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# REGULATORY AND POLICY IMPLICATIONS OF EMERGING TECHNOLOGIES TO SPECTRUM MANAGEMENT

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## **EXECUTIVE SUMMARY**

Regulatory and Policy Implications of Emerging Technologies to Spectrum Management

This paper provides an overview of the policy implications of technological developments in the field or radio technologies, and how these technologies can accommodate an increased level of market competition. It is based on the work currently carried out in the SPORT VIEWS (Spectrum Policies and Radio Technologies Viable in Emerging Wireless Societies) research project for the European Commission (FP6).

This paper surveys new and emerging radio technologies and their relevant characteristics with regard to spectrum management and the economics of spectrum. It provides an analysis of the challenges facing existing radio technologies, spectrum usage, management and existing mechanisms for spectrum allocation.

Within the survey made in this study the focus is on technology innovations in fixed, mobile (including nomadic) and broadcasting systems. At certain points connections and dependencies with other forms of spectrum use may be observed (such as radars, navigations systems, astronomy etc). Only the effect on the technology developments in radio communications of these other forms of spectrum use is mentioned.

The focus is on frequencies below 6 GHz that is considered the prime frequency range for mobile and broadcast services.

In this paper, the most important innovations in radio technology are surveyed:

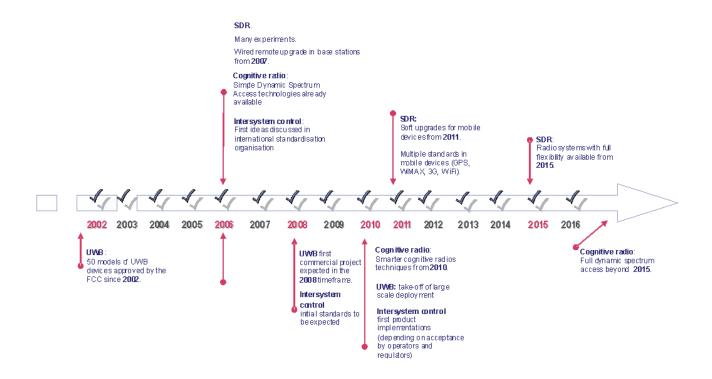
- Spread Spectrum technologies: OFDM, Ultra Wide Band technologies
- Dynamic spectrum access technologies : Software Defined Radio, Cognitive Radio and Intersystem Control
- Mesh and Ad'hoc networks
- Low power devices
- Advanced antenna technologies

It is concluded that many new radio technology developments attribute to increased spectrum efficiency and system performance. Also these innovations form the enabling technology for better frequency utilization or flexible access to the spectrum.

There are 3 innovations in radio technology that are considered as disruptive in the sense that the current spectrum management framework requires amendments to enable further development and introduction of these technologies. These innovations in radio technology are:

- Ultra Wide Band
- Cognitive radio (with SDR as important enabling technology)
- Intersystem control.

The estimated technology roadmap for these technology innovations is shown in the next figure. It can be seen that UWB is a development currently coming up and resolving the spectrum management issues for this technology is urgent at this time. For cognitive radio and intersystem control the time line is longer and the urgency is not so high yet. Implementing possibilities for these last technological innovations is a process that can be started now to keep up with the developments that are expected.



## **CHAPTER ONE: INTRODUCTION**

This paper provides an overview of the policy implications of technological developments, and how these technologies can accommodate an increased level of market competition. It is based on the work currently carried out in the SPORT VIEWS (Spectrum Policies and Radio Technologies Viable In Emerging Wireless Societies) research project for the European Commission (FP6).

The Radio Spectrum (RS) is a precious commodity that one can't touch or see, that one does not create, but it can be worth a lot of money. It is a key access to markets since no frequency means no business. RS is a unique, ubiquitous natural resource shared by various types of services. Unlike many other natural resources, it can be reused. In practice, it remains a finite resource and can only accommodate a limited number of simultaneous users. This restriction requires careful planning and management for maximising its value for all services. This is especially true since the demand for communication spectrum worldwide is rapidly increasing. Within this context, the merits of new technical solutions have to be evaluated in terms of their adaptation in order to ensure an efficient use of spectrum.

New high-speed wireless applications are driving demand for RS. Policy aims to facilitate spectrum access across the EU through market mechanisms. The planned switching-off of analogue terrestrial television by 2012 will assist this. The Commission consolidated its proposal by defining a strategy in2005 for efficient spectrum management to be implemented in the 2006 review of the electronic communication framework. The Commission's strategy for a coherent EU radio spectrum policy as part of the i2020 initiative is to encourage the development of the digital economy. In particular, the need for a gradual but systematic liberalization of radio spectrum use is essential. While bearing in mind national interests in this matter, common action at EU level will give a critical contribution to the coherence and final success of this task.

Growing requirements on radio spectrum usage have led, in the last decade, to a search for greater technical and economic efficiency. However, a conflict exists between the harmonisation trend, which aims at achieving roaming end-users requirements and economies of scale through technical standardisation – requiring rigid ties between frequency band, service(s), and technologies on the one hand and, on the other, the impact of new technologies, enabling efficiency through increased flexibility.

European successes in the past have relied on dual strategies, combining the unlashing of competitive forces across Europe, with coordinated technological efforts like GSM and UMTS. Defining the most appropriate balance between those two approaches in wireless technologies and spectrum management methods is a major challenge for the future of the European economy and society.

This paper surveys new and emerging radio technologies and their relevant characteristics with regard to spectrum management and the economics of spectrum, an analysis of the challenges facing existing radio technologies, spectrum usage, management and existing mechanisms for spectrum allocation. It also assesses the possible consequences of these technical evolutions for spectrum management from different perspectives and the way spectrum management can support innovation and economic efficiency.

## Scope

Within the survey made in this study the focus will be on technology innovations in fixed, mobile (including nomadic) and broadcasting systems. At certain points connections and dependencies with other forms of spectrum use may be observed (such as radars, navigations systems, astronomy etc). Only the effect on the technology developments in radio communications of these other forms of spectrum use will be mentioned. Investigating the technology developments in all fields of spectrum use is outside the scope of this study.

The focus is on frequencies below 6 GHz that is considered the prime frequency range for fixed, mobile and broadcast services.

# **1 PRESENTATION OF THE SPORT VIEWS PROJECT**

# 1.1 PLACE OF NEW TECHNOLOGIES IN THE WIRELESS MARKET AND THEIR IMPACTS ON REGULATION AND LICENSING

Emerging technologies will impact all segments and usages even beyond telecommunications market from personal communications to global networks, from very short to long range distances and also from commercial to governmental and science applications. Moreover, these technologies will impact with very different Quality of Service requirements from "Consumer Business" up to "Safety of Life" applications and also with very different needs in terms of "Spectrum", requested protection and very different impacts in terms of interference potential. The growing need for wireless transfers will demand more spectrum and therefore, one way to avoid it would be to jump to unused or less used higher frequencies (mm or above mmbands) although it may not be feasible for most of the new technologies. In addition, these technologies generally require reduced time to access the spectrum and more flexibility in the regulatory process. Concerning the impact of the new technologies on licensing and regulation, nowadays, there is no single and simple solution since

- Some technologies may hardly live within the current regulatory framework and they may also require a modification in the definition of radio services (like technologies at the convergence of Fixed, Mobile and Broadcast services). Moreover, some technologies will need higher protection levels that can be ensured within the current regulatory context, but it may be difficult for them to share the spectrum with other applications,
- Some incumbent applications can move to other (generally higher) bands or even their services could be partly satisfied by alternative non-wireless technologies,
- Others, are wireless by nature, some of them even can not be moved to other bands since they exploit physical characteristics of specific spectrum bands.

Solution to these can be found at three different levels: by changes in the regulatory framework, by changes in the licensing practices and also by implementation of a friendly technical environment for sharing. Solutions cannot be found only at regulatory level, but also at system/equipment level by adopting techniques that will facilitate sharing with other systems.

As far as the impact on licensing is concerned, for the term of licenses, strong specific requirements in tems of technology may be avoided and one should provide more flexibility in the definition of applications/services. Additional flexibility could be offered by secondary market – however protection of other users should be guaranteed and change of use by secondary market should be considered very cautiously. One should also be ensured for the adequate level of competition: number of licenses to be limited by the amount of available spectrum.

We should also look at the effects of the disparity in licensing costs for wireless players in a Multi-Technology environment. For the legacy situation, we know that there are very different licensing costs depending on the type of service: from no fees for some services to very high cost as resulting from 3G auctions. Even for a given applications, fees could vary on the basis of criteria like the frequency bands, etc. Ideally, all these issues have to be reconsidered in a converging environment in order to prevent unfair competition between players.

# **1.2 SPORT VIEWS APPROACH**

Taking all the considerations in the aforementioned sections, the SPORT VIEWS project specific workpackage is dedicated to carry out a comprehensive study on spectrum management optimisation, putting together radio technologies impact assessments and exploring new options for spectrum management. It is aimed to serve as a contribution to supporting the Commission initiatives, as well as to national regulatory authorities (NRAs), and international spectrum coordination bodies such as ITU and CEPT. In addition, close co-operation with other IST Projects like WINNER, E<sup>2</sup>R, PULSERS and ORACLE are foreseen by the project. The studies are being conducted at 4 different tasks/levels:

## 1.2.1 New and Emerging Technologies: Survey of impacts on Spectrum Management

Innovations in radio technology are driven by the aspiration to have optimal means of communication anywhere and at any time. Fulfilling this aspiration requires reliable radio connections that can support the services that are envisaged in a beyond 3G (recently named as IMT-Advanced by ITU-R) environment. IMT-Advanced will include the long term evolutions towards higher data rates (up to 100 Mb/s with full mobility and 1Gbps in nomadic applications) that will be possible with additional spectrum and improved signal processing and waveform definition and all will be mainly driven by the technology improvements. In other words, within this framework, the technical innovations are aimed at improving data rates, QoS, mobility and availability in wireless systems. The effect on and use of the frequency spectrum has become an important aspect to take into account. Improving the spectral characteristics of a wireless system can be a motive per se, e.g. aimed at higher spectral efficiency and better sharing conditions. On a higher level however, it is important to look how technological innovations influence the allocation of spectrum or can even create new opportunities and methods for spectrum management.

Trends that can be observed are intelligent (smart) and autonomous behaviour of systems that has a profound impact on future spectrum management policies. A study on new methods for spectrum planning requires insight in these developments, which are in particular in the fields of transmission technology (modulation schemes, front-ends), antenna systems, system concepts and topology. Although SPORT VIEWS aims at IMT-Advanced generation of wireless systems and the associated spectrum use, its scope is aimed be broader, considering important technological development that can be seen in IMT-Advanced type of wireless systems.

The expected outcome of this task is a clear vision of radio technology challenges and requirements for spectrum optimisation. This is the major objective of the project and we try to present some initial outcomes at this event.

## **1.2.2** Impact of Market Developments on Business Models

Business models have to be considered simultaneously with the feasibility of technologies and alternative management methods, when looking at ways to optimise spectrum usage and management. Indeed, the existence or absence of adequate industry structure and of profitable business will determine the diffusion and fate of future radio technologies. We must identify the possible pitfalls in the development of new business models in terms of technology adoption and regulation framework. Models would allow exploring the impact of spectrum management choices on several issues like: usage of radio frequencies, how to manage radio networks using alternative radio technologies. The linkage has to be explored between spectrum management at the national level, and network management and the economic added value (financial metrics for operators, consumer benefits, etc.). This methodology is applied to explore the business feasibility of emerging technologies.

The outcome of this task aims to clarify the conditions for spectrum optimisation from an economic and business perspective.

## 1.2.3 Novel Spectrum Management Approaches

This task will contribute to "Optimising the Impact of EU actions" of COM(2005) 411 Final "Forward Looking Radio Spectrum Policy), i.e. "Regulatory impact assessment: appropriate methodologies are needed to assess the economic and societal consequences of specific decisions" by looking directly into spectrum management methods. The debate on the impacts of new radio technologies on usage, planning and management of spectrum revolves at two levels:

At a general management level, there is an issue on:

- Whether administrative methods are able to cope with the rapid pace of technological innovations in wireless,
- Or, if the extension of property rights is, in the area of spectrum, a necessary incentive for innovation,
- How far the WLAN phenomenon (e.g. WiFi) provides a lead for a possible extension of unlicensed bands as conducive to innovation.

The project is to explore these options as confronted to the implementation of future radio technologies detailed in task 1.

Integration of Technology and Management Approaches and Recommendations to Regulators

The objective of this specific study is to put together the analyses and outcomes of the aforementioned study levels and to build a table of possible options and alternatives conducive to the objectives of COM(2005) 411 of 6 September 2005 in looking at harmonisation measures, and the progressive national implementation principles consistent with the single market perspective. Moreover, this task will be performed in the context of more integrated approach to spectrum policy alongside the review of the Electronic Communications Framework (due to be open July 2006 and end Autumn 2006 – legislative proposal end of 2006).

# 2 SPREAD SPECTRUM TECHNOLOGIES

## 2.1 Introduction

In this chapter we discuss the group of radio technologies with spread spectrum properties, but not just in the classical sense. The classical spread spectrum technologies such as Direct Sequence and Frequency Hopping are shortly described but only for tutorial reasons. Recent and emerging technologies like OFDM and Ultra Wide Band and corresponding standards are of more interest.

The spread spectrum class of signals as we define it here is confined to those technologies which generate a (ultra) wide spectral profile, either instantaneously or within a longer period of time. This property makes this class suitable for spectrum underlay and/or overlay techniques<sup>1</sup>.

# 2.2 Legacy spread spectrum technologies

Classical spread spectrum technology is based on the concept that the narrowband and modulated RF signal is manipulated (scrambled) prior to transmission in such a way that its profile in the frequency domain changes significantly, i.e. the signal occupies a much larger part of the RF spectrum, either instantaneously or over a certain time. The manipulation requires a pseudo random code which is, in the original concept, only known to the parties at each end of the radio connection. Spread spectrum technology was invented in the 1940s, and has been used extensively since then for military and other applications that require robustness and resistance to jamming or eavesdropping<sup>2</sup>. Nowadays, 3G mobile communication systems use spread-spectrum today mainly to improve system efficiency and flexibility within licensed bands, but the technique is even more powerful when used for underlay or in unlicensed bands. Ultra Wide Band (UWB) can also be regarded as a spread spectrum technique.

## 2.2.1 Direct Sequence Spread Spectrum (DSSS)

The direct sequence approach (DSSS) is based on multiplication of the original signal with a wideband pseudo noise spreading code, which results in a wideband time continuous scrambled signal. DSSS significantly improves protection against interfering signals, especially narrowband. It also provides a multiple access capability, when the several different (orthogonal) spreading codes are being used simultaneously. It can provide transmission security if the spreading codes are not published (in case of 802.11 they are). Direct Sequence is also used as a technique to generate UWB signals.

## 2.2.2 Frequency Hopping Spread Spectrum (FHSS)

In case of frequency hopping spread spectrum (FHSS) the time continuous scrambling code is used to quickly change the RF frequency of the narrowband transmission within a certain range. Hence, a hopping pattern can be observed in the spectrum. As the instantaneous signal is still narrowband, spectral power density levels are comparable to classical narrowband systems. In terms of spectral coexistence with other systems, FHSS is an avoidance technique, i.e. if the hop coincides with someone else's transmission on the same channel, the collision will take only the duration of the hop, which is typically in the order of milliseconds or even less. Thus frequency hopping would in principle be suitable for spectrum overlay. Like DSSS, FHSS also provides a multiple access capability by using orthogonal hopping codes for different (logical) communication channels. It can also provide transmission security if the hopping codes are not published (in case of 802.11 they are).

# 2.2.3 Time Hopping Spread Spectrum

In case of time hopping a train of short duration pulses is transmitted which is derived from the narrowband information carrying signal through scrambling with a pseudo random modulated impulse train. The short

<sup>&</sup>lt;sup>1</sup> Spectrum <u>underlay</u> technique is a spectrum management principle by which signals with very low spectral power densities can coexist as secondary users in channels with primary users deploying systems with higher power density levels. Spectrum overlay technique is based on 'intrude and avoid' where a secondary user uses a primary channel only when it is not occupied.

<sup>&</sup>lt;sup>2</sup>Only an authorised receiver knows how the signal is spread across the range of frequencies

pulse duration generates the spread spectrum profile. Time Hopping is used as a technique to generate UWB signals.

# **2.3 OFDM**

## 2.3.1 Description and characteristics

OFDM stands for Orthogonal Frequency Division Multiplexing. The principle is patented in 1966 (Chang, Bell Labs) and its practical use emerged in the 1980's with the rise of mobile communications technology. Nowadays it is often the modulation type of choice in systems for mobile and short range wireless (WLAN) communications, digital audio/video broadcasting and fixed wireless access (particularly non-Line Of Sight). Hence OFDM is a legacy technology, but none-the-less it deserves treatment in this report for two reasons. Firstly, OFDM still has a strong interest in the R&D community and industry, for example on the topic of combining state-of-the-art OFDM with other technologies to improve radio performance or even arrive at new concepts. Secondly and more important, there are some interesting spectrum management aspects related to its use.

The principle of OFDM is that a data symbol is transmitted using a certain number N modulated sub-carriers which form a comb in the spectrum. For sub-carrier modulation simpler modulation schemes are typically used such as BPSK or QPSK, in combination with error coding. The key advantage is that the symbol transmission is made resilient to frequency dependent propagation effects (outages, multi-path) because an array of (sub-) carrier frequencies is used for its transmission rather than a single frequency. The sub-carriers should be chosen orthogonal to prevent adjacent channel interference. The sophisticated signal structure and the ambition to improve modem performance, give rise to several challenges in OFDM modem design to cope with modem and channel impairments and imperfections. However, significant improvements in semiconductor technology and digital signal processing have boosted OFDM modem specifications and performance, particularly with respect to bit rates.

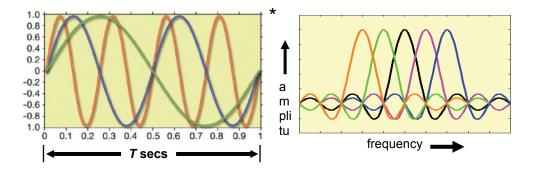


Figure.1: Principle of OFDM modulation: Left: data symbol and supporting carriers (wavelengths) in the time domain. Right: the resulting multi-carrier spectrum (source: MBOA)

## 2.3.2 Spectrum usage and regulatory aspects

OFDM is very often used for wireless communication systems supporting mobility and/or facing difficult propagation conditions (built-up areas), with reference to the physical layer specifications in various international standards. OFDM is used both in unlicensed bands (2.4 GHz, 5 GHz, 60 GHz) and licensed bands (e.g. VHF/UHF bands, 2.6 GHz and 3.5 GHz bands). Spectrum usage and conditions are conventional from a regulatory point of view.

With OFDM, symbol transmission is robust against single channel impairments such as deep fades. This also means that channels can be switched off deliberately, for example for spectrum management reasons. OFDM allows the designer to shape the spectral profile of the signal (spectral sculpting). This makes OFDM in principle suitable for as a spectrum overlay technique to be used in larger portions of the RF spectrum. The picture below illustrates the use of notches in channels that require protection. The signal shown is a UWB

signal based on OFDM modulation ('multi-band OFDM'). The art is to improve on the width and the depth of the notch such that the OFDM signal even in very narrow frequency channels can be sufficiently suppressed.

The spectral shaping can be made very adaptive to local temporal environment characteristics (regulations).

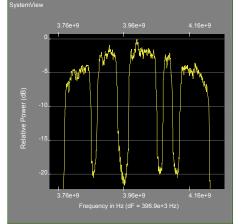


Figure.2: Imposing notches in the OFDM spectrum for interference cancellation

The MB-OFDM variant of UWB (IEEE 802.15.3) is being promoted because of this spectral sharing feature which could improve coexistence of UWB with existing services.

In the Dutch AAF-project the TUD (Technical University Delft) conducts research into the possibilities to apply spectrum pooling<sup>3</sup> based on adaptive OFDM, based on the spectrum overlay ideas just described. Subcarriers will be deactivated in certain channels where licensed users exist. Challenges are a reliable channel estimation (reliable assessment of the presence of active primary users, see section on Cognitive Radio) and the ability to perform steep filtering and maintain sufficient orthogonality between sub-carriers in order to minimize adjacent channel interference issues.

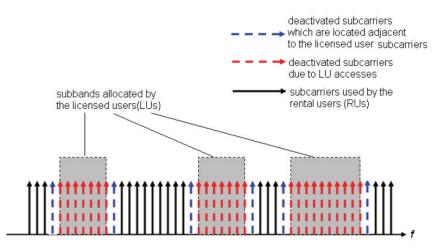


Figure.3: Deactivation of sub carriers to allow spectrum pooling with licensed and rental users.

## 2.3.3 Spectrum Management issues

The principle spectral shaping capability of OFDM raises the issue what this means from a spectrum management perspective. Should wideband OFDM be considered as a serious candidate for spectrum overlay arrangements? What opportunities and issues does it bring?

<sup>&</sup>lt;sup>3</sup> In case of spectrum Pooling, licensed (primary) users put their unused spectrum into a pool from which (secondary) users can rent the spectrum. The dynamics of this arrangement are not limited in principle.

# 2.4 Ultra Wide Band Technology

# 2.4.1 Description and characteristics

Ultra-Wide Band (UWB) is a technology developed to transfer large amounts of data wirelessly over short distances, typically less than ten metres. Unlike other wireless systems, which use spectrum in discrete narrow frequency bands, UWB operates by transmitting signals over wide portions of spectrum (up to several GHz). For example, the US regulator FCC has defined a radio system to be a UWB system if it has a spectrum that occupies a bandwidth greater than 20% of the central frequency or an absolute bandwidth greater than 500 MHz. Under FCC rules, UWB devices are subject to certain power, frequency and operational limitations including being limited to the 3.1 to 10.6GHz frequency band.

The concept of UWB dates back many decades. However, it was only in the late 1990s that technology had advanced sufficiently for it to be practical in consumer electronics. It was at this point that regulatory interest also started. From the history it can be seen that the commercial exploitation of UWB has been under consideration for around five years. The first part of this, from 1999 to 2002 was less intensive. However, after the FCC approved UWB in 2002, many of the international and national fora dealing with spectrum management concentrated their research efforts on the frequency bands specified by the FCC. A clear thread running through this history is the difficulty in reaching definitive technical assessments in the absence of data on UWB deployments and experimental evidence.

The main characteristics of UWB and other short range wireless standards are presented in the table below:

Technology	Data rate	Range	Cost	Power	Spectrum	Issues
UWB	50-100 Mbps	150 m	Low	Low	3.1-10.7 GHz	High data rate for short range only
Bluetooth	0.8-1.0 Mbps	10 m	Low	Low	2.4 GHz	Speed and interference issues
802.11a	54 Mbps	30 m	High	High	5 GHz	High power consumption, high costs, bulky chipset
802.11b	11 Mbps	100 m	Medium	Medium	2.4 GHz	Speed and signal strength issues for more range
802.11g	54 Mbps	30 m	High	High	2.4 GHz	Connectivity and range problems. High cost
HIPERLAN	25 Mbps	30 m	High	High	2.4 GHz	Only European standard. High cost
Home RF	11 Mbps	50 m	Medium	Medium	2.4 GHz	Speed issues
Zigbee	0.02-0.2 Mbps	10 m	Low	Low	2.4 GHz	Standard still under consideration, very low communication range, low data-rate

 Table 1.1: Comparison between UWB and other short range wireless standards (data)

UWB has a variety of possible applications. Those that are estimated to bring most economic benefits to consumers are likely to be in the  $PAN^4$  environment, which includes homes and offices. Other potential applications for UWB include ground probing radar, positioning location systems, wireless sensors, asset tracking and automotive systems. It is generally assumed that the majority of UWB applications will fall into the category of consumer communications and high speed networking within PAN environments.

Until recently, almost all data connections between electronic devices in the home and office environments were made using cables (both wire and fibre), with limited deployment of infra red (IR). However, in recent years, there has been increasing interest in replacing cable and IR connections by 'wireless' links that transmit signals using radio spectrum. Prominent wireless technologies deployed to date include Bluetooth

<sup>&</sup>lt;sup>4</sup> PAN: Personal Area Network

and the 802.11 series of wireless LAN (WLAN) technologies. Wireless links offer a number of benefits to the consumer, including greater flexibility in positioning devices, ease of making occasional connections and the aesthetic advantage of cable replacement.

UWB is a potential alternative to other local area wireless technologies, such as Bluetooth, WiFi and other WLAN technologies. The principal advantage of UWB over existing wireless alternatives is that it should offer much faster data transfer rates (100 Mbit/s up to 1Gbit/s) over short distances thereby using frequency spectrum in stealthy fashion (hardly noticeable).

# 2.4.2 Spectrum usage and regulatory aspects

One of the important issues of UWB communication deployment is the protection of incumbent and future spectrum users. Due to the implicit use of a very wide spectrum range, UWB systems are not planned to operate under any specific allocation but there are lots of existing and planned wireless systems operating under allocated bands within the UWB signal band. Some companies in the USA are working towards removing the restrictions from the FCC's regulations to be able to deploy UWB technology. These companies have established an Ultra Wideband Working Group (UWBWG) to negotiate with the FCC. Other companies and organizations in the USA choose the opposite side and lobby for protection of existing narrow band allocated services against possible interference generated by UWB systems or in their "out of band" field. Similar discussions on protection of other radio services from interference have also emerged in Europe. Currently, there are no dedicated frequency bands for UWB applications identified in the ETSI, in the ECC (European Communication Committee) decisions or in the ITU Radio Regulation treaty.

The figure below shows how UWB uses already allocated radio spectrum.

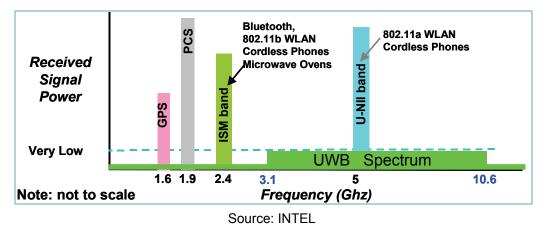


Figure.4: underlay-example of the UWB band in the USA

If UWB can be deployed without undue interference to other allocated services then it effectively increases the availability of spectrum. It would not do this in the conventional sense of making more frequencies available, but by more efficiently using spectrum already allocated.

Some recent theoretical and experimental investigations show that UWB emissions do not cause significant interference to other devices operating in the vicinity. Low power-spectral-density causes UWB signals to lie below the unintentional emitter noise limits defined by the FCC regulations. As a consequence, a UWB system in the USA is deemed not to cause any more interference to a narrowband receiver than the spurious emissions from a computer, a microwave oven or a car's ignition.

A conventional interference mitigation technique for narrowband systems is adaptive equalization at the receiver. Since adaptive equalizers require one or more filters for which the number of adaptive tap coefficients is on the order of the number of data symbols spanned by the multi-path, they are not suitable for UWB indoor communications with over 100 MSym/s and inter-symbol interference (ISI) with more than 30-50 symbols. Frequency-domain equalization (FDE) is however a suitable candidate, which is the analogue of

the conventional equalizer. This type of frequency domain detector for indoor UWB impulse radio communications has been shown to provide multi-user orthogonality in extremely frequency-selective environments.

#### Regulatory situation in the EU (including member states)

The European approach is somewhat more cautious than that of the USA, as Europe requires that a new technology must be shown to cause little or no harm to existing radio services. The European organisations have of course to bear in mind the FCC's decision, in full awareness of the potential commercial benefits of achieving globally-compatible conditions of radio spectrum use for UWB.

The European Commission, through the Radio Spectrum Committee established under the Radio Spectrum Decision, issued a Mandate to CEPT on 12 March 2004 under Article 4 of that Decision. CEPT was mandated to undertake all necessary work to identify the most appropriate technical and operational criteria for the harmonised introduction of UWB-based applications in the European Union. This work is being taken forward within ECC Task Group 3 with contributions from administrations and industry. The Commission may decide to produce a Decision, following completion of the CEPT's work which, as explained above, would become binding on EC Member States.

In September 2005, UK regulator OFCOM made recommendations for UWB standardization in Europe. Two studies conducted for OFCOM estimated that the consumer benefit of UWB-technology may amount to £4 billion by the year 2020. While the benefits are great, however, the studies also estimate that UWB could interfere with existing uses of the spectrum; these studies looked into broadband fixed wireless at 3.4 GHz and 3G networks.

In order to avoid interference with existing systems, OFCOM recommends that UWB systems have a "detect-and-avoid" facility. With this functionality, the chipset listens out for a BFWA transmission in the part of the frequency band where BFWA is currently deployed and if it finds a transmission then it would not use this particular frequency band. OFCOM is also recommending that, in order to protect 3G networks, the power level of UWB devices outside of the core and be much lower than that allowed by the FCC.

A recent study by the CEPT (presented in ECC report 064) contains a similar warning for interference by UWB-devices. This study shows that the emission limit as specified by the FCC does not protect all radio communication services that access the same spectrum.

## Regulatory situation within CEPT

In 2004, the CEPT's Electronic Communications Committee (ECC) created a new Task Group, ECC TG3, to develop a European position on UWB. ECC TG3 took over the work which was being carried out in a number of other areas within the CEPT. ECC TG3 is open to ETSI members in accordance with the terms of the CEPT/ETSI MoU. For comparison, we also draw the mask defined by the FCC, and the US Part 15 limit that lies at -41.3 dBm/MHz. This is the limit imposed on so-called unintentional radiators (devices such as TVs and monitors that also emit radiation at these frequencies).

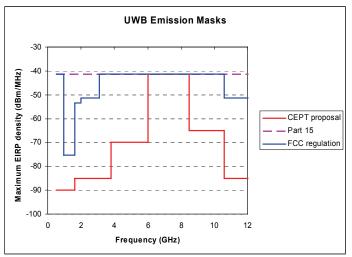


Figure.5: FCC and CEPT Emission Masks for indoor UWB-systems.

Although precise regulations for UWB-technology are still subject to debate within CEPT, it is expected that UWB-technology will be admitted soon in Europe. We may conclude from the discussion within CEPT (including the OFCOM-comments and the ECC report 064 as mentioned above), however, that the CEPT takes a much more conservative approach towards UWB-emissions than the FCC.

#### Regulatory situation within ITU

The ITU-R Study Group 1 (SG1) set up task group 1/8 (TG1/8) to provide a single focal point in dealing with regulatory and technical aspects of UWB. TG1/8 has completed its work in October 2005, producing 5 deliverables:

- One report on sharing studies
- Four recommendations :
  - A framework for the introduction of ultra-wideband devices
  - Measurement techniques of UWB transmissions from devices using ultra-wideband technology
  - Characteristics of ultra-wideband technology
  - Impact of devices using UWB technology on systems operating within radio communication services

#### 2.4.3 Spectrum Management issues

Today, Ultra Wideband systems represent an opportunity for the development of consumer and PAN (Personal Area Network) applications. The different spectrum masks adopted by the USA and Western Europe are likely to slow down the penetration of UWB equipment.

The main question surrounding the introduction of UWB systems is the question of interference caused to existing spectrum users. Mobile operators generally warn regulatory bodies about the potential consequences of introduction of UWB in Europe. CEPT is carrying out studies in order to precisely evaluate the potential interferences generated by UWB systems.

In order to prevent interference over the wide frequency range that UWB utilizes, their application will probably be limited to short range. Therefore, they are not seen as potential candidates for mobile applications offered today by cellular systems.

They will probably be used in the framework of unlicensed systems in "commons" type frequency bands in Europe.

# **3** DYNAMIC SPECTRUM ACCESS TECHNOLOGIES

# 3.1 Introduction

In this chapter we will describe various radio technologies that provide ways of dynamic spectrum access. "Dynamic Spectrum Access" (DSA) is any form of spectrum usage that is flexible, which implies that the set of transmission parameters is not fixed beforehand, but can be chosen and changed dynamically. This involves the selection of the appropriate band, channel, bandwidth, transmission power, modulation and coding scheme, and access method. The added value of this type of adaptivity is to be able to operate and maintain system or network performance under different and dynamic (spectrum) environment conditions.

The technology that allows flexibility in the transmitted waveform exists today and is continuously improved and extended. A key research topic is the concept of smart or cognitive radio systems. These systems must be able to sense and interpret their (spectral) environment, make decisions how adapt their own spectral behaviour and evaluate the effect of their decisions (learning aspect).

We will start this chapter with a description of some forms of flexible spectrum usage existing today (legacy). Next, we will describe the ongoing developments in Software Defined Radio (SDR) technology, which is not a disruptive technology in itself, but is an important enabler for truly advanced forms of DSA. We will then conclude the section with a treatment on Cognitive Radio, a development that determines what the ultimately capability will become with respect to DSA.

# 3.2 Legacy dynamic spectrum access mechanisms

Automatic frequency selection mechanisms can be seen as early forms of flexible spectrum access. Several examples can be given:

- The automatic frequency selection principle can be found in modern car radio sets. The radio scans for another frequency for the radio station the user had selected, if the received signal quality of the present frequency the radio is tuned to deteriorate. It is important to note that this mechanism applies to a spectrum passive device (the car radio itself does not transmit). A later development is FM transmitters for MP3-players. They produce a low power FM-signal that the car radio can tune on. The transmitter device looks for an unused FM-frequency, and transmits at very low power to prevent interference with licensed radio stations.
- DECT<sup>5</sup> cordless communication systems for use in residential and business environments apply the dynamic channel allocation mechanism (DCA). At call-setup, DCA looks for a vacant channel within its available band of 1880 to 1900 MHz. The vacancy of a channel is determined through channel measurements. It is continuously monitored during a call, and if the quality of the channel deteriorates below a certain threshold, the call is transferred to another available channel out of the 10 frequency channels within the DECT band.
- Dynamic Frequency Selection is a (mandatory) feature incorporated in IEEE 802.11h compliant WLAN devices operating in the 5 GHz frequency band where these devices have a secondary status. The DFS mechanism facilitates the avoidance of radio channels already in use by primary users (e.g. radar systems) or by other WLAN systems. In combination with a Transmitter Power Control (TPC) feature it also improves the spreading of occupied WLAN channels which keeps the aggregate spectral power density below certain limits required to protect satellite earth observation services with primary status in this band. DFS measurements are performed by the WLAN terminals under control of the access point and used to make decisions if a channel change is required and what will be the best channel to jump to. A specific challenge is the ability to reliably detect radar signals, especially frequency hopping radars.

The listed examples have in common that:

<sup>&</sup>lt;sup>5</sup> DECT stands for Digital Enhanced is a European standard for coreless telecommunications

a) The systems' behaviour is based on predefined pre-programmed algorithms and thresholds and is therefore predictable and reproducible;

b) They are examples of unilateral coordination: the decisions and actions of a radio system are not based on information provided by systems with peer or higher status that coexist in the band.

# 3.3 Software Defined Radio

## **3.3.1** Description and characteristics

The essence of a Software Defined Radio (SDR) is that the functionality of the radio physical transmission level (physical layer) is almost completely implemented in software. This is a major technological advancement away from traditional radios, which operate with a predetermined built-in waveform, which is produced at the time of manufacture and cannot subsequently be modified. In a fully SDR based radio system, nearly all (except for the antenna) physical layer functions are implemented in software which creates the possibility for the radio to generate a wide variety of possible waveforms and associated settings. The radio architecture will be layered where the bottom layer comprises generic (but powerful) digital signal processing hardware and the top level the parameterised waveform applications. A middleware layer takes care of the abstraction of the hardware into software objects evocable from the application layer. There is a clear analogy with the PC architecture.

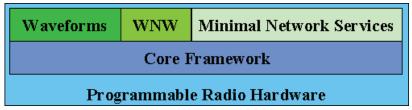


Figure.6: Core framework as the middle layer between waveforms and the hardware. Source: JTRS.

SDR technology is a logical step in the evolution of wireless systems. The following benefits of SDR can be identified:

- **Cost reduction:** "Every new IC process generation has higher initial costs, so the minimal production volume to be cost-effective becomes higher and higher. If a manufacturer can make fewer chip designs by using for example SDR technology, manufacturing costs could be reduced due to higher volumes. Moreover, SDR could reduce the number of ICs in a radio which also reduces costs."
- **Patchable devices:** Design flaws can be repaired
- **Prolonged lifetime:** Support of new technology standards can be implemented in a radio through software updates.
- User convenience: Several radio services are provided by a single device.
- Adaptability: Through its software a SDR can be made to operate on multiple channels and communication standards, using multiple modulation schemes and access methods. Thus, it is able to adapt to its spectral environment. Also, the radio can minimize power usage of the transmitter and the modulation.

The specific benefits as well as the SDR design choices are very much application domain specific. In the 3G/4G domain, there is an interest in network reconfigurability. Full reconfigurability of mobile terminals has a lower priority. Solutions have been proprietary so far. Standardisation of reconfigurable radio architectures is not (yet) a clear goal in Europe. Typical challenges in the 3G/4G domain are reductions in complexity, power consumption and costs. The military industry and the JTRS program<sup>6</sup> in particular have a strong focus on waveform portability to solve interoperability problems with legacy systems and to simplify

<sup>&</sup>lt;sup>6</sup> JTRS: Joint Tactical Radio System

complex legacy system configurations. Cost per item is less of an issue (compared to the 3G/4G domain). Although JTRS does not match European requirements, there is not yet a convincing answer in Europe to the JTRS program.

Both the military and the 3G/4G industry could play a role in SDR developments for the Public Safety sector (P&GS agencies). Because P&GS agencies were the first to deploy wireless technologies, much of the available spectrum is fragmented into small segments that reflect various improvements in frequency capabilities over the past 5 decades. As a result, many different wireless standards exist in Europe to support each of these frequency bands, exhibiting varying capabilities, technologies and protocols, e.g.: Conventional radio, Trunked radio, MPT-1327, APCO P25, TETRA, TETRAPOL, etc.

These systems are designated Private Mobile Radio (PMR) or Land Mobile Radio (LMR). Historically most P&GS agencies make their own, independent sourcing decisions based on spectrum availability, their agencies unique communications needs, and their publicly allocated budget.

Often these factors varied considerably from one agency to another. As a result, most of the radios systems in the field today were never intended to work together. New digital wireless standards, as TETRA in Europe and APCO P25 in US, are developed to standardize PMR / LMR wireless interfaces and network devices, and compliance to these standards will improve interoperability.

However, due to existing PMR / LMR systems lifetime, P&GS agencies will not be in a position to deploy these new wireless standards in a short time frame. Therefore, in a short and medium time-frame the generalized system incompatibility will continue to be a common challenge across all levels of P&GS agencies. This provides an opportunity for SDR technology. Both the military and 3G/4G industry could play a role in the development and standardisation of SDR for the Public Safety sector.

# 3.3.2 Spectrum usage and regulatory aspects

The subject spectrum usage in relation to Software Defined Radio has a straightforward analysis. SDR based radio systems are being developed such that they are able to accommodate different types of waveforms. These waveforms can be existing ones that are currently used in legacy systems operating in specific bands under appropriate regulations. Also new waveforms will be developed which are likely to have a flexible or even agile definition, depending upon the application domain. This is closely linked to the subject of cognitive radio which deals with smart adoption of waveform characteristics.

The deployment of legacy waveforms does not raise new issues, other than the system integrity issue that we will address later. These waveforms will fall under existing spectral regulations.

Newly developed waveforms may have quite different spectral properties compared to legacy systems. From a systems point of view, the spectral profile of a radio node or network may adapt very dynamically depending upon service requirements imposed upon the radio and upon local environment conditions (propagation), and possibly pricing aspects. Such chameleon behaviour can be very beneficial to the performance of the node and the network the node is a member of.

From a regulatory point of view, this development has some implications. It rises the question what SDR implies for standardisation (harmonised standards) and global harmonisation of spectrum. The use of spectral masks specifying frequency dependent power density limits is in fact the only viable way to regulate bands in which SDR technology will be deployed. On the other hand, the flexibility that SDR provides can also be used by the regulator to apply specific location and time dependent regulations in certain bands.

Another important issue from a regulatory perspective is the certification of SDR based systems. Radio systems have to comply with industry regulations and spectrum regulations. With SDRs, given their swift and easy re-programmability, certification and assurance concerning the system behaviour will become far from trivial. Any software upgrade has the potential to modify the radio's behaviour in such a way that compliance with standards and regulations is lost. Such an illegitimate SW modification could either be intentional (in a parallel to the PC-world, one should think of hackers and/or viruses), or unintentional (bug). From a spectrum usage perspective, the risk of SDR reprogrammability is that the signal coming from a modified SDR could interfere with signals transmitted by other users, notably those who have been granted a license by the spectrum authority. The problem is exacerbated if the illegitimate software modification

would be implemented into multiple radios simultaneously, thereby extending the region of harmful interference.

The problem of harmful interference through illegitimate SW modifications poses a challenge to the spectrum regulator, given their task to prevent interference as much as possible. The most advanced system that deals with SDR consequences for spectrum management can be found in the US. In their rule change of March 11 2005, the FCC demands that:

SDR-manufacturers take steps to ensure that software that can be loaded into the radio "must not allow the user to operate the transmitter with operating frequencies, output power, modulation types or other radio frequency parameters outside those that were approved". Also, manufacturers must provide "a high level operational description or flow diagram of the software that controls the radio frequency operating parameters".

## 3.3.3 Spectrum Management issues

The spectrum management related recommendations produced by E2R, based on the E2R regulatory questionnaire are summarized here because they cover quite well the set of issues that SDR raises in terms of spectrum management:

• Harmonisation of standards (standards for reconfigurable hardware):

Interface specifications should be published as adopted and as defined on EU level. But the levels of what should be harmonised should be agreed between the equipment manufacturers.

• Certification of reconfigurable equipment:

Regarding the certification/type approval of equipment, the current mechanisms (e.g. R&TTE directive) may be sufficient to cover the vertical model; extensions may be required to also facilitate the horizontal model.

• Global circulation of reconfigurable equipment:

A global circulation agreement similar to that one adopted by the ITU-R with regards to IMT 2000 Terminal should be developed for reconfigurable Terminals. As it is necessary to follow the rules of conformity assessment, which already exist, reconfigurable equipment will not be usable in many parts of the world. It would be advisable to transfer RTTE directive experiences made in Europe to other ITU regions, and then an amended scheme could be applied on global scale.

• Development of new harmonised standards for reconfigurable equipment (i.e. precondition for the applicability of R&TTE directive):

The use of a harmonised standard for SDR equipment does not provide sufficient regulatory certainty since it would not result in an obligation for the hardware or software manufacturer. Consequently, the R&TTE directive needs to be amended.

To this list of issues, the question can be added how the regulator can exploit the existence of SDR technology, i.e. new instruments to regulate frequency bands.

# 3.4 Cognitive Radio

## **3.4.1 Description and characteristics**

A Cognitive Radio (CR), as its name readily implies, is a radio that is capable of cognitive behaviour. In the description of CR-pioneer Mitola, a CR's cognitive abilities form a six-phase cognition cycle "Observe, Orient, Plan, Learn, Decide, Act". This cycle is adequately described in:

The process begins with the observation, or awareness, phase during which the radio autonomously acquires information about and recognizes its environment. For example, the radio acquires information regarding its physical environment including time (temporal context), space (geographical context), and frequency (physical interface context). Using this information, a fully

flexible cognitive radio is able to process its sensory perceptions, orient itself, and establish a radio presence based on this existing knowledge. This knowledge base provides a foundation for the development of alternative options to planning phase of the cognition cycle. In a fully flexible cognitive radio, the radio will learn based on its past actions and experience, and incorporate that into its deliberations during the next two steps in the cognition cycle - the decision and act phases of the process.

In summary, we describe a CR as a radio that is aware of its environment (with characteristics such as vacant frequencies, user preferences, prevailing spectrum rules, and operator tariffs), and employs this acquired information in a reasoning process, that leads it to decide on its transmission behaviour. Additionally, it is capable of learning, through an evaluation of its own behaviour and experiences.

An important consequence of a CR's cognition, is that, unlike other forms of "thinking radios"<sup>7</sup>, the radio's behaviour may become unpredictable.

Generally, a radio system's cognitive behaviour is not strictly limited to its spectrum usage; it may show cognitive features in a multitude of other functions. However, given our focus on spectrum policy, we will primarily address the consequences of cognition for a radio's spectrum usage, and not take cognitive behaviour at higher system levels<sup>8</sup> into account. Software Defined Radio is widely regarded as an important enabler for Cognitive Radio.

## Main obstacles

In the evolution of Cognitive Radio, numerous technical challenges still remain. Related to a CR's awareness of its spectral environment, the main issues are the following:

- *Wideband sensing* The radio must be able to assess actual spectrum use over a wide tuning range. The challenge with wideband spectrum sensing is the combination of a large instantaneous bandwidth and sufficient measurement accuracy. Also a vast amount of data must be pre-processed to perform opportunity identification
- **Opportunity identification** The radio must be able to detect whether a frequency band is in use. Several signal detection methods are available for this purpose, all of them suffering of the following trade-off in the signal detection: *higher* precision in a *wider* monitored frequency band require *more* processing time and a *higher* power supply.
- *Interference prevention* If a frequency band is free, and therefore available to an opportunistic spectrum user, interference with a primary user is still possible. The CR might not detect the primary user's signal, but it doesn't know whether its transmission is detectable at the site of the primary user. For this purpose it would need location-information of all neighbouring primary users, either provided by the primary network itself, or through a costly network of sounders that monitor the spectrum for primary users and share this information with the CR.
- *Dynamic coordination* Many methods to provide coordination among users of the same spectrum are currently under study. These methods are described in section 3.5 of this report.
- *Spectrum policy compliance* Is transmission in a certain band permitted, at a given location and time? As stated above, a CR is able to verify this and adjust its transmission behaviour accordingly. A requirement for this feature is the availability of some policy-based meta language that translates policy rules into radio behaviour controls.
- *Software challenges* The challenges of SDR exist for CR as well. In addition, the decision and learning processes are still under study. (several DySPAN publications [[7]], e.g. GS1-2, TT1-3, TT5-6)
- *Hardware challenges* These challenges are the same as for SDR.

<sup>&</sup>lt;sup>7</sup> These include adaptive and aware radios, i.e. radios that are aware of their spectral environment and are able to adjust their behaviour in a pre-determined manner.

<sup>&</sup>lt;sup>8</sup> An application of higher level cognitive behavior would be the CR as a member of an Ad-Hoc Network. It communicates with another radio by, for every specific situation, creating its own transmission path involving several hops of other radios. Such advanced forms of information networks are discussed in section 2.5.2.

In addition to these technical issues, the same authorization-issue that was discussed in the context of SDR plays a role for CR: how to prevent an unauthorized system modification that could harm radio communication by other spectrum users?

Also, we note that telecom operators may not favour the development of full CR-radios. Although they may welcome CR-technology as a part of their network system – given its potential for easily reconfigurable base stations, and a more efficient use of their scarce spectrum resources – but they may be wary of cognition implemented in terminals, as this would take a significant part of the network control out of their hands.

# **3.4.2** Spectrum usage and regulatory aspects

The intelligence offered by a CR has important consequences for its spectrum usage. Features that CRs can incorporate to allow for more efficient, flexible spectrum use include:

- *Frequency Agility* the ability of a radio to change its operating frequency to optimize use under certain conditions
- **Dynamic Frequency Selection (DFS)** the ability to sense signals from other nearby transmitters in an effort to choose an optimum operating environment
- *Adaptive Modulation* the ability to modify transmission characteristics and waveforms, thereby exploiting transmission opportunities in the spectrum<sup>9</sup>, and adapting to the throughput required by the user.
- **Transmit Power Control (TPC)** to permit transmission at full power limits when necessary, but constrain the transmitter power to a lower level to allow greater sharing of spectrum when higher power operation is not necessary.
- Location Awareness combined with Policy-based transmission the ability for a device to determine its location and the location of other transmitters. Consequentially it can first determine whether it is permissible to transmit at all, and then select the appropriate operating parameters such as the power and frequency allowed at its location.
- **Negotiated Use** a cognitive radio could incorporate a mechanism that would enable sharing of spectrum under the terms of a prearranged agreement between a licensee and a third party. Cognitive radios may eventually enable parties to negotiate for spectrum use on an ad hoc or real-time basis, without the need for prior agreements between all parties.

In principle, these features may be delivered by less revolutionary radios. CR takes these features to a higher level, where there is less need for the environment to be predefined (i.e., what sort of signal with which interference is to be avoided do we expect? what radio-infrastructure is present? what are the user preferences? etc.).

Practical examples of the cognitive radio concept illustrate its capacities further. Take for instance the user who wants to send a 10 MB email, while driving to his office. Based upon experiences on previous days, his cognitive radio knows that in a few minutes the office's WLAN will become available, and via a pop-up suggests the user to postpone the email until a connection to this – free of charge – network is established. As another illustration, consider the user who enters an important audio-conference; his cognitive radio might suggest upgrading to a network that is slightly more expensive, but offers more quality.

As explained in the general description, Cognitive Radio makes spectrum use more flexible. The radio's spectrum utilization, as well as the type of service that the radio is supposed to deliver, are not fixed during production at the factory, but can be dynamically altered, with a varying degree of user intervention. This flexibility enables a much more efficient use of the available radio spectrum.

Current spectrum regulations must find a way to deal with this flexibility appropriately, making room for innovation while protecting users from harmful interference. Most current spectrum allocations are specific for one type of service (e.g., mobile wireless voice communications, or television broadcasts), one type of technology (GSM, or analogue TV), and one licensed spectrum user. The new radio technologies CR and

<sup>&</sup>lt;sup>9</sup> Heteromorphic waveforms and other new techniques would allow two or more waveforms to co-exist by using different polarity, code, orthogonality, etc.

SDR ask for a more flexible approach, one that is technology and service neutral, and allows for spectrum sharing by multiple users.

## **Regulatory trends**

In the current situation, the general approach of spectrum regulators remains one of "Command & Control", where changing uses of spectrum is a deliberative process involving study and opportunities for public comment. However, we can recognize some trends towards a more flexible approach.

As an example, the US spectrum regulator (FCC) has issued a range of rules and comments that can be seen in this light:

- Interference Temperature (ET Docket 03-237 NPRM/NOI); the relevant characteristic for interference is the received power at the interfered user, not the power at the transmitter. See Appendix B for details.
- Cognitive Radio ([[5]], ET Docket No. 03-108 NPRM, R&O) dealing with certification issues and highlighting the possibility of reliable secondary use of spectrum with CR-technology
- License-exempt Operation in the TV Broadcast Bands ([[11]], ET Docket No. 04-186) a proposal to require unlicensed devices to incorporate "smart radio" features in order to identify unused TV channels.

In Europe we can see similar examples, take for instance the EC's R&TTE-directive ([[9]]) that permits license-exempt operation *unless* incumbent users can prove that they experience harmful interference.

## Future situation: unattainable or inevitable?

The ultimate form of flexible spectrum utilization is given by "no-regulation-at-all". Cognition that is present in each radio device allows radios to make decisions on their transmission behaviour – based on their spectrum sensing and mutual coordination – avoiding any harmful interference to the transmissions of their fellow-users of the spectrum. Regulations that award or deny spectrum to users are thus unnecessary. Whether such a situation will ever emerge depends on many factors:

- Technical feasibility (are technical challenges met, and can development lead to affordable radiotechnology that can provide this extremely flexible spectrum access?)
- Are the more fundamental issues addressed properly?
  - a. authorization of software modifications rendering non-cooperative transmission behaviour
  - b. interference prevention –radio A can sense the spectral environment at A's location, but not at the location of radio B that is potentially undergoing harmful interference due to A's signal.
     Present solutions are limited to short-range systems like WLAN and DECT – a network of sounders may remain too costly.
- Willingness of telecom operators (do they want to share information on the architecture of their network? will they be willing to transfer this much control from their "own hands" into the hands of terminals)
- Willingness of military, public safety services (to abandon their exclusive bands)

Given these open questions we may conclude that this regulation-free situation is still a remote prospect – if even practically feasible at all. CR- and SDR-technologies will have to demonstrate firmly that they can deliver on their promises of extremely flexible yet reliable and non-interfering spectrum use. They must do so in the laboratory, but to gain goodwill a practical application is vital. The unlicensed bands form an opportunity where these sharing technologies may already prove themselves. Successful application in these bands may then persuade incumbent spectrum users to allow these technologies into their piece of spectrum.

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# 3.4.3 Spectrum Management issues

We have described the working principles of Cognitive Radio, and its relevance for spectrum usage. In summary, Cognitive Radio has the potential to improve spectrum utilization as follows:

- Dynamic Spectrum Allocation
- Allow multiple, independent communications devices to coexist within shared spectrum
- Enable secondary markets and spectrum leasing
- Multi-mode terminals: overcome incompatibilities among communication services

Like SDR, CR offer flexibility in their use of spectrum. SDR delivers this through its re-programmability: it makes it possible to modify the transmission parameters dynamically. Still, such modifications would require a lot of user intervention. CR – probably built on SDR-technology - takes re-programmability a step further by bringing intelligence to the radio, so that it is able to decide on its transmission parameters autonomously.

Given the advances in SDR-technology (enabler for CR), and the many initiatives in CR-research, CR-technology may develop rapidly over the coming years. Even though it will take several years at least, within the span of ten years the major technical obstacles may be removed. Spectrum regulators will then play a big role in shaping the eventual use of CR-technology.

On one hand the flexibility in spectrum utilization by these new technologies poses a challenge to the spectrum regulator: a significant amount of **control over the spectrum use is lost**. The amount of parties to divide the spectrum over increases drastically: whereas first there were only network managers to divide spectrum among, now in principle each individual radio-terminal forms a party of its own as it is free to determine its own spectrum use. Also, the flexibility of hardware renders certification difficult (certification issue).

Yet, on the other hand the flexibility has the potential to induce a much more **efficient** use of spectrum. The emerging CR/SDR-technology may deliver flexible forms of spectrum sharing, allow negotiation of

frequency use between users, access of unlicensed users when the spectrum is not in use, and it may overcome incompatibilities among existing communication services.

# **3.5** Intersystem control

## **3.5.1** Description and general characteristics

Multiple radios making use of the same frequency band requires some form of coordination. Within a single radio system this is relatively easy to implement. For instance, in the GSM-system, there is a pilot channel through which radios can announce their intention to access the spectrum, and through which the GSM-network allocates a sufficient share of the available spectrum. Coordination between different radio systems is a more challenging task, since a network "administrator" – in the GSM-case: the operator – is not naturally present.

As radio designs and systems attain higher levels of intelligence, it becomes possible to fill holes in the spectrum, through spectrum sharing. Therefore, in the context of the perceived brimming of spectrum, and the progress in radio technology, inter-system coordination becomes ever more relevant.

The coordination process may involve the negotiation of many parameters: technical (frequency, location, time, transmit power, modulation, etc.), financial (price, payment options, etc.), and service quality (interference protection, signal-to-noise ratio, etc.).

The various forms of coordination that have been suggested in recent years fall into two categories: one in which the coordination is provided by some central controller or database, and one in which coordination is delivered by the radio systems themselves, without such a central entity.

## Central coordination – Spectrum sharing based on a central controller

A method to improving spectrum sharing that is momentarily under study is based on the principle of a separate entity that is in hierarchy above the radio access networks. This central controller is in charge of the spectrum management and controls the assignment of spectrum resources to different radio networks. The concept of a central controller realizes flexible spectrum sharing since the spectrum allocation between operators or different access technologies changes over time. This dynamic spectrum management can take place for radio access networks based on:

- the same technology
- different radio technologies.

We note that at this moment the developments of this method for spectrum sharing restrict itself to radio access networks, but a broader applicability extended to other radio systems is certainly possible.

## Central coordination – Spectrum sharing based on a central data base

This way of flexible spectrum sharing is based on the establishment of a central data base or spectrum registry that administers the spectrum resource status and acts as an information facilitator. The central management in this case only receives spectrum utilisation updates, processes the information and provides the information to the cooperating radio systems. The autonomous radio systems and networks themselves, based on the information in the central spectrum registry, identify from this released information available spectrum resources and assign frequencies for their specific communication purposes.

## **Distributed Coordination**

In this form of coordination the radio-systems work together to compose some sort of coordination agreement, in order to prevent interference. It is possible that the systems have an equal status, or one is superior to the other. In the latter case the secondary system has the obligation to coordinate its spectrum use with the primary, in case of equal status both users are responsible.

Two forms of distributed coordination are possible: unilateral or mutual coordination. In unilateral coordination a transmitter has to identify a vacant piece of spectrum before it can start transmissions, while

in mutual coordination radio users communicate their spectrum needs with each other in order to coordinate the spectrum access. Existing forms of unilateral coordination are described in section 3.1: DFS and DCA. Mutual coordination in its most straightforward form comes down to using a beacon signal, as proposed by the FCC in its rule change dealing with cognitive radio ([4]). If the beacon signal is interrupted, the secondary spectrum user must halt its transmission. More sophisticated forms of mutual coordination require a language to communicate in: a coexistence protocol. Several groups are taking steps to develop such protocols, as we will describe in the following section.

## 3.5.2 Spectrum usage and regulatory aspects

Techniques for intersystem control facilitate spectrum sharing. Thus, they provide an opportunity to the spectrum regulator: multiple spectrum users can be allowed into a specific band, under the requirement that they implement some form of intersystem control themselves.

Such a regulatory approach has already been seen in the US. In a move to encourage the expansion of wireless broadband services (e.g., WiMAX), particularly in rural areas, the FCC opened spectrum access to the 3650-3700 MHz-band under the requirement that some "contention-based protocol" be implemented. Although this can be seen as a regulatory approach that does a lot of things the right way – maximizing spectrum access while minimizing interference levels and minimizing regulatory burden – the technology to provide this solution is not implemented yet. It must still prove its functionality, especially in the coordination between systems of different technology. Also, we note that legacy systems operating in the same band are not included in the coordination process, so that operation is limited to regions in the frequency/time/space-domain without incumbent users.

## 3.5.3 Spectrum Management issues

The clear benefit of intersystem control for spectrum management is that under-utilized spectrum can be taken into use while interference can be prevented.

We identify the following challenges for implementing intersystem control:

- Finding fair allocation policies, rules or mechanisms for spectrum sharing
- How to determine whether one user has priority over the other? How to determine whether a user has the right to access the spectrum?
- The willingness of operators to cooperate in this new spectrum management approach
- Are they willing to disclose detailed information about their network?
- In distributed coordination, updating the policies when the system is already in use is not straightforward, as the actual frequency assignment decision mechanism is distributed between networks and systems.

Central coordination provides a way for the regulator to remain in control over the spectrum access, also when there are multiple licensees of varying status and a wide range of transmission equipment. Thus, through implementing central coordination the regulator can safeguard against interfering spectrum use.

Distributed coordination has other advantages. Not only does it provide a more lightweight form of spectrum management, it also stimulates innovation incentive to coordinate their spectrum access. An example of this is the creation of IEEE 802.16's task group "h" following the FCC's decision to open a piece of spectrum under the condition of implementation of a coordination protocol.

## 4 MESH AND AD'HOC NETWORKS

## 4.1 **Description and characteristics**

Mesh networks are radio communication networks in which radio nodes provide retransmission capabilities to neighbouring nodes, allowing end-to-end connectivity in the network based on multi-hop routes. There are two main categories of mesh networks:

- 'Structured mesh networks': in which the radio nodes have fixed positions
- 'Ad-hoc mesh networks': in which the radio nodes act as mobile terminals

## 4.1.1 Structured mesh networks

The term 'mesh network' (in the meaning of structured mesh network) is often used in relation to Fixed Wireless Access (FWA) systems which are applied to provide access services to small and medium enterprises, home offices and residential users.

Common FWA systems are based on a Point-to-MultiPoint (P-MP) architecture, in which a base station serves several fixed terminal stations within its service area. Each base station can be equipped with a single omni-directional antenna or, more usual, multiple antennas each serving a separate sector (e.g. 90° or 60° wide). To each base station one or more frequency channels are assigned (depending on the number of sectors). By installing multiple base stations a larger area can be covered, in a similar way as is done with cellular networks for mobile communications.

(Structured) Mesh networking is in fact an extension of the FWA concept in which terminals are equipped with the functionality to directly communicate with other terminals within their reach, i.e. ignoring the base station. The terminals are able to relay their transmissions, so a meshed communication network is formed as shown below.

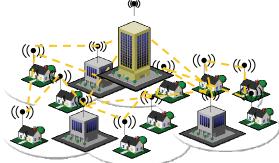


Figure.7 Schematic representation of a mesh network for fixed wireless access [Nortel Networks].

## 4.1.2 Ad-hoc mesh networks

Ad-hoc mesh networking is based on mobile terminals and/or devices which form an autonomous network as they come into each others vicinity. Ad-hoc networking functionality pursues a high level of self management and self healing functionalities and minimal requirement for intervention of the users or a network operator. Within the ad-hoc networking framework several network management protocols are defined e.g. to admit additional terminals which come in range of the other network nodes protocols, to optimise transmission power levels, and update route selection algorithms to improve the overall transmission efficiency. A schematic example of ad-hoc mesh networking is schematically represented.



Figure.8 Schematic representation of an ad-hoc network [Nortel Networks].

The self organising and automatic network management features make ad-hoc networks easy to use and convenient in many applications:

- Personal Area Networks (PAN): interconnection of devices in the home environment such as TV, PC, organiser, mobile phone, video recorder;
- (Temporary) Local Area networks: for instance at conferences, exhibitions or business meetings;
- Mobile communications;
- Sensor networks: communication between intelligent sensor devices;
- Robotics: swarms of wirelessly interconnected robots or similar 'mobile autonomous systems'
- Communications for military and public safety operations: fast connection establishment in areas where no communication infrastructure is present or communication means are damaged;
- Communication between vehicles: for intelligent transport systems, safety increasing applications or to provide road-side information

## 4.1.3 Benefits of mesh networks

Mesh networking can offer benefits compared to the more commonly applied cellular network topologies based on the deployment of base stations en central network management. The most important benefits of mesh networks are listed below.

#### Benefits of mesh networks:

• No single point of failure;

In cellular networks the base station forms a critical factor in the communication infrastructure. When the base station fails all communication within that cell is disrupted. In mesh networks terminals the nodes on which the communication is based and there is no dependence on a base station. If one node fails, this will have just a limited performance effect on the total mesh network.

• Robustness due to alternative routing possibilities in the network;

Terminals are nodes in the mesh network and are able to route the data traffic through the network. Communication between terminals is possible even if they don not have a direct connection, as long as there is a path through the network (formed by terminals relaying the transmission) along which the transmission can be routed. As the density of nodes (terminals) increases, multiple paths in the mesh network may be created along which the traffic can be routed, which increases the robustness of the end-to-end connection. When a certain radio link between two terminals is interrupted, in a dense mesh network there often will be an alternative path along which the traffic can be routed so that communication is still possible.

• Range extension and coverage enhancement;

At the very high frequencies that are used for broadband communications nowadays, the range of radio links attainable is limited. Mesh networks may be used to extend the range of base stations in a cellular network. In this case mesh networking terminals (just) within the coverage area of a base station are used to relay transmission to terminals that are beyond the range of the base station. This way the coverage are of a cellular network can be extended without the direct need for deploying additional base stations.

• Another effect related to the use of very high frequencies is that obstacles in the radio path, such as buildings and trees, result in a significant attenuation of the radio signal. Therefore many broadband radio systems require a (nearly) free line of sight between base station and terminal (in a cellular network) or between individual terminals in a mesh network in order to establish reliable communication links. In a cellular network it often occurs that many geographical locations that fall with in the theoretical range of a base station can not be served due to signal blocking caused by obstructions in the radio path. With the relay function in mesh networks the coverage can be

significantly be improved as the radio signal can be diverted around obstacles by relayed from terminal to terminal. This coverage improvement is considered as a significant benefit of mesh networking, which applies under the condition that there is a sufficient number of terminals within the mesh network.

Benefits specifically related ad-hoc mesh networks:

- No fixed for installed infrastructure;
- Networks are self organising;
- There is no need for network planning.

## 4.1.4 Technical challenges in mesh networking

The dynamic network topology (terminals moving within, joining and leaving the network) and realising efficient and reliable multi-hop communication are the basic challenges for mesh ad-hoc networking. An additional complicating factor is the distributed nature of mesh ad-hoc networks, where there is no central management entity controlling the network, but networking functionalities are distributed among the nodes. Nowadays research is aimed at solving these challenges for mesh ad-hoc networking and optimising communication possibilities offered by these networks.

Besides the benefits that can be offered by (ad-hoc) mesh networking there are also a number of issues to be resolved. The most important issues are:

- Transmission delay in the network when in case of routing along multiple hops;
- Optimisation of routing protocols,
  - Realising fairness among the network nodes;
  - To offer end-to-end quality of service guarantees;
  - To support terminal mobility of nodes within mesh networks;
- Scalability,
  - High node densities
  - Effective data throughput deterioration in case of much transit traffic;
  - Spectrum reuse; tackling interference;
- Security,
  - Authentication;
  - o Admission control;
- Information security;
- Increased terminal costs;
- Willingness to relay.

# 4.2 Spectrum usage and regulatory aspects

## 4.2.1 Spectrum efficiency

It is often claimed that mesh networks are significantly more spectrum efficient than conventional cellular network topologies. The reasoning behind this claim is as follows. In mesh networks every terminal forms a node in the network that has a relaying function for data transmission. With an increasing node density in the network the distances between the nodes becomes smaller and therefore less transmit power is required for the radio transmission links. Due to the lower transmit power levels the overall interference level is lower and therefore more links are possible.

Several studies however show that (ad-hoc) mesh networks do not have good scaling properties. As node density and geographical size of a (ad-hoc) mesh network increases, the traffic rate available to any particular user decreases. In larger networks much of the available radio link capacity is used to relay the

data transmission from source to destination along a path of intermediate nodes. The relaying of transmissions in a large mesh network undoes the advantages completely. Pure (ad-hoc) mesh networks do not scale: the capacity does not increase with growing number of nodes in the network. The assumption that in a mesh network users can 'self generate' transmission capacity is not valid.

Mesh networks can offer scalability and capacity improvement by using hierarchy in the form of:

A secondary mesh network providing backbone functionality (routing data traffic between clusters of mesh nodes);

A topology in which point-to-point or point-to-multipoint links are used to interconnect clusters of mesh nodes and deliver connectivity to communication networks like the internet.

In both cases generally special mesh nodes exist which offer the relaying functionality to the secondary mesh or point-to-point/point-to-multipoint infrastructure for a cluster of mesh nodes. These special mesh nodes are referred to as 'cluster heads' or 'relaying nodes' and are more or less equally distributed across the mesh network. By forming clusters of mesh nodes (in localised regions) and routing data traffic between different clusters on a separate hierarchical level the scaling possibilities of mesh networks can be improved.

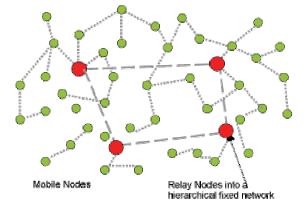


Figure.9. Hierarchical mesh network topology

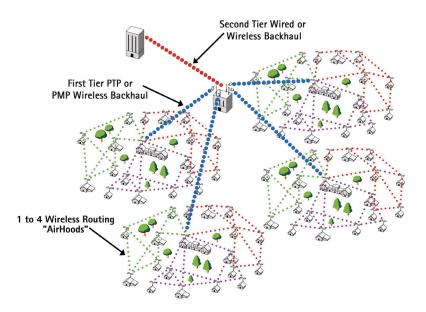


Figure 10. Hybrid Point-to-Multipoint mesh topology with clustered mesh nodes [Nokia]

## 4.2.2 Spectrum usage

Mesh and ad-hoc networking offer new interesting possibilities for communication applications. Regarding impact to spectrum management it can be observed that (ad-hoc) mesh networking is often related to autonomous operation with no or very little operator intervention. Therefore (ad-hoc) mesh networking is generally associated with operation on a license exempt basis. For the autonomous operation of (ad-hoc) mesh networks there are two main implementation concepts:

- The use of low power devices as node terminals;
- The use of cognitive radio technology in the node terminal equipment.

In fact (ad-hoc) mesh networking is a specific utilization of low power devices or cognitive radio technology. The spectrum management issues of both technology developments are described elsewhere in this report. The specific implications for spectrum management for these technology developments were treated these chapters. The specific application of low power devices or cognitive radio technology for (ad-hoc) mesh networking does not bring along additional consequences related to spectrum management.

In fact mesh networking as such does not impose significant implications for spectral management. It however can be observed is that with mesh networking new communication possibilities and services will be provided for various applications. When (ad-hoc) mesh networking finds broad application and deployment this may lead to additional spectrum requirements (licensed or license exempt). For certain (ad-hoc) mesh networking applications specific spectrum claims are made. An example is the application of (ad-hoc) mesh networking for road traffic safety applications in vehicles for which a spectrum allocation is aimed for by the industry. When different applications of mesh networking require separate spectrum allocations this could have a significant impact on the total spectrum requirements for these systems. Compatibility and coexistence possibilities for these devices are therefore an important issue.

# 4.3 Spectrum management implications

Contrary to what is often claimed, mesh networks do not provide improvement of spectrum efficiency compared to cellular network topologies. Pure mesh networks do not scale well, since in mesh networks with large numbers of nodes the relaying of transmissions will significantly reduce efficiency. For the reason of spectrum efficiency the mesh networking concept does not have any important implications for spectrum management.

Ad-hoc meshed networks are in general operating autonomous with little or now intervention of users or a network operator. To enable this autonomous operation generally low power devices or cognitive functionalities are used to avoid interference. Ad-hoc and mesh networking is an implementation of these technology developments that does not introduce spectrum management implications other than those that are treated in the specific chapters.

Ad-hoc and mesh networking however provides some practical benefits over cellular networks and also offers new communication possibilities and services. Therefore (ad-hoc) mesh networking finds employment in various applications e.g.: mobile communications, local area networking, sensor networks, machine-to-machine communications. The new possibilities that ad-hoc and mesh networking offer may lead to an increase in wireless communications which could result in a corresponding spectrum requirement.

A spectrum management issue related to (ad-hoc) mesh networking could be if separate spectrum requirements come forward from specific application areas. As mentioned earlier in this report, for ad-hoc mesh networking in car-to-car communication for road safety applications a separate spectrum allocation is pursued. If there are more (ad-hoc) mesh networking applications requiring a separate spectrum allocation this may have an impact on the spectrum scarcity.

# 5 **LOW POWER DEVICES**

## 5.1 Description and characteristics

Low Power Devices (also indicated with the term Short Range Devices) cover radio transmitter that have low capability of causing interference to other radio equipment.

The low transmit power in general implies that communication is possible only over short distances (up to circa 100 m) and that the interference potential is very local. Low power devices in most cases operate on a license exempt or license free basis. The consequences of license free operations is that Low Power Devices:

Generally can not claim protection from interference caused by other radio services;

Often share spectrum with other (primary) radio communication services to which they are not allowed to cause interference to.

Nowadays Low Power Devices are used almost everywhere. There are very many different applications of Low Power Devices, e.g.:

- Cordless telephones;
- Short range wireless audio and video transmissions;
- Radio microphones;
- Radio Local Area Networks (RLANs);
- Alarms;
- Remote control;
- Monitoring;
- RF Identification (RFID) systems ;
- Medical implant communication systems (MICS).

# 5.2 Spectrum usage and regulation

Internationally (within CEPT and ITU) different frequency bands across the spectrum have been allocated for license free operation of Low Power Devices. Some of these frequency bands are allocated for a specific application of Low Power Devices while in other bands a broader use of Low Power Devices (not related to a specific application) is allowed. Although an international harmonisation in the allocation of frequency bands for license free use of Low Power Devices is pursuit, the actual availability of frequency bands for Low Power Devices and the applicable conditions may vary on a national basis. In ERC Recommendation 70-03 an overview of the spectrum allocations and conditions for Short Range Devices is given for the countries associated in CEPT.

The fact that spectrum has been made available for license free use of Low Power/Short Range Devices, has shown to be very successful. In the license free bands many new technology innovations have been taken place over the last years and are still continuing. This has lead to significant economic benefits and a high spectrum utilisation in these specific bands. The success obtained by enabling license free use in certain frequency bands, is often used as an argument to make more spectrum available on a license exempt or license free basis to further boost technology innovations and consequently the economic benefits.

The success of license free use of Low Power Devices also has drawbacks. In frequency bands where license free use of low power devices is goes together with another primary radio service, the risk of interference exists. A high density of low power devices may cause a cumulated interference effect that can have a

harmful effect on the primary radio service. Usually interference analyses, based on deployment scenarios and assumed application, are used to establish the conditions for co-existence. The conditions are technical limitations posed on the low power devices. When the actual deployment and use (for instance in numbers of devices or way of application) of the low power devices strongly deviates from the assumptions in the sharing scenarios an unexpected high accumulated interference level. This is an issue for many of the current low power devices and technical innovations taking place nowadays. A good example is the discussion about the limits for UWB as described earlier of this report.

With the wide deployment of short range devices in various applications, these systems are in some cases also introduced in essential applications as for instance:

- Safety of life services;
- Medical applications;
- Crucial communications (military, public protection);
- Security.

Since license free use of the spectrum of these low power devices is in principal on a non-interference and non-protection basis, application of this technology has an inherent risk of encountering interference. Depending on low power devices in unlicensed bands for offering guaranteed unhindered operation and reliable radio services is not advisable. To avoid risk the regulator may formulate conditions for the use of these systems in critical applications or provide exclusive bands for safety related low power devices.

# 5.3 Spectrum management issues

To provide optimal possibilities to the technological developments and implementation of low power devices (short range devices) there is a need for more globally harmonised spectrum where these systems can operate on a license free basis. International harmonisation of licensee free bands provides the following benefits:

- A larger market (economy of scale);
- Possibility of cross border mobility (free circulation of radio devices).

Another condition for optimal developments in low power devices is that for the available license free frequency bands minimal restrictions should be posed. Only conditions that are essential to prevent harmful interference should apply. This aspect often raises discussions with the existing (licensed) users of frequency bands in which license free use is introduced, since they fear their systems or radio services are not protected adequately. For some new innovations in low power devices it is also the question if it is possible to integrate these new technologies under the traditional spectrum management scheme or if a renewed spectrum management system is required.

Congestion in license exempt spectrum is a continuous point of concern. When a license free band gets over occupied mutual interference between low power devices (or to other radio services in case of a shared band) may deteriorate the overall performance and usability of the frequency band. Therefore regulating authorities should consider measures to prevent congestion. Possibly a limit to the maximum number and type of equipments brought to the market should apply.

The co-existence in license free bands depends on 'politeness' or 'spectrum etiquette'. All equipment is supposed to meet the established conditions and requirements to use the spectrum. (Usually maximum transmit power and canalisation). It is essential to ensure that when devices get on the market and systems are being deployed in practise these requirements are met. Therefore it is essential that a regulatory authority supervises the actual use of the spectrum and uphold the conditions that were established.

## 6 ADVANCED ANTENNA TECHNOLOGIES

## 6.1 Description and general characteristics

There are many antenna technologies that can be categorized under the term "advanced antenna technologies. The basic aim of deploying advanced antennas is to increase coverage or increase capacity by limiting the interference. To achieve this you either deploy antenna techniques on the transmitter side to direct the transmitted energy in a narrow beam towards the user, or on the reception side, to intelligently combine weak signals received by different antennas.

Advance antennas can be applied at the network side (base station) or user side (terminal). Use of advanced antennas is often limited on the user side because terminal size limitations and the nature of use of a mobile terminal. On the other hand, on the network side there are more opportunities for implementing advance antennas, though the use is here also limited by space limitations imposed by site owners or zoning laws. Also the performance of advanced antenna technologies is dependent of the constantly changing propagations environment where mobile systems are used.

## 6.1.1 Space Time Coding

The approach for advanced antennas is to get a better signal by taking advantage of the dimension:

- Space; by combining signals received by antennas placed apart,
- Time; by combining copies of signals received within a specific time frame
- The combination of time and space.

## 6.1.2 Antenna diversity

Antenna diversity techniques exploit the dimension space, while Multiple Input Multiple Output (MIMO) techniques exploit the dimension space and time. In theory large capacity gain can be achieved with advanced antennas.

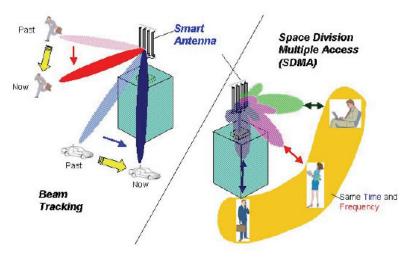
The most commonly used antenna diversity technique is space diversity. A mobile network is made up of many base stations to provide coverage. In UMTS (CDMA systems in general) as oppose to GSM the fact that a mobile can receive signals from different base station is used to enhance the received signal. Also on the network side this aspect is used, where so called "maximum ratio combining" is used to select the signal of either of the base stations that receive the best signal from the mobile.

Traditionally all mobile operators exploit the space aspect of antenna diversity to improve spectrum use. In areas of high capacity demand, a high power base station is often replaced by for example 5 lower power base stations to offer the same coverage but to improve frequency reuse.

Indirectly, requirements imposed by regulators on maximum transmit power of for example; CT2, DECT, Wifi, mandates the use of many small antennas and thus assures efficient use of spectrum.

## 6.1.3 Multiple Input Multiple Output (MIMO)

The expectations of achievable capacity gain through the deployment of advanced antenna systems are high, but that was also the case 20 years ago. The big difference between theory and practical use of advanced antennas is that in practice there is seldom a Line of sight (LOS) as depicted in the figure below. Antenna beams are often reflected or blocked by objects (buildings, trucks, trees, etc) leading to sudden loss of signal, causing dropped calls. This, combined with the relatively high costs of an advanced antenna has resulted in limited use of advanced antennas in cellular (GSM/UMTS) systems.



Smart Antenna Technology

Figure.11. Principle of advanced (also named smart) antenna applied on the network side

On a limited scale there are advanced antenna implementations (MIMO) for WLAN type of systems in use today. For a fact one can buy a WLAN base station in the shop today with multiple antennas, but at a premium compared to the more common single antenna WLAN base stations.

# 6.2 Spectrum usage and regulatory aspects

Antenna technology is generally not considered a regulatory issue, because the effects of the antenna technology that is use is considered an operational issues for which the benefits largely depend on the environment where the antenna is deployed.

For low power devices there are however regulatory requirements in place to certify that the devices remain low power to ensure effective use of the assigned spectrum. Such regulatory measures should prevent users from connecting boasters (amplifiers) or high gain/directional antennas to low power devices to increase coverage, but at the same time increase interference for other low power users in the same frequency band.

# 6.3 Spectrum Management issues

To investigate the impact of advanced antenna technologies on spectrum use is the main focus of this section. We argue that advanced antenna technology, over the past 20 years or so, did not live up to its promise of large capacity increase for cellular systems. Advanced antenna technology never the less still hold the promise of improving capacity. There is still a lot of ongoing research in this field that may result in increased bit rate for devices that use advanced antennas.

For fixed wireless access systems and short range indoor wireless systems the choice to use advanced antennas should best be left to the market, because it may not always be possible to implement advances antenna technology in small devices and the achievable gain largely depend on the environment where the devices are used.

# 7 **CONVERGENCE**

## 7.1 Mobile – Broadcasting convergence

Mobile TV is an example of convergence between Mobile and Broadcasting services that currently finds a great interest. Digital TV services can be offered to mobile users based on different radio technologies. DVB-H (Digital Video Broadcasting to Handheld terminals) is a standard derived from the regular DVB standard initially targeted at fixed digital TV reception. Besides TV broadcasting both DVB-T and DVB-H can also support data services (data casting). With the data casting possibilities to mobile end user terminals the service offering of DVB-H gets closer to the 3G Mobile networks. On the other side the 3G networks can, besides voice calls and data services, also support TV delivery to mobile terminals. This way broadcasting services can be offered using a mobile network.

What can be observed is that mobile and broadcasting technology is often complementary but technology developments lead to convergence of both services in the close future. Looking at the spectrum management point of view the allocation of spectrum exclusively to a radio service is getting less appropriate. In order to fully benefit of technology innovations that make the separation of mobile and broadcasting services disappear, this development should also be reflected in spectrum management.

## 7.2 Fixed – Mobile convergence

The technology developments that are going on in Broadband Wireless Access systems give rise to a comparable convergence between fixed and mobile services. In specific the evolving standardization of Broadband Wireless Access systems (within IEEE 802.16) and the erection of the WiMAX brand shows this converging trend. WiMAX initially was a standard for Fixed Wireless Access and therefore applied to spectrum allocated for Fixed Services. Eventually more sophisticated transmission technologies are becoming feasible that make the necessity for end user terminals to be fixed superseded. With the enhanced radio transmission techniques introduced in the WiMAX standardization broadband radio communication services can be provided to nomadic and even mobile users. For a telecommunications operator the possibility of providing fixed, nomadic and mobile services using the same network infrastructure will offer economic benefits and enables new user applications in the concept of ubiquitous communications.

The convergence of fixed and mobile services raises some spectrum management challenges. In the current spectrum management framework in general separate frequency bands are allocated to Fixed and Mobile radio services. To provide maximum possibilities for technology innovations that support converged fixed, nomadic and mobile services, steps should be taken to ensure that spectrum management does not form an obstacle. At this moment fixed mobile convergence is treated by CEPT ECC working groups, for several specific frequency bands. The Joint Project Team Broadband Wireless Access is considering the possibilities to introduce converged fixed, nomadic and mobile systems in the 3.4 to 3.8 GHz band. Another example is the 2.6 GHz band that was designated for IMT-2000 systems but within the scope of technology neutrality now also other technologies like WiMAX could be applied.

# 7.3 Wireless Access Platforms for Electronic Communications Services (WAPECS)

In line with the convergence of radio services, within the Radio Spectrum Policy Group (RSPG) a coordinated EU policy approach regarding spectrum for Wireless Access Platforms for Electronic Communications Services (WAPECS) is discussed.

## The objective of WAPECS is:

'to harmonize frequency band on an European basis in which a range of electronic communications networks and electronic communications services may be offered on a technology and service neutral basis, provided that certain technical requirements to avoid interference are met, to ensure the effective and efficient use of the spectrum, and the authorisation conditions do not distort competition.'

The WAPECS concept uses the term 'electronic communications services' which includes e.g. IP access, multimedia, multicasting, interactive broadcasting and datacasting that could seamlessly be provided by a variety of radio communications technologies and networks. The WAPECS concept foresees a further convergence of communication technologies and networks in the future. The next generation wireless communication systems will be a merge of fixed, mobile and broadcast technologies as exist nowadays.

The frequency allocation to specific radio services (in the sense of the ITU Radio Regulations) does not fit the WAPECS concept. In WAPECS converged applications there will be no clear distinction between fixed mobile or broadcasting services. In order to give WAPECS the full opportunity to develop there is a plea to allocated spectrum resources for broader application possibilities. The allocation should be as broad as 'electronic communication services' without stating if this is Fixed, Mobile or Broadcasting use.

# 7.4 Spectrum management issues imposed by convergence of radio services

What can be observed nowadays, are technological innovations that lead to a changing environment in which the clear distinction between the radio services as defined in the ITU Radio Regulations disappears? The convergence between fixed, mobile and broadcasting technologies imposes challenges for the spectrum management. For spectrum management there is the challenge to remove existing regulatory barriers in order to give these new technological developments sufficient possibilities to become successful. In fact this means that not only technology neutrality should be introduced in spectrum management but also service neutrality. The first steps to adjust the spectrum allocation to technology and service neutrality are undertaken at this moment, but to fully meet the conditions for an unhindered introduction of emerging technologies offering converged services a more flexible spectrum allocation will have to introduced related technical and policy issues have to be solved.

# 8 SPECTRUM MANAGEMENT IMPLICATIONS OVERVIEW - CONCLUSION

Findings regarding spectrum management implications of recent and coming technological developments are gathered in the following table:

Technology	Characterisation	Implications for Spectrum Management	
OFDM Multi Carrier - CDMA	Modern efficient transmission technologies Robust / Adaptable Improvement of radio performance	<b>Opportunities</b> Spectrum Shaping Adaptive to local temporal environment characteristics (regulations) Enhanced Spectrum Efficiency Clever multiple-access schemes Throughput optimization	Enabling Technology
Ultra Wide Band	Spreading signal power over ultra wide bandwidth Low power / short range New application possibilities • high data rates • radar applications • indoor location determination	<ul> <li><i>Opportunities</i> New applications Enhanced spectrum utilization through 'underlay' </li> <li><i>Issues</i> UWB does not fit in current spectrum allocation regime Doubts about 'underlay' use interference aggregation effect Discussion about spectral masks for UWB transmission</li></ul>	Disruptive Technology

39

Software Defined Radio	Radio functionality implemented in software Flexibility in: • radio signals • radio transmission standard • frequency utilization	OpportunitiesAdaptability to spectral environment.Adaptability to new transmission standards.Re-configurability.Enhanced flexibility of spectrum use.Basis for dynamic spectrum allocation systems.Might help solving interoperability difficulties	Enabling Technology
		and legacy issues. <i>Issues</i> Risk of unintended behavior. Equipment certification / standardization. Distributions of responsibilities.	ш
Cognitive Radio	Flexibility of SDR Awareness of the environment (sensing) Autonomous decisions on its radio transmission behavior Ability to learn from its behavior, observations and feedback	Opportunities         Dynamic spectrum allocation / access         Opportunity based spectrum use         Autonomous coexistence in shared spectrum         Issues         Guaranteeing interference free coexistence         • sensing capabilities         • preventing undesirable behavior         Declining control of the regulator	<b>Disruptive Technology</b>
		Similar issues as SDR	

		<i>Opportunities</i> Dynamic spectrum allocation / access	ogy
	<ul><li>Central spectrum coordination over:</li><li>multiple networks</li></ul>	Optimize overall spectrum resource allocation	golon
	<ul><li>multiple radio technologies</li><li>multiple operators</li></ul>	Enhance spectrum utilization	ech
Intersystem Control	• multiple spectrum users	Enable economic mechanisms on a 'real-time' basis	e T
Note: Intersystem control is in some cases seen as a variants of cognitive radio	Central automated spectrum resource controller (Spectrum Policy Server) Transmission protocols to share spectrum control information (Common Spectrum Coordination Information Exchange)	<i>Issues</i> Implementation of the new concept Forming a regulatory framework Establishing policies and rules for dynamic spectrum allocation	Disruptiv
		Acceptance by operators	

	Terminals have relay functionality Capabilities to autonomous form a network of relaying nodes Independence of infrastructure (no base stations)	<ul> <li><i>Opportunities</i></li> <li>Enhanced capabilities</li> <li>Optimization of transmission power levels</li> <li>Enhanced coverage (overcome line of sight issues)</li> <li>Robustness due to alternative routing possibilities in the network</li> <li>Autonomous operation with no or very little operator intervention independence of infrastructure</li> <li>Robustness</li> </ul>
		New application opportunities
Mesh / Ad hoc networks	<ul> <li>Regulation / extension of unlicensed frequency bands</li> <li>Most of the available radio link capacity is used to relay data transmission</li> <li>Different applications of meshed and ad hoc networks may require separate spectrum allocations</li> <li>Low power devices or cognitive radio technology challenges</li> </ul>	<ul> <li>Issues</li> <li>Pure mesh networks do not provide enhanced spectrum efficiency (mesh networks do not scale)</li> <li>Manageability of autonomous radio nodes</li> <li>License free (low power or cognitive radio) implementations of autonomous operating radio nodes in mesh networks</li> <li>Willingness of nodes to relay</li> <li>Large variety of applications may result in additional (exclusive) spectrum requirements</li> </ul>
	Radio systems with low transmit power	<b>Opportunities</b>
	(density).	Various application possibilities.
	The second sheet as a second	Technology associated with:
	In general short range.	- license free operation
		- 'underlay'
	Low capability of causing interference to other radio services.	- spectrum sharing
Low power devices		Can improve spectrum utilisation
		Issues
		Need for globally harmonised spectrum.
		These technologies usually are based on 'politeness' and 'spectrum etiquette'.
		The co-existence rules have to be obeyed.

Enforcement is important.

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	Enhanced signal transmission through smart	Omennetumities	
	antenna systems. Transmit and receive in the direction of the user(s).	<i>Opportunities</i> Better transmission performance contributes to improved spectrum efficiency.	u qu
Advanced Antenna technologies	More robust communication and higher data rates can be obtained	<i>Issues</i> Additional system complexity Higher equipment costs Technical issues to be solved (power consumption, signal processing capacity, integration of multiple antennas)	T publing T

In this report the most important innovations in radio technology have been surveyed. It is concluded that many new radio technology developments attribute to increased spectrum efficiency and system performance. Also these innovations form the enabling technology for better frequency utilization or flexible access to the spectrum.

There are 3 innovations in radio technology identified that are disruptive in the sense that the current spectrum management frame work requires amendments to enable further development and introduction of these technologies. These innovations in radio technology are:

- Ultra Wide Band
- Cognitive radio (with SDR as important enabling technology)
- Intersystem control.

The estimated technology roadmap for these technology innovations is shown in the next figure. Here it can be seen that UWB is a development currently coming up and resolving the spectrum management issues for this technology is urgent at this time. For cognitive radio and intersystem control the time line is longer and the urgency is not so high yet. Implementing possibilities for these last technological innovations is a process that can be started now to keep up with the developments that are expected.

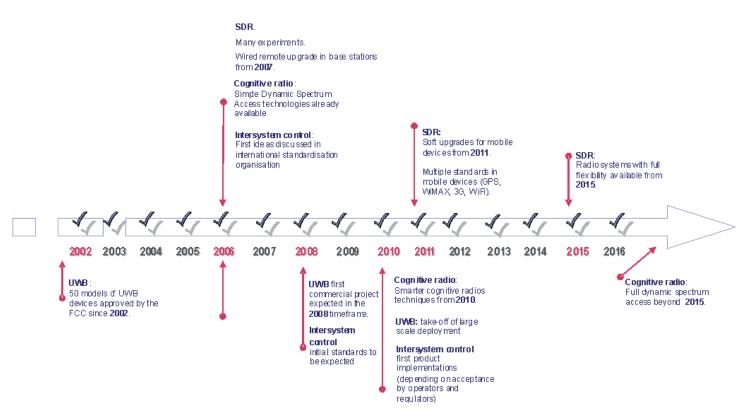


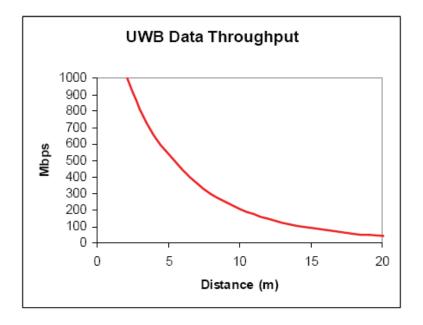
Figure 12. Technology roadmap estimation

#### **9 REFERENCES**

- [1] SPORT VIEWS WP3 Task 1 'Future radio technologies and their impact on spectrum management' TNO & IDATE
- [2] AAF/D3.12, "Adaptive Base-band Processing, state-of-the-art"
- [3] R. Schiphorst, "Software Defined Radio for Wireless Local Area Networks", Enschede, 2004, ISBN 90-365-2071-1
- [4] V.J. Arkesteijn, E.A.M. Klumperink, and B. Nauta. "An Analogue Front-End Architecture for Software Defined Radio". 13<sup>th</sup> proRISC workshop, November 2002.
- [5] Report and Order, Federal Communications Commission, "Rule changes for Smart Radios", FCC 05-57, March 2005
- [6] J. Mitola III, "Cognitive Radio for Flexible Mobile Multimedia Communications", IEEE International Workshop on Mobile Multimedia Communications, 1999, pg 3-10
- [7] 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), Baltimore , November 8-11, 2005
- [8] "Cognitive Radio: Brain-Empowered Wireless Communications", S. Haykin, IEEE Journal on Selected areas in communications, Vol. 23, No. 2, pp. 201-220, February 2005
- [9] Directive 1999/5/EC, art. 3.2 (in effect as of 2000)
- [10] "Understanding the Issues in Software Defined Cognitive Radio", presentation by Jeffrey Reed and Charles Bostian, Virginia Tech, 2005 (http://www.mprg.org/publications/presentations/CognitiveRadioIssues.pdf)
- [11] Federal Communications Commission, Notice of Proposed Rule Making FCC 04-113, ET-Docket 04-186/02-380, May 2004
- [12] Arnon Tonmukayakul and Martin B.H. Weiss, "Secondary Use of Radio Spectrum: A Feasibility Analysis", 25 August 2004
- [13] Stefan Mangold, Zhun Zhong, Guido R. Hiertz, Bernhard Walke, "IEEE 802.11e/802.11k wireless LAN: spectrum awareness for distributed resource sharing", <u>Wireless Communications and Mobile Computing</u>, <u>Volume 4, Issue 8</u>, Pages 881 – 902, December 2004
- [14] Wikipedia on IEEE 802.11k (http://en.wikipedia.org/wiki/802.11k), dd. May 3d 2006
  [15] IEEE 802 Working Group 16: "Air Interface for Fixed Broadband Wireless Access Systems", February 2006, Working document available on http://ieee802.org/16/le/docs/80216h-06 004.zip
- [16] Report and Order, Federal Communications Commission, ET Docket 04-151, FCC 05-56, March 2005
- [17] WWRF SIG1 White Paper, "Methods for Flexible Spectrum Use", Version 0.2 November 2005
- [18] PULSERS Official IST Short Description (March 2004), http://www.pulsers.net/documents.shtml
- [19] Pekka Ojanen et al., Spectrum for Future Mobile an Wireless Communications, WWRF SIG1 on Spectrum Topics, White paper, November 5, 2004
- [20] WWRF, Srdjan Krčo et al., "Ad-hoc networking", WWRF Ad hoc networking Subgroup, White paper 2003
- [21] WWRF, Petri Mähönen et al., "Co-operative and Ad-hoc networks", WWRF Working Group 3, April 13, 2004
- [22] COMeSafety EU Support Activity, Presentation for: DG INFSO Workshop on V2X Communication Spectrum Requirements, Brussels, 28 February 2006, http://europa.eu.int/information\_society/activities/esafety/doc/esafety\_2006/spectrum\_28feb2006/4\_20060228
- [23] Car2Car Communications Consortium, http://www.car-to-car.org/
- [24] AEGIS, (In a contract for the Radiocommunications Agency UK), "Examination of issues related to spectrum efficiency of point-to-multipoint and mesh multimedia wireless system architectures proposed for 40.5 – 43.5 GHz", April 13, 2000
- [25] Plextek, (In a contract for Ofcom UK), "Final Report Study of efficient mobile mesh networks", January 2006
- [26] OFCOM (UK), "Mesh networks", http://www.ofcom.org.uk/research/technology/overview/emer\_tech/mesh/
- [27] http://www.onlab.ntt.co.jp/en/ws/antenna/fig.png
- [28] ERC Recommendation 70-04, "Relating to the use of short range devices (SRD)", Version 17 November 2005.
- [29] S C. Swales, M A. Beach, D.J Edwards a d J.P. McGeehan, "The performance enhancement of Multi-beam adaptive base station antennas for cellular land mobile radio systems", IEEE Trans Veh. Technol, vol 39 pp 5667 I 990
- [30] www.ist-oban.org
- [31] European Commission, "Green paper on convergence of the telecommunications, media and information technology sectors and the implications for regulations", COM(97)623, December 1997
- [32] CEPT, European Communications Committee (ECC), Working Group Spectrum Engineering, Joint Project Team Broadband Wireless Access (JPT BWA), http://www.ero.dk/
- [33] OFCOM (UK), Impact Assessment: "Technology and Application Neutrality in the 2.6GHz Band", September 15, 2005
- [34] RADIO SPECTRUM POLICY GROUP, Opinion on Wireless Access Policy for Electronic Communications Services (WAPECS) "A more flexible spectrum management approach" FINAL, November 23, 2005
- [35] "Value of UWB Personal Area Networking Services to the United Kingdom", report for OFCOM, November 2004
- [36] "A Summary of the Economic Evaluation of the Effect of UWB on Broadband Fixed Wireless Access in the 3.4 GHz Band", report for OFCOM, August 2005
- [37] ECC Decision on the harmonized conditions for devices using Ultra-Wideband technology in bands below 10.6 GHz (ECC/DEC/(06)04), 24 March 2006
- [38] First Report and Order, FCC on UWB, FCC 02-48, ET-Docket 98-153, 22 April 2002
- [39] ECC Report 064, "The Protection Requirements of Radiocommunications Systems below 10.6 GHz from Generic UWB Applications", February 2005
- [40] First Report and Order, FCC on UWB, FCC 02-48, ET-Docket 98-153, 22 April 2002
- [41] ITU-R Recommendation SM.1538-1, Technical and operating parameters and spectrum requirements for short-range radiocommunication devices;2003
- [42] ADHOCSYS, http://www.adhocsys.org/
- [43] The MANET charter, http://www.ietf.org/html.charters/manet-charter.html
- [44] MAGNET Beyond, http://www.ist-magnet.org/magnetbeyond
- [45] C. Evci, "Technology Developments Impacting on Radio Spectrum Management", Conf. on Spectrum Policy, March 2005, London, UK
- [46] J.P.Bonin and C.Evci, "L'evolution du cadre reglementaire problematiques et solutions pour futur", CNFRS Scientific Day on SDR an Spectrum, March 28-29, 2006, Paris- France
- [47] J.W.Burns, "Measuring Spectrum Efficiency- the art of spectrum utilization metrics", IEE Conference on getting the most out of Radio Spectrum, 25 October 2002, London, UK.
- [48] "Market-based approach to spectrum management in the European Union", CEC, COM(2005)400 Final Report, September 2005.

# 10 ANNEX

UWB technical characteristics



*Figure C.1: UWB data throughput – typically quoted system performance* 

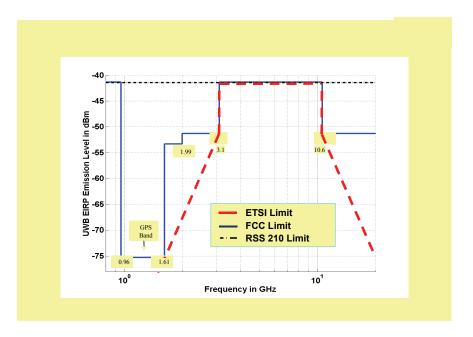


Figure C.2: FCC and ETSI emission masks for indoor UWB systems

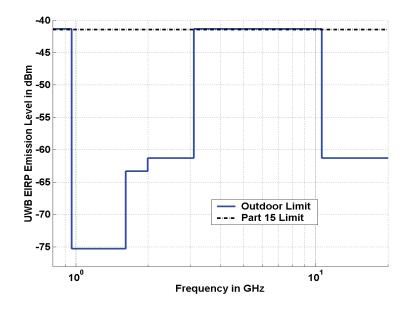


Figure C.3: FCC and ETSI emission masks for outdoor UWB systems