the current and new policy developments (international and national) determine the impact of dynamic spectrum technologies on spectrum management?*

This chapter reviewed regulatory and standardization activities around the world at the international and national levels. At the international level, the review was done for the following organizations: ITU, IEEE, CEPT, ETSI and European Commission. Regulatory and standardization activities on CR in these organizations are mainly concerned about the protection of existing services from potential interference from services using CR. Therefore, their regulatory instruments focus on protecting existing services. To protect such services they recommend the use of geo-location database as the most mature and reliable in the short term. Spectrum sensing is considered in the long term, when the current challenges have been solved.

Pertaining to standardization activities in IEEE and ETSI. IEEE DySPAN standards committee works on new techniques and methods of DSA systems focusing on improved spectrum management and interference management. IEEE 802 LAN/MAN standards committee works on the use of TVWS by CR to provide broadband services. ETSI's work on the standardization aspects of CR is conducted within TC RRS and is complementary to that of IEEE focusing on CR/SDR standards with European specific needs.

At the national level, regulatory activities in Australia, the UK and the US were reviewed. Australia has not yet started making specific rules for the introduction of CR even though it has expressed its intention to start process in several documents. On the other hand, the UK and the US have developed regulations on the operation of CR in TVWS on licence exempt basis. The rules in the UK and the US concluded that geo-location database is the most reliable approach in the short term for detecting white spaces, even though they allow sensing. There are differences in terms of the regulations. The US has taken a rather less flexible approach. For example, sensing only devices require additional testing in the US. Some of the differences are attributable to different regulatory frameworks of spectrum management in these two countries. For example they have different channel spacing for television transmission, their certification processes for equipment are different, they use different DTT standards and the amount of TVWS may be different as well.

For CR to be implemented successfully it requires to be standardized at a global level or at least at a regional level for interoperability and economies of scale. Therefore the current standardization and regulatory developments will determine the introduction of CR and in turn determine the impact of CR on spectrum management. These developments will give stakeholders confidence to develop equipment and invest in CR networks to enable commercial deployments. The developments will also provide assurance to existing users that their services will be protected from interference from CR. Moreover, for CR to be implemented successfully sufficient spectrum should be made available for use by CR for secondary access. The current regulations in the US and the UK are specific to the operation of CR devices in TVWS and therefore limit the operation of CR to these bands. Even though these regulations are limited to television bands, the regulations will have an effect not only in the US and the UK but in other countries as well. Particularly, the countries that have adopted a “wait and see” approach, may be encouraged to embark on a regulatory process for the introduction of CR. The successful implementation of CR in the TVWS is likely to lead to further introduction of CR in other bands. These developments will determine the impact of CR on spectrum management however the extent of the impact is not clear at the moment and requires further investigation.

4. Market developments in the wireless communications market relating to cognitive radio

This chapter answers sub-research question 3.

3. *How will the markets affect the take-up and ultimately the success of dynamic spectrum access technologies from a spectrum management point of view?*

This chapter explores the market aspects of cognitive radio systems in the wireless communications market. This is relevant to answer sub-question 3 of this thesis. In order to understand the potential effects of the market aspects of cognitive radio systems on spectrum management, it is essential to understand the structure of the wireless communications industry and how the industry will evolve as a result of the introduction of cognitive radio. The evolution of the industry due to cognitive radio is verified by means of interviews, refer to chapter 1. The chapter is structured as follows. The first section provides an overview of the current wireless communications industry structure. The second section briefly presents Porters five forces model that is used to analyse the wireless communication industry. The third section employs Porters competitive forces to analyse the industry structure and the potential impact of cognitive radio systems on the industry. The fourth section discusses the evolution of the industry in light of the current trends and uncertainties relating to cognitive radio. The fifth section discusses the impact of the implementation of CR on spectrum management. The sixth session concludes the chapter.

4.1 Structure of the wireless communications industry

In this section the industry structure of the current wireless communications industry is analysed using Porters five forces. This model is mostly used to assess the attractiveness of an industry. As, stated in chapter 1, this chapter focuses on mobile communications services and wireless data services (Wi-Fi). This is because of the increasing demand for spectrum in this industry due to accelerating growth in wireless data traffic generated smart phones, tablets and other portable internet access devices.

Radio spectrum is a key resource which makes it possible for the wireless communications industry to provide services. The industry provides services via wireless access facilities including mobile voice, mobile data, and wireless internet access. The current industry structure in the wireless communications industry is based on static spectrum access. As a result services are grouped into well-defined, distinct value chain silos [97]. Operators deploy purpose built networks in dedicated spectrum bands to provide specifically a class of narrow applications. Consequently, mobile services and wireless LAN (Wi-Fi) services are based on different and incompatible business models and spectrum management regimes [97]. The industry consists of several providers offering various services. First, mobile network operators (MNO) provide network facilities to service providers and also provide services to the end-user such as mobile voice, messaging and data services. The traditional MNO exhibit vertical integration with a dedicated infrastructure. Network and service provisions are integrated and provided by one entity. For example, a MNO invests on network equipment and spectrum rights and then sells service to end users who pay a fee for usage. These providers can be nationwide or regional. The regional providers offer services in multiple large and medium sized metropolitan areas around a country. Second, resellers or mobile virtual network operators (MVNO) buy wholesale mobile services from MNOs and resell these services to end-users. Third, wireless internet service providers (WISP) provide internet based technology networks such as Wi-Fi. Wi-Fi is based on horizontal integration which adheres to the LAN architecture and other protocols from the computer industry. Fourth, service providers (SP) provide services and content. The current industry structure is analysed below employing Porter's five competitive forces.

4.2 Porters five forces model

This section presents briefly Porters five forces model based on [98] and [99].

Porters five forces model is a framework that was developed by Michael Porter in 1980, which is used for industry analysis and business strategy development [98]. Porters five forces model is one of the mostly used models to analyse competition and attractiveness in an industry. The model is relevant to the wireless communications industry in that it provides insights into the competitive environment in which the existing firms operate as well as potential opportunities and threats they face. The model attempts to explain the competition and industry structure of the wireless communications market in terms of its competitive forces and how the introduction cognitive radio systems will affect it.

According to Porter, in order to understand competition and profitability in an industry, you need to analyse the industry structure in terms of the five competitive forces. The fives forces are threat of new entrants, bargaining power of suppliers, threat of substitute products or services, bargaining power of buyers and rivalry amongst existing competitors. These forces collectively determine how profitable an industry is and the strongest force/s is the most important when formulating the strategy. In each industry, different forces are dominant and in turn shape the former. When applying this model, analysis of industry structure (reflected in the strength of the forces) is fundamental as it identifies the basic characteristics of an industry embedded in its technology and economics. The five competitive forces are shown in figure 4.1. The five competitive forces are briefly discussed below.

First, the threat of entry refers to threat posed by new entrants to existing competitors in an industry. An attractive industry in terms of profitability will attract new entry if it is easy for them to enter the market entrant i.e. if barriers of entry are low. According to Porter, the threat of entry in an industry depends on the current barriers and on the reaction that the entrant can expect from the existing competitors [99]. The major determinants of threat to entry are: economies of scale, product differentiation, capital requirements, and cost disadvantages independent of size, access to distribution channels and government policy. The expected reaction from the existing competitors will also affect the decision of the potential new entrants of whether to enter the industry or not. Threat of entry changes as its determinants change.

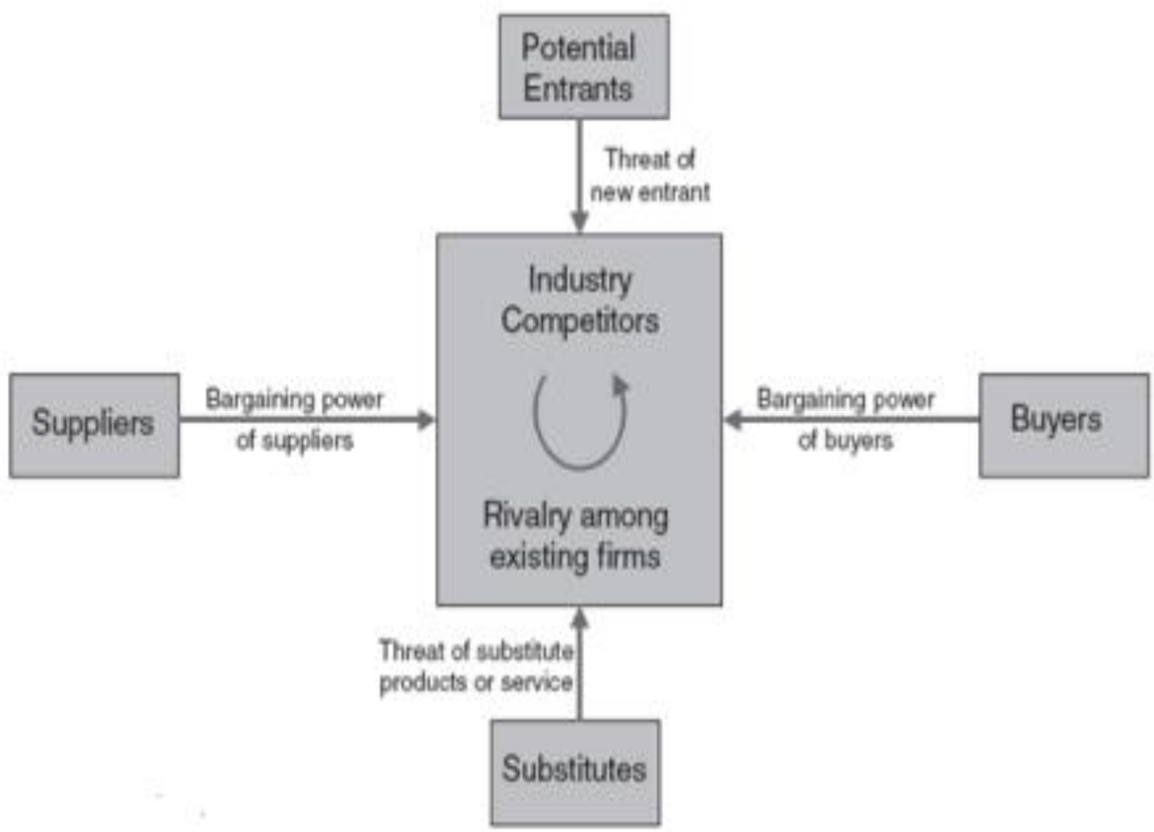

Figure 4.1 Five competitive forces [Source: [99]]

Second, bargaining power of suppliers refers to the ability of suppliers to determine the price and terms of supplies. An industry requires suppliers who provide raw materials, components, services and other supplies. Bargaining power of suppliers can be exercised in an industry by raising prices or decreasing the quality of purchased goods and services [99]. In doing so, the suppliers can therefore reduce profitability in an industry. The bargaining power of a supplier group depends on a number of factors including the following: it is dominated by a few companies and is more concentrated than the industry it sells to, its product is unique or least differentiated or has high switching costs and the industry is not an important customer of the supplier group.

Third, bargaining power of buyers refers to the ability of buyers to influence the setting of prices. Similar to suppliers, buyers can exercise bargaining power on industry participants by demanding higher quality, forcing down prices and playing competitors against each other, in doing so driving down industry profits [99]. The bargaining power of buyers depends on a number of characteristics of the market including the following: if buyers purchase large volumes, if the products the buyer purchases from the industry are standard or undifferentiated, switching costs, if buyers can backward integrate and if the buyer has full information about the product. These characteristics can be attributed to commercial buyers and consumers with some modifications.

Fourth, threat of substitute products refers to the availability of substitute products. Porter refers to substitutes as products that can perform the same function as the product of the industry [99]. Firms in one industry compete with other industries that provide substitute products. The maximum price firms can charge for a product is determined by substitutes. Therefore substitutes limit industry profits if the prices for substitute are more attractive to buyers.

Fifth, rivalry occurs when competitors feel the pressure or the opportunity to improve their positions in the market [99]. Rivalry takes place in the form of competitors engaging in price competition, advertising battles, launching new products, and increased customer services. When a firm initiates rivalry tactics that are noticeable to its competitors, the latter may strike back to counter the move. This can be detrimental to the industry if it escalates. For example, price competition can result in lower profitability. Factors that determine the strength of competitive rivalry change overtime. For example, when an industry reaches maturity its growth rate declines and that results in declining profits and thus increased rivalry. The intensity of rivalry in an industry is determined by a number of factors namely: numerous competitors, slow industry growth, high fixed costs, and lack of switching costs, diverse competitors, high strategic stakes and high exit barriers.

4.3 Analysis of the wireless communications industry

The next step as an attempt to investigate the impact of market developments in the wireless communications industry relating to cognitive radio systems is to do an industry analysis utilizing Porter’s five forces model. This section analyse each of the five forces in the wireless communications industry.

4.3.1 Threat of entry

Entry depends mostly on technical, regulatory and market developments. Threat of entry in the mobile communications industry is fairly low due to high barriers of entry. Access to spectrum is crucial for a potential entrant to enter the market. Access to spectrum is determined by spectrum policy. Access to spectrum can be obtained in various ways including auctions as discussed in chapter 2. Buying spectrum through auctions requires huge initial acquisition costs while leasing spectrum can reduce the initial acquisition costs distributing it over time. The number of spectrum licences that can be granted depends on how much spectrum is available. Therefore spectrum policy is a major source of barriers to entry in the wireless communications market. Spectrum policy also drives standardization of equipment on a few dominant technologies, in turn causing barriers of entry for network and operator markets [100].

In addition to the spectrum costs there are also costs for deploying a network. As such a new entrant network provider is required to invest billions or millions of dollars in capital expense depending on the geographic scale of the network. Economies of scale is one of the major sources of barriers to entry in the market in that a high level of network deployment costs pertaining to the number of customers can limit the number of firms that can enter and survive the market [101]. As a result areas with low population density tend to have fewer network based facilities than high population density areas. A new entrant is also required to secure distributions channels for its products. Considering that existing firms have distribution channels, a new entrant has to convince the channels to distribute its products through discounts and cooperative advertising allowances [98]. Marketing and distribution expenditures to develop distributions channels play a key role on how the new entrant competes for customers. For example an entrant that has an existing customer base for other services is likely to have lower expenditures on marketing and distribution than an entrant that has no customer base. In many countries mobile operators are not only dominant in network and communication services but also in distribution networks. This makes it difficult for new entrants to establish their own distribution networks.

These high entry barriers can be lowered, if the new entrants enter the market as an MVNO. In addition, technological developments can have an impact on entry for both potential entrants and incumbent forms [101]. For example the introduction cognitive radio systems and LTE. Licensing of spectrum for LTE can provide an opportunity for new entrants to enter the industry. Dynamic spectrum access through cognitive radio systems will lower entry barriers. DSA encourages vertical disintegration and horizontal integration in the wireless communications market similar to what has been taking place in the wired communication services [97]. Similarly [102] argues that horizontal integration lowers barriers to entry for application developers since the infrastructure is made readily available. DSA promote horizontal integration and allow new type of business offerings to emerge such as MVNOs, spectrum brokers and vendors of customer equipment that support end user provisioned ad hoc networks [97]. New types of smaller scale, low cost entry will be feasible in the data communications services. A new entrant can start with an affordable limited spectrum access and later increase its spectrum access to match its capacity needs as the business grows. Consequently, business models of incumbents that are developed around spectrum scarcity will become less viable [97].

4.3.2 Bargaining power of supplies

The suppliers of equipment, IT and software platforms to MNOs and Wi-Fi service providers is dominated by few companies. The major IT and software platform vendors serve many firms in several industries. The suppliers of handsets also have wider networks of buyers as they can sell the handsets to other buyers besides the MNOs. The bargaining power of these suppliers has a significant impact on the attractiveness and the profitability of the mobile communications and wireless data industry. Equipment suppliers do not only sell equipment to MNOs but also build and maintain the latters' networks and offer consultancy services as well. Moreover, the MNO revenues are declining due to the following: declining voice revenues, increasing wireless data traffic which generates 80% of the traffic but only contributes to 2% of the revenues and flat rate charging for mobile data [103]. As such they are under pressure to embark on cost saving strategies and that include lowering prices for equipment and network upgrades. So they need to have a higher bargaining power to lower the prices of equipment. Given that on the face of it, it looks like the bargaining power of suppliers is high. However, this is not the case. Even though equipment suppliers are not that many, competition between them is quite high. Increase in standardization has led to increased competition among suppliers which in turn has lowered the bargaining power of suppliers. Similarly, the emergence of Chinese telecommunications equipment vendors has led to increased competition among suppliers.

Furthermore, MNOs are an important customer of the network supplier group because the former represent a significant fraction of the latter sales. As such that diminishes the bargaining power of equipment suppliers over MNOs. However, it seems the introduction of cognitive radio systems is likely to increase the bargaining power of suppliers as this gives them the opportunity to upgrade equipment and offer more services to a wider group of buyers.

4.3.3 Bargaining power of buyers

Traditionally the bargaining power of buyers of MNO services is very weak as the services are provided by few firms and the switching costs are quite high. First, each market is served by three or four MNOs serving millions of end users. Second, the switching costs for end users are significantly high. The high switching costs are attributed to the following. Acquiring information about other service offerings of other MNOs in the market, costs associated with changing your telephone number or number portability, liability due to early termination costs of a two year subscription contract and costs associated with unlocking the phone or buying a new one in countries where SIM locking is allowed. On the other hand Wi-Fi services are offered by several firms and the switching cots are low. As such buyers of Wi-Fi services possess a stronger bargaining power over their suppliers. The integration of Wi-Fi and cellular through a smart phone, high mobile data plans and slower download speeds is making it easier for buyers to switch between cellular and Wi-Fi services. The introduction of cognitive radio systems will increase the number of MNOs or service providers due to lower barriers to entry in doing so increasing the bargaining power of buyers.

4.3.4 Threat of substitute products or services

The threat of substitution relating to mobile voice services is relatively low. Even though fixed telephony and VoIP offers a cheaper substitute for voice services. These services have limitations as substitutes to mobile voice services because they do not offer mobility. However, the threat of substitution for broadband services is higher. Wi-Fi systems provide substitute services to end-user even though they do not provide actual mobility. As such Wi-Fi systems services can be seen as threat substitute services to cellular services. For example, the SFC associates Ltd study views Wi-Fi and other WLAN as potential substitutes for cellular roaming services and that they can put pressure on MNO to reduce retail prices for roaming [104].

Furthermore, due to declining revenues and increasing wireless data traffic MNOs are considering different strategies including investments in Wi-Fi networks. The integration of cellular and Wi-Fi systems is increasing the threat of substitution of mobile broadband services. MNOs view integration of cellular and Wi-Fi systems as a way to reduce their risks and gain more benefits [104]. Considering the following [103] :

- data traffic is mostly (90%) generated indoors
- The users are stationary or nomadic
- The users are known at (at the office or at home)
- No need to deal with wall attenuation

MNO can offload their heavy mobile broadband traffic to local networks instead of deploying out door base stations. Studies suggest that capacity expansion using femtocells or Wi-Fi systems compared to expansion using macro or micro base stations results in large cost savings in the range of 20 times [103]. The choice between femtocells and Wi-Fi will depend on the availability of spectrum and interference risk. Substitution may be fast-tracked by the increase spectrum sharing spectrum through cognitive radio systems.

4.3.5 Rivalry among existing firms

Rivalry among the MNOs is expected to intensify as the industry growth is declining due to the saturation of the market. MNOs need to develop retention strategies and customer service improvement and also innovative strategies to attract new customers. As discussed in the previous section traditional MNOs are encountered with declining profitability in the industry. This is accelerated by the integration of Wi-Fi and cellular systems through smart phones and tablets which reduce the switching costs between services. In addition, the large internet and software based firms are willing to enter the mobile communications network market and see spectrum sharing through cognitive radio systems as an opportunity to do so [104]. The white space coalition (Dell, Google, HP, Intel, Microsoft and Phillips) participated in the FCC rulemaking on white spaces in an attempt to influence the rules. Google is involved in content and application value chain and in device operating systems i.e. Google android. Google, Microsoft and Amazon have entered the mobile access market by offering bundled services to the end-user including mobile broadband access, services and devices. For example; Amazon kindle is a device with built in cellular access capability to down load and read electronic books. MNOs are not only competing amongst each other but with internet and software large firms as well. Consequently the attractiveness of the market is declining causing rivalry to intensify.

4.3.6 Summary of the analysis of the wireless communications industry

This section summarises the analysis of the wireless communications industry.

This section above analyses the impact of market developments relating to cognitive radio systems in the wireless communications industry, using Porter's five forces model. In summary, threat of entry in the mobile communications industry is low due to high barriers of entry. The barriers of entry result from access to spectrum and costs associated with network deployment, marketing and distribution networks. However, the introduction of CR can lower entry barriers by allowing easy access to spectrum as it encourages vertical disintegrations and horizontal integration. Bargaining power of suppliers is low due to competition within the suppliers. CR introduction may change this as suppliers will have the opportunity to upgrade the equipment and offer services to a wider group of buyers. Bargaining power of buyers of MNO services is weak due to high switching costs when switching to competing services. The high switching costs are attributed to costs associated with changing numbers or number portability, early termination of the subscription, buying a new phone or unlocking the phone and acquiring information about service offerings. CR introduction will increase the bargaining power of buyers as the number of firms providing the service will increase due to lower barriers of entry. Threat of substitute products or services is low particularly in mobile voice services. The threat of substitution for broadband services is higher as Wi-Fi services can be considered a substitute. Substitution can be accelerated by the increase in spectrum sharing through CR. Rivalry among the MNOs is expected to intensify as the industry growth is declining due to the saturation of the market. Large internet and software based firms see spectrum sharing through CR as an opportunity for them to enter the market. This analysis demonstrates that the threat of entry is the strongest force in this industry as it has an impact on other forces as well. CR has a potential to change the structure of the wireless communications industry as it will increase the threat of entry.

4.4 Evolution of wireless communications market

The next step is to analyse the key factors that impact the industry evolution. This section first briefly discusses a few determinants of industry evolution based on [99] that are most relevant to the wireless communications industry. Second, it discusses the industry trends that have an impact on the introduction of cognitive radio systems. Third, it discusses the uncertainties in the wireless communications industry that will determine the introduction of CR and ultimately determine the success of cognitive radio systems from a spectrum management point of view.

Changes in competitive forces results in changes in the industry structure. Industry evolution can make an industry more or less attractive. It is important for firms to understand the process of industry evolution in order to make strategic adjustments. Porter lists a number of determinants of industry evolutions that can be used to predict industry changes [99]. First, trends in needs. Demand for a product in an industry is affected by a lot of factors including lifestyle, tastes philosophies, and social conditions of the buyers that change over time. Second, reduction of uncertainty. A great deal of uncertainty in most industry is about the size of the potential market, nature of potential buyers and whether technological problems can be overcome. Overtime these uncertainties can be solved for example a technology can be proven or disproven. Reduction of uncertainty can attract new entrants into the industry. Third, product innovation plays a significant role in industry structural change. Product innovation can stimulate industry growth by widening the market or enhancing product differentiation. Fourth, Government policy change can have significant effect on industry structural change through regulation of certain parameters such as entry to the industry, competitive behaviour and profitability. Fifth, entry and exit, firms make a decision to enter the market when they see opportunities and growth that surpass the cost of entry. According to Porter, based on case studies potential entrants view industry growth as the most important indicator for profitability in an industry, although this can be a wrong assumption. Entry can also occur subsequent to indications for growth such as regulatory changes and product innovation. Exit changes an industry structure by decreasing the number of firms, in turn increasing the dominance of the leading ones. Firms exit when they believe that there is no possibility of earning their return on investment that exceeds the cost of capital. In the following section industry trends and uncertainties are analysed as they the key factors that will determine the introduction of cognitive radio systems in the market.

4.4.1 Industry trends

Wireless data traffic is growing exponentially. This growth is generated by traffic from smart phones, tablets and other portable internet access devices. According to Cisco internet traffic from wireless devices will surpass the volume of traffic from wired devices by 2016 [105]. Figure 4.2 shows the growth of wireless traffic generated by mobile or portable devices in relation to traffic generated by wired devices. Figure 4.3 shows traffic by device and demonstrates that smartphones and laptops lead traffic growth but tablets and M2M devices will account for a more significant portion of the traffic by 2016. This is the most significant trend in driving the demand for spectrum as the growth in data traffic requires additional network capacity.

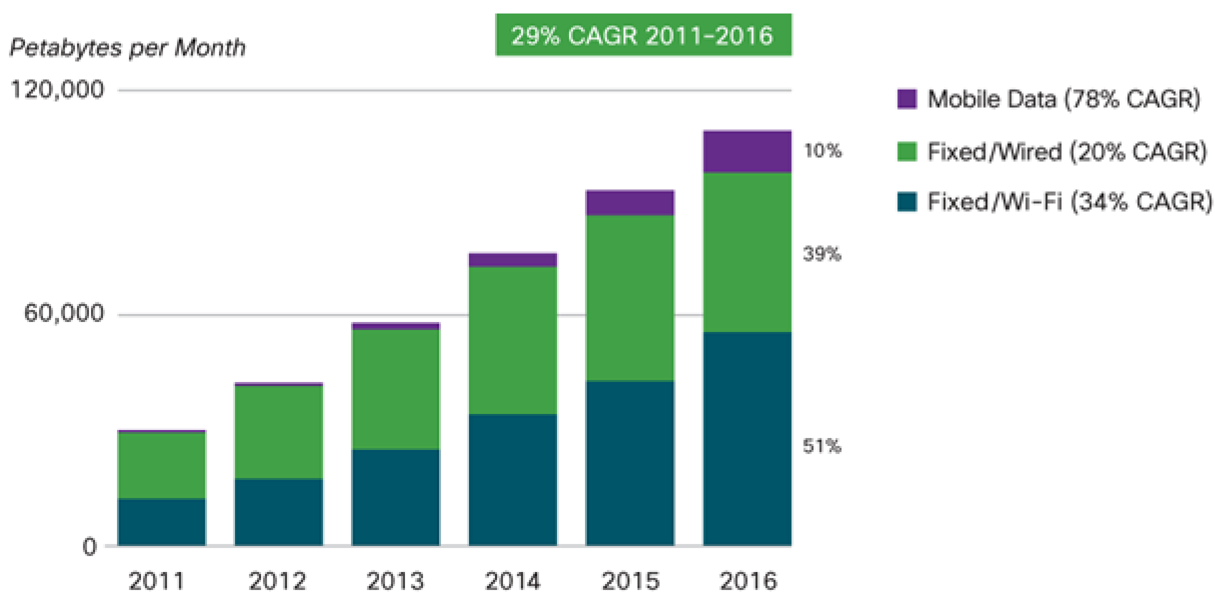

Figure 4.2 Global IP traffic - Wired and Wireless [Source: [105]]

This demand is dependent to a greater extent on the growth and diffusion of high bandwidth consuming applications. In addition this demand is attributed to flat rate pricing of mobile broadband [106]. Wireless broadband access is based on two technologies namely: Wi-Fi based local network systems and UMTS/LTE systems. These technologies fall into two different spectrum licensing approaches and they are integrated through a smart phone which is the main driver of spectrum demand in Europe [104]. Wi-Fi networks provide relief for congestion of MNO networks through data offloading. To cope with this demand MNO impose data caps and throttle end users who are heavy users of bandwidth, as a consequence end-users switch to Wi-Fi for internet access whenever possible. Globally, Wi-Fi accounted for 70% of the smart phone data traffic in the beginning of 2012 [107]. The growing demand for wireless broadband also arises from applications such as machine to machine (M2M) communications, refer to figure 4.3. The trend of increasing data traffic on Wi-Fi networks will lead to a significant increase of commercial services on licence exempt bands and gaining a significant market share. This is likely to lead to an increase in spectrum bands that allow dynamic spectrum sharing.

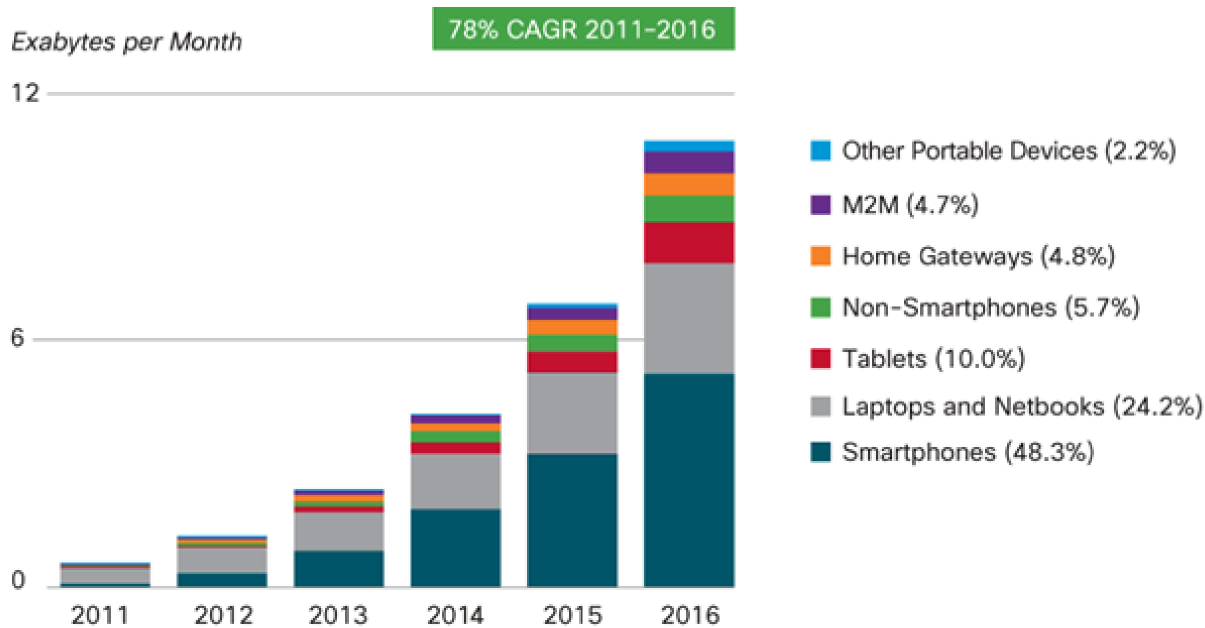

Figure 4.3 Traffic growth by device [Source: [108]]

These trends result in increasing demand for spectrum for both licensed and licence exempt spectrum for UMTS/LTE systems and Wi-Fi systems respectively. Dynamic spectrum sharing through cognitive radio is viewed as one of the solutions to this demand. There is a growing interest from academics, industry and regulatory bodies in the use of CR for dynamic spectrum sharing resulting in the emergence of many research projects. As discussed in the previous section the introduction of CR will promote new entry due to the lowered entry barriers, as a result competition in the market will increase. It is expected that MNOs will diversify their business models to deal with vertical disintegration. Furthermore, as discussed in previous sections, MNOs are faced with declining revenues, in order to solve these challenges there are number a strategies available for them such as reduction of network costs, increased revenues from existing services and new types of services for new sources of revenue [103]. It is expected that MNOs will provision multiple RAT in their networks to secure new business models. Furthermore, MNOs are turning into Wi-Fi and other WLAN systems to off load their mobile data, it is expected that in the future they will support the need for more licence exempt spectrum to satisfy their customer needs [104].

As discussed in chapter 3, there are a number of activities relating to CR undertaken by regulatory bodies at the international, regional and national level. The interviews argue that dynamic spectrum sharing through CR is the solution to the increasing demand of spectrum. The interviews indicate that MNOs are interested in CR but not necessarily for secondary use of spectrum in their licensed frequencies but for their own benefits. One interviewee mentions that MNOs are interested in CR for their own use to optimize their networks to the different radio access technologies (RAT) and they are focussing on network sharing and traffic offloads as strategies to increase their revenues. The success of dynamic spectrum access through the use of cognitive radio to address the future demand for spectrum will depend on flexible policies, advances in CR technology and feasibility of business cases.

4.4.2 Uncertainties in cognitive radio systems market developments

Even though it is widely agreed that cognitive radio is an enabling technology for dynamic spectrum sharing and that it has a potential to meet the current demands of spectrum. It is still not clear when CR will be commercially implemented. The reason for this is that there are uncertainties around CR deployments and they range from technical, policy and market aspects.

4.4.2.1 Technical aspects of cognitive radio systems relating to market development

As discussed in chapter 2, the key technical issue is the risk of interference. The risk of interference should be reduced to acceptable levels and this can be done by demonstrating safe operation with early deployments in bands where spectrum access rules for non-interfering operation is less complex [97]. Similarly, the interviewees argue that one way to reduce uncertainty about interference is to gain experience from test cases while at the same time providing a stable framework to invite investors and protect the interests of incumbent spectrum users. This will gradually build trust in cognitive radio. The interviewees went on to say that conducting experiments and trials that are based on proven methods such as database methods to protect primary users and use sensing for less critical systems or intra systems protection will build trust amongst the stakeholders. A transition to sensing can be made later as the solution to the hidden node problem becomes available. It should be noted that sensing cannot be used for some systems as hidden node problem cannot be solved with sensing alone. So experiences in the TVWS will be an important determinant of whether further steps will be taken to implement of CR. Interviewees note that some spectrum bands are not feasible for CR such as passive services and safety of life services; as they cannot cope with the risk of interference. The interviewees agree that TVWS will either make or break CR implementation in that if it becomes a success there will be incentives to go forward with it or if it fails the industry will be reluctant to launch commercial deployments.

As discussed in chapter 2, the other technical issue is that CR devices bring about new challenges for the certification process as it is difficult to prove that the device will remain within the operational boundaries considering that they are capable of reconfiguring themselves. As a result, this requires new certification mechanisms that strike the balance between mitigating the risks and cost of certification. One interviewee suggests that equipment vendors are interested in CR as it provides new opportunities for them. However, the equipment vendors are cautious when it comes to reconfigurable devices as this gives the opportunity to parties other than them to reconfigure the devices. Another interviewee suggests that in order to solve this problem reconfigurability protocols should not be open to the user.

4.4.2.2 Commercial deployment of cognitive radio systems

There is hesitation in the commercial implementation of CR due to a lack of trust in business models [109]. According to the interviewees timing for the commercial implementation of CR is difficult to predict. Some interviewees argue that it depends on how CR is defined. For example, one interviewee indicates that if the ITU definition of CR is adopted, it might take a very long time to implement because in this definition CR does not only adapt from its environment but also learns from it. Similarly, another interviewee argues that if Mitola's definition of CR is adopted, which is a truly cognitive radio it will take a very long time to make it a reality. The interviewees further mention that some of the cognitive functionalities already exist in different systems. For example the RLAN systems in the 5GHz band that use dynamic spectrum sharing with radars. So, if a less strict definition of CR is adopted it could be argued that CR systems are already commercially available. The interviews argue that CR will be introduced on step by step approach with smart radios of different cognitive functionality. There are also views from the interviewees that the industry is still looking for "killer'' applications for CR. As with many earlier technologies killer applications are not likely to be predicted, but the chances that they will emerge is increased by the lower cost of entry enabled by CR for new service providers [97]. One interviewee points out that the current state of CR can be referred to as the "chicken and egg" situation in that NRAs are seeking certainty from industry players before proceeding with developing regulations while industry players are waiting on NRAs to develop regulations to gain certainty.

[109] argues that the dominant uncertainties affecting the future prospects of CR business development are the cost and complexity of the technology and the viability of the CR business case and concludes that the CR business system is very complex and difficult to predict. Interviewees argue that implementation also depends on the availability of CR devices and the prices of the devices, the applications and also the business models for the databases. There are no commercial mass deployments of CR because of the uncertainty around it. At the moment there are a handful of companies developing CR products. Some interviewees argue

that economies of scale is the most important factor so a significant step would be to harmonize frequencies and regulations and develop standards in order to give certainty for investments in CR.

Business viability depends on the intended service and the specific business cases, the demand, the deployment scenario and the cost structure of the network [110]. The Commission project QUASAR conducted a study on business feasibility of services based on the use of CR for secondary use of spectrum focussing on cellular use of TVWS and cognitive machine to machine using cellular bands scenarios [58]. This study concludes that business viability for both scenarios depends to a great extent on the type of the actor (new entrant or incumbent) as well as the type of business case. In the case of using TVWS for cellular, the study concludes that new entrants will incur higher costs as they have to invest in new infrastructure including building up customer base, distribution channels and billing platforms. The use of TVWS by MNOs to existing sites is more cost efficient than deployment of new sites in licensed bands. With regard to M2M services the study concludes that the business case for new entrants is less viable since they have to build new base station sites. This challenges the view that CR systems will lower barriers to entry and lead to new entry in mobile communications industry. New entrants can also offer the service as MVNOs by leasing the infrastructure from MNOs. In this case the new entrants need to set up agreements with MNOs. Interviewees argue that CR will not only create new business opportunities for the new entrants but for the incumbents as well.

4.4.2.3 Policy aspects of cognitive radio relating to market developments

There is a strong push from international organizations for spectrum sharing and they are looking into CR as an enabling technology. This is evident in the review conducted in chapter 3. On a national level NRAs are working towards allowing the operation of CR in their own countries. Some interviewees argue that there are different ways of giving certainty to the market through policy. One way, the NRA first makes frequency bands available for the implementation of CR through regulation in order for the industry to develop equipment and business cases. The other way is to first look into possible business cases and then later determine regulatory requirements. For example the UK and the Netherlands have taken two different routes towards the implementation of CR. The UK has first developed regulations to enable the implementation of CR in the TVWS without looking into the business cases. The Netherlands established a CR platform to investigate business cases in specific localised use cases of CR and will later look into regulatory requirements for CR implementation. So, as a NRA you have to first decide on how you want to introduce CR as there are a number of scenarios for CR implementation, and then decide on the regulatory requirements. For some applications you hardly require any regulations. For example the use of CR by MNOs to optimise their spectrum resources.

4.5 CR implementation and its effect on spectrum management

The reduction of these uncertainties and the current trends will determine the commercial implementation of CR and the success of DSA from a spectrum management point of view. The success of CR will be measured by whether the potential benefits of CR will be realized. As discussed above the trends are steering the industry towards spectrum sharing that will be facilitated by DSA technologies such as CR. However the trends alone will not result in the commercial deployments of CR. So the uncertainties discussed above have to be reduced to a reasonable level for CR systems to be commercial implemented. As such uncertainties should be reduced to a level that will give trust and confidence to the industry players. When these uncertainties are reduced to a reasonable level, it is likely that CR will be deployed commercially. Then the benefits of the technology will be realized and this will have a positive impact on spectrum management.

The interviewees are of the view that dynamic spectrum sharing through CR will not lead to a move away from exclusive licensing *per se*, but spectrum licensees will know beforehand that there is a possibility that spectrum assigned to them may be used by other users and that may result in lower spectrum fees. Similarly, [111] argues that exclusive licensing will remain so as to protect the substantial investments made by MNOs in network infrastructure and spectrum licences even in the advent of dynamic spectrum access. Impact of CR on spectrum management will be to make more spectrum available and easier access to spectrum. The interviewees argue that CR implementation will not change spectrum management completely. One interviewee is of the view that CR is an evolution of smart radios with capabilities to facilitate spectrum sharing and will not completely change spectrum management and will not make the role the NRA superfluous but will change it to some extent. For example, the use of the geo-location database to manage spectrum dynamically [58]. DSA could create a new role for the NRA or a third party known as the spectrum broker[6]. Some interviewees state that CR introduction could result in less work for NRAs because there will be less regulatory reviews as most of the work will be done in standardization through technical protocols.

4.6 Conclusion

As stated at the beginning of this chapter, this section answers sub-research question 3.

3. *How will the markets developments affect the take-up and ultimately the success of dynamic spectrum access technologies from a spectrum management point of view?*

[6] Refer to section 2.5.3

This chapter explored the market aspects of cognitive radio systems in the wireless communications market by analysing the current industry structure and its evolution as a result of CR introduction. The analysis of the current industry structure conducted using Porter's five forces reveals that the attractiveness of the industry is currently low due to high barriers to entry and slow growth. It also reveals that the introduction of CR will increase attractiveness of the industry. CR will lower entry barriers by allowing easy access to spectrum, increasing substitute products and services through spectrum sharing using CR and increased competition from large internet and software based firms. This analysis also reveals that the threat of entry is the strongest force in this industry as it has an impact on other forces as well.

The chapter further analysed the industry trends and uncertainties as the key factors that will determine the implementation of CR on the market. The analysis of the trends reveals that one of the key trends is the exponential growth of wireless data traffic generated through smart phones, tablets and other portable internet access devices. The other trend is that MNOs off load their traffic to Wi-Fi networks to relieve congestion. These trends drive the demand for both licensed and licence exempt spectrum. Dynamic spectrum access through cognitive radio systems is considered as a solution to the high demand for spectrum. This has led to a growing interest in cognitive radio systems for dynamic spectrum access from academics, industry players and regulatory bodies around the world, resulting in a number of research projects. Despite this overwhelming interest, there is still reluctance amongst industry players to deploy the cognitive radio systems commercially. This is due to uncertainties that exist around cognitive radio implementations such as the risk of interference, lack of business models and policies allowing the deployment of the systems. These uncertainties will have to be reduced to a reasonable level that gives trust and confidence to the industry players.

The interviewees agree that the uncertainty pertaining to the risk of interference can be minimised by demonstrating safe operation of cognitive radio systems in early deployments to build trust in CR. The interviewees argue that the lack of business models, cost and complexity of CR create uncertainties as they are critical element in the evolution of cognitive radio systems for all stakeholders that have interest or necessity in adopting the technology. It is difficult to develop business cases when the cost of the equipment is not yet known. Business cases are likely to emerge once the cost of the equipment is known and the equipment is widely available. There are also views from the interviewees that the industry is still looking for "killer" applications. The interviewees argue that CR will not only create new business opportunities for new entrants but for the incumbents as well. However, the view that CR will lower barriers to entry and lead to new entry in the mobile communications industry is to some extent challenged by [57]. As they concluded in their specific study that business cases for new entrants are less viable than those of the incumbents. Furthermore, policy developments are crucial as the industry requires certainty in terms of standards and regulations. Policy activities are taking place at different levels (international and national) as discussed in detail in chapter 3. However, very few countries are in the process of developing such policies. Some countries have adopted a “wait and see” approach.

5. Conclusions

This chapter presents the conclusions and answers the research questions. The chapter also discusses some limitations of the study and makes recommendations for further research.

5.1 Summary and conclusions

The purpose of this thesis is to investigate the potential impact of DSA technologies on spectrum management, as stated in chapter 1. The main research question is:

What is the potential impact of dynamic spectrum access technologies on spectrum management?

Three sub-research questions were formulated to answer the main research question. Chapter 2 answers the first sub-research question by focusing on the technical aspects of dynamic spectrum access (DSA) through cognitive radio (CR) and its effects on spectrum management. Chapter 3 answers sub-research question 2 by focusing on the current regulatory and standardization developments of DSA through CR and its effects on spectrum management. Chapter 4 answers sub-research question 3 by focusing on the market aspects of CR in the wireless communications industry. The conclusions of each research question are presented below. The conclusions draw strongly on the conclusions of the respective chapters.

1. *What are the benefits and challenges of dynamic spectrum access technologies relevant to spectrum management from a technical point of view?*

Introduction of CR will determine whether its benefits will be realized. If these benefits are realized this will have a positive impact on spectrum management as CR will make more spectrum available and provide easier access to spectrum. The technical challenges will be solved as the developments of CR technology advances. The main benefits of cognitive radio are increased spectrum efficiency, better spectrum utilization and flexible access to spectrum. It is often argued that spectrum utilization is very low as spectrum sits idle at any given time and location. Spectrum sharing through cognitive radio improves spectrum utilization and increases spectrum efficiency as it provides access to this idle spectrum while protecting existing users from interference. In licensed bands, the licensed users can be protected by using one of the CR enabling techniques to identify white spaces. In licence exempt bands CR can significantly reduce the risk of interference between users and improve quality of service. Cognitive radio has a potential to increase flexibility in spectrum access in that it allows access to spectrum through dynamic transfer of spectrum usage rights in secondary markets while changing the specific use of spectrum. Other potential benefits relate to the regulatory role of NRAs in the long term. CR could create a new role for NRAs or a third party often referred to as the spectrum broker. Geo-location database can also be used to manage spectrum dynamically apart from using it for Television White Spaces (TVWS). There may be less regular reviews of regulations as most regulatory work can be done in standardization through technical protocols instead of regular reviews of regulations by the NRAs.

The challenges of CR are interference, certification and security issues. Even though CR promises spectrum sharing while protecting existing users from interference, there are still some issues regarding interference. Interference issues are particularly associated with spectrum sensing as sensing is currently viewed as the least reliable technique for determining white spaces due to fading, noise uncertainty, aggregate interference and hidden node problem. These challenges can be improved by the on-going research on spectrum sensing. Nevertheless, the interviewees suggest that meanwhile CR can be implemented using the database method alone or in combination with spectrum sensing until a solution to the latter has been found.

The other issue is certification of CR equipment. CR devices can be altered after certification due the reconfigurability capability. This is a concern for equipment manufactures and NRAs. Consequently, new certification mechanisms that strike the balance between mitigating the risks and cost of certification are required. There are suggestions from literature for instance, implementing a device operational duration or limited duration certification lease. Interviewees suggest that reconfigurability protocols should not be open to the user in order to restrict reconfiguring of CR equipment to the manufacturers. Another issue is security of CR networks. Security threats can be intentional or unintentional. These threats can be addressed in a number of ways but have trade-offs of increase in complexity of the CR networks and cost of the equipment. Further investigation on the benefits and challenges of CR are required since these may change as the technology development advances.

2. *To what extent will the current and new policy developments (international and national) determine the impact of dynamic spectrum technologies on spectrum management?*

Introduction of cognitive radio systems (CRS) depends on the degree they are allowed by national regulatory authorities (NRA) that is often linked to availability of technical standards. Regulatory and standardization activities on CR are taking place around the world at the international and national levels. At the international level regulatory and standardization activities on CR in ITU, IEEE, CEPT, ETSI and European Commission were reviewed. These regulations focus on the protection of existing services from CR services. Accordingly; they recommend use of geo-location database for detecting white spaces as the most reliable method in the short term. Sensing is considered for the long term since it is currently considered the least reliable method. At the national level, CR regulatory activities in Australia, the US and the UK were reviewed. Australia has not yet started making specific rules for the introduction of CR even though it has expressed its intention to start the process in several documents. The US and the UK have developed regulations for the operation of CR devices in Television White Spaces (TVWS) on licence exempt basis. These regulations provide for the use of geo-location database as a method to detect white spaces, even though sensing is allowed. There are differences in the regulations in the UK and the US that are based on the different spectrum regulatory frameworks in these countries.

The current regulatory and standardization developments will have an impact on the introduction of CR, which will in turn determine the impact of CR on spectrum management. These developments will provide confidence to the equipment manufactures to develop CR equipment and to the potential CR service providers to invest in CR networks and more importantly to provide assurance to existing users that their services are protected from interference from CR. Furthermore, CR regulatory developments underway in the US and the UK for the introduction of CR in TVWS will have an impact on the extent of the implementation of CR not only in the US and the UK but in other countries as well. As this may encourage other countries that have adopted a "wait and see'' approach to start the rule making process for the introduction of CR. However, CR regulations developed in the UK and the US are limited to the operation of CR in TVWS. This limits the implementation of CR to only television bands and therefore limits the impact of CR on spectrum management. Nevertheless, the successful introduction of CR in TVWS may lead to further implementation in other spectrum bands as well. The current and the new policy developments will determine the impact of CR on spectrum management in a positive way as it allows dynamic and opportunistic spectrum access and use. However, the extent of the impact is not clear at the moment; further investigation is required to determine the extent of the impact.

3. *How will the markets affect the take-up and ultimately the success of dynamic spectrum access technologies from a spectrum management point of view?*

The increasing demand for spectrum has led to a growing interest in CR. As discussed in Chapter 2, CR has a potential to improve spectrum utilization and increase spectrum efficiency thus providing a solution to the increasing demand for spectrum. CR also has a potential to lower high barriers of entry in the wireless communications market. However, the interest in CR has not yet translated into commercial deployments as there are uncertainties regarding the current state of the technology, business models and policies allowing the deployment of these systems. It is likely that CR will be deployed commercially once these uncertainties are reduced to a reasonable level. It is expected that the proliferation of CR will come at a slower pace as it will take a step by step approach. However, when it penetrates the market deeply in the long term the impact on spectrum management will be great. The take up and success of CR from spectrum management point of view depends on the mass commercial deployments of CR and it will be measured by whether the potential benefits will be realized. At this moment it is not clear when CR will be deployed and how the deployments will unfold. Therefore, it is difficult to determine the effects of the market developments on the success of CR on spectrum management. This requires further investigation.

The analysis of the current industry structure conducted using Porter's five forces model reveals that the threat of entry is the strongest force in wireless communications industry as it has an impact on other forces as well. The current threat of entry in the mobile communications industry is low due to high barriers of entry related to access to spectrum and costs associated with deploying networks, marketing and distribution channels. The industry is based on static spectrum access which resulted in operators building networks in dedicate spectrum bands to provide specific services. MNOs exhibit vertical integration with a dedicated infrastructure and WISP are based on horizontal integration in line with the LAN architecture. Nevertheless, CR has a potential to change the structure of the wireless communications industry as it will encourage entry into the industry by removing barriers to entry.

Despite the overwhelming interest on CR there is still reluctance amongst industry players to deploy the cognitive radio systems commercially, due to uncertainties mentioned above. Early deployments of safe operation of CR will reduce uncertainty pertaining to interference. The lack of business model is critical element in the evolution of CR for all stakeholders to have interest or necessity in adopting the technology. It is difficult to develop business cases when the cost of the equipment is not yet known. Business cases are likely to emerge once the cost of the equipment is known and the equipment is widely available. Furthermore, policy developments discussed in detail in chapter 3 are crucial as the industry requires certainty in terms of standards and regulations.

5.2 Discussion

This section discusses some limitations of the study and makes recommendations for further research.

First, the interviewees did not represent the whole spectrum of the relevant stakeholders. This is a constraint because even though the interviewees are experts in the field they do not necessarily know the views of other stakeholders that were not represented. Furthermore, the interviews for both technical and market aspects of cognitive radio were combined in one interview. This is a constraint because while the interviewees are experts in spectrum management some have technical expertise and others have economic expertise. As a result the level of detail anticipated was not always reached. So it is recommended that interviewees should at least represent a whole spectrum of the relevant stakeholders. It is also recommended that interviews on technical aspects and economic aspects should be separated according to the expertise of the interviewees.

Second, as mentioned in chapter 1 that most studies focus on technical aspects of CR. Even though this study contributes to filling that gap by studying the interplay between technical, market and technical aspects. There is still a lot of research that can be done in this regard, of different research scopes. For example the country policy review in chapter 3 focused on three countries. It would be interesting to do a study that focuses on several countries. It would also be interesting to make a comparison between countries that have a large manufacturing industry of mobile communications and or large mobile communications (multinational) firms against countries that do have such industries. It would also be interesting to compare developed countries and developing countries, as mobile communications is often used as a primary mode of communications in the latter countries.

Third, chapter 4 that deals with the market aspects of CR does not have a geographic scope. The reason for this is to get a broader view of the industry evolution relating to CR. However, the broader scope limits how far the analysis can go in terms of details to get a deeper understanding of the market evolution. So it would be interesting to conduct a study on market aspects in smaller geographic areas to get a deeper understanding on how wireless communication markets evolve as a result of CR.

Appendices

Appendix A: Interviewees

1. Peter Anker, Senior Policy Advisor: Ministry of Economic Affairs, Agriculture and Innovation
2. Fokko Bos, Senior Policy Advisor: Ministry of Economic Affairs, Agriculture and Innovation
3. Simon Delaere, Senior Researcher: IBBT-SMIT, Studies on Media, Information and Telecommunications
4. Lilian Jeanty, Coordinator International Affairs: Agentschap Telecom
5. Erik van Maanen, Technical Advisor: Agentschap Telecom
6. Przemek Pawelczak , PHd, Senior Researcher: Fraunhofer Heinrich Hertz Institute
7. Ben Smith, Senior Advisor: Agentschap Telecom
8. Peter Trommelen, Consultant and Project Leader Wireless Technologies: TNO

Appendix B: Interview questions

Part A: Questions on the technical aspects of cognitive radio systems and their potential impact on spectrum management.

There are claims that Dynamic Spectrum Access technologies such as cognitive radio systems will change spectrum management. However at the moment it is not clear what impact these technologies will have on spectrum management.

1. In your opinion, what are the potential benefits of cognitive radio systems for spectrum management and how can these benefits be fully realized?
2. What are the challenges of cognitive radio relating to spectrum management?
3. How can these challenges be addressed in order to realize the full benefits of cognitive radio systems?
4. How to deal with the risk of interference from the operation of cognitive radio systems?
5. It is expected that spectrum policies will undergo some changes to allow the implementation of cognitive radio systems. In your view what policy changes are

required at various levels (International, Regional/European and national), and whether or when such changes will actually be implemented?

Part B: Questions on how market developments (relating to cognitive radio systems) will affect the success of the cognitive radio systems from spectrum management point of view?

It is expected market developments relating to cognitive radio systems will have an impact on the take up and the ultimate success of the latter from a spectrum management point of view.

1. In your view, how will the current market developments on cognitive radio systems affect its introduction?
2. Who are the stakeholders that will affect the development of cognitive radio systems market and what are their respective interests?
3. How much influence do these stakeholders have on how cognitive radio systems develop on the market?
4. When do you expect that cognitive radio systems will be introduced in the market and why?
5. How will cognitive radio systems open up new business opportunities and threats in the wireless communications market?
6. How will the current policy developments (International, Regional and National) affect the introduction of cognitive radio systems?
7. How is the commercial viability of cognitive radio systems for both the new entrants and incumbents?
8. How will the introduction of cognitive radio affect the wireless communications industry?
9. How will the market developments (relating to cognitive radio) determine the success of cognitive radio from a spectrum management point of view?

List of abbreviations

ACMA Australian Communications and Media Authority

A-GPS Assisted Global Positioning System

ARNS Aeronautical Radio Navigation Service

ATSC Advanced Television Systems Committee Standards

CCC Cognitive Channel Control

CEPT European Conference of Postal and Telecommunications Administrations

C-NMS Central-Network Management System

CPC Cognitive Pilot Channel

CWN Composite Wireless Network

CR Cognitive Radio

CRS Cognitive Radio Systems

CTM Cordless Terminal Mobility

CUS Collective Use Spectrum

DECT Digital Enhanced Cordless Telecommunications

DSA Dynamic Spectrum Access

DoS Denial of Service

DTT Digital Terrestrial Television

DTV Digital Television

DVB-T Digital Video Broadcasting-Terrestrial

ETSI-European Telecommunications Standards Institute

EU-European Union

ECC Electronic Communication Committee within CEPT

FCC Federal Communication Commission

FA Functional Architecture

GSM Global Systems for Mobile Communications

GPS Global Positioning System

IEEE Institute of Electrical and Electronics Engineering

IMT International Mobile Telecommunications

ISDN Integrated Services Digital Network

ISM Industrial Scientific and Medical

ITU-R International Telecommunication Union Radiocommunication Sector

LTE Long Term Evolution

LAN Local Area Network

MAC Media Access Control Layer

MAN Metropolitan Area Network

M2M Machine-to-Machine

MD Mobile Device

MNO Mobile Network Operator

MVNO Mobile Virtual Network Operator

MPT Ministry of Posts and Telecommunications

NRA National Regulatory Authority

ONP Open Network Provision

PABX Private Automatic Branch Exchange

PSTN Public Switched Telephone Network

PTT Post, Telephone and Telegraph

PU primary User

PMSE Programme Makers and Special Events

PHY Physical Layer

QoS Quality of Service

RAT Radio Access Technology

RLAN Radio LAN

RR Radio regulations

RSC Radio Spectrum Committee

RSPG Radio Spectrum Policy Group

SIM Subscriber Identity Module

SNR Signal to Noise Ratio

SPTF Spectrum Policy Task Force

SU Secondary User

TVWS Television White Spaces

UMTS Universal Mobile telecommunication System

UWB Ultra Wide Band

UHF Ultra High Frequencies

VHF very High Frequencies

WAPECS Wireless Access Policy for Electronic Communications Services

WLAN Wireless LAN

WRC World Radiocommunication Conference

WSD White Space Device

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