Advanced coexistence technologies for radio optimisation in licensed and unlicensed spectrum

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Abstract:

Dynamic Spectrum Access (DSA) has been described as a technology that offers considerable benefits for regulators, telecommunication operators and users. However, despite this it suffers from a lack of understanding and clear market position, partly imposed by several technical, standardisation and regulatory research challenges.

This report captures the first phase investigation into a broad market analysis of DSA. It begins with an overview of recent developments in DSA around the world and moves on to highlight the lack of sound research concerning its real application. It then discusses the major reasons identified in the literature as the driving force behind DSA, pointing to some potential application areas. It also underscores some of the main barriers in its path. We then isolate the public safety domain and the commercial sector for areas of further investigation. In the case of the former, we note significant interest in the use of DSA in improving communications. In the case of the later, while there is enormous market potential, we note a lack of empirical and rigorous studies which illuminate upon the potential application areas. The report concludes by identifying some future prospects and outlining our future research.

Keywords: Dynamic spectrum access; cognitive radio; market; business analysis

Document Revision History

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0.1	21.02.2011	UnivLeeds	Initial structure of the document
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0.3	25.07.2011	IASA	Input and feedback on draft
0.4	07.02.2011	UnivLeeds	Second draft
0.5	10.02.2012	UPRC	Refinements in section 4.2 (commercial applications)
0.6	14.02.2012	JRC	Review of sections 3.1.4, 3.1.4.1, and 4.1 (public safety and military)
0.7	17.02.2012	UnivLeeds	Final draft
0.8	21.03.2012	Executive Committee	Review of document. Suggestions to include aspects related to WRC2012 and WPANs, amend Figure 4-1, correct terminology and editorial changes
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1. Introduction

Like most common natural resources, spectrum is finite and prone to overuse and "crowding". Most of today's radio systems are not aware of the spectrum environment and operate in a pre-given, static frequency band. While this traditional approach to spectrum management has been successful at avoiding interference it has exacerbated the problem of spectrum scarcity. It is increasingly difficult to identify new spectral bands to be allocated for new wireless services, while already-allocated spectrum is often underutilized by the existing services and users. This lack of available spectrum can curb innovation and can limit the availability of broadband connectivity and other economically beneficial services to the citizen.

Several measurement campaigns have shown that spectral bands assigned with the aforementioned "command and control" approach are often underutilized in time or space [1, 2]. Further, as demand for ubiquitous broadband connectivity and the range of capacity-hungry applications and devices such as smart-phones, notebooks and machine-to-machine radios continue to increase [3], spectrum management becomes critical and the impetus to implement more efficient use of spectrum grows (Ericsson, the mobile phone company, projects that there will be 50 billion devices connected the Web by 2020). Moreover, the energy consumption implied by such increases in the promised data rates of future communication systems must be dealt with; cognitive radio (CR) and dynamic spectrum access (DSA) technologies play a major role in addressing such issues [4].

Enabled by advances in CR and DSA, over the last several years there has been a fundamental shift (and challenges to) how regulators, the telecommunications industry and academics approach spectrum utilisation and regulation; with some national regulators moving away from the traditional command and control approach towards more "lighter touch" regulation.

There have been several important developments in the past few years in the spectrum policy and regulatory domains to accelerate opportunistic uses of spectrum. The most recent of these are the publication of the US National Broadband Plan (NBP) in March 2010. In other countries, such as the United Kingdom, Australia, Japan, Canada, India and New Zealand, regulators are producing numerous consultations, vision reports, memoranda of opinion and other documents considering or highlighting the potential of CR to increase use and access to radio frequency, with some regulators progressing towards the creation of appropriate vehicles to realise those markets. Ongoing activity is also taking place by the International Telecommunications Union (ITU) and the European Telecommunications Standards Institute (ETSI) in developing definitions, standards, and regulatory regimes for using this new technology.

Already concepts such as TV White Spaces (TVWS) are being realised, even if the sole requirement of a geolocation database (a database of the frequencies which can be used at certain locations and the applicable rules) is very different from the pretext under which work on TVWS was initiated in the early 2000's. In two of the key markets, the United States and the United Kingdom, regulators have given conditional support to this new sharing mode of access, and there is also significant industry effort underway toward standardisation, trials, and test-beds [5].

1.1 Cognitive Radio and Dynamic Spectrum Access

It has been over ten years since Mitola and Maquire [6] introduced the concept of CR as an evolution in wireless communications, which merged the concepts of software defined radio (SDR), developed in military quarters in the 1980's with machine-intelligence concepts. Some observers also see this type of radio technology as inevitable [7, 8].

Mitola and Maquire [6] defined CR as the point a wireless device and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs. Over the last decade CR has "morphed into DSA, adaptive networks, and heterogeneous networks as communications enablers", as underscored by Mitola [9].

Now, DSA has emerged as the "cornerstone" of CR. The IEEE Standards Coordinating Committee 41 (SCC 41) defines DSA as:

> "The real-time adjustment of spectrum utilization in response to changing circumstances and objectives", where, "changing circumstances and objectives include (and are not limited to) energy-conservation, changes of the radio's state (operational mode, battery life, location, etc.), interference-avoidance (either suffered or inflicted), changes in environmental/external constraints (spectrum, propagation, operational policies, etc.), spectrum-usage efficiency targets, quality of service (QoS), graceful degradation guidelines, and maximization of radio lifetime" [10 p.9].

More simply it can be defined as set out by the IEEE 1900.1 workgroup:

> "a technique by which a radio system dynamically adapts to select operating spectrum to use available (in local time-frequency space) spectrum holes with limited spectrum use rights"

DSA is based on the notion that inefficient usage of the spectrum as a finite resource can be improved through access to the unlicensed/licensed bands without interfering with the existing users [11]. In other words, rather than being given a static range of frequencies on which to operate, radios could instead be allowed to use whatever spectrum or white space they find free. The dynamic approach has the potential to make use of what are otherwise wasted resources.

DSA technology has been described by engineers, policy makers, academics and other observers as an exciting frontier in wireless communications [6, 12-17]. It is also generally accepted as a rapidly developing technology that "should" in time offer great benefits to all members of the radio community, spanning regulators to users [18]. This "should" dimension is framed by market, standardisation and regulatory challenges that shape immature technologies; rather than purely technical dimensions. Several questions emerge alongside the development of DSA, such as, what will DSA be used for and by whom, and, which social and commercial problems is it addressing? We note that there was significant hype amongst other recent telecommunications technologies (notably WiMAX) that promised performance, economic and social benefits, which did not materialise. For this reason it is necessary to be somewhat critical of some of the extant literature.

1.2 Overview of this report

DSA has been described as a technology that offers considerable benefits for regulators, telecommunication operators and users. However, despite this glossy picture, DSA, suffers from a lack of understanding and clear market position, partly imposed by several technical, standardisation and regulatory research challenges. It is also complicated by the potential restructuring of the telecommunications industry landscape, which could also provide economic and innovation benefits. Perhaps this should come as no surprise, given the widely discrepant views presented on DSA. An analysis, therefore, is useful to position the technology and understand its potential, applicability and utility.

This report captures the first phase investigation into a broad market analysis of DSA. It is to be treated as a “living document” and expanded and developed over the duration of the project. In this report, we have identified a number of important issues that require further investigation and understanding. A guiding principle behind this report is the view that in order to understand the influence of any future development of DSA we must first of all review the current situation and stakeholder perspectives.

The conduct of this research predominantly involves desk-based research, relying on a thorough review of the literature, placing emphasis on academic and market research. Given the divergent views in the market research we have treated much of the literature with caution. Further, the authors have participated in several key workshops and events relevant to the subject domain. These include:

- 1st Annual Workshop on and Expert Panel on “Advanced coexistence technologies for radio resource usage optimisation” 4-5th October 2011, Barcelona, Spain.
- 4th meeting of COST Action IC0905 TERRA (within the framework of the COST-European Cooperation in Science and Technology) 15-17th November 2011, Brussels, Belgium.
- Fourth IBBT-MIT Joint Workshop on Cognitive Radio Standardisation & Markets “TV White Space: real standards, real applications?” 15th November 2011 Brussels, Belgium.

In this report we have purposefully omitted technical language to maintain a clear understanding of the issues we discuss. We also avoid technical issues, to avoid duplication with other deliverables, except for issues that are directly related to this report. The report is structured as follows. It begins with an overview of recent developments in DSA around the world and moves on to highlight the lack of sound research concerning the real application of DSA. It then discusses the major reasons identified in the literature as the driving force behind DSA, which points to some potential application areas. It also underscores some of the main barriers in its path. We then isolate the public safety domain and the commercial sector for areas of further investigation. In the case of the former, we note significant interest in the use of DSA in improving communications. In the case of the later, while there is enormous market potential we note a lack of empirical and rigorous studies which illuminate upon the potential application areas.

2. DSA: Current research and development

As has been reported by a number of observers [19, 20], there has been significant theoretical work in the field of CR, with over 30 special issue scientific journals and more than 60 dedicated conferences and workshops and innovative developments. It has also been showed that while hardware and system development for CR/DSA is progressing at a slower pace some commercial and governmental organisations have completed prototype implementations and submitted them for varying degrees of technical or operational scrutiny [21].

The USA still dominates research and development of CR/DSA like systems; while almost 60 percent of the demos are from Canada, the European Union (EU) and Asia [19]. However, while the R&D priorities are similar, a distinction is that in the US a major part of such research is supported directly by military agencies, as opposed to civilian bodies. In Europe a number of EU projects have taken place, that have focused on dynamic spectrum management, Pilot Channel technology (Project E3), spectrum sharing and reuse (WINNER+), CR implementation (QUASAR), self organisation methods (SOCRATES), opportunistic spectrum access (ROCKET and ORACLE), spectral awareness of future wireless systems (FARAMIR), amongst others. Nonetheless, the major contributor to CR-like systems however remains the US military and the Defence Advanced Research Projects Agency (DARPA). (DARPA advances in the field of DSA and CR are discussed section 3.1.4.1).

The list below (adapted from [22]), provides a chronology of DSA, which indicates dominant role played by the EU/US regulators and DARPA in the development of DSA.

- 1999: Mitola introduced the concepts of CR [23]
- 1999-2000 (US): localised set of measurements conducted by the DARPA indicated that spectrum use was not very high
- 2002 (US): DARPA initiates the XG project to investigate the potential for the military to share spectrum spatially and temporally with multiple devices
- 2002 (US): the Federal Communications Committee (FCC) Spectrum Policy Task Force (SPTF) concludes that spectrum access is a more serious problem than spectrum scarcity. The SPTF recommends that new rules be developed to allow more intensive access to spectrum, including opportunistic spectrum
- 2003 (EU): EU Sixth Framework Programme include DSA technologies as part of research and development
- 2003 (US): The National Science Foundation (NSF) initiates research projects in a spectrum measurements and dynamic spectrum access
- 2003/4 (US): The FCC issues a Notice of Proposed Rulemaking on Facilitating Opportunities for Flexible, Efficient, and Reliable Spectrum Use Employing CR Technologies
- 2004 (US): The FCC proposed to allow opportunistic access to TV bands
- 2005 (US): DARPA XG, and NSF projects complete a series of spectrum occupancy measurements indicating less than 10 percent occupancy in time space under 3GHz
- 2006 (US): FCC issues Rule and Order on permitting low-power devices in unused portions of the TV broadcasting spectrum (Whitespace)

- 2007 (US): FCC begins testing of prototype TV Whitespace devices
- 2007 (UK): An Ofcom Consultation creates new opportunities for CR to use interleaved spectrum without causing interference
- 2008 (US): DARPA XG successfully demonstrates Opportunistic Spectrum
- 2008 Feb (US): FCC ruling on TV whitespace
- 2009 Jul (UK): Ofcom conclude that geo-location (while hoping to allow detection) the most suitable way to determine whether spectrum is used or not (beacons considered least appropriate) [5]
- 2009 Mar (US): Broadcasters sue FCC over WS access [24]
- 2009 Feb: IEEE 1900.4 Standard Approved [25]
- 2009 Feb (UK): Ofcom Consultation regarding the exploitation of CR in TV white spaces
- 2010 (US): FCC Commissioners proposed to promote the use of DSA technologies.
- 2010 Sep (US): FCC ruling frees spectrum sensing as a requirement for TV white space [26]
- 2010 Nov (UK): Ofcom databases consultation [27]
- 2011 Jan (EU): Conference of Postal and Telecommunications Administrations (CEPT) release technical and operation requirements for CR systems in white spaces [28]
- 2012 Feb (Global): ITU-R Resolution 58 at the World Radiocommunications Conference (WRC) recognises the benefits of CR systems and the need for future development.

2.1 DSA/CR demonstrations and test-beds

Investigating the demonstration track at DySPAN and the Wireless Innovation Forum (previously SDR Forum) Pawelczak et al., [19] found that almost all test-beds presented publicly were primarily focused on DSA functionality. They argue that while it shows progression on DSA, it also highlights that there is little demonstration of the concepts of CR envisaged by Mitola and McGuire, like AI usage in spectrum selection. In their review they noted a number of themes:

(1) That the majority of platforms enabling real-world communication and presented since 2007 were designed to work in license-exempt bands, where no requirements on primary user (PU) protection are necessary. In other words, the platform cannot be analysed properly. This is a common limitation of demonstration and research platforms, for instance SpiderRadio, a CR prototype for DSA networking, was built using commodity IEEE 802.11a/b/g hardware and used unlicensed spectrum [20].

(2) The field is not mature enough to provide meaningful demonstrations with AI features.

(3) The lack of publicly viewable commercial applications is indicative of an emerging technology because DSA based systems are the basis for commercialisation. Similar observations of the limited nature of demonstrations have been made by others [29, 30]. However, commercial leaders are emerging (cf. http://www.ict-acropolis.eu/index.php?option=com_content&view=article&id=90&Itemid=32 for

list of companies in the field). On the other hand, university-created prototypes and research publications concerning these tend to emerge more. For instance, Virginia Tech has published their extensive work that addresses the broad research agenda of CR and networks [31].

(4) There is very little focus on IEEE 802.22. While this might be the case, commercial and government organisations have progressed in the space of IEEE 802.22. Notably, the first large-scale “Smart City” network in Wilmington, North Carolina, which is able to dynamically assign non-interfering frequencies to WS devices throughout the service area to effectively provide bandwidth where and when it’s needed [32] (discussed in Section 3.1.3).

Based on their review, Pawelczak et al., recommend (1) open collaboration between research groups to help progress toward comprehensive demonstrations better linked to real-world scenarios; (2) that research groups make use of spectrum regulators wireless test and trial licensing options to help facilitate experiments in non-license-exempt spectrum (i.e. real-world scenarios); and (3) more industry-led research is needed to increase the number of prototype systems from the small set of systems focused on long-term research-only concept ideas [19].

The first point is being addressed by efforts across the EU such as the ACROPOLIS network of Excellence, amongst others. The second point has been addressed by some governments. Some regulators have allocated test bands to encourage development of CR technologies in their national markets. The third point remains the most difficult, yet most pressing to address, given that for regulators to permit DSA approaches, conclusive proof must be supplied that CRs can use the empty spectrum while at the same time not unduly interfering with PU’s [16, 17].

2.1.1 Business application research

While research tracing the technical development of DSA has received much interest over the past several years the immature nature of the technology has meant that analysis of its potential impact has been problematic. Few studies have attempted to investigate the commercial opportunities and the industry changes generated by the disruptive nature of DSA and most that have done have addressed the issue as a “thought experiment” rather than drawing upon empirical data.

Fomin et al,. [33] identified a compelling case that the regulatory domain and regulatory stakeholders are the most fundamental enabling factors that could guide the future of CR and its progress toward commercial success. Work by Grøndalen et al., [34, 35] has focused on the techno-economic aspects of a business case, producing promising models; however, these have not yet been empirically tested or explored outside of the discussion of relatively high-level hypothetical scenarios. Nolan [36] suggests that progress in his area has moved beyond the “frenzy” stage and into the period of “experimentation and understanding”; the next stage is where “value is understood, recognised and demonstrated widely”. Work by other academics [37] drawing on projects CONSERN, CREW, ESSENCES and NGWINETS has provided a detailed techno-economic evaluations of DSA in a factory environment, however, this description of the organisational context remains rudimentary. Barrie et al., [38] have focused on the potential business model configuration and the role of the intermediaries in a number of spectrum sensing scenarios relying upon extrapolation and logic to develop the cases. Medeisis and Delaere [39] are some of the few authors to present an analytical frame for the construction of high-level scenarios, in their case using Intuitive Logics. Barrie et al, [40] provide a different structure for the development of use cases based on four variables: ownership, exclusivity, tradability and neutrality. Others [33, 39] have highlighted the significance of the political and regulatory [41] environments as factors which will "make or break" the success of the technology and the form of its use.

While this work provides useful frameworks for the analysis and development of cases there is a clear need to both draw together the economic-technological and political regulatory strands of the research into a single study and to ground the frameworks in an understanding of the market conditions based on empirical research. In this *report* we provide one step towards this goal by outlining some of the challenges faced, key drivers and market opportunities emphasising the significance of the socio-political challenges.

3. Market issues in the development of DSA

As a technology which has emerged, both rapidly and relatively recently, DSA both faces and raises regulatory, technological and economic challenges that require significant attention by academia, industry and standards and regulatory bodies if they are to be sufficiently addressed. During our systematic literature review we have uncovered a number of pertinent market related issues that influence and define the current state of play in the DSA field and may have implications for future of DSA.

3.1 Major drivers

3.1.1 Efficient spectrum use

Like most common property resources, spectrum is prone to overuse and depletion. As observed, several measurement campaigns have shown that spectral bands assigned with the aforementioned "command and control" approach are often underutilized in time or space [1, 2]. For instance, a field spectrum measurement, which was taken in New York City, showed that the maximum total spectrum occupancy is only 13.1% from 30 MHz to 3 GHz [2]. Further, there are legacy applications such as ship-to-shore that use infrequently used spectral band assignments [42]. At the core of this problem lies outmoded spectrum licensing and management. Such static spectrum assignment, applied to radio frequencies for almost a century, lead to a so-called quasi-scarcity of the spectrum [43]. That is, the perceived scarcity is caused by the management of the spectrum, rather than actual consumption of the spectrum. Against this backdrop, the predominant driver for DSA is more efficient use of spectrum [7, 17]. From a regulator's perspective, DSA techniques could minimise the burden of spectrum management whilst maximising spectrum efficiency, reducing the need for centralised (command and control-style) spectrum management [7]. Likewise there are significant benefits to be absorbed by the market as new opportunities arise [41]. Telecommunication operators, for instance can offer new services [44] and reduce deployment costs [45], while at the same time the additional bandwidth deliver new wireless services for the growing demand of devices [16, 46].

3.1.2 Market and economic drivers

Based on simple economic principles, a finite supply of spectrum, and increasing demand for it, will result in an increase in its value. Technology that allows for more efficient use of spectrum is of high economic value. Ofcom examined the economic benefits of CR by analysing the 2G/3G band, an extremely competitive and valuable part of the spectrum, where usage and economic data is available. The study found that increasing spectrum efficiency may translate into economic benefits for both consumers and producers of CRs because of the reduction in cost of providing the service, which could then be passed on to the consumer in the form of a lower price [7]. However, while this is a theoretical possibility, it is unlikely that DSA will result in any short-term lower prices for consumers.

Commercial telecommunications operators that are finding it increasingly difficult to obtain additional spectrum to satisfy their requirements such as adding new users or improving QoS for existing customers are a key commercial driver for DSA, as they stand to gain from spectrum efficiency gains [17]. Understanding the economic implications of DSA technologies some organisations have advocated the need for DSA and raised concerns about spectrum congestion. Microsoft and Google (members of the Wireless Innovation Alliance and the White Space Coalition) recently reported to the FCC on a Notice of Inquiry that dynamic spectrum sharing can substantially address a pending US spectrum crisis. Microsoft explained, as was demonstrated in the TVWS “greater use of dynamic spectrum access technologies will enable consumers to make more productive use of limited spectrum resources”. Shared Spectrum Company (a company heavily involved in DSA technology and DARPA’s XG program) also recommended the FCC take constructive, incremental steps to encourage more dynamic use of spectrum [47, 48].

3.1.3 The TV white spaces

Analogue TV uses large amounts of spectrum. For instance in the UK (BBC1, BBC2, ITV, Channels 4 and 5) use nearly half of the most valuable bands of spectrum below 1 GHz. Digital TV (DTV) is roughly six times more efficient, allowing more channels to be carried across fewer airwaves [c.f. 49]. Most developed countries have completed the transition to DTV, or will do so by, with only a few deferring the transition. Therefore the DTV switchover and the potential for a large amount of TVWS to be released for new services and the provision of wireless broadband (IEEE 802.22 Wireless Regional Area Networks (WRAN)), driven by technical achievements and regulatory acceptance of the use of TVWS, may facilitate a range of new services and applications. The benefit lays in the use of the lower frequencies, which could provide Internet connectivity up to 100km without limitations imposed by buildings, weather etc.

In November 2008, the FCC adopted rules to allow unlicensed radio transmitters to operate in the broadcast television spectrum at locations where that spectrum is not being used by licensed services. The Commission decided to rely on a combination of spectrum sensing and geo-location combined with access to a database of existing spectrum use to determine if a channel is available. In September 2010, the Commission eliminated the sensing requirement for Television Band Devices that include geo-location/database functions, as petitioners argued that sensing technology was not sufficiently mature for consumer devices and would delay market entry [50]. Concerns about the TVWS were initially echoed in Europe where the CEPT announced that it is early to judge the capability of CR in the TVWS. In November 2010, Ofcom launched a consultation about the use of the TVWS and is expected to make proposals about the matter in 2011; however in 2010 it was not legal to use the TVWS for data transfer in the UK. More recently, as reported by Fitch, et al., [51] following recent rulings by FCC and Ofcom and the emergence of a series of related industry standards, CR operation in the TVWS is moving beyond research and speculation towards implementation and commercialization, with use-cases that are of interest to fixed line operators that have a significant fibre and copper infrastructure, as well as potential new entrants, such as Google and Microsoft (cf. deliverable 6.2 for up to date discussion on regulations).

There are serious supporters in favour of DSA; The While Space Coalition and the Wireless Innovation Alliance (WIA) are composed of innovators, consumer groups, think-tanks and education organisations that believe that more efficient use and expanded access to the nation’s spectrum resources are fundamental to the future of US economic policy and global competitiveness. The entities involved in these include large technology companies, including Microsoft, Google, Dell, HP, Intel, Philips, Earthlink, Spectrum Bridge and Samsung

Electro-Mechanics (some are involved in both), that plan to deliver high speed broadband internet access existing in the TVWS. Google also launched an initiative called "Free the Airwaves" to bring users together on the matter of freeing up the TVWS, however this appears to have achieved minimal momentum.

Various groups are also emerging to assess and promote the potential of the TVWS to deliver cost-efficient broadband access to rural communities, offload wireless data demand in urban centres and open the way for innovative business models (i.e. Cambridge TVWS's Consortium). Alongside, reports have emerged suggesting significant economic benefits enabled by the TVWS [52]. Other significant opportunities exist such as more localised or free and micro wireless Internet Service Providers (WISP) and localised broadcasting [53], femtocells and smart metering, which could provide significant cost saving to utility companies and better tailored tariff packages for consumers. These opportunities have led some observers to point to the emergence of a "white space economy" [53].

At the WRC 2012 a decision was made to allocate additional spectrum (694–790MHz) to mobile services in Europe, Africa and parts of the Middle East (ITU Region 1), which is proposed to come into force in 2015. This has been labelled the "second digital dividend", following the first digital dividend at 800MHz (from 790-862MHz), which emerged from the WRC in 2007.
Several reasons have been highlighted for the second digital dividend: (1) it allows Africa and Middle East countries to move towards awarding spectrum in the 700MHz band; (2) in Europe, the 700MHz band will provide additional bandwidth that can be used to accommodate mobile broadband services in order to meet future demand; and (3) it will increase harmonisation efforts with other parts of the world.

Expected benefits will include more spectrum for mobile services in Africa and the Middle East, and providing European countries with additional bandwidth resources for commercial mobile broadband. Of interest, a noted benefit is the potential for satisfying European public safety organisations needs for more spectrum for future mission-critical mobile broadband networks [54].

Analysts reason however that this will create a number of challenges, which have been acknowledged by the ITU through its delay of the allocation to 2015. In Europe, there may be an expensive and messy "re-tune" of existing networks to accommodate the 700MHz for mobile use. Programme-making and special events (PMSE) will also be affected by any re-planning of UHF frequencies through the future availability of spectrum for those services, including wireless microphones.

Another challenge in making the 700MHz band available for mobile use, stemming from heritage decisions in WRC 2007 which allocated a slightly different 700MHz band in other ITU regions, is to determine an appropriate band plan that will facilitate harmonisation with other world regions [54].

There are a number of implications, in particular, there is the potential to take opportunities away from TVWS devices, which could reframe the benefits for the TV white space. There are concerns from broadcasters, which are yet to be voiced in detail. We expect some significant market impacts from this decision that will become more evident over the course of the year.

3.1.4 Innovation in the military and public safety domain

The defence and public safety domains have emerged a source of state-of-the-art development of SDR and CR technology [8, 55-57]. In both settings, the interest lies in maximising efficiency, aligning systems with future high-bandwidth systems and creating robust, capable and flexible interoperable next-generation networks [8, 58]. A principle that is fundamental in these domains is the distinction between interruptible spectrum (typically civilian use of spectrum) and un-interruptible spectrum (anything to do with safety or defence). For instance, the interruptible use of commercial spectrum would mean that resources could be “grabbed” when needed (however, in some emergencies existing commercial infrastructure can be destroyed) [16]. The opposite scenario can also be envisaged for public safety and military spectrum allocations [16] .i.e. if military use of spectrum is only used for training purposes at a certain time or place [42]. Public safety spectrum could therefore be made available for more commercial orientated services, if and only if, it is possible to quickly reclaim the spectrum on need [16].

While the defence and public safety domain represent key markets for DSA, there are several significantly different business cases between these and civilian markets:

- <u>Civilian markets</u> are based on economies of scale. At present the number of existing mobile phones is well exceeds four billion devices; which is many orders of magnitude larger than the public safety market or defence market. Non-recurring costs for mobile phones are largely based on the design of the Application-Specific Integrated Circuit (ASIC) components. These costs are minimized by the huge number of devices sold on the market, even for a single manufacturer. At the same time, the current trend for handheld devices is to support various air-interfaces/communications standards (GSM, UMTS, Wi-Fi, LTE) and spectrum bands (Europe, USA, East Asia), therefore the civilian market could benefit by multi-standard or multi-mode devices.
- <u>Defence markets</u> are not based on economies of scale; however they benefit by very large budgets, especially in the USA. The US Defence Joint Tactical Radio System (JTRS) program cost 6.8 billion USD and the price of a single terminal is obviously orders of magnitude larger than commercial mobile phones. The high price of the defence terminals is especially due to very severe operational requirements (e.g., security, frequency hopping), which do not exist in the commercial market. Another difference is that most of the defence communications are link-based or tactical networks because they are designed to operate without an existing fixed infrastructure.
- <u>Public safety markets</u> are usually considered as a niche market because of the smaller volume of networks and terminals in comparison to the commercial market and smaller budget in comparison to the defence budget. Public safety networks like Terrestrial Trunked Radio (TETRA) are usually dedicated networks: they are specifically built and dedicated for one or more public safety organisations (e.g., fire-fighters). Given the recent interest in improving communications in the sphere of

disaster response [59] and improving public safety efficiency [60], this could remain a strong niche market for DSA.

3.1.4.1 Military innovation

Because of the significant contribution of the military to progress in the sphere of CR/DSA technology here we described some of the key developments. Military communications have evolved from the days of a voice only communications to include a range of data services. The first radios deployed in large numbers were “single-purpose” solutions, capable of analogue voice, which were limited in the ability to communicate information. This approach to tactical communications was radio centric and led to a proliferation of radios in each service, which weren’t able to talk to other radios across the military system [17]. Later technological advancements allowed for a generation of data-only radios [61]. By some accounts the US military uses more than 40 different types of radios, not including variants [8, 61]. Many of the radios have diverse characteristics and are highly specialised, such as the radios employed exclusively to communicate with Army rotary-wing aircraft or for voice communications between infantry soldiers [61, 62].

The spectrum available to armed forces is less than the need and hence DSA techniques available with cognitive networks have immense potential in this setting [17]. This is a paradoxical situation given that in the case of the US military, the Department of Defence (DoD) claims that its spectrum requirements are growing by 25% annually while at the same time the temporal and spatial use of the spectrum by its emitters is much less than one percent [16].

The first implementation of the SDR concept was driven by the JTRS program. The US government allocated close to US$ 30 million to its air force units under the JTRS program, which is the a software-programmable radio system providing secure, reliable, multi-channel voice, data, imagery and video communications for mobile military users. Beyond, JTRS, in 2009, the US government is estimated to have provided close to $63.3 million to Virginia-based National Science Foundation (NSF) for carrying out research initiatives in this space. The US government is also expected to continue its financial support to internal defence units such as the office of the Secretary of Defence (OSD) and DoD. Investments in the scale of $70 million are expected to be rendered to these organisations supporting their research initiatives in the domain of information protection and assurance [23].

DARPA is funding a number of cognitive science applications, including the Next Generation or XG program, Adaptive Cognition-Enhanced Radio Teams (ACERT), Disruption Tolerant Networking (DTN), Architectures for Cognitive Information Processing (ACIP), Real World Reasoning (REAL), and Wireless Network After Next (WNAN) [61]. The XG communications programme started in 2002 with the goal to develop both the enabling technologies and system concepts to dynamically redistribute allocated spectrum.
Under the XG program, several contractors demonstrated that a CR could achieve substantial spectral efficiency in a non-interfering method, and that the spectrum allocation process could be simplified. The first demonstrations of these systems took place in 2004 and in 2005. The first XG field test occurred in August 2006 (possibly the first private CR trial) and demonstrated three two-node DSA networks that operated on unused channels

after sensing PUs operating between 225 and 600 MHz [63]. Further field trials demonstrated the technical feasibility of the technology [57]. Tests were performed at different locations in Virginia. Six mobile nodes were involved in the demonstrations that successfully proved that the idea of listen before talk communication equipped with policy-based reasoning in radio access is fully realisable [19].

DARPA work on DSA continues with the development of Wireless Network After Next (WNAN) tactical radio. WNAN field trials conducted in June 2010 demonstrated a 52-node DSA network operating over a range of 1.5 km [64, 65]. WNAN uses DSA as its fundamental operating principle and trades high performance individual transceivers for replicated, but lower performance transceivers [21]. One of the stated objectives of this program is to demonstrate that CR can produce at least the performance of a conventional radio, but accomplish this with reduced performance components through use of adaptation to mitigate the performance-stressing environments that would otherwise drive energy consumption and cost. In late 2010, it was stated that Raytheon BBN Technologies Corporation will provide additional tasking to support the DARPA and Army experiments at Fort Benning, GA, and will add the software radio waveform to the WNAN radio [66].

Because the WNAN CRs are able to access the best available spectrum at a moment's notice, the devices do not have to include expensive components designed to overcome interfering traffic, which is how the Army plans for these radios to cost less than $500 per unit when built in quantities of 100,000 or more [65]. To date, the military has declined to release the results of this year's WNAN tests, but DARPA has begun soliciting proposals for a $22 million project called Advanced Wireless Networks for the Soldier (AWNS) that "will use the cost-effective radio developed under the WNAN program as the base platform," the agency said in a press announcement [65].

3.2 Major challenges

3.2.1 Regulations

The key to the realisation of the DSA opportunities sketched out in this report is a pro-DSA regulatory environment. Regulatory and standardisation issues are discussed in detail in deliverable 6.2. These developments are particular important in the development and acceptance of DSA. It merits mentioning that surveys of the acceptance other telecommunication innovation has revealed the fundamental role of standardisation and regulatory efforts in technology acceptance and explaining the fluctuating interest of industry [67].

3.2.2 Cautious primary users

While there is a pressing need for efficient spectrum use, there is also a concern from licensed users who fear interference and hence degradation of service in their areas of operation. The concern is that of coexistence between PUs and SUs [7, 68-70], partly due to lack of strong technical data from field trial [17]. Incumbent users also fear it as a possible competitor for revenue producing services and the possibility for changes to the telecommunications value chain.

This issue was raised earlier by PUs such as broadcasters who initially adopted a cautious approach to spectrum sharing, citing interference issues and the "hidden node" problem. While broadcasters had no problem with fixed networks with stringent norms such as the 802.22 WRANs they did not favour the introduction of unlicensed use in TV bands and operation by portable devices. This is a shifting landscape, however. Recent responses to the FCC Notice of Inquiry [71], "In the Matter of Promoting More Efficient Use of Spectrum Through Dynamic Spectrum Use Technologies" showed that there was a positive perspective concerning cognitive access and encouragement for identifying bands for suitable for DSA deployment. There was however some concerns raised that dynamic spectrum sharing in licensed commercial mobile radio service bands could result in interference to incumbent licensed services. Likewise, in the UK, in response to Ofcom's consultation [27] the majority of responses were supportive of cognitive access as long as it would not cause harmful interference to licensed uses, including digital TV and PMSE. Echoing the concerns in the USA, those against it were concerned about interference. One way to ease concerns is through demonstrated safe operation with initial deployments in simpler bands [41]. This is linked to the concerns raised by Pawelczak et al., [19] concerning the lack of demonstrations in bands where protection of the PU is necessary.

3.2.3 New power structures

The approach adopted by spectrum managers around the world to managing the radio spectrum has been highly prescriptive and static. Typically, regulators decide on the use of a particular range of frequencies, or a frequency band, as well as specifying what services should be delivered in the band, which technologies (whether technology neutral or specific) are permitted in the delivery of services and who gets to deliver and perhaps use the services. This is referred to as the *administrative approach* or the *command and control* approach. This has relied on the involvement of management agencies, both private and government. Therefore, the ability of a radio to be aware of its environment and to adapt to enhance its performance, and the performance of the network, allows a transition from a manual, oversight process to an automated, device-oriented process [22]. This transition will undoubtedly change the telecommunications industry landscape in the long-term.

3.2.4 Moving beyond conceptual stages and the multidisciplinary nature of development

A criticism of DSA research is that the directions are fragmented and a more centralised view for the future of the technology is required [72]. Research and development requires an interdisciplinary approach including software engineers, computer scientists, electrical engineers and so on [17]. This is linked to the call of observers for open collaboration between research groups to help progress toward comprehensive demonstrations better linked to real-world scenarios and the requirement for more industry-led research to increase the number of prototype systems from the small set of systems focused on long-term research-only concept ideas [19]. Considering the significant amount of simultaneous research and development efforts required the overall development costs of CR are expected to be significantly high. This is particularly critical as the development of the CR concept is still in the conceptual stage due to the multitude of open research challenges in functional areas [73]. The combination of the embryonic nature of implementation of DSA, the complex nature of the interdisciplinary work and the high-cost of development are seen by some as potential stumbling blocks. This is particularly relevant against the backdrop of the global financial downturn, as discussed in the following section.

3.2.5 Uncertain business potential

While there are a number of private, research and governmental entities across the globe experimenting with DSA technologies, there remains a considerable degree of uncertainty concerning DSA as a technology, and its market potential [74], and even if it should be allowed. As observed, observers claim there is a guaranteed market demand for DSA technology [23]. Despite this, the commercialisation of CR and DSA requires a strong business case, which has not been established [17, 75]. A problem here lies in the waiting game played by regulators and technology developers, both who are waiting for concrete action by the other before committing in a certain direction. At the same time, we have seen some prominent organisations emerging, including: Cognitive Radio Technologies (www.crtwireless.com), Xt Technology Inc (xgtechnology.com), Nuel (www.neul.com), Spectrum Bridge (spectrumbridge.com) and Shared Spectrum Company (www.sharedspectrum.com).

An important consideration that has not received much attention by market researchers in the area of DSA is the consequences of the financial crises. While strong economic data does not exist on the financial crunch and the appetite for DSA R&D and expenditure, lessons from the case of other telecommunications innovation (namely WIMAX) showed that due to the financial crises observers suggested that operators and customers re-evaluated their position in the wake of fiscal restraints and concerns. Operators found it difficult to justify investment against the backdrop of bailouts and low shareholder confidence [76, 77].

3.2.6 Technical issues

As observed, the technological maturity of DSA itself plays a significant role in the broad acceptance of the concept. Technical issues have been described in detail in other ACROPOLIS deliverables and will not be duplicated here.

4. Potential and emergent key domains

4.1 Public safety

The adoption of DSA technologies by the public-safety community can better align systems with the future of wireless services, in general, and can contribute to making next-generation public-safety radio systems more robust, capable, and flexible
Lehr and Jesuale [58 p. 103]

Over the last decade a number of large scale environmental and industrial disasters and human triggered incidents have illuminated the need for greater focus on communications in the public safety domain. These events sharply illustrated the importance of communication systems [78]. In most cases, spectrum bands are not enough to provide the necessary traffic capacity or broadband connectivity (ETSI 2010). There are also issues of interoperability and diverse spectrum allocations across Europe because of different wireless technologies (i.e. TETRA). SDR and CR technologies could be applied to the development of multi-standard terminals able to communicate in different frequency ranges.

Like the military domain, earlier approaches to tactical communications were radio centric, leading to the proliferation of radios in each service that lack inter and intra agency interoperability i.e. with police not being able to talk to other police forces in a different county, and police and fire departments not being able to talk to each other [17]. Current communication systems used for public safety largely lack crucial characteristics such as support for multimedia applications that nowadays come standard with low budgeted mass marketed mobile phones [58, 78, 79]. For example, the TETRA standard based systems hardly support data communication. Other communication systems rely for data communications on public radio networks like General Packet Radio Service (GPRS). Sometimes in disaster situations, even GSM is used for voice communication between relief workers. However, in case of an emergency the public networks may get overloaded.

Against this backdrop, increasingly public safety workers use wireless laptops, handheld computers and body cameras to improve their efficiency and share information by instantly collaborating with various actors. The uses of these devices include voice communication, messaging, email, web browsing, database access, sensor data, picture transfer and video surveillance [68]. This has resulted in demand for more bandwidth and regulators have responded by allocating more bandwidth (such as the FCC in the US). Further, the demand for spectrum usage is likely to grow with greater emphasis being placed on the role of ICT in disaster response and environmental application such as the use of sensors for monitoring and early warning systems and ICTs to improve response efforts [59, 80].

Table 4-1, from [58], highlights the trajectory of the past, current and future dimensions of public safety radio and demonstrates a clear path to complex radios utilising DSA techniques.

	Past	Present	Future
Key characteristic of public safety radios	Proprietary, single user, single channel, single locale.	Multichannel, trunked, narrowband (voice only). Regional Proprietary.	Multichannel, multimedia (voice, data, integrated) National Open, interoperable, broadband (data), Mesh/ad hoc.
Shared infrastructure?	No. All dedicated to a single department.	Yes. Shared access infrastructure and base stations via trunking. Channels shared within trunk group but not otherwise.	Yes. Shared access infrastructure and radios. Pooling of spectrum for sharing among multiple trunked groups.
Shared spectrum?	No.	Channel sharing within trunk calling group only.	Yes. Sharing of spectrum across bands. Pooled spectrum.
Infrastructure/spectrum tied?	Yes/ Closely coupled, closed system. Limited interoperability via gateways, tying up additional spectrum.	Yes. Spectrum still tied to infrastructure. Gateways used to link systems.	No. DSA facilitates unbundling of infrastructure and spectrum. Infrastructure shared across multiple bands.
CPE	Single-channel radios.	Multichannel radios.	Multiband radios and flexible CPE.

Table 4-1: Past, present and future of public safety radios [58 p. 104]

Based on these demands, the public safety sector has emerged as a driver and beneficiary of CR and DSA techniques [17, 81], based on its ability to acquire this spectrum when it is needed [78, 82, 83] and address critical interoperability concerns [50, 84]. There is also the argument that public safety cannot rely on the improvement of existing designs; rather there is an opportunity to replace outmoded legacy infrastructure with “leapfrogging” technology to enable the wireless future required by public safety [58]. One reason for this is that it is not sensible from an economic perspective to permanently reserve the large bandwidths required for public safety applications - this worst-case planning is the paradigm that has been operated under since the invention of the radio, leading to “stockpiling” of spectrum [58]. The interruptible use of commercial spectrum and systems for public safety would mean that resources could be 'grabbed' when needed. The opposite scenario can also be envisaged. Public safety spectrum could therefore be made available for more commercial orientated services, if and only if, it is possible to quickly reclaim the spectrum on need [16]. That is, that the Secondary User’s (SU) (commercial users/civilians) vacate the spectrum bands on the arrival of the PU’s (public safety users). While this idea permeates the literature, in our experience of dealing with emergency services we do not see public safety entities making available spectrum until there has stronger evidence that it will not hamper activities of the public safety agencies.

Some authors [58, 85] suggest that facilitating the commercialisation of DSA radio technologies for public safety use, requires the creation of spectrum pools. Lehr and Jesuale [58] argue that this will address the problem of lack of spectrum for shared use and the lack of commercially available equipment. Spectrum pooling involves multiple users sharing access rights to a common pool of spectrum. Lehr and Jesuale [58] envision an environment where holders of exclusive-use licenses for public-safety spectrum voluntarily agree to contribute their spectrum to a “closed common pool”. In essence, the license rights would transfer to the pool from the individual based on compliance with certain enforceable rules. This offers a way to access spectrum without individual licenses and creates the mechanism for spectrum policies to be authored, adopted, and transmitted to DSA/CR radios [58]. They also identify real challenges that need to be overcome, namely 1) technology may not work as expected; 2) Government regulations currently do not permit it; 3) there will be a challenge in obtaining early-adopters; and 4) cost of NextGen Public Safety wireless systems. To justify the cost of this technology there needs to be monetary value placed on the benefits it provides (such as the reduced need for purchasing new equipment because the CR will be software defined [84]).

Despite this push and apparent demand for DSA and possibility for commercial-public safety spectrum pooling there are a number of concerns and need for new regulations [16]. Doyle [79] suggests that the dynamic management of radio resources for the unplanned provision of broadband services in a non-permanent environment, such as an incident area, is currently poorly defined [79]. Proposal for DSA in the public safety domain has also received sharp rebuttals from public safety association groups. In response to the FCC announcement that it proposed to promote the use of DSA technologies the Association of Public-Safety Communications Officials (APCO) cautions:

> “[D]ynamic spectrum technologies are still in early stages of development, with little or no deployed operations”…“Long before dynamic spectrum technologies are rolled out for public consumption, there must be extensive testing in both labs and in the field to ensure that existing radio systems will not be harmed, especially those systems that are used to protect the safety of life and property” [48].

4.1.1.1 Proof-of-concept and developments

Pawełczak et al., [82] proposed the Next Generation Emergency Network (xGEN) emergency network for where there is an acute spectrum scarcity, and introduced the concepts of SDR and DSA into the xGEN (named Adaptive Ad-Hoc Freeband [AAF]). The project aimed to apply the ideas of CR to the field of public safety and emergency control communications, using the principles of Opportunistic Spectrum Access (OSA) [86]. Some results from xGEN showed promisingly that xGEN is a complete architecture which can take care of the non-availability of dedicated bandwidth and can maximise throughput as well [82].

The Wireless Innovation Forum Special Interest Group (WIF-SIG) on Public Safety demonstrated through their theoretical emergency response scenarios (July 7 bombings and a chemical plant explosion) that CR technology can allow for: (1) improved communication and coordination among first responders not just the capability to be interoperable, but a communications capability that manages interoperability; (2) allocation of communications resources to meet the highest priority needs of incident response; and (3) most effective and efficient use of the spectrum resources available for incident response, and the means to access additional spectrum when needed [87, 88]. In order to realise these possibilities some of the requirements they call for are: (1) to develop additional technical capabilities and functions; (2) address regulatory restrictions that impact the ability to implement those technical capabilities and functions; and (3) develop operational policies and procedures to harness the power of a more dynamic communications capability [87, 88].

In this space we are observing some firms establishing proof-of-concept scenarios. For instance, the Cognitive Radio Access Management (CRAM), proposed by Shared Spectrum Company, is a multi-band, reconfigurable CR technology identified as offering key solutions to public safety spectrum access problems [89].

In the USA the FCC has licensed public-safety spectrum by segregating uses/users into eligible and non-eligible categories to control radio interference. Eligible users compete for very small slivers of available spectrum. Going back as far as 1993, the US Congress established the Public Safety Wireless Advisory Committee (PSWAC) to assess the spectrum needs of public safety entities in the US through the year 2010 [79]. The President's Spectrum Policy Initiative focuses on identifying methods that use emerging technologies, such as CR, to increase the efficiency and effectiveness of spectrum usage [90]. The Department of Justice (DoJ) CommTech Program, is funding research and development in the areas of CR and SDR and is providing input to the SDR Forum to ensure emergency response needs are met by these technologies [90]. CommTech explored the development of CR technologies that will operate both within the public safety radio bands and the current operational environment [91].

The U.S. Department of Homeland Security (DHS) released its first National Emergency Communications Plan (NECP) in July 2008. The more recently released NBP clearly reflects the effort to promote public safety wireless broadband communications. The recommendations include creating a public safety broadband network, creating an administrative system that ensures access to sufficient capacity on a day-to-day and emergency basis, and ensuring there is a mechanism in place to promote interoperability [68]. The premise is that with CR, public safety users can use additional spectrum such as license-exempt TVWS for daily operation from location-to-location and time-to-time. With appropriate spectrum sharing partnerships with commercial operators, public safety workers can also access licensed spectrum and/or commercial networks [68].

A number of questions remain to be answered before DSA in the public safety domain can be realised. Primarily, concerns need to be addressed that DSA will lead to a disruption in communications rather than facilitate communication and maximise spectrum. The work of the WIF-SIG goes someway to addressing this. Other questions include can DSA radios be deployed in a seamless manner to replace existing public safety radios [50]? Are there some public safety bands that would be better candidates than others for an initial transition to DSA radios? [50].

4.2 Commercial applications

As observed, few academic and practitioner studies have attempted to investigate the commercial opportunities and the industry changes generated by DSA; most that have done so, are largely speculative. Here we review this literature and discuss some of the commercially relevant applications, business models and market issues.
Before reviewing the literature, it is worth examining some of the classical management/ business literature on disruptive innovation for possible lessons and guidance on how disruptive technology presents challenges and opportunities in the telecommunications market. Some traditional market theories relevant to the case of DSA are [92]:

- Disruptive technologies are different to incremental or less radical technologies. For instance, companies which focus on extending the performance of incremental and more conventional technologies, and choose to be followers in adopting new ones, can remain strong and competitive. However, this is not the case with disruptive technologies. Large-scale returns and significant first mover advantages are associated with early entry into the emerging markets in which disruptive technologies are initially used.
- Companies should invest in technology risky products only when their customers need them. So far there has not been a critical-mass of demand for more spectrum from consumers, who may not be aware of spectrum crunch issues. At the same time, this might explain the interest of companies such as Google and Microsoft in DSA and the TVWS. Their customers are generally high-technology web users, giving these companies the potential for additional revenue streams that link to their existing products and services. Consider for example, the following quote from Google co-founder "We make most of our money on advertising on search, and there are a lot of times I can't easily do a Web search even with 3G or open Wi-Fi networks," Google co-founder Larry Page said. "If people can get easily connected anywhere [with white spaces], we can make 20% to 30% more money" [24].
- Large-scale growth oriented companies (like today's major telecommunications incumbents around the world) are faced with the problem that small-markets for new technologies (like DSA, at present) do not satisfy their growth and profit demands. Equally, the companies that cultivated small-markets are probably companies that started small. This suggests that smaller organisations, small players or those not presently involved in telecommunications, will view the potential of DSA as being critical to their success rather than a distraction or threat as would be by incumbents.
- Organisational investment and planning processes are typically founded on "quantification of market size and financial returns"; such companies are "paralysed" when faced with disruptive technology because they "demand data on markets that don't yet exist" [92 p.333]. This holds true in the case of DSA, where a real lack of evidence, monetized market value and business models has meant that most analysis of the market are lacking in convincing arguments.

In light of these principles, the following section will explore some of the commercial directions proposed by some of the key thinkers in the field of DSA.

4.2.1 Consumer demand and new applications

While the point that DSA should allow for more efficient use of spectrum and lead to some changes in the telecommunications landscape, one area that has received little attention is that of new applications, or the so called “killer app”; this is a difficult distinction with DSA as its scope covers a range of possibilities. Providing some thoughts on what DSA services may look like, Chapin and Lehr [41] suggest that, while it appears that DSA based services would have a strictly lower QoS than radio services that enjoy guaranteed spectrum access, it is more appropriate to say that DSA based services will offer a *different QoS*, one that is more appropriate to some applications. They give the example, of a hotel that may wish to expand the capacity of its wireless network during an event by temporarily acquiring secondary access to additional spectrum. They suggest that the level of demand by customers in the secondary spectrum market is highly dependent on the QoS versus price trade-off achievable with DSA. That is, a communications service with lower QoS may still generate significant end-user demand if it is cheap enough. Such price versus QoS trade-off is a hallmark of competitive markets [41].

Therefore, the QoS challenge is as much about most suitable and novel applications as it is about improving the communications capability of DSA radio technology itself. For instance, DSA can be used to build networks that communicate more effectively through building walls than Wi-Fi (through Very High Frequency [VHF]). In the case of a theoretical service that keeps the entertainment system in a user’s car automatically updated as the new media is loaded on the user’s home PC, would not be concerned with an occasional delay in updating, due to spectrum access limitations, especially if there are cost savings [41].

Pricing remains an unresolved issue and involves developing business models that need to be established, which prove the merit of spectrum access systems [64]. This is an area of immaturity given the lack of strong evidence and business models. Questions remain such as how much should users pay to gain access to spectrum: should it be free, cost or incentive based, and for what type of QoS?

4.2.2 New opportunities & market structure changes

Figure 4-1, adapted from [41], outlines the types of changes that could be engendered by the introduction of DSA. As illustrated it suggests that DSA could enable more efficient spectrum utilisation, an active secondary market and as a direct affect of this, or possibly through DSA itself, could lead to new services and revenue streams. More efficient spectrum utilisation could also enable the need for spectrum database operators, a decrease in spectrum costs and increased competition, which could lead to increased innovation and new revenue streams.

An active secondary market, enabled by DSA, could also encourage the potential for new types of intermediaries to exploit these opportunities, including: mobile virtual network operators (MVNO) that operates a service in multiple bands; spectrum brokers that specialise in managing the transference of access rights in secondary markets; or vendors of customer equipment. This could initiate decreased spectrum costs, faster innovation and technology cycles leading to ultimately increased innovation. Decreased barriers and reduced spectrum costs may enable small-scale, low-cost entry, which enhances competition in data communication services, driving down service prices. This may force incumbents to introduce more value-differentiated services to justify price margins, which will stimulate innovation in wireless communications even from operators who do not exploit it [41].

Increased innovation leads to a mutual beneficial relationship with increase use in SDR and more flexible radio design, which could further spur the use of DSA. While, increased lifecycle speed also makes it more challenging to recover the fixed costs associated with introducing new technologies, services, or business models, successive generations of technologies will overlap [41].

Chapin and Lehr [41] caution that such positive flows can only take transpire if there is sufficient liquidity in the spectrum market to enable the deployment of DSA based services. Further, we caution that such changes are suggestive. Alternative scenarios are possible; for instance, where the increased number of entrants leads to increased spectrum availability but higher costs for consumers as each new entrant into the value chain adds to the cost of spectrum, siphoning financial benefits that could be absorbed by consumers.

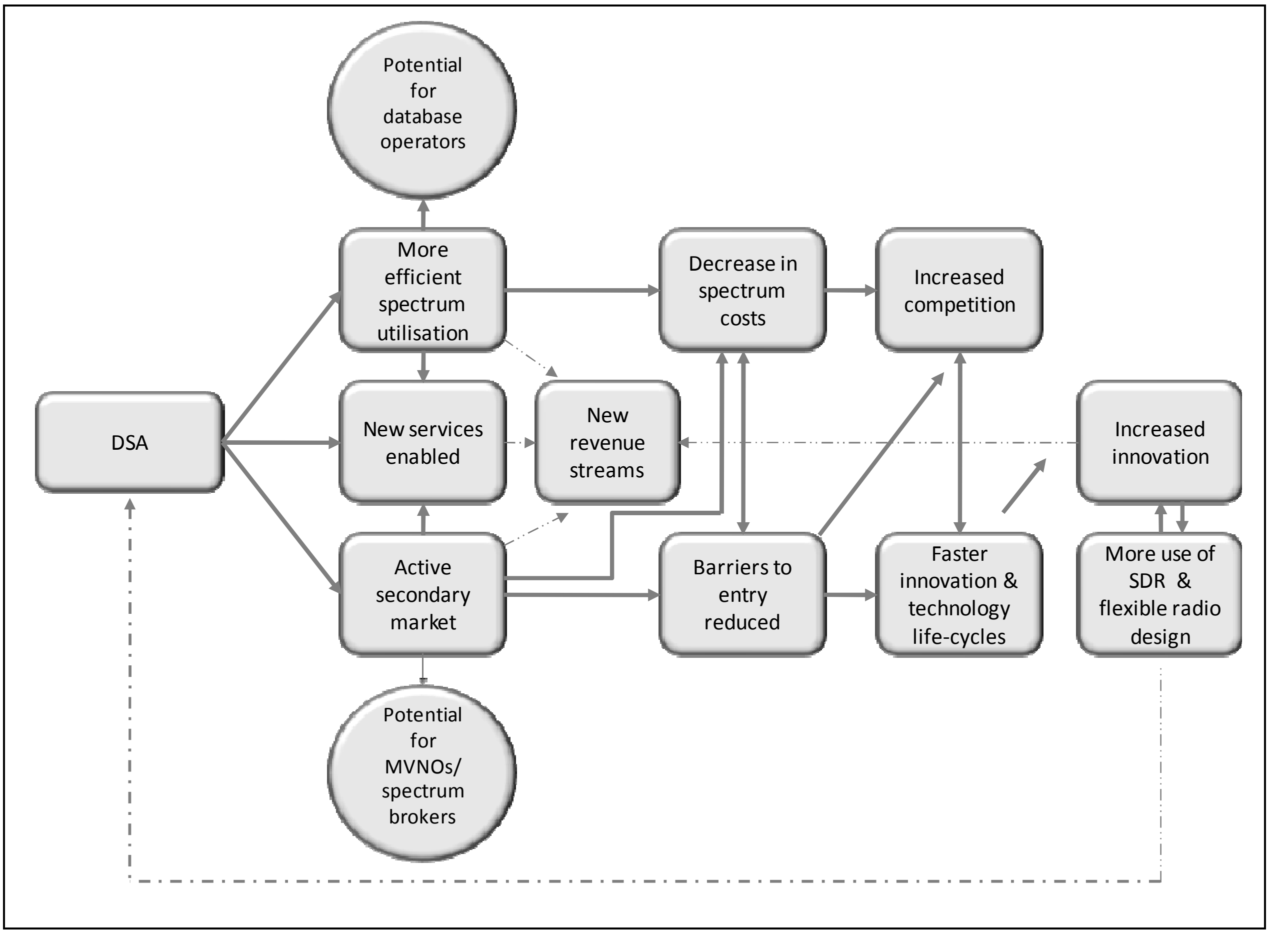

Figure 4-1: DSA inspired changes to market structure [41 p. 97]

4.2.3 Operators

Despite the growth in telecommunication services over the last two decades, it has been observed by some authors [93] that telecommunication operators face a number of challenges in the existing market: including declining average revenue per user (ARPU) (despite a 42% increase in world-wide mobile service revenue from 2005-2010, the average revenue per user dropped 16%), demand for increasing capacity, performance and differentiated services and increased competition. More efficient use in spectrum through DSA can be exploited to address these challenges. Some suggest DSA offers operators the

opportunity to realise a multitude of new services [44], yet these are not yet defined in the academic or industry literature. Operational benefits such as uniform spectrum utilisation, rapid introduction of new technologies, lower cost of deployment and increasing service provider competition [45] are also possible.
A SWOT analysis of DSA from the perspective of operators is presented in Table 4-2. Commercial market drivers include spectrum access for increased capacity and new wireless internet services, as well as international harmonisation.

Strengths	**Weaknesses**
Improved spectrum efficiency Eliminated need for expensive and lengthy spectrum licensing process More flexible spectrum assignment Less technology dependent access to spectrum Seriously considered by US regulators > potential leverage effect	Protection of licensed radio systems in interference may not be reliable May not be sufficient for services that require restrictive QoS Low acceptance by license owners and regulators Increased complexity of devices Additional infrastructure may be required Multiple value chain participants
Opportunities	**Threats**
New types of services like operator assisted dynamic spectrum assignment (to protect licensed services and to enable QoS) may provide new revenue stream Spectrum trading (lease, reselling, etc.) and inter-operator spectrum sharing Potential for new very high bit rate systems (Gbs/s)	Thresholds for entering market of commercial wireless communication are lowered New upcoming competitors CR devices may be allowed to operate in incumbent operators spectrum Operators may lose competiveness if trend is missed

Table 4-2: Analysis of DSA from incumbent operator's perspective (today's license holders). Adapted from: [44 p. 206]

4.2.4 Possible areas of future development

Amongst the partners of the WP deliverable there are several areas identified for future research concerning possible application areas of DSA. This will be explored in greater detail in the next iteration of the deliverable. These include:

4.2.4.1 Femtocells

Femtocells are small base stations designed specifically for residential and small-enterprise environments and constitute a good candidate for DSA technology in order to address interference and spectrum-scarcity, while reusing extant infrastructure [93, 94]. Femtocells are also often naturally shadowed from the exterior environment, thereby enhancing the performance of OSA. There are also large potential benefits in applying the CR techniques to WiMAX with femtocells [95]. We note here, however, that for all these techniques to be applicable the problem of managing the interference created either between the femtocells themselves or the femtocell and the devices of the broader overlaying network must be solved satisfactorily. This comprises a major field of research, since such interference mitigation or avoidance is far from trivial.
To be more specific, in the type of DSA flavor envisioned, femtocells can be exploited for opportunistic capacity extension. More specifically, in a situation where a system operating in a licensed/ unlicensed band is overloaded and cannot guarantee the provision of the

required QoS anymore, the traffic can be re-distributed to neighboring femtocells. This dynamic, cognitive exploitation of femtocells enables devices to maintain the required level of QoS for a wireless communication link, even though a congestion situation occurs. For the access providers the main benefit is that more users can be supported that otherwise would be blocked, since the new incoming users can now be served. At the same time, end users can enjoy improved QoS, as the congestion problems can be resolved.

4.2.4.2 Intra-operator spectrum management

This gives the opportunity to the operator to perform Dynamic Spectrum Allocation on its licensed spectrum. The operator optimizes the utilization and management of its spectrum resources in an autonomous and flexible manner based on measurements (this has been explored by the EU Project FARAMIR, from a technical perspective).

4.2.4.3 Opportunistic networks

One approach for exploiting CR technologies for efficient application provisioning is the concept of Opportunistic Networks (ONs), which are dynamically created, operator-governed, temporary infrastructure-less extensions of the main cellular infrastructure. ONs are governed by operators through the provision of policies, e.g. regarding resource usage, as well as context/profile information and knowledge, which is exploited for their creation and maintenance. They are dynamically created in places and at the time they are needed to deliver application flows to cellular users. ONs can consist of various devices/terminals, potentially organized in an *ad hoc* mode, as well as elements of the infrastructure itself [96, 97].

Cognitive Management Systems (CMSs), comprising self-management and learning capabilities are exploited so as to ensure the fast and reliable establishment of ONs, tackling the highly dynamic nature of the environment, including traffic and applications issues' as well as the potential complexity of the infrastructure. Several scenarios of exploiting this concept of ONs and CMSs for efficient application provisioning can be considered [96, 97]: (i) opportunistic coverage extension, to serve devices that are out of coverage of the infrastructure or are not capable of operating at the provided Radio Access Technology (RAT); (ii) opportunistic capacity extension, where ONs are exploited to offload service areas with high traffic; (iii) infrastructure supported opportunistic *ad hoc* networking exploiting the closeness of location of application end-points so as to reduce application traffic; (iv) opportunistic traffic aggregation in the radio access network where a only sub-set of ON terminals exchange data with the infrastructure; (v) opportunistic resource aggregation in the backhaul network where backhaul bandwidth is aggregated to match the bandwidth of wireless access technologies towards the user. In all cases (see Figure 4-2) terminals participating in an ON are those terminals that are made available by their users for such use/creation.

The establishment of ONs that are managed through CMSs is expected to provide benefits to all involved stakeholders. More specifically, access and service providers are enabled to provide applications/services in challenging situations, e.g., when the infrastructure has limited coverage or exhibits congested access. Access providers benefit from the fact that more users can be supported since new incoming users who would otherwise be blocked, can now be served, while already connected users experience improved QoS since congestion situations can be resolved. Furthermore, resource efficiency can be increased by putting into effect under-utilized and available in a particular local area resource for use by ONs. ONs can also allow for more cost-efficient handling of various situations, such as unexpected or not-frequently occurring events. Through ONs, handling of such cases can be done without large investments in infrastructure, thus keeping low the total cost of ownership and cost associated with the management of customer relations.

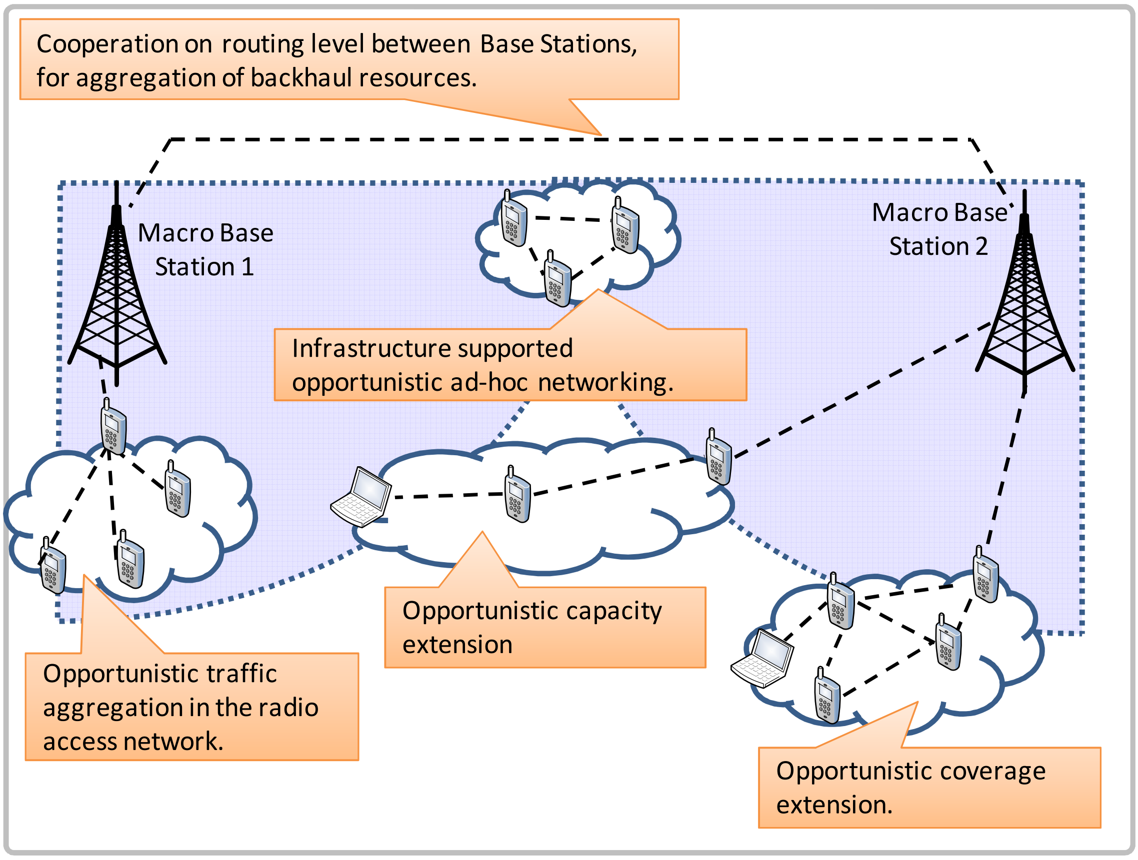

Figure 4-2: Example of ON scenarios

4.2.4.4 TVWS

One area that has been hyped as offering the most potential for DSA is the TVWS. It has been suggested as having the potential to increase broadband access, facilitating growth in the Internet service industry and providing better access to rural users. IEEE 802.22 has been opened for unlicensed use by the FCC. IEEE 802.22 is thought of as an alternative technology to Wi-Fi with an unlicensed spectrum like that of Wi-Fi, but a better spectrum between 54MHz and 863 MHz. Similar to TV signals, the access to the Internet could be over tens of kilometres (30 km to 100 km in rural areas [98]) and no restrictions regarding in-building environments and the like.

It has also been suggested that the IEEE 802.22 standard could be used for wireless home networks, mobile broadband, and TVWS femtocells. However, the technical challenges ahead are manifold [43]. At the same time, it has been noted that “*quantitative techno-economical studies of the commercial feasibility and cost versus benefit associated with use cases of cognitive radio crucial in influencing the take up of the technology by wireless network and service providers but are currently very limited*” [99 p.10].

Shared Spectrum Company believes that economical, long-term solution for implementing sustainable rural broadband Internet access networks is to deploy DSA technology, which is the only technology that can use both free and leased spectrum below 1 GHz and, to the greatest extent possible, existing radio towers and infrastructure. In mountainous terrain for instance, coverage would be assured with DSA by using the best frequencies available for customers furthest from their serving tower, and higher frequencies for customers closer to the tower. The DSA solution represents an elegant, sustainable way to solve the rural digital divide challenge [100].

In 2009, the first public WS network was launched in Claudville, Virginia, using devices from Spectrum Bridge, Microsoft, and Dell. In order to prevent inference with TV broadcasters and other protected users, the radios in Claudville are managed by Spectrum Bridge's white spaces database. This database assigns non-interfering frequencies to the radios, and can adapt in real time to new TV broadcasts [101]. Taking this forward Spectrum Bridge launched the first large-scale “Smart City” network in Wilmington, North Carolina, in 2010, which is able to access available TVWS spectrum. The Smart City network is able to dynamically assign non-interfering frequencies to WS devices throughout the service area to effectively provide bandwidth where and when it’s needed [32]. These developments show that TVWS has current and future market potential and from a more technical standpoint shows a clear trend towards the use of databases for managing spectrum, rather than sensing techniques.

As observed in section 3.1.3 there are several implications from the decision concerning the release of 700MHz for frequencies for mobile use arising from WRC2012. The implications of this are yet to be fully explored and will be investigated in the next deliverable.

4.2.4.5 Machine-to-machine and wireless personal area network applications

While it has been stated by a number of sources that machine-to-machine devices will increase many fold in the coming years, by placing increasing burden on spectrum availability, there has been little attention in the way of research outlining this as a possible application area. As observed, DSA could offer different QoS applications and low QoS applications may be suitable to some machine-to-machine application areas. Nolan in his presentation “Rise of the Machines” at the 4th COST Action IC0905 TERRA (15-17th November 2011, Brussels) outlined interesting possibilities for application. Others have suggested that ad hoc, sensor and mobile networks are the ones that might benefit the most from DSA type technology.

Similarly, wireless personal area networks (WPAN) are a likely application niche for DSA and CR. WPAN is a term used to describe a specific type of network that centres around an individual person or their workspace, using the standard IEEE 802.15. It is similar to machine-to-machine as it involves devices interacting, albeit within a small (often metres) geographical area, guided by the activity of an individual. Several authors have focused on WPANs as a niche market for DSA [44]. One particular area that has received significant attention is medical wireless body area networks [102]. At the COST-TERRA ISO905 meeting in November Chavez-Santiago proposed CR for wireless body area networks based on UWB in a hospital environment. While an embryonic area, WPANs could provide niche market for the application of DSA.

5. DSA and CR: future prospects

Although the precise shape of the future of radio may be difficult to discern, some aspects appear certain. The future radio environment will include more wireless entities of all kinds, greater demand for mobility and portability, and more heterogeneous wireless networks. These future developments have concrete implications for the design of radio networks, including a requirement for more broadband capacity, which would enable more dynamic and flexible services, and a requirement for spectrum sharing [58].

We identify certain characteristics of DSA that suggest that it offers both significant opportunities, and explains the in part, some of the barriers to its acceptance: (1) it has the potential to be a disruptive technology, meaning that it can create and disrupt existing markets, leading to a paradigm change; (2) it is an immature technology, and the technological maturity of DSA itself plays a significant role in the broad acceptance of the concept; (3) it is not well understood, particularly by non-technical people; (4) it is cross-disciplinary, involving significant interaction between engineering R&D, software developers, regulators etc, leading to high costs, and (5) in many aspects it presents a "counter-culture" technology whereby technology enables the sharing of a natural resource which differs greatly from the ownership model that dominates telecommunications and resource ownership in modern economic culture.

It is not clear what business models will prove most valuable in a DSA-enabled market. There are also new types of entrants anticipated such as MVNO and database operators, amongst others. However, these are not unequivocal; the market must experiment to determine the arrangements of the value chain and new intermediaries that make the most sense [41]. It is important that regulations provide enough flexibility to allow experimentation and the most "fit" structure to emerge.

Once DSA technology is widespread, we can expect reduced entry costs for new service providers to speed up product and business lifecycles. The technology also will enable new value chains and business models for providing communication services.

It is clear that progress is being made towards the adoption of DSA ideas. Already concepts such as TVWS are being realised, even if the sole requirement of a geolocation database is very different from the pretext under which work on TVWS was initiated in the early 2000's. Regulatory visions are facilitating the dynamic sharing of spectrum between spectrum owners, with regulators worldwide producing numerous consultations, memoranda of opinion and other documents on open spectrum markets, with many of these progressing towards the creation of appropriate vehicles to realise those markets. Identification of the way forward in addressing challenges and accelerating development is nevertheless important, and the realisation of the nature of those challenges, e.g., related to market capitalisation for some players and possible erosion of revenues for others, and commercial feasibility, is an essential step. If such issues are overcome, relevant authorities can be persuaded to accept technologies.

We also underscored some of the underlying market challenges experienced in the diffusion of DSA, focusing in particular on the lack of clear market application, technical concerns over the extent of interference and the interests of incumbents. Incumbent service providers must be weaned from reliance on spectrum scarcity as a barrier against competition and the tendency to hoard spectrum [41]. The key to the realisation of DSA in these areas, however, is a pro-DSA regulatory environment (explored in deliverable 6.2). We believe one example of this is the acceptance by the FCC of TVWS with the sole geolocation requirement and reserved channels for wireless microphones, which is sufficiently protective of primary and legacy users of the spectrum, while also being technically achievable for the secondary user at absolutely minimal manufacturing cost. In the short-term we hold the view that DSA will initially have a significant impact in the spheres of defence and public-safety. This is an area we are keen to explore in the next phase of our research. The initial market rationale will be driven by the opportunities in the TVWS and the “white space economy”. However, given the embryonic nature of the market, it is likely that opportunities and revenue streams not identified here could materialise.

6. Conclusion & next phase of research

Clearly, immense opportunity exists through CR and a wider range of DSA related technologies. There are, however, numerous challenges that must be overcome in order for these technologies to be realised in a reliable and sustainable way; these challenges are not only technical in the form of spectrum sensing for example, but also relate to business and markets, for instance, in ensuring that sufficient incentives are present for all involved stakeholders to realise or accept such technologies.

In the next phase of our research we will explore in more detail the issues in this report. There are two major areas on which we will focus upon. The first involves public safety; the literature suggests this is one niche market for DSA technology. In our previous research we have identified that public safety (police, fire, ambulance and government agencies) are concerned with a range of issues concerning disaster response communications, interoperability and spectrum for the increasing number of spectrum hungry devices. The second aspect will focus on the market issues surrounding DSA in more detail. It was observed on a several occasions that there is a lack of empirical and robust research on the DSA applications and business scenarios. We also identified several potential future areas of application. To address these two aspects in the next phase of research we will undertake a series of interviews with policy makers/regulators, telecommunications manufacturers and operators, and specific domains such as public safety to illuminate upon these issues and provide more concrete analysis on these issues.

Glossary and Definitions

Acronym	Meaning
2G	Second generation wireless telephone technology
3G	Third generation mobile telephone services
4G	Fourth Generation Technology
GHz	Gigahertz
ACERT	Adaptive Cognition-Enhanced Radio Teams
ACIP	Architectures for Cognitive Information Processing
AAF	Adaptive Ad-Hoc Freeband
APCO	Association of Public-Safety Communications Officials
ARPU	Average Revenue Per User
ASIC	Application-Specific Integrated Circuit
AWNS	Advanced Wireless Networks for the Soldier
CEPT	Conference of Postal and Telecommunications Administrations
CR	Cognitive Radio
CRAM	Cognitive Radio Access Management
DARPA	Defence Advanced Research Projects Agency
DHS	Department of Homeland Security
DTN	Disruption Tolerant Networking
DoD	Department of Defence
DoJ	Department of Justice
DSA	Dynamic Spectrum Access
DTV	Digital TV
ETSI	European Telecommunications Standards
FCC	Federal Communications Commission
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
ITU	International Telecommunications Union
JTRS	Joint Tactical Radio System
LTE	Long Term Evolution
MHz	Megahertz
MVNO	Mobile Virtual Operator Network
NBP	National Broadband Plan
NECP	National Emergency Communications Plan
NSF	National Science Foundation
OSA	Opportunistic Spectrum Access
OSD	Office of the Secretary of Defence
PSWAC	Public Safety Wireless Advisory Committee
PU	Primary User
QoS	Quality of Service
RAT	Radio Access Technology
REAL	Real World Reasoning
SDR	Software Defined Radio
SPTF	(FCC) Spectrum Policy Task Force
SU	Secondary User
TETRA	Terrestrial Trunked Radio
TVWS	TV White Space
VHF	Very High Frequency
Wi-Fi	Wireless Fidelity
WIA	Wireless Innovation Alliance
WiMAX	Worldwide Interoperability for Microwave Access
WIF-SIG	Wireless Innovation Forum Special Interest Group
WNAN	Wireless Network After Next
WPAN	Wireless Personal Area Network

WRAN	Wireless Regional Area Networks
WRC	World Radiocommunication Conference
xGEN	Next Generation Emergency Network

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