Dynamic Spectrum Access

Phase 1: Scenarios and research challenges

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Abstract/executive summary

The currently used mechanisms for spectrum management are a contributing factor to the long lead times from innovation to market in wireless technologies and systems. This has in turn been a major contributing factor to the dominance of the large telecom companies in the European and World markets, whereas very few innovative enterprises have exhibited consistent growth, although the technical competence in Sweden is very high in this area. Alternative spectrum management regimes, such as the introduction of "unlicensed bands" have proven very effective in lowering entry thresholds for smaller companies (e.g the WLAN business). In addition, experts claim that the spectrum requirements for communication purposes will increase by as much as 200-300 % up to 2010. At the same time the actual usage of the electromagnetic spectrum is very inefficient.

The project aims at studying new more, flexible, spectrum allocation regimes which, in combination with new technologies, such as multi-radio access, novel broadband access techniques, software defined radio and spatial techniques (e.g. smart antennas, multi-hop schemes) have the potential of lowering the entry thresholds for new actors and provide radical improvement to the efficiency of spectrum usage. Further the aim is to investigate the economic and regulatory consequences of such Dynamic Spectrum Access technologies and management regimes. The results will provide input to future policies in spectrum management.

The project has been divided into a first, pre-study phase and a second, research phase. The first phase was launched in Dec of 2004 and the second phase is planned to start in Jan 2005. The first phase of the project, reported here, has the aim to provide a qualitative assessment of the potential benefits of dynamic spectrum access regimes. The analysis in the report and other studies in the area, indeed indicate there is a potential to both lower the entry thresholds for new actors as well as provide radical improvement to the efficiency of spectrum usage. The area is definitely of significant issues and the project should be continued studying the DSA concepts in more detail.

Further, using a systematic procedure, a number of critical areas and bottleneck problems were identified. Our conclusion is that more research is needed in these areas to achieve the abovementioned benefits. As "side effect" in this procedure, a number of novel and interesting spectrum management concepts were derived, e.g. the "real-time spectrum trading" and "use rights" concepts. Out of this gross list of interest problems, a number of highly important problems were selected, matching the competence of the project team. These problems are proposed to be the focus of the next phase in the project.

Finally, the report provides an overview of the most important ongoing research and policy-making activities in the DSA-area

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1 Introduction

1.1 Background & Rationale

The development of the mobile telecommunication industry has been dramatic in the last decades. The Nordic countries have managed to seize a dominating role in this field. The currently used mechanisms for spectrum management with their very slow and consensus based processes have driven market actors into lengthy and complex standardization procedures. The consequence has been long lead times from innovation to market in wireless technologies and systems. This has been a major contributing factor to the dominance of the large telecom companies in the European and World markets, whereas very few innovative enterprises have exhibited consistent growth, although the technical competence in the Nordic area is very high in this field. Most emerging SMEs (Small and Medium size Enterprises) are either quickly assimilated into the larger companies or become highly integrated sub-contractors and thus heavily dependent on the dominating actors in the arena.

A trend that has the potential to change the current industrial structure is the emergence of alternative spectrum management regimes, such as the introduction of so called "unlicensed bands", where new technologies can be introduced if they fulfil some very simple and relaxed “spectrum etiquette” rules to avoid excessive interference on existing systems. The most notable initiative in this area is the one of the FCC (Federal Communications Commission, the regulator in USA) in the early 90’s driving the development of short range wireless communication systems and WLANs (Wireless Local Area Networks). Although it is not obvious if such spectrum allocation regimes are indeed scalable and efficient in the long run, some of them have proven very effective in creating business opportunities and lowering entry thresholds for smaller companies (e.g. the WLAN business).

In the US, with its entrepreneurial industrial tradition, the FCC is determined to actively use spectrum policy to further stimulate the wireless industry and the innovation system. During a number of years the commission has studied alternatives to the traditional spectrum management regime with this purpose [1], [2]. During October 2002, the FCC published a new regulatory framework [3] that was put in operation Jan 1 this year. The consequences of this new framework are that the spectrum management model of today is abolished for large parts of the spectrum. Instead, ”free” spectrum trading becomes the preferred mechanism and technical systems that allow for the dynamic use and re-use of spectrum becomes a necessity. This may introduce a secondary market for spectrum licenses, hoping this market itself would arrive at more effective resource allocation. These secondary markets could arise if trade, lease and rent of licenses were possible without incurring excessive administrative procedures and overhead costs.

In the US, the development toward a more dynamic spectrum management has thus already started. This will, no doubt, very soon have consequences for Swedish and European companies and regulatory bodies. American companies, in particular SMEs, may soon get competitive advantages in the US market compared to European companies, which will not be able to create a home market for products with dynamic spectrum management. In addition, not allowing dynamic use of the spectrum in Europe may also spark a debate between the EU and the US regarding trade barriers for US wireless products in Europe.

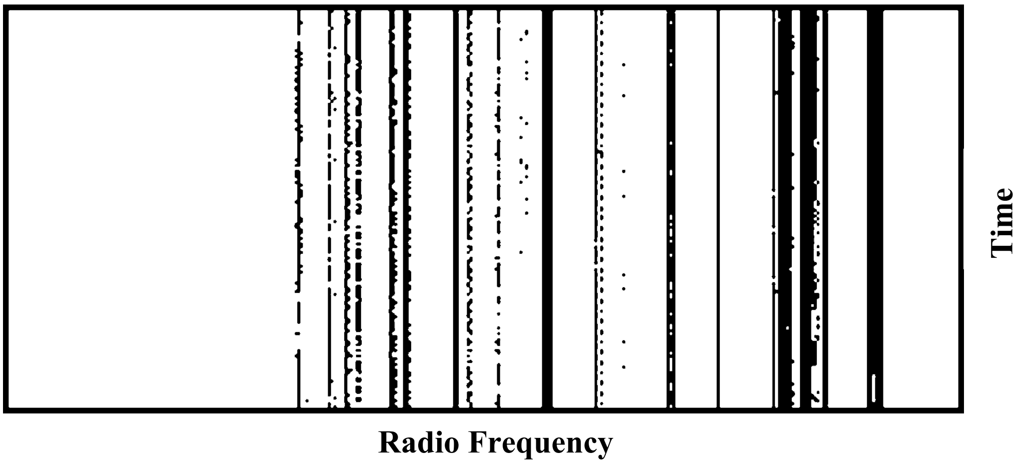


Figure 1. Spectrum usage of approximately 700 MHz below 1 GHZ during 1 hour in Atlanta in June 2002. A black dot denotes "in use" [7].

From a Swedish perspective, these developments should be seen as an opportunity rather than a threat. The Swedish innovation system with its high-level competence in wireless systems should be able to do well in this new technology field, provided that effort is spent in building competence in this area, both regarding technology as well as the regulatory and economic implications of more dynamic spectrum management.

The other important rationale for investigating dynamic spectrum access regimes is large potential demand for wireless devices and services in the near future. Most future scenarios contain an ever-growing plethora of wireless devices, where every household appliance, every consumer electronics device is communicating wirelessly. In addition, experts claim that the spectrum requirements for communication purposes will increase by as much as 200-300 % up to 2010 [4][5][6]. At the same time the actual usage of the electromagnetic spectrum, as a result of traditional spectrum management is not very efficient, see Fig 1.

The current regulatory framework has as its primary target not only to reduce interference between different users and devices using different technical standards, but also to some to extent guarantee a low interference level to the primary users of the spectrum. Since real-time coordination and day-to-day policing of interference between users has this far been costly, fixed allocation of non-overlapping frequency segments ("bands", "channels") to each system/user has been the preferred method. Such an exclusive allocation guarantees low interference from other users but becomes very rigid and difficult to change. The reason for this is two-fold: Firstly, older wireless equipment was typically of fixed frequency type which means that using some other frequency band for a certain service meant replacing large number of transmitters/receivers (e.g. TV broadcasting). Secondly, interference management is a truly global activity since radio-waves (and thus interference!) propagate irregardless of national border. Reaching agreements regarding changing the use of a certain frequency band requires international negotiations and consensus based solutions – processes that operate on, typically, a 10-year time scale. The result is that existing systems and services are well protected and guaranteed interference-free operation, whereas new systems and services experience high entrance barriers and in, from a propagation perspective, attractive frequency ranges, severe spectrum shortage.

This combination of a slow (re-)allocation process and strict interference guarantees is fatal when it comes to efficient utilization. This is verified by measurements conducted by the FCC and others [1] [7] [8] [9] that show that the actual occupancy/use of licensed spectrum in fact is quite low over time and in different geographical areas, see Figure 2. Even in the most dense population centers and busy hours less than typically 1/3 of the frequency spectrum seems to be used. We have thus reason to believe that the poor utilization of existing spectrum is a more severe problem than the creation of "new" frequency bands (preferably at higher frequencies).

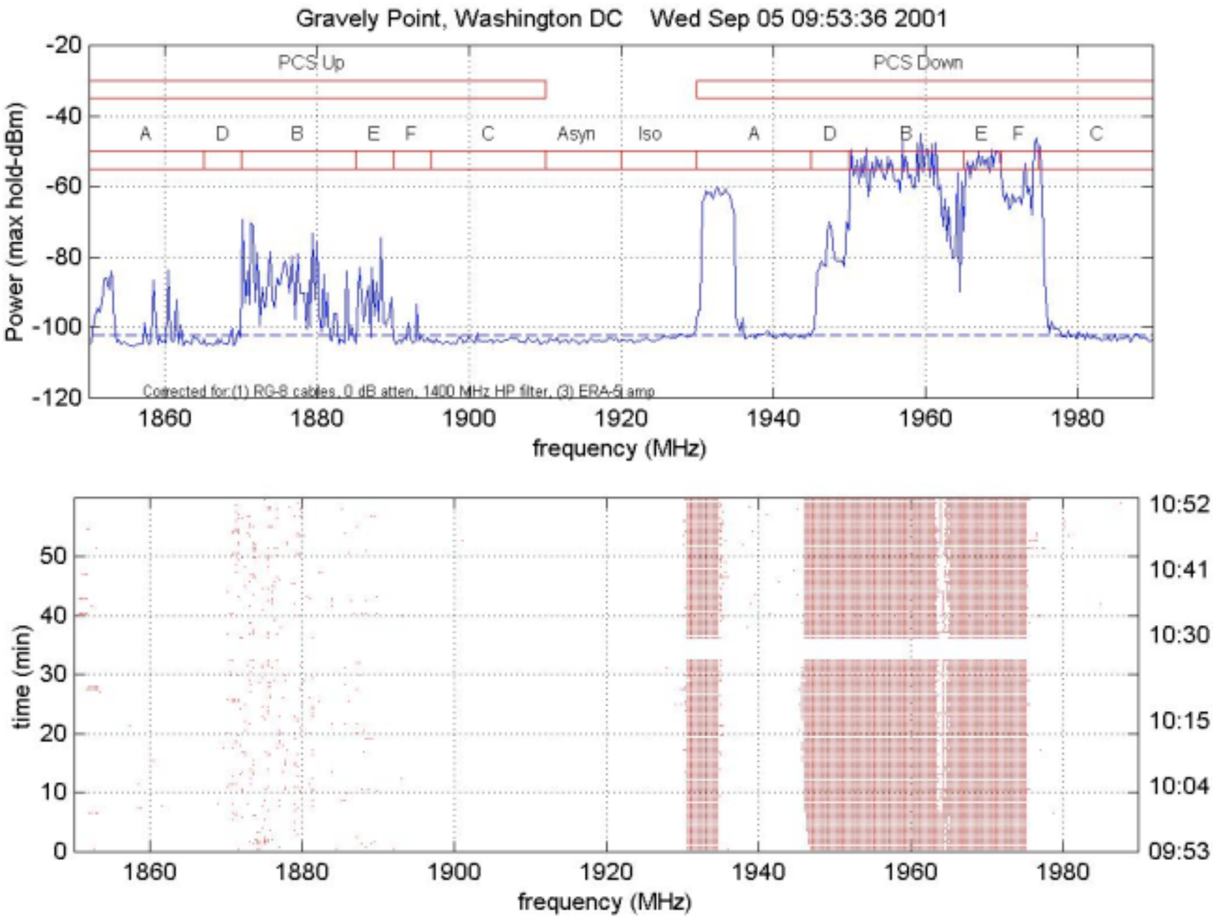


Figure 2. Typical spectral occupancy measurement result [9]

On the other hand, in the "unlicensed" bands the situation is very different. Anyone can design and use equipment in the band, as long it adheres to some simple etiquette rules typically governing transmitter behavior, power and emission limits. The obvious advantages is the unlimited access for new and innovative technologies and the utilization of the spectrum under this regulatory regime is likely to be very high The drawback, however, is that existing (commercial) systems and services are not guaranteed any explicit protection from interference, in particular not from systems not yet known that may be introduced into the band later.

The term (spectrum) efficiency has a widespread use but it is often misused and not very well defined, see [7] and [10]. To complicate matters even further the meaning of the term is dependent on the context. When discussing technical details of a system it may refer to how well the system manages to move data bits and when discussing business matters it may refer to how well the market manages to bring new services to the users. Thus we cannot give a strict definition and in the report the term tends to be strongly context dependent.

However, potentials of DSA-capable systems is not solely a matter of spectrum usage efficiency. From a systems operator's point of view, it is also a matter of rolling out new products and services meeting end-user demands and quickly making use of new technology. This can be done without the delays usually associated with the traditional spectrum allocation process. And, with the advent of more flexible radio systems and terminals, having a significantly higher degree of frequency agility and interference environment measuring ability, together with a much higher signal processing ability than traditionally and the flexibility of adapting its waveforms to whatever spectrum available and interference situation possible, we see a great potential in the combination of software defined, reconfigurable, radios and dynamic spectrum access communication systems. It is not the scarcity of spectrum that is the problem, rather it is the lack of ability to dynamically access spectrum that is holding development of services back.

1.2 Previous and ongoing work

How regulation and etiquette rules should be designed to strike a commercially interesting balance between the high efficiency of the unlicensed regimes and the interference protection of the fixed allocation schemes is very much in the focus of ongoing research both in academia as well as in regulatory authorities, in particular in the US and in the UK [6], [11]. Research and systems design activities towards a more efficient use of the spectrum have already started.

Dynamic frequency management is in itself not a new research field. The area has been under intense investigation during the last two decades in the development of cellular telephony systems. Here, however, the problems investigated here can be labelled as *cooperative resource management* problems, i.e. there is a single operator that controls all entities, i.e. base stations and mobile telephones/terminals in the system, inside a fixed allocated frequency band, well protected from "outside" interference. The operator has the objective to provide a service to the users and looks for solutions that maximize the resource utilization (i.e. his revenues) with some constraint on the quality-of-service (QoS) perceived by the user. The latter is usually related to the interference level experience by the users. Implementations of such resource management schemes may be *distributed* over the various terminals and base stations in order to avoid excessive exchange of control information but there is no conflict of interest involved. What we are focusing on is the more general spectrum management problem, which is a *non-cooperative resource management* problem. In these problems we have multiple entities using the spectrum, each with their (potentially selfish) objective. In this emerging research area, not very much has been published.

Previous work has shown that the technology enabling dynamic spectrum access is almost there. In the DARPA SUO SAS project [12] and the following neXt Generation (XG) initiative [13] it is demonstrated that low-cost, wide-band radio technology allowing for rapid frequency changes is feasible. An inherent feature of Dynamic Spectrum Access interesting in military rapid deployment scenarios is that it drastically reduces the requirement of advance planning of communication networks. Non-cooperative DSA and so-called "cognitive radios" [14], [15], [16] are therefore integral parts of the XG-concept.

1.3 Objectives

The Dynamic Spectrum Access project is designed as a two-stage effort where the outcome of the first phase is presented in this report. The objective in this phase is twofold:

- To provide a qualitative assessment of the potential benefits of dynamic spectrum access regimes, e.g. lowering the entry thresholds for new actors and provide radical improvement to the efficiency of spectrum usage etc., and
- To identify a number of critical areas and bottleneck problem where more research is needed to achieve these benefits

In the second phase of the project, the key issues identified above will be researched. Concrete system and regulatory proposals will be investigated. In addition input to future policies in spectrum management as well as recommendations for regulatory action will be provided.

The work has not been limited to technology issues but has spanned over both regulatory and economical issues. Most importantly the question on how various spectrum allocation regimes may impact the Swedish innovation system has been investigated.

The report is organized as follows. First, in section 2, existing work in the area of dynamic spectrum access is reviewed. Section 3 describes the methodology used to assess the potential of new DSA schemes and to identify the research problems involved. This involves the investigation of a large number of candidate spectrum management concepts, among which 5 concepts are chosen for more detailed study. These concepts are described in more detailed in section 4. In sections 5-8 the selected concepts are then analyzed with respect to technical, regulatory and economic issues and a number of critical issues and research problems are identified. In section 9, finally those issues and problems selected for further study in phase 2 of the project are selected.

2 Spectrum management

2.1 The legacy regulatory framework

The regulatory framework for management of the radio spectrum resource can in many ways be seen as a historical description of the development of radio. The international regulations as found in the ITU (International Telecommunication Union) Radio Regulations have traces from the earliest days of radio. Over time the national and international frameworks have been amended to enable new use of the radio spectrum. As a result of history and the technical evolution, the national and international frameworks are an organised patchwork of different generations of regulation and solutions. One of the prevailing thoughts is that allocations on international level are made for infinity or at least for a very long time. This makes it more and more difficult for new generations of radio technologies to enter the stage.

In some instances the “refarming” tool has been used to free up underused or unused spectrum for new applications. The situation has over history been fairly successful since radio applications have been designed for a specific frequency band, often in close relation between national regulators, international organisations, equipment manufacturers and the monopolistic operators in each national market.

When discussing the regulatory framework for radio spectrum it is important to describe the difference between two main processes in spectrum management, namely *allocation* and *assignment*. *Allocation* is the process of allocating a piece of spectrum to a specific use or service, *assignment* is the process of assigning licenses to use the spectrum to a specific user. The allocation of spectrum is mainly done in the international arena, whilst the assignment of licenses is mainly a national concern.

The regulations of the radio spectrum can be seen as a three layered pyramid, where the three layers are global, regional and national.

At the global level, the framework is governed by the Radio Regulations (RR) which is under the control of the International Telecommunications Union’s Radiocommunications Sector (ITU-R). The Radio Regulations provide an overall global framework for the use of spectrum. In the RR, the radio spectrum is allocated to certain use or services, examples are fixed, mobile, broadcasting or radionavigation. The RR has status of international treaty, thus the national administrations are required to comply with the terms. The main application of the RR is in national border areas to ensure that the use of radio spectrum in one country does not cause interference to users in another country. Given this, there is an element of flexibility in the use of radio spectrum as long as interference is not caused in another country.

At the regional level, there are in Europe two main paths for spectrum management, The European Union (EU) and the European Conference of Postal and Telecommunications Administrations (CEPT).

On the EU-level, initiatives are taken under the Spectrum Decision [21] and other directives under the EU Framework for Electronic Communications[1]. In some cases,

[1] The Electronic Communications framework is made up of six directives and one decision: Framework Directive 2002/21/EC, Access Directive 2002/19/EC, Authorisation Directive

specific harmonisation measures may constrain national authorities in how spectrum is used through harmonisation of frequencies. The Electronic Communications framework has been, or is being integrated into national legislation in all EU member states. Directives and decisions from the EU based on the directives are mandatory for member states.

The CEPT is an organisation of 45 member states. The CEPT has set up the Electronic Communications Committee (ECC). The ECC brings together the radio- and telecommunications regulatory authorities of the CEPT member states. The ECC makes decisions and develops recommendations on the use of radio spectrum in the member states. The national adoption and implementation of decisions and recommendations is optional.

Nationally there are a number of national rules, laws and regulations regarding the use of spectrum that govern the national allocation and assignment of licenses.

Apart from the regulatory framework for the allocation and assignment of spectrum there is also regulation on different levels when it comes to the placing on the market and the use of equipment using the spectrum.

2.2 Current trends in spectrum management

Over the last decade the markets for electronic communication have been opened up to competition and the relation between regulators, operators and developers of equipment is no longer as close as it has been.

The technical development is generally heading in the direction of smarter and more adaptable systems and solutions. One of the main drivers behind this development is the perceived scarcity of spectrum for new technology.

In a recent report [22] the European commission concluded the following regarding spectrum management:

> *All radio-based devices use the radio spectrum to transmit or receive information. The use and therefore the value of the radio spectrum has dramatically increased in recent years, as wireless applications have been very successful in addressing many of society's changing needs, such as for mobility and for data transmission. But spectrum availability is also critical for many other applications, e.g. for accurate weather forecasting, radio astronomy, air and maritime safety, broadcasting and for devices simplifying everyday life such as remote controls and hearing aids.*
>
> *Because of possible interference between different radio services operating in the same or adjacent frequencies, access to the radio spectrum has historically been closely regulated. Spectrum management has long been seen as a "technical" domain dealing with the avoidance of harmful interference and the technical optimisation of spectrum use. More recently, it has been identified as a means of generating public revenues in proportion to a perceived "spectrum scarcity" value. However, a long-term, policy-based*

2002/20/EC, Universal Service Directive 2002/22/EC, Directive on privacy and electronic communications 2002/58/EC, Competition Directive 2002/77/EC, The Radio Spectrum Decision 676/2002/EC *approach to the management of this resource aiming at fostering innovation and the introduction of increasingly added-value applications could capture much greater overall benefits for society.*

The general development in the spectrum management world is towards increased flexibility and a more liberalised approach to the assignment and management of spectrum. This said, the processes are slow and the hurdles are high.

Some of the hot topics in spectrum management at the moment are:

- Flexibility – how can licenses be made more flexible. There are two different flavours of flexibility currently on the agenda, namely the market oriented approach and the technical liberalisation. The two flavours can be seen as two sides of the same coin, and in many cases the one requires the other.
- Market oriented approach – in the market oriented approach to flexibility lies the aim to make licenses and the values of licenses visible, and to create a market for the natural resource spectrum. One potential goal of a market oriented approach is the property rights model, whereby a license holder actually owns the spectrum. The license is indefinite in tenure and the spectrum can, under a limited interference and power level rulebook, be used for whatever purpose the license holder wants.
- Technical liberalisation - the technical aspect of flexibility includes the removal of unnecessary restrictions on licenses to enable a wider use. Such restrictions can include non-radio related obligations, references to services, standards and systems etc.
- The topic of flexibility includes a number of different dimensions;
- Secondary trading – the possibility to sell, buy, rent or lease a license. Secondary trading can be introduced under an ex ante (beforehand) approval regime or under an ex post (after the fact) regime. The ex-post regime would in most cases be equal or similar to general competition law.
- Reconfiguration – the possibility to reconfigure a license in time, geography and frequency. With reconfiguration a licensee can for example sell unused spectrum in a region or buy additional spectrum for popular services.
- Change of use – the possibility to change the use of a license outside the limitations given in the license. This could include the changing from fixed services to mobile services, from broadcasting to mobile use etc.
- Digitalisation – more and more services are being digitalised. To name a few, mobile services have gone from 1G analogue systems to 2G digital systems, Digital television is being introduced, etc. Digitalisation is interesting since many old legacy systems are being replaced by standardised systems with known interfaces. One interesting example of the results of digitalisation is the potential to free up spectrum for new areas of use. This is a major discussion in the digitalisation of broadcasting. As a result of the potential to free up spectrum through the digitalisation of broadcasting, the so called digital dividend has been identified. The planning of digital broadcasting will to some extent be made technology neutral and thus enable the use of non-broadcasting solutions in broadcasting bands.

- Technology neutrality – in recent year's technology neutrality has become an important aspect of assigning licenses. Under previous regimes, spectrum for new services has very often been pinpointed to a system, a technology, a standard etc. Rather than allocating a piece of spectrum internationally for e.g. GSM which was made through an EU-directive, spectrum is allocated to enable different types of services.
- License exemption – in recent years, the proliferation of services using license exempt frequencies is apparent. The success of licence except spectrum is one of the major trends in spectrum management.
- Harmonised flexibility – the notion of harmonised flexibility is to some extent driving the international discussions on increased liberalisation. The boundaries of harmonisation are being explored and harmonisation will in the future become more open and technology neutral. In order to maintain some level of harmonisation, to achieve economies of scale and to avoid complete fragmentation the methods and framework for flexibility will have to be harmonised in some way.

2.3 Current initiatives and trends in spectrum management

The traditional model for spectrum management and the assignment of licenses is often referred to as the "command and control" model, whereby the SMA (Spectrum Management Authority) awards licenses to specific applications and to a specific license holder under a non-interference regime, the licenses are assigned exclusively and for a limited time. The restrictions on the license are based on internationally developed standards and interference calculations.

Over the last decade new models for spectrum management have emerged internationally, namely the commons model and the market model. Furthermore, relaxations have in many instances been made in the command and control model.

The regulatory challenges ahead are generally in the direction of increased flexibility. This transition is towards leaving more of the decision making to the users of spectrum rather than predefining the use and the framework based on rigid technical limitations in old "dumb" radio systems. The main problem is however not in going in that general direction, the main problem is that many of the different flavours of flexibility cannot be combined at the same time. A commons model cannot be combined with any level of exclusivity with regards to interference, thus these different models (commons and command & control) are in direct conflict. Furthermore, frequencies that have been assigned to license exempt use are very difficult, if not impossible to remodel to host other types of systems that require some level of non-interference.

One of the main tasks for spectrum managers in the future is to balance the demand for spectrum under the three different models.

- There will for an unforeseen period of time be a need for certain radio based applications to be under a strict command and control regime, examples are aviation and certain satellite applications.
- The demand for more spectrum for the commons model will be on the increase for quite some time to come.

- The demand for liberalisation of the use of spectrum is relatively high in many bands and for a number of applications.

2.3.1 The commons model ("unlicensed spectrum")

Over the last couple of years there has been an explosion in the use of the so called free frequencies, or more rightly labelled licence exempt spectrum. The model of setting a minimum set of rules for a piece of spectrum has attracted developers of equipment and users of many different applications, such as WLAN and Bluetooth to name a few. This trend has led to initiatives to open up more spectrum for license exempt use.

Generally license exempt use is very well suited for short range devices (SRD) that are inexpensive and large in numbers.

Within the commons model there are a number of different flavours which are described below.

	Strict technical rules	Relaxed technical rules
Strict service definition	• DECT • PMR446 • DSA concept "License exempt operation"	• Radio controlled model aircraft • Canine location
Relaxed service definition	• 5 GHz	• 2,4 GHz • 433 MHz • DSA concept "Open spectrum access"

2.3.2 The market model

In the market model the assignment and use of spectrum should mainly be decided by the market players. Thus the key elements of the market model are liberalisation through secondary trading and flexibility.

Secondary trading of licenses has become one of the main topics of liberalisation of spectrum management regimes over the last couple of years. Implementation of secondary trading is underway in Europe. In Sweden limited trading with ex-ante approval was introduced July 25, 2003. In the US, Australia and New Zeeland, secondary trading has been available since some time. It is thought that the introduction of secondary trading will not reach its full benefit without the introduction of a more flexible policy regarding change of use and reconfiguration of licenses.

2.3.3 Relaxations in the command and control model

The model used for most of the radio spectrum today is known as licensed spectrum. Under this so called command and control model some relaxations have been made and most of the incremental changes to the regulatory framework will initially be part of the command and control model. One example of such relaxations is the increased use of block assignments. In frequency bands where assignment and planning of the networks has been performed by the national regulator the trend is towards block assignments, whereby the users of radio are given the possibility to coordinate and design their own networks. A block assignment can be made with very few restrictions on the use, as long as out of band interference is under control.

3 Methodology

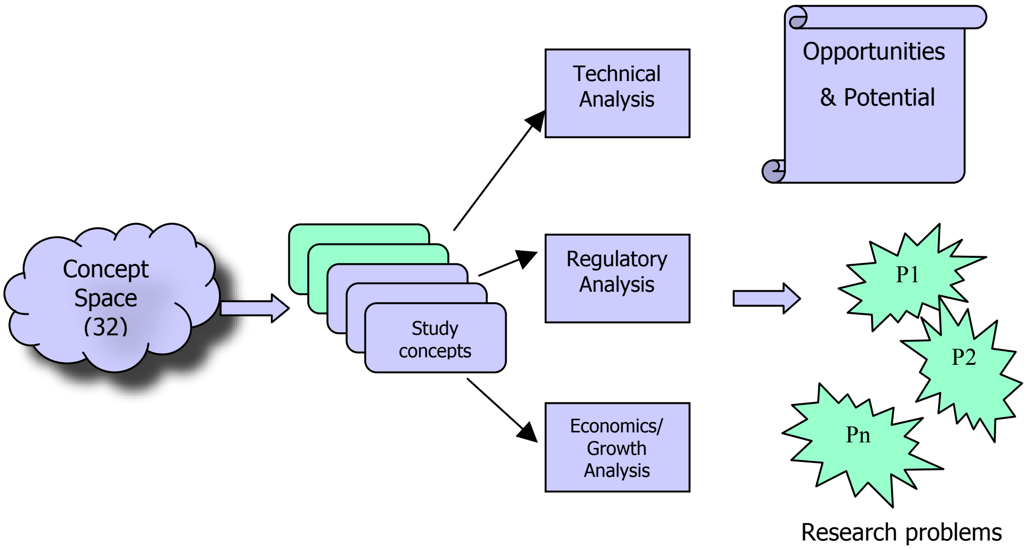


Figure 3. Overview of the methodology used in this project.

3.1 Concept selection procedure

One of the main objective of the project is to identify key research issues in current but mainly in future spectrum management regimes and the impact of the these regimes on the innovation system and on regulation policies. This is a somewhat difficult task since these future management regimes are not well defined and in some cases even unknown. In order to enable any further analysis, we would need to define some management regime and its supporting technologies, business models etc., at least on the conceptual level. For this purpose we have developed a number of study system concepts as the common basis for our analysis. Such a system concept describes a technical solution and the environment the system is placed in. Thus, a system concept also describes the regulatory framework and the market mechanisms that surround the technical system, which enables us to understand the interworking of technology, regulation and markets.

From a regulatory and management point of view, the system proposals should cover and stress aspects that are not so critical in today's exclusive-use policies.

- **Access –** Licensing, auctions, purchase and lease of spectrum.
- **Management** – Government, owners or brokers.
- **Transferability** – Approvals, aggregation and subdivision.
- **Use** – Flexibility and change of use.

In particular, we foresee many interesting principal research issues regarding spectrum as a property versus the primary policy of today, i.e., command-and-control. Combinations of these rights and properties have different consequences for the investment, technological development and the innovation process. It is therefore of importance to evaluate the above concepts and their impact of spectrum efficiency, investments and adaptability to changing demand.

Since we do not know which system concepts will actually become reality (or at least serious candidates) the design and selection of study concepts is a non-trivial task. The selected concepts should both reveal interesting research issues and also point to problems that must be solved in order to enable dynamic spectrum usage. The approach of this project has been top down. A systematic search through a number of possible spectrum management regimes was done in the following way.

First, we identified what we believe are the five most important features of spectrum management. These features where

- Transferability of spectrum usage rights
- Exclusiveness of spectrum usage rights
- Strictness of spectrum regulation
- Centralized/Decentralized management of spectrum access
- Time-scale of management

The features in the list play the role "dimensions" than span the space of possible spectrum management concepts. In a systematic manner we have gone through all the 32 extreme points of this space along with some interior points and developed short descriptions of the corresponding system concepts. This list can be found in Appendix A. As a sanity check we could verify that the main contemporary regimes could actually be found in our space. Many of these in total 40 concepts make very little sense, were very similar to others or had very limited practical application. Anyhow, five study concepts were selected for further studies. Two of these were reference cases, corresponding to existing spectrum management regimes, and three were "novel" approaches, with interesting properties and the capability to reveal interesting research problems as well as substantially improving spectrum usage efficiency. Note that the three "novel" approaches have some qualities and methods already in use today. Some of them are also in line with current trends in spectrum management. The procedure is outlined in Fig. 3.

It should be noted that we do not see any specific system concept as the most *probable* candidate for future spectrum use. Rather, the concepts are selected to reveal problems that are not yet solved. Our procedure, albeit systematic, cannot guarantee that all possible concepts are captured, since there may be other important features not in the list above. However, it is reasonable to believe that we in the concept space spanned by the above features could find important and interesting research problems and at least some of the more promising candidate systems for future implementation. Another important limitation that we have made in the definition of the system space is to leave out changes over time in the spectrum management regime. All system concepts represent a quasi-static situation. Changes in spectrum management regime would correspond to moving around in the system space.

3.2 Some assumptions and definitions

In an emerging field like the DSA area, there is bound to exist different and confusing terminology used by different researchers and organizations. The terms described here are the ones used here in this report.

A *license* is the right to transmit on specific frequency on a specific geographic position for a specified time. There may also be a number of other *rules* coupled to the license. As a minimum there are rules about out of band emissions.

The spectrum resource is ultimately governed by a national regulator. His interest is usually to ensure the most efficient use of radio spectrum to the benefit of society, i.e. the nation. The regulator has ultimate power over the spectrum in the same sense as a government has the ultimate power over a nation. Of course there are laws and rules to follow, but these can be changed in the long run or by certain unexpected events.

3.3 Key concept features – “Dimensions”

The key concepts used in this work are not usually seen in other DSA studies. We believe that this is the result of the rather wide scope used to span spectrum management.

3.3.1 Transferable – Non-transferable transmission rights

In the transferable end of this dimension, a license (right to transmit) can be transferred between actors without explicit consent of the regulator. In addition, the use of spectrum can be changed, i.e. the rules in the license do **not** state the use. Note that this makes is possible to sublet parts of the spectrum controlled by the license.

With non-transferable spectrum access, a license cannot be transferred and its use cannot be changed without intervention of the regulator. However here we assume that the regulator can not, or is not willing to, make changes except in some extreme cases.

Note that in the really long term perspective, it is possible for the regulator to change both owner and usage. However, in practice this time is so long that it, within the scope of this work, can be regarded as infinite.

3.3.2 Exclusive spectrum use – Shared spectrum use – Commons

With exclusive use, there is only one license to the spectrum band. The licensee should not experience any intersystem interference.

For shared use, there are a few license holders. Depending on the co-operation ambition among licensees, there may be intersystem interference.

In the commons case, an infinite number of users can access the spectrum band and there is no guarantee that signals will not be interfered with.

3.3.3 Strict spectrum rules – Etiquette

This “dimension” captures the number of rules specified in a license. With strict rules we mean a thick rulebook. There are few degrees of freedom. For etiquette, the rulebook is thin and there are many degrees of freedom.

In general the license rules can specify if use of the spectrum can be changed or not. However here that aspect is covered in the transferable, non-transferable dimension and not covered by this dimension.

There are different entities that the rules apply to. Some are tied to the transceivers used. These rules may specify output power, modulation methods used or protocol details. Other rules apply to the users, for example what information is sent, or how payment for services is to be extracted. Depending on which part of the system the rules apply to, their implementation will be different.

There is also the aspect of ensuring that rules are followed. That may either be done by a strict certification procedure or it may be enforced by strict control of how the spectrum is actually used.

3.3.4 Short term – Long term spectrum usage rights

This dimension describes the lifetime of the rights to use spectrum. The scale ranges from milliseconds to several decades.

3.3.5 Centralized – Decentralized technical solutions

This dimension describes the technical implementation aspects. In the centralized case all decisions are made at a central point where all information is available. In the decentralized case decisions are made by the users of the spectrum themselves based on local information. As long as the end user equipment will take its own decisions, e.g. which part of the spectrum to operate in or what waveform to use, a solution is considered decentralized.

Note that other things than the technical implementation can be centralized or distributed, e.g. markets can also have this property. However it is in the technical domain that the difference is most notable and thus we have limited this dimension to the technical aspects to avoid confusion and complexity. Specifically it is the spectrum access mechanisms that we focus on in this key feature.

3.4 System space and selected concepts

The five dimensions span a five-dimensional space, which is hard to envision. However a three-dimensional space can be illustrated by selecting a subset of the dimensions. We have somewhat arbitrarily selected the first three and the resulting space is drawn in Fig. 4.

The choice was not completely arbitrary; rather we picked the dimensions we believe will make the largest difference. Since one of the recent trends in spectrum management is the ability to trade spectrum that seems like an important aspect. The number of .users is also important since more than user in a piece of spectrum generates problems with uncooperative interference. Also the number of rules that control the use of spectrum seems important. It would seem reasonable to assume that the timescale and the localisation of the decisions are mainly parts of the implementation and thus they do not generate radically different concepts.

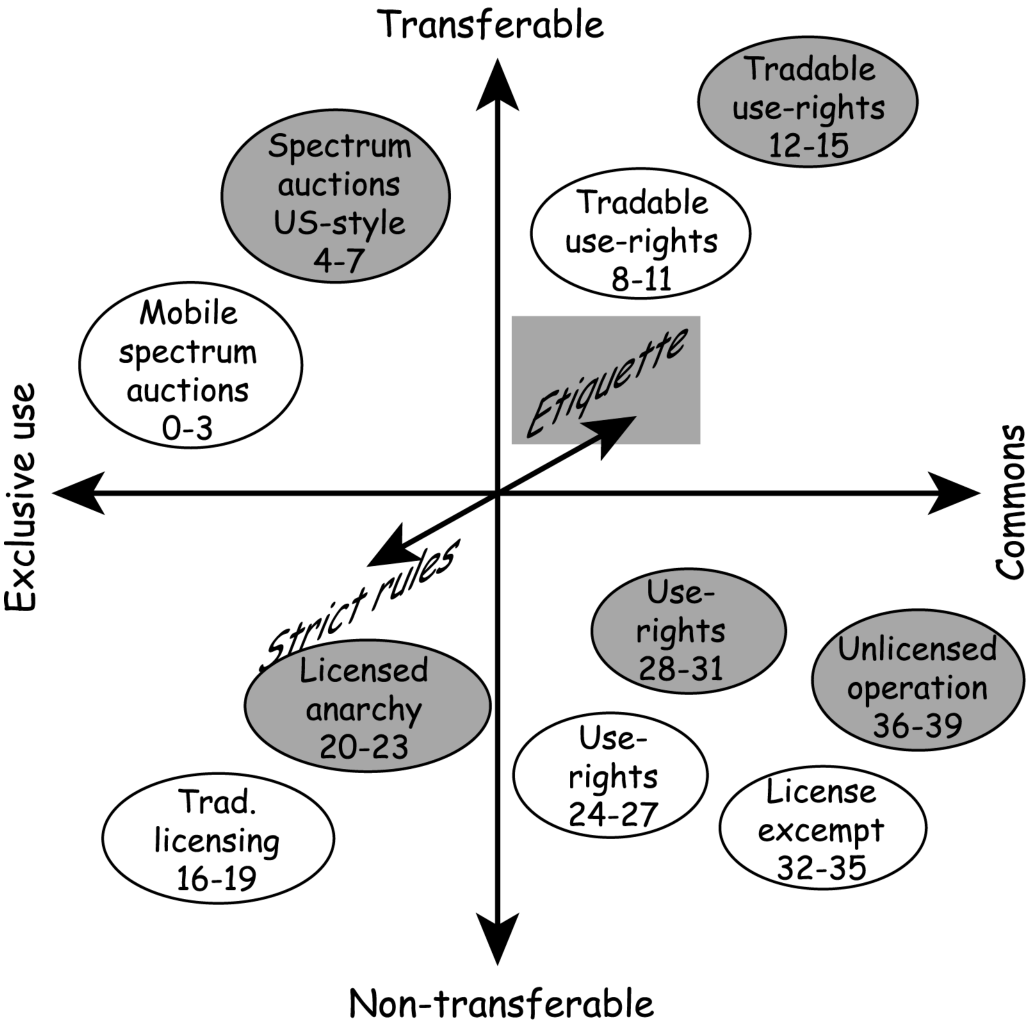


Figure 4. An example of three dimensions with different policies mapped to the space. The third dimension is colour coded. The number refer to the descriptions in Appendix A.

3.5 Concept evaluation

The five selected concepts were evaluated to try to identify some of the most important possibilities, challenges and pitfalls in implementing DSA. This was done to find out important areas for continued research in order to promote technical development that could be transferred to industry. We do not claim to have identified all or even the most important issues. This latter is hard to obtain and is also heavily dependent on personal and professional values. The tricky thing is to find and use an assessment method that ensures a reproducible result without subjective values.

3.5.1 Evaluation of the technology aspects

To evaluate the technology aspects of the concepts we have used a simple approach with a comparison chart.

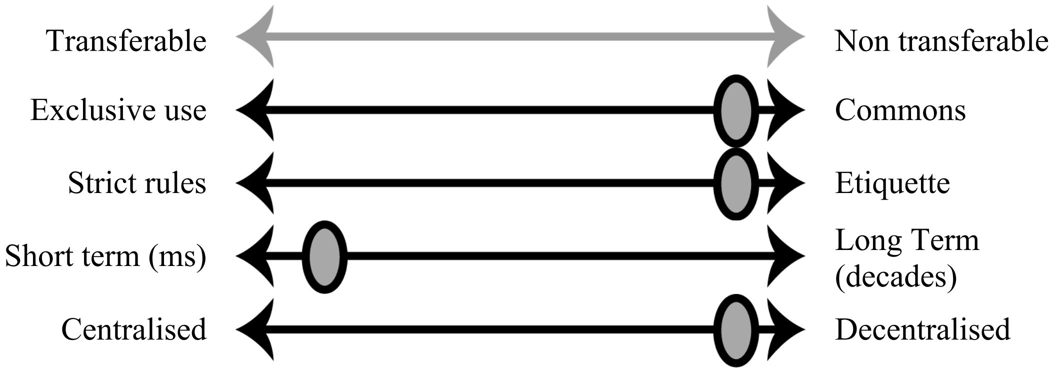
We started with a very long chart and used it to compare the three DSA concepts and the two reference cases. The comparison chart consisted of almost 200 items, including QoS, time to service, interference control parameters, use of “The Electrospace” [27], legacy system handling, standardization issues, spectrum monitoring issues, RF technology performance, component development, signal processing capacity, power efficiency, software design, security, reliability etc. The chart also included use of features like SDR, cognitive radio [14], [15], [16], autonomous functions, space time coding, MIMO, adaptive antennas and so on.

Even this simple approach showed up to be rather complicated due to the complex nature of the subject itself and also because it was hard to find comparison items that didn't assume a system approach instead of a pure concept.

The chart was then studied to find issues similar to all concepts and issues that are very dissimilar among the concepts. The issues that are common to all concepts signal that the area with high probably is going to be a research field in the future. The issues that are very dissimilar indicate research questions that may make or break a concept and that the research question will be important in determining the direction of the future of DSA.

4 Possible DSA concepts

4.1 Open spectrum access



4.1.1 Overview

Government spectrum agencies allocate a certain spectrum for “any-kind” of equipment meeting just a few requirements such as maximum allowed emitted power and in-band as well as out-of-band interference handling requirements (very relaxed etiquette rules). The spectrum usage is not constrained to a specific service but could be used in any fashion. Note that spectrum trading is a non issue. Since the spectrum is free to use for anyone it is unlikely that there will be any buyers[17].

The concept of unlicensed or open access operation is very close to the very successful use of license exempt spectrum. This concept is however based on an even thinner rulebook, and a set of etiquette rules. These rules will have to be agreed upon entering the spectrum. The rules that can and should be imposed for the concept frequencies include out of band emissions, power and emission levels. Furthermore there might be a need to include other general rules such as listen before talk, automatic power level corrections, etc. in order to enable the highest possible use without risking that systems become greedy and only increase the noise floor.

This system concept relies on etiquette, but the central institutions could still imply inclusion of some rules controlled by these institutions. We will probably see interference rules, but few other rules (or etiquette) in the licenses. In order for this concept to have a significant effect, more spectrum will have to be assigned to the commons model. The spectrum assigned will have to be of the same nature as the 2.4 GHz band, i.e. without any constraints as to the service or to the technical nature of the use. Limitations will still have to apply regarding out of band emissions and output power.

- Small, medium-sized, and large traditional telecom equipment suppliers push government bodies to initialize a portion of the spectrum to be used for “any-kind” of equipment meeting just a few power level and interference related issues on a consumer market.
- The commons case makes the spectrum usage *transferable* or *non-transferable* a non-issue but still governed by *etiquette* and equipment use also governed by *etiquette*.
- Usage of spectrum is down to *milliseconds*, typically a few seconds/minutes/tens of minutes, thus, the system concept is *short term (ms)*.

- End terminal access to the channel is governed by each terminal in a distributed fashion, thus, the system concept is a *decentralized* one.
- Regardless of from whom the telecom equipment is bought, that specific equipment can be used. No telecom operator is required to be involved in the loop of providing services. No fee for usage is necessary. Thus, this is truly a *commons* system concept. However, there might be a need for *policing* of spectrum use, and coupled with that, a fee might be appropriate to finance that policing need.

Key regulatory aspects of the unlicensed or open access operation concept include;

- More spectrum for license exempt use
- Surveillance of power levels and usage
- Avoiding the tragedy of the commons[18][19]

4.1.2 Examples of similar contemporary systems

The 2.4 GHz band for license exempt use has a very limited rulebook. This is one example of this kind of band. The 2.4 GHz band hosts a number of very successful applications such as WLAN and Bluetooth.

4.1.3 Role of the regulator

The regulators focus of today, aiming for eliminating interference will change to keep the interference low enough to provide the wanted system behaviour.

The objective of spectrum policy would not be to minimize for example interference, but to maximize usable capacity.

The use of methods to dynamically handle interferences opens up the need for policing of spectrum usage such that fairness is achieved. This may be implemented both by rules for the equipment to be used in the allocated spectrum and by policing from a government agency. This means that the regulatory agencies roles will change (away from command-and-control), and perhaps dramatically. The movement from long-term planning towards operational issues will commence. There is a choice of strategy to be made here: Should the regulation require certification of interference handling prior to market entry or should the policing effort notice and on occasion fine that specific device, operator, user, or equipment seller?

4.1.4 Regulatory changes required

In order to assign more spectrum to unlicensed use there are not all that many changes that will have to be made on national level, the main change that has to be made is in the general policy for assignment of unlicensed spectrum. If spectrum is to be made license exempt on a regional or global scale and in a harmonised way to enable economies of scale and global circulation of equipment the changes that have to be made is of a completely different order of magnitude. In this case the matter will have to be established on the CEPT and possibly on the WRC agenda, and the process for that is in the range of 2-7 years minimum. If such a proposal is put on the WRC agenda it will after a WRC resolution take quite some time before the resolution is implemented in all countries.

To sum up, changes on national level are quite easily made, on an international level it will take many years.

However, given the fact that there is already spectrum available for license exempt use, new technology and new systems are possible to launch in the currently available frequency bands.

	Global	Regional	National
Policy	• Actively promote use of license exempt spectrum	• Actively promote use of license exempt spectrum	• Actively promote use of license exempt spectrum
Regulation	• Introduce the definition of license exempt spectrum in the radio regulations • Identify spectrum for license exempt use	• Harmonise more spectrum for license exempt use	• Assign more spectrum for license exempt use
Processes	• Propose an agenda item to a future WRC	• Propose a work item to WGFM	• Propose to national administrations • Notify to commission

4.1.5 Possibilities and challenges

With such a strategy, business opportunities for non-established, small and medium sized established businesses, as well as larger established corporations, are enhanced. The prime potential for individual businesses for this lies in a reduced time to market.

This concept will probably favour networks without the need for large investments in infrastructure due to the short term approach. A long term approach will on the other hand open up for larger infrastructure investments.

The nature of imposing a rather high level of flexibility and dynamic behaviour in this system concept makes it really interesting to study. We believe that this concept has a challenging potential of a large gain in spectrum effectiveness improvement.

With a smaller regulation of what technologies to use, there is a need for more flexibility and a dynamical handling of events that occur. The main issue to take care of is interference handling, both in a sense of measuring the environment and from there, to take action when we are subject to interference and to respond to situations where we cause interference. Several sophisticated solutions may be considered; frequency hopping, adaptive antennas, software defined and agile radios and ad-hoc mesh networks. This system concept demands frequency adaptive systems (software defined radio) that can change operating frequency on a daily, hourly or even millisecond basis like. Areas of technology that are of importance are:

- Standardized Software Defined Radio (SDR) complying to, e.g., SCA (Software Communications Architecture [19])

- Mobile ad hoc networking, with multi-hop functionality
- Dynamic interference management
- Spectrum usage policing (government bodies)
- Spectrum usage measurements and characterization (end-terminal wise)

There might be issues regarding large, traditional style, industrial programs, where the need for risk capital is great and pay-off times are long. This track is a bigger initial step in how development is done in this business area, but leads to, potentially, many more but smaller steps in evolution and thus many more but smaller risks per investment. There might be an issue with a greater investment, end-customer wise, up-front, alongside with lesser payments while the system is in use.

One problem with a free spectrum, i.e. there is no fee for using it, is that it may be overused and that the technology may not be very spectrum efficient since spectrum is for free anyway. Due to overuse the quality of the communication would drop to really low levels. This problem is known as the "tragedy of the commons" and that problem is something that has to be dealt with.

4.1.6 Regulatory SWOT analysis

Strengths

- Very low entry barriers
- Enables fast introduction of new technology

Weaknesses

- No regulatory rights for the users apart from the thin rulebook
- Global allocation of license exempt spectrum is a very lengthy process
- Users of license exempt spectrum have very few rights

Opportunities

- New spectrum has been allocated for license exempt use
- License exempt spectrum is innovation friendly and enables quick introduction of new technology into the marketplace

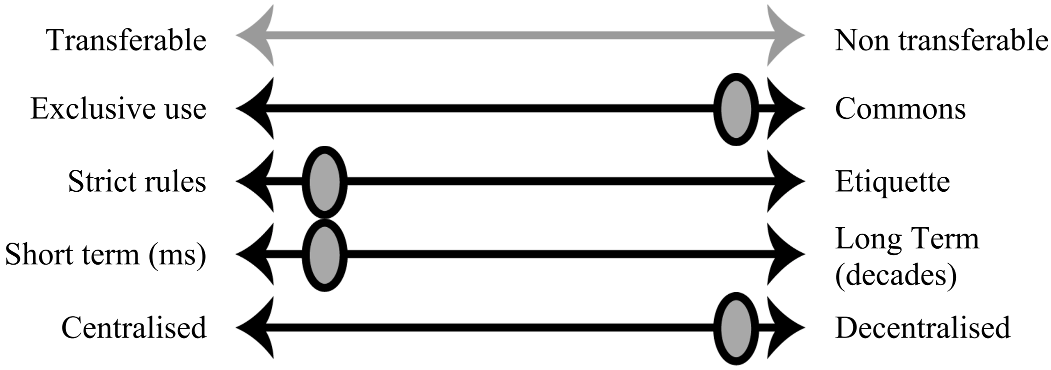
Threats

- The tragedy of the commons is a general threat to any commons model
- Under a commons regime users are not protected from potential interference

4.1.7 Impact on the innovation process

By opening up for spectrum use, and not by regulating/licensing equipment, the time to market for new products is potentially reduced. Smaller firms with bright ideas have an opportunity to test/market these ideas. This, in turn, yields an improved speed in the innovation process. Also, by not supporting a specific technical solution, multitude and competition is encouraged. However, the simple fact that competition prevails is not to everybody the same as improvement in the innovation process.

4.2 License exempt operation - (reference)



4.2.1 Overview

The main issue with this system concept is that a few industrial actors join efforts and create a standard for a certain kind of equipment. Alongside with creating the standard, an effort is made to have government bodies controlling spectrum usage to allocate a certain part of spectrum in as many nations as possible (to create a potential market as big as possible). Dependent on what end-user value is targeted, and the estimated potential in what the end-users are willing to pay for that specific value, different degrees of complexity is designed in the system.

- Large traditional telecom equipment suppliers push government bodies to initialize a portion of the spectrum to be used for "standardized" equipment on a consumer market. This makes the spectrum usage *transferable* or *non-transferable* a non-issue but still governed by *strict rules* and equipment use also governed by *strict rules*.
- Little effort may go into handling in-band interference problems as transmitters/receivers conceptually might be operating not too densely.
- *Strict rules* support that a greater effort can be made for handling in-band interference. Nevertheless the rule book may be rather thin.
- *Strict rules* also support tougher requirements on out-of-band operational aspects.
- Usage of spectrum is down to *milliseconds*, typically a few seconds/minutes/tens of minutes, thus, the system concept is *short term (ms)*.
- End terminals access to the channel is governed by each terminal in a distributed fashion, thus, the system concept is a *decentralized* one.
- Regardless of from whom the telecom equipment is bought that specific equipment can be used. No telecom operator is required to be involved in the loop of providing services. No fee for usage is necessary. Thus, this is truly a *commons* system concept.

The commercial success for systems that, to some extent like WiFi-systems, conform to this concept makes this particular concept ideal as a reference case.

4.2.2 Examples of similar contemporary systems

Short range devices (SRD) for instance the European DECT concept is one place holder for this concept in our work. Note that other examples, quite different from

DECT, may fall within this conceptual category, Bluetooth, remote control devices (car port opener), IEEE802.11x, WiFi, WiMax…

This concept does to some extent make out a subset of the Open Spectrum Access concept. The main difference is that there are more rules in this concept. Here 2.4 GHz WLAN has been taken as an example of a type of system, not an example of rulebook for the use of a specific piece of spectrum.

The commons model has very successfully been introduced already in the 2.4 GHz band for WLAN type applications, furthermore the 5GHz has been allocated at WRC03 as spectrum suitable for license exempt use. The 5 GHz band has more limitations than the 2.4 GHz band when it comes to the technical domain. For example due to the existence of radar systems in the 5 GHz band all equipment must use DFS-technology (Dynamic Frequency Selection).

Currently three bands are available for license exempt use, namely 2.400 - 2.483 GHz, 5.150 - 5.350 GHz and 5.470 - 5.725 GHz, furthermore there are a number of frequency bands where equipment generally can be used without a licence.

4.2.3 Role of the regulator

This might be considered as one of the traditional ways of how a regulation of spectrum usage is done, at least if we consider the last ten years.

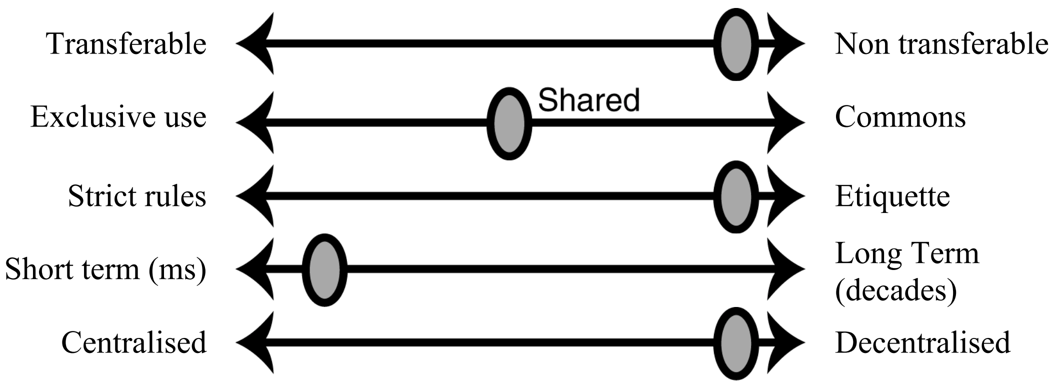
4.2.4 Possibilities and challenges

Since this concept is well supported by larger corporations with its traditional investors behind them, this concept could perhaps be said to be well-known financially with risks and opportunities. However, also due to the traditional kind in this concept, it is associated with high investments and long term pay-off times. It may also be the case that this concept impedes non-established businesses entry into the market. Small companies are entirely dependent to production or maybe development of minor system components.

4.2.5 Impact on the innovation process

Large industrial corporations are well supported in this concept, non-established, small and medium sized businesses have a hard time entering the market. New systems with high development costs and/or high introduction/deployment costs and/or long pay-off times on the investment are perhaps better supported in this concept.

4.3 Shared spectrum access



4.3.1 Overview

In this case a (fairly small) number of permissions to use a specific band are allocated to a number of licensees.

Allocating a limited number of licenses to a piece of spectrum may be a middle way between the dynamic behaviour seen in the license exempt bands and the control of QoS that is possible in exclusive spectrum. Also knowing who the competitors are makes it easier to agree on how to cooperate.

The shared concept allows dynamic spectrum sharing, but without risking a complete breakdown, which could be the case with the commons. It is up to the licensees how to cooperate in the band. When the capacity requirements are low some simple, maybe obvious, methods for cooperation can be used.

One way is to simply split the spectrum among the licensees. This case is very similar to the traditional licensing schemes, but the licensing procedure is in some sense decentralized.

Another obvious solution is to build one network that all licensees use. This method is superior in capacity. But there are problems as well it becomes more difficult for the users of the network to differentiate service offerings. The issues here are similar to the issues for infrastructure sharing in the UMTS networks being built now.

The licensees may also choose to cooperate through a central instant spectrum manager, or access broker. The task of this may range from fairly simple frequency assignments to complicated real-time radio resource management regimes. The methods for achieving this are not completely new, but there are obviously unresolved issues.

The licensees may also choose not to cooperate and use the available technologies available for license exempt spectrum. For example frequency hopping, dynamic channel allocation, ad-hoc networking, adaptive antennas, software defined and agile radios and mesh networks etc. may be used. In this case the issues are similar to the unlicensed spectrum.

Key regulatory aspects of the shared spectrum concept include;

- New definition of shared spectrum, how many users in one frequency band
- Develop an interference management framework

A less trivial case is when there are no or very few limitations to the types of technologies and services that could be used under a shared spectrum regime. In a case where for example a radar application and a mobile system are used in the same spectrum the situation becomes more interesting. It is under a secondary trading regime relatively easy to envision a case where a license holder, such as the military could sell or lease some part of its spectrum as an “interference right” whereby the military sells or leases the right for a mobile system to cause interference to the military spectrum.

Another example of this concept is when there is an incumbent user present in the bands, and a new entrant can use part of the spectrum of that licensee. One example of this is the discussions in the US regarding the use of FWA-services (Fixed Wireless Access) in broadcasting bands (IEEE 802.22) where intelligent equipment is allowed to use broadcasting spectrum for FWA services as long as the equipment uses DFS to not cause interference to the primary user of the spectrum. This type of secondary non-exclusive use can make good use of many of the white spots as displayed in Fig. 1.

This concept can be viewed as a mix of the other concepts presented here. Thus many problems and opportunities are similar in this and the other concepts. However some issues are unique since there are a few, not one and not many, license holders. Thus there are not too many license holders to keep track of, but there are too many for the solutions to be trivial.

4.3.2 Examples of similar contemporary systems

The case of shared spectrum is not new; as a matter of fact it is a very common model for licenses, to take an example most taxi radio dispatch systems are using shared spectrum. So in a very simple case shared spectrum could be realised for a mobile data system as long as the different users are using technologies and etiquette rules that are relatively similar, as the case is for taxi radio.

Another example of current sharing of spectrum can be seen in broadcasting where the broadcasting industry is using wireless microphones in broadcasting bands. These “Services Ancillary to Broadcasting” (SAB) is a very good example of sharing based on different services, or use of “interference rights”.

4.3.3 Role of the regulator

The regulator leaves most of the decisions of how to use the spectrum to the licensees. For example usage, technology choices and emission limits are left to the licensees. There may however be some limitations to protect users of adjacent bands.

4.3.4 Regulatory changes required

	Global	Regional	National
Policy	• -	• Perform studies aimed at promoting the possibility of unorthodox sharing models	• Investigate the possibilities for novel sharing models
Regulation	• -	• Develop regulatory framework for shared spectrum	• Develop regulatory framework for shared spectrum
Processes	• -	• Recommend rules for sharing and interference	• Processes for interference resolutions

4.3.5 Possibilities and challenges

Since only a few licenses are allocated there is an obvious risk of an oligopoly. However there may be other means of realizing services and there may be enough players in the market to make it a functioning market.

There may be a first mover advantage. The licensee who first starts to populate the spectrum may have an upper hand when it comes to making agreements with the others.

With a shared spectrum among a moderate number of actors, co-operation and stability could be encouraged. Thus the financial risks are limited.

The risk of spectrum holding is reduced since there is a group of licensees that can use the spectrum.

4.3.6 Regulatory SWOT analysis

Strengths

- Potentially efficient use of the spectrum
- Enables for the introduction of new technology
- Can relatively easily be implemented nationally

Weaknesses

- Potentially not very high demand for shared spectrum
- Difficult to harmonise the introduction on regional or global basis
- Adding a new user will impose changes to the current user(s)

Opportunities

- Different cognitive systems could share a piece of spectrum

Threats

- One user with more aggressive equipment could dominate the spectrum space thus suppressing the other users
- Potential conflicts and difficult conflict resolutions between the license holders.

4.3.7 Impact on the innovation process

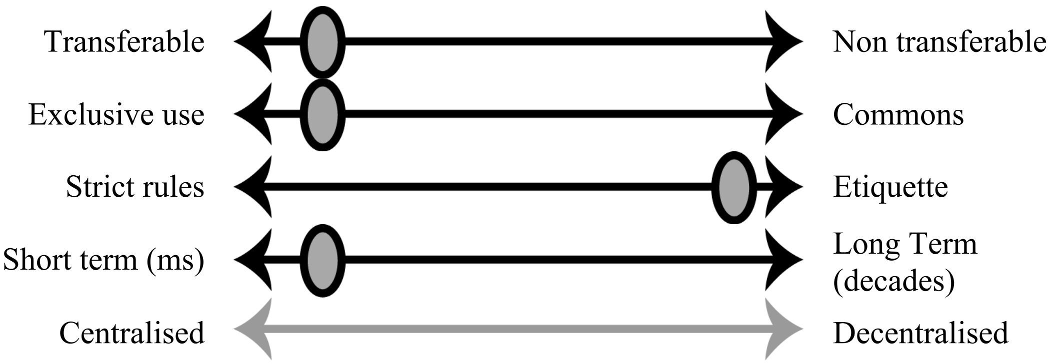
Since there are few rules for the use of the spectrum it may be relatively easy to introduce new technology. However depending on the agreements between the licensees there may be a resistance to use technological advances.

Also there is an inbuilt incentive for using new technology. As technology matures there will be a point where the gains from switching to new technology is larger than the losses incurred by breaking agreements and investing in new equipment.

Rules can be formulated to encourage co-operation which may improve spectrum use. How this should be done or how large the gains are is an open issue. A drawback with a very strict rule policy is less of dynamics and lower degree of innovations.

The whole description of this system concept is that there is a lot to gain by cooperating. However it is not trivial and the possible gains should be investigated. This will also affect how agreements are made.

4.4 Real time spectrum exchange



4.4.1 Overview

The real time spectrum exchange concept is the most challenging of the concepts presented in this report when it comes to spectrum management and the regulatory domain. The concept represents the full realisation of a market model for spectrum management. The concept as such implies that spectrum should be treated as the property of its holder, and that the license holder has a large number of degrees of freedom regarding the use of the license.

In this system concept, conventional exclusive licenses are initially sold out by the regulator (e.g., in a license auction) or given out by a beauty contest etc. The spectrum usage is not constrained to a specific service but could be used in any fashion by the spectrum usage rights holder with no, or within some very relaxed, etiquette rules. The licenses thus acquired can be resold fast by means of electronic trading mechanisms. The trading can be done through the regulator, through some central "license exchange" actor or by bilateral agreements.

The degree of decentralization is naturally interesting here. Although the trading is decentralized, a central register for responsibility is probably required. But one can also play with the thought of a total deregulated trade with licenses. Information processes are becoming too complex and varied to be run in any other way as through decentralized decision processes.

Any DSA system may include real-time trading mechanisms enabling trade with the limited spectrum resource. This could be done either with a third party entity, i.e., broker, or directly between telecom operators with rights to use certain parts of spectrum and interested in selling and buying these rights to use them. From a technical point of view, the implementation of such mechanisms could either be of central control or with local control.

By a central control, we mean that any telecom operator engaged in such real-time trading of spectrum usage rights have one, and only one, central point where decisions are made whether or not that operator itself should keep the right to use a specific spectrum, during a specific time frame, or if they should sell its rights to an other operator. If there is a broker involved, or not, seems not to have impact on the needed implementation for the telecom systems involved. Furthermore, traditional telecom systems such as GSM and the like, and UMTS need little change, mainly in the telecom control plane, to support secondary use trade. It is mainly a matter of keeping track of how to debit or we could say roaming in all national networks as we do while out-of-nation use.

A local control is defined by that the end user terminals themselves have authority to buy spectrum usage rights, and use them instantly, and where network access points, e.g., base stations, have authority to sell spectrum usage rights and provide service instantly. This variant does indeed require add-on functionality and puts extra attention to security aspects of system use and reliability aspects of spectrum use.

Key regulatory aspects of the real time spectrum exchange concept include;

- Fully implemented secondary trading without prior consent from the regulator
- Liberalisation of license restrictions enabling change of use
- Full reconfiguration of licenses in frequency, geography and time
- Establishment of a trading place, centralised or decentralised

The regulatory framework must in this concept be very light when it comes to restrictions in use. However, the restrictions that can be associated with a license under this concept can be relatively strict when it comes to boundary conditions such as maximum power and out of band emission levels.

This system concept relies on etiquette, but the central institutions could still imply inclusion of some rules controlled by these institutions. We will probably see interference rules, but few other rules in the licenses.

In regulatory terms, one of the possible solutions for implementing the concept is through the introduction of a “spectrum manager”. A spectrum manager holds the license and manages the use of the spectrum. The concept of a Spectrum manager has been introduced in Australia. Such a spectrum manager could make agreements with potential users of the spectrum and lease a particular piece of the license for a period of time. The potential interference between users is a business issue between the spectrum manager and the users, restrictions and obligations can be part of the business arrangement. The Spectrum Management Authority (SMA) will only hold the spectrum manager responsible for interference outside the license. If a user is in breach of the restrictions for the license and causes harmful interference to services in other bands the spectrum manager is responsible. Whatever the operation is within the license held by the spectrum manager it is part of the business arrangement between the spectrum manager and the users.

The role of a spectrum manager can easily be taken by the current license holder given that the regulatory tools to implement the concept are in place.

4.4.2 Examples of similar contemporary systems

Some real-time clearing of frequencies already today occurs every time we leave our home country. The typical example is roaming in GSM. Here it is not the frequency spectrum per se that is traded, but rather capacity. However the trading mechanisms are similar.

As for monetary streams and timing of payments, even if there is an initial auction it has not necessarily to be on the format of an upfront lump sum to be paid in advance. Another option can be that the winner of the initial auction has made the best bid on the percentage of future revenues to be paid to the coffer of the Government. A real world test of this option has been carried out in the 3G licensing process in Hong-Kong [23]. In this system concept the original license-holder could then be seen as a "reseller", perhaps charging also others on a “pay as you go" format. Extra high prices for short-term peak leases, lower prices for those willing to make a commitment for say 3 years. This principle has been used for decades in the context of reselling of capacity on satellite transponders, or IRUs (Indefeasible Rights of Use) on intercontinental cables.

Interesting examples of the introduction of tradable rights can be found in Guatemala, New Zeeland and Australia [24].

4.4.3 Role of the regulator

This system concept is using etiquette instead of strict rules. This could either mean that the central control structures of today (e.g. in Sweden the PTS) would be maintained, but they would act as the meeting place for trade. Or that the market mechanism in itself creates one or several central market places for the trade. In both cases the real time element of the trade will point towards a ‘perfect market’.

Regulation is here traded in for pure market forces or loose industry etiquette. Major regulatory changes would have to be made in order to make this system concept a reality. The emphasis is changed from market regulations, to stepping in and saving situations when market failure occurs. The Government is in this scenario moving away from command-and-control and towards a diversity of legal regimes. The objective of spectrum policy would not be to minimize, e.g., interference, but to maximize usable capacity.

4.4.4 Regulatory changes required

	Global	Regional	National
Policy	• -	• Change focus from non-interference regime • Define tradable rights • Set up frameworks for real-time spectrum exchanges	• Change focus from non-interference regime • Leave decisions to the market players • Rely more on general competition law
Regulation	• Change the RR allocations and service definitions	• Define tradable rights	• Define tradable rights • Change rules for transfers of licenses to ex-post
Processes	• Proposal to agenda for future conferences	• -	• Set up processes for interference resolution • Change the processes for management of the national frequency registry

4.4.5 Possibilities and challenges

This system concept implies frequency adaptive systems (e.g. software defined radio) that can change operating frequency on a daily, hourly or even millisecond basis. This can be done in a centralized or decentralized fashion. Some real-time clearing of frequencies already today occurs every time we leave our home country. Our devices, within a specific international open standard, automatically pick the strongest signal available (albeit in given frequency bands). This is a clear advantage from a user's perspective, even if it comes at "bank-robbery" rates. A possible solution could be to extend to the home captive market at more reasonable rates, even if the operators might hate the concept on both counts. Or, are there also technical constraints blocking any more large-scale surfing between any net which can offer the "lowest rate in town" at any given location and time? This should be looked into.

From an economical point of view this scenario gives a much shorter feedback-loop between success on the market and assignment of the scarce spectrum resource. Getting down to each and every base-station, and down to milli-seconds can be expected to give the most efficient use of spectrum where the least possible part of the spectrum is left idle at any point of time. This is one step towards the perfect market as described in macroeconomics [24][25].

4.4.6 Regulatory SWOT analysis

Strengths

- Theoretically very high use of available spectrum
- The decisions regarding use of spectrum is left to the market players
- Disruptive technology shifts are potentially not hindered by the inertia of the regulatory system

Weaknesses

- "Everything has to change"
- Interference management can become a big problem
- Unclear situation for future large infrastructure investments

Opportunities

- Market based refarming
- Frequencies will ultimately be used by those who value the resource the most

Threats

- Hoarding and anti competitive behaviour
- High transaction costs
- Low demand
- Low supply

4.4.7 Impact on the innovation process

Opportunities for easier trading with spectrum licenses should lower entry barriers for newcomers. This should encourage trials with new services and uses of spectrum.

4.5 Traditional licensing – (reference)

4.5.1 Overview

In this concept an application for a license is made to the regulator who grants exclusive use for an extended period of time. However there are a number of conditions connected to the license. For example a 3G license requires that equipment adhering to a specific standard should be used and coverage everywhere must be ensured. The license cannot be transferred to another party and if the license holder does not fulfil the requirements the license may be revoked.

4.5.2 Examples of similar contemporary systems

This is the traditional regime for licensing and there are many examples. GSM spectrum may be one that many know of.

4.5.3 Role of the regulator

This might be considered as one of the traditional ways of how a regulation of spectrum usage is done, at least if we consider the last ten years.

4.5.4 Possibilities and challenges

The philosophy behind this system concept is that interference problems should be planned away. The planning process performed by the regulator when giving out licenses ensures that a license holder is not interfered with. This planning in advance makes it possible to simplify equipment since a lot of functions for mitigating interference are not needed. Also the lack of interference makes it possible to make global optimizations to maximize capacity. However since planning must be done for the worst case most of the time a lot of capacity is sitting empty most of the time.

In this system concept the time span is quite long. Thus planning can be done on a quite long time horizon since the rules are known beforehand. This reduces risks for actors. However it also creates an entry barrier to new operators since there may not be licenses available. Thus there is a risk of reduced competition and higher prices.

Since planning is a slow process the time scale that licenses are granted on is quite long to minimize the planning overhead. For example if the planning takes half a year then the license should be granted for at least some years to avoid spending too much of the time planning. On the other hand since everybody has adapted to a slow planning process there is little incentive for the regulator to speed up the process.

4.5.5 Impact on the innovation process

Since the license process is quite slow, the standards that must be followed are kept for a long time. This makes innovation slower since it is not possible to take advantage of new technical developments. The slow timescale for licenses makes it possible to create complex standards that only large companies can handle. This excludes small companies.

5 Technology issues

5.1 Interference management

Relevance of proper interference handling	**Low**				**High**
Open spectrum access					X
License exempt operation				X	
Shared spectrum access				X	
Real time spectrum exchange			X		
Traditional licensing		X			

Table 1 Relevance of proper interference handling for the different concepts.

Measuring interference and the impact of the interference may seem easy, but is in fact quite complicated. The details and the history of interference analysis are outlined in Appendix B. The problem is to be able to assess how the presence of an interferer or multiple interferers will influence a system. Traditionally planning has ensured that there have been relatively few cases critical of interference. However in the DSA concepts there are many more situations where one system will interfere with another. In some of the concepts, the amount of interference will be part of an agreement between the actors and thus it is important that the items agreed on are both relevant and easy to check. The table above shows the relevance of proper interference handling for the concepts.

5.1.1 Interference analysis and control

Existing state-of-the-art analysis methods for intersystem interference in wireless services are often based on algorithms for analogue systems, modified with simplified algorithms to analyse the impact on digital communication receivers. The underlying algorithms for analogue systems require detailed information of the systems being analysed. System parameters not specified in the system specification are assumed to be determined by additional measurements. These kinds of measurements are normally very expensive to perform and, therefore, the needs for new analysis methods that do not need such detailed information have been recognized [28]. Furthermore, existing methods are focused on the single transmission/ receiver link level. In a DSA scenario, interference consequences on a higher system level must be possible to handle. For instance considering QoS (Quality of Service) could be a necessary evaluation parameter in such analysis. The rapid development within the area of digital communications has given an increased variety of system parameters that an analysis tool must be able to handle. The development of analysis tools for intersystem-interference analysis has not been fast enough to handle all new digital systems in another way than with simplified models. Furthermore, existing analysis methods are designed to analyse static scenarios both in space and time, i.e. the analyses are performed for a limited amount of interference-victim combinations. In a DSA scenario, the fixed assignment is no longer an available solution to the intersystem-interference problem.

In the case of *Exclusive use*, existing methods for intersystem interference analyses are used. The intersystem-interference analyses and control are performed on a centralized level. Typically, the final result is obtained by worst-case assumptions where the simultaneous impact from different interference sources is considered. This means a situation that is statistically unlikely to occur. The major difficulties for the real time spectrum exchange concept (decentralized?) will be the potential interference cases that can occur when different parts of the license (in frequency, geography and time) are used for different applications and services.

In the general case of *Shared spectrum (including commons),* the intersystem-interference analyses cannot be performed in advance for a limited number of static cases. This is because the number of potential intersystem-interference cases will be too large, almost infinite. Furthermore, the necessary intersystem-interference analyses must include the total actual interference environment, i.e., not only the known intentional/unintentional transmitters. The intersystem-interference analyses must be done on a decentralized level and more or less online.

In our concepts using shared or commons the intersystem-interference analyses must be done online for each case. This means also that all kinds of background interference will affect the result of these analyses for a certain system. Since the analyses must be done online, no detailed information, such as system specification parameters, of the actual interference signal will be available. The analyses will be based on some kind of more or less simple measured value of the total interference at the moment. Thus, reliable analysis methods based on a reduced number of interference-signal parameters must be available.

Because of this, completely new methods for intersystem-interference analyses are needed. The development of such new methods is a necessary condition for interference avoidance in any DSA concept chosen, since all three concepts proposed are based on etiquette rules. However, the real-time spectrum exchange concept contains an amount of centralized functions and will therefore require less new methods for intersystem-interference control than the other proposed concepts. The open spectrum access concept will require the largest amount of new methods for intersystem-interference control.

5.1.2 Method development for dynamic interference control

In general several major evolutions of present analysis methods for intersystem interference are needed for dynamic spectrum access:

- Intersystem interference analysis methods for on-line (on-demand) use must be developed to handle dynamic changes both in space (physical location) and time.
- Analysis methods for a reduced number of in-going system parameters such as output power, frequency range, etc must be developed.
- Analysis methods that can aid the prediction of consequences on a higher system level than separate links are needed.
- Current spectrum policies are based on “interference-limited” rather than “ambient noise-limited” environments. “Interference limited” means that only other users are considered in the intersystem-interference analysis. In a dynamic network scenario the total environment must be considered which requires new methods that are “ambient-noise limited”.

Independent of DSA concept chosen, there are several fundamental research problems that must be solved concerning dynamic spectrum interference control. Furthermore, depending on DSA concept chosen, different specific technical problems will appear. It is however difficult at this stage to decide which of these concept-specific problems will be of most importance to solve.

The FCC has released a Notice of Inquiry and Notice of Proposed Rulemaking [35] seeking to use an "interference temperature" model for quantifying and managing radio frequency interference. In contrast to the Commission's current method, which is based on transmitter operations, the interference temperature metric focuses on the actual RF environment surrounding receivers. Under this approach, new devices would be permitted to operate in a band if their operation does not cause overall emissions in the band to exceed a pre-set limit. One difficulty with such approach is that the wave form, not only the power, of an interfering signal can significantly affect the performance of a disturbed system. This is a well-known result in intersystem-interference research. Thus, this metric could be too blunt and must be further investigated to determine the risks of under/overestimation the interference impact if used.

In the following, research questions of fundamental importance for dynamic spectrum access, independently of DSA concept chosen, are proposed for further investigation. Suggested research activities for phase two are:

- Investigation of convenient decision metrics for intersystem interference control online. What kind of interference measurements (metrics) is convenient for instant decision making online? Convenience includes both parameters that give relevant information of the interference impact and parameters that are convenient for practical implementation in systems. Is for instance the "interference temperature" a convenient metric although the interfering waveforms are not considered in that metric?
- What overall system performance properties should have most influence on the final decisions given a certain convenient interference metric? Several alternative performance properties could be of interest such as QoS, reliability, capacity etc.
- What metrics are convenient in order to control that given rules/etiquette are followed by the users?
- How high degree of freedom can be given in an etiquette rule without risking interference-caused spectrum "breakdown" (anarchy) among the users?

5.1.3 Need for standardization

In the *open spectrum access* concept it is not that important to have standards for interference. The rules that the transmitters have to conform to are simple and thus they should be easy to check. In the *license exempt operation* concept the rules are more complicated and thus more difficult to test. For the *shared spectrum access* and the *real time spectrum exchange* concept the interference rules will probably be part of an agreement between the license holder and thus it is important that they are useful. In the *traditional licensing* concept these issues are indeed present and relevant, however so far most of the tools already exist.

5.2 Flexible radio systems – an opportunity or necessity

From early days' radio receivers until now, interference protection has been achieved mainly by regulatory actions. The regulatory interference protection means a cheap but in a sense "dumb" receiver with very little, or no, flexibility. Such a radio is not favorable for dynamic spectrum access.

Introducing radios that have greater flexibility may have a number of benefits. A more flexible radio can be viewed as an enabling technology for DSA. The radio may be able to use "holes" in the spectrum and the net result is that more bits can be transferred per second. Another benefit lies in the commoditization of the radio design. Since the radio can be configured for many different tasks there are economies of scale to gain when the same hardware can be used for many different tasks. In addition design becomes easier which reduces time to market.

The radio technology evolution is now in the beginning of a new era which means a transition from "Dumb" via "Smart" towards "Cognitive" radios. Here we present our characterization for each of those radio types with no intention to be complete or even fully accepted. Especially the term "cognitive radio" has a wide range of possible definitions [14], [15], [16].

"Dumb" transceiver

- Intelligence in system – not in end user terminals (except for fancy things like games, Java consoles etc…)
- Centralized control
- Low demands on end user terminals
- High system costs – low end user costs
- Low flexibility
- Low spectrum usage efficiency

"Smart" transceiver

- Some intelligence in end user terminals
- Both centralized and decentralized control
- Higher demands on end user terminals
- Lower system costs – higher end user costs
- Higher flexibility
- High spectrum usage efficiency possible

"Cognitive" transceiver

- Intelligence in end user terminals
- Knows; where it is, user demands, available services
- Learns and recognizes usage patterns from the user
- Both centralized and decentralized control
- Higher demands on end user terminals
- Lower system costs – high end user costs (initially?)
- High flexibility
- High spectrum usage efficiency possible

The higher we climb in flexibility, the higher the end user terminals cost, at least initially. On the other hand, it might lead to lower infrastructure costs, remembering that the infrastructure cost is one of the reasons why it is hard to introduce new technology, thus leading to long time to market.

What makes the RF (Radio Frequency) parts of a transmission system suitable for DSA-operation?

First of all, it must have a kind of agility. This could be achieved in many ways, for instance with tunable and adaptive RF components. Wideband power amplifiers, broadband antennas, and adaptive filters open up for dynamic bandwidth operation. Better filters allow for better interference rejection which provides better use of the spectrum and tunable power amplifiers enable the radio to efficiently operate across a wide frequency range. To be able to adapt to the signal environment by switching waveform, good linearity in RF-components as well as A/D-D/A-converters is advantageous or in some cases like power amplifiers, a prerequisite.

Heteromorphic[2] [34] waveforms can use gaps in the spectrum based on time, space frequency, bandwidth, data rate, modulation, coding and other characteristics. This will stress the demands even further.

The spectrum measurements also put strong demand on for instance the detectors used to handle the hidden node/silent receiver problem (see Chapter 5.4 Hidden node/terminal and silent receiver handling).

The use of a lot of signal processing will probably lead to tough demand on high power efficiency in all parts of the system, especially in the end user terminals (this demand may be the case in other terminals too because of heat dissipation problems).

Software Defined Radio, SDR, offers much of the desired flexibility, especially if we consider *standardized* SDR. DSA might be the real "killer application" for standardized SDR. A flexible radio based on standardized SDR has a huge potential to improve interoperation between different systems and system components.

Even in the future, there will be a very wide range of transceivers, the main categories are; non DSA aware, aware of DSA but not using it and finally using DSA. DSA systems will range from rather simple units with some DSA capability to very sophisticated devices that may utilize the available spectrum for many parallel connections and with high QoS as well as high reliability. A nice example of the latter is outlined in the XG-project, see [13].

A DSA system must adapt to the environment in order to optimize the "network capabilities" using all available "dimensions". The fundamental thing here is waveform orthogonality, the parameters are often termed the "Electrospace" [27] Time - frequency - code - hop/chirp – spatial. The "flexible" radio prepares the ground for this. Techniques to achieve this waveform orthogonality includes, for example, adaptive TDMA (Time Division Multiple Access), beam steering and null steering, OFDM (Orthogonal Frequency Division Multiplex) techniques, interference suppression & multi-user decomposition, adaptive power control and ad-hoc networking.

In order to promote high system flexibility, as much as possible of functional requirements of such systems should be included in open standards. Furthermore, implementations of such functionality exemplified with open source implementations are also beneficial in promoting such products and systems.

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[2] Heteromorphic waveforms; waveforms that dynamically can adapt its parameters and characteristics to the electromagnetic spectrum environment thus introducing a flexible air interface.

The three different DSA concepts have very different demands on transceiver flexibility. The *real-time trading concept* has as good as no demands on end-user transceiver flexibility, if the implementation is centralized. There is an opportunity to offer multiple air-interfaces in networks access nodes, e.g., base stations, for a telecom operator owning such a node and wanting to be able to offer more end-user terminal variants to access their network. There is also an opportunity of multiple telecom operators to share an access point and offer multiple air-interfaces and networks at one site, sharing construction and maintenance costs for such a site. Depending on what systems are involved for the distributed variant, end-user transceiver flexibility demands vary. For this variant, there is a need for better understanding how such end-user terminals should interact with network access nodes, e.g., base stations, and how they should interact with adjacent end-user terminals if an opportunistic relaying of such nodes, ad hoc networking, should be possible. Similar opportunities exist in this distributed implementation variant as well as in the central implementation.

For the *shared spectrum access concept*, there is a need for terminals to measure the spectrum such that when the opportunity to use spectrum comes, we are ready to use it. In this concept, we should perhaps make a distinction between the case with a limited number of telecom operators with a right to, on a fairness basis, share spectrum use, and the more restricted case where these telecom operators also have a limited number of waveforms to use in the shared spectrum. In the more restricted case, each end-user terminal has to measure the spectrum for a finite number of waveforms potentially being used. If no such detection is made, and the issues with hidden nodes and silent receivers have reasonable solutions implemented, we go ahead and transmit if we have anything to send. If, on the other hand, the spectrum use does not limit the number of waveforms allowed to be used, we have a more difficult detection to do. First, we should consider whether or not there is a potential signal present that matches the spectrum use etiquette, which is mainly a matter of integrating over the signaling space to a suitable amount of time, and then, if there is a signal, we should classify it and detect if it is a legal use signal. These systems could be implemented infrastructure-less and use any networks access nodes available. Such nodes, in turn, belonging to any of the telecom operators that have a shared right to use the spectrum at hand, should provide transparent access to any end-user terminal that are willing to pay for network access demanded.

For the *open access concept*, we have an unlimited number of users and unlimited number of waveforms that could be used. This case actually puts the same requirements on transceiver flexibility as does the unlimited number of waveforms variant of shared spectrum access. However, there is an added opportunity for wireless internet access providers here. Anyone with a business idea to provide such access can commence operations very fast and does not need an end-user customer basis to start up with. They can evolve as business takes off.

There is a common opportunity for the DSA to make use of *technology for standardized software defined radio* in support of high degree of flexibility mainly re-programmability of waveforms. There is also a need to better understand *how to conserve energy* both for mobile devices to support longer service provision times as well as for stationary devices, i.e., fixed power line supply, in terms of longer mean time before failure due to lesser heat dissipated and smoother operation of equipment. Specifically, if software defined radio technology becomes a core technology for telecom system providers, how do we develop transceiver flexibility without paying for it in terms or greatly increased power consumption? Furthermore, using SDR technology, how do we implement radio functions on general purpose processor equipped devices and *incorporate the radio function* to a great extent *into standard computing environments* and still keep power consumption at acceptable levels and also how should *cross-layer design* of such implementations be done to be power consumption driven? Another mainly common demand is more *frequency agility* in both end-user terminals as well as network access nodes. Last, but not least, with more and more flexibility in end-user terminals, as well as network access nodes, how do we ensure reliable spectrum usage, when demanded?

5.3 Spectrum usage measurements

There are three major reasons for spectrum usage measurements; spectrum access control, interference control and policing (including cheating control). Those measurements may be conducted on a global, regional or local basis to support these objectives. The complexity of the measurements handled by each terminal/node depends on the objective and type of DSA concept. We will elaborate with two types of measurements;

- Pure energy detection, only bandwidth and time considered.
- Signal characterization, which includes the whole signal space.

5.3.1 Spectrum access control

Here we are looking for an opportunity ("hole") in the electromagnetic environment where we may establish a connection. In other words, we want to find inactive areas mainly in frequency and time. This applies for all terminals and all individual radios will, in real-time, measure its local environment. The major questions are;

- Is there any transmission going on affecting us?
- What kind of transmission (signal characteristics, waveform)?
- Is it a continuous transmission or is it intermittent?
- Time-constant for on/off signaling?

With the gathered information the system may quantify the amount of usable spectrum. From this it is possible to decide where and how to operate (frequency, waveform) in order to provide a demanded quality of operation. Critical issues are how to handle the found unused, or empty, spectrum, what is empty enough and how to determine the "empty" spectrum threshold in a dynamic manner? Of course there exist occasions where the signal strength is high but we are unable to characterize the signal. For instance there is interference from microwave ovens, etc. If no global or regional restrictions apply, operation may still be possible using robust waveforms. In the case of intermittent sources, measurements may be done repeatedly down to 10s of milliseconds. More stable sources like radio and TV broadcast stations may be measured less often [34]. Another possibility is to provide the node with information about fix broadcast stations through other means which will decrease the need for measurements.

In all our decentralized DSA concepts, signal strength measurements seem required. Such measurements would also be beneficial for good operation of the license exempt operation concept. In the centralized real time spectrum exchange case, it is more unlikely to be a requirement.

Signal characterization increases the complexity and we believe that none of the concepts require this but for all except traditional licensing it would be beneficial. The open access case is probably the concept that can achieve the largest advantage from such a measurement and characterization and also might require it.

Using traditional licensing, those measurements are of course possible but not necessary.

5.3.2 Interference control – Avoid interfering with others

Radio environment measurements are necessary to support the interference control function. It is important to avoid interfering with non DSA aware terminals and reduce interference to hidden terminals/silent receivers. Signal energy detection might not be enough. The reliability of the measurement is vital.

5.3.3 Policing

In a world of DSA, "spectrum hogs" may monopolize the spectrum to the exclusion of others. To avoid cheating and misuse, it might be necessary to have some kind of central monitoring of the spectrum. Main issues here are how to do this in an affordable and secure way. To what level do we aggregate the data obtained at the monitoring stations, regional-wise, nationwide or even globally? Data aggregated nationwide may become a security issue hard to handle, global data even worse.

5.3.4 System demands

The system requirements are based on real-time measurements, dissemination and opportunity identification. Independently of the purpose of the measurements, there will be high hardware as well as high software demands, especially if we consider the DSA operating mode of short term operation.

Theoretically, a high end DSA system must be able to monitor the full spectrum where it has capacity to operate. This will probably be unrealistic for systems with a large frequency range. A more realistic approach is a part of the spectrum. A priori information will probably lessen this demand. Use of "cognitive radios" may also ease this burden.

In all three DSA concepts the usage of spectrum is down to milliseconds, typically a few seconds/minutes/tens of minutes. This indicates the system and processing capability that is needed.

The RF parts of the system must handle large bandwidths and be capable of handling very weak signals in the presence of strong signals, thus putting high demands in the dynamic range and linearity of the RF front-ends. This also applies to filters and A/D-converters, both must be capable of handling large bandwidths at a large dynamic range. Especially in the end user terminals, the power efficiency will be critical. This applies to the hardware (RF-parts and processors) as well as the software and software architecture.

Other problems that must be handled are e.g. shadowing of the receiving antenna – a problem using smart antennas with different receive and transmit patterns, time – not possible to look ahead and finally algorithms for spectrum usage characterization.

5.4 Hidden node/terminal and silent receiver handling

There are other technical problems related to the spectrum access using agile transceivers that we will need to address due to their high impact on system performance. Two of these problems are commonly referred to as hidden node/terminal problem and silent receiver problem.

The hidden node/terminal may occur in a situation where some primary transceivers in a network operate on a certain frequency and another network is looking for a suitable frequency to operate on. A transceiver (A) in the secondary network is trying to access a transceiver (B) in close vicinity to any of the transceivers in the primary network. Due to terrain or signal blocking transceiver (A) is unable to detect the transmissions from the primary network and starts to transmit on the frequency already in use by the primary network. Transceiver (A) will then interfere with the primary network. This interference could not have been anticipated by either of the two networks.

Another problem is the silent receivers, which are assumed not to have any transmitting capability and it is therefore impossible to detect the use of its operating frequency. This is typical for broadcast networks like terrestrial and satellite TV distribution networks.

This is not a new problem, for instance it is well known in WLAN scenarios. Nevertheless it is a serious problem with large impact on the spectrum access (and interference levels) especially as it is difficult to control or predict. How to avoid this problem? The following spectrum access methods, available today, address the problem to some extent;

Cooperative user case:

- Electronic feedback. Information about receiver location, frequency, used waveforms etc. is broadcast, so everyone can avoid interfering.
- Spectrum planning. Similar to the licensed case where interference problems are planned away

Non-cooperative case:

- Listen before talk – may be required by all three (decentralized) DSA concepts
- Probing
- Geo location (database assisted?)

These techniques all have their pitfalls when it comes to reliability in a DSA system. Failures in this function may also have a substantial effect on QoS and system reliability. Other already existent and possibly new methods must be revised.

Technologies supporting fast radio resource management making use of simultaneous spectrum occupancy measurements at different geographic locations in a system might be useful and should be investigated. Military technology and methods used for Electronic Support Measurements (ESM) could be considered.

For the case of energy detection, the possibility to use more advanced detectors have to be studied. Detectors like those outlined in for example [37] offer very high sensitivity, actually below noise floor, which would be useful for the hidden node problem.

Suggested research activities for phase two are:

- Investigation of the possibilities to overcome the common pitfalls of already available methods for the decentralized non-cooperative case (tightly coupled to dynamic interference control).
- Investigation of new methods to support both cooperative as well as non-cooperative scenarios.
- Investigation of advanced detectors for energy detection of low energy signals. This should include achievable processing gain, computational requirements, implementation complexity, measurement reliability including influence of signal characteristics, propagation channel effects and antenna influence.

5.5 Quality of Service

Systems sharing resources and using them more dynamically face the problem of not really having any guarantees of the service level they can get from such resources. In a looser regulation, there is thus a need for a mechanism negotiating who gets to use what resources and which service levels then can be offered. Furthermore, there is a need for re-negotiation as the usage changes due to the dynamics of use.

It is simply so that having dynamic spectrum access means that you have access to over-time varying amounts of spectrum. This means that systems using varying amounts of that specific resource inherently gives different service levels in terms of possible offered bit rates, network throughput, varying setup times of services, delay variations in traffic, forwarded both in terms of average delays as well as time-jitter. It is also so that there is additional overhead traffic normally added to such systems if they are to provide QoS in a controlled way due to the additional signaling need.

Last, but not least, if we have systems where end-user terminals determine for themselves what spectrum to use, we have further additional overhead in controlling QoS also in a distributed fashion.

One problem is to determine if QoS can be ensured in the *shared spectrum access* concept. This is probably determined by the degree of cooperation between the license holders. If there is centralised real-time radio resource manager the function of this is not trivial. Not only the “traditional” function of assigning power, waveform, time and access-point has to be implemented, but the resource manager must include side information related to the agreements made between the licensees. Radio resource management research has studied some of these problems, but they may have made overly simple assumptions about the agreements between operators. Thus there may be interesting things to learn by making better assumptions about these agreements. The agreements between operators and how they cooperate and what kind of agreements they are likely to make is probably researchable and interesting.

In the *open spectrum access* concept the issues are: Capacity estimation and QoS handling in a network. How can a certain level of QoS be assured, if at all, with this concept? This is probably determined by how successful the interference management is.

5.6 Reliability and security issues

Opening up access more dynamically makes the concept vulnerable if no considerations of accompanying reliability and security issues are addressed. Flexibility and reliability/security are easily contradicting and openness and distributed control have to be balanced with reliability, dependability and security. For example, the software defined radio forum, promoter of SDR technology, which is relevant here as a potential key technology enabling DSA-capable systems, has addressed the FCC's request for comments on reliable spectrum use, see [34] and [36].

The questions specific for spectrum access are:

- How would a bidirectional access control be made reliably and securely, that is, how does the device access the spectrum reliably and securely?
- How does the system do admission control and authenticate the device?
- How does the device control that the spectrum about to be accessed is safe to access and that the spectrum control management aiding is authentic?
- The traditional issues here are key management and specifically key distribution.

If dynamic spectrum access is not done reliably and securely, the whole concept may fail to be successful. If dynamic spectrum access is to be made reliably and securely, adding such system properties to the designs may very well be cost driving.

5.7 Radio resource management

In all radio systems there is a need to share the available radio spectrum among the users. The main question is who can transmit what and when? The answers to this question lie within the radio resource management domain. The research in this field is extensive but when the DSA concepts are introduced there are a number of new issues to consider.

In general there is little research done on joint radio resource management for heterogeneous systems. Both centralized and decentralized algorithms need to be investigated. Including external, possibly external, access brokers also adds a new dimension of resource allocation problems.

One underlying assumption of most radio resource management is that all users share the same common goal. For example an operator wants to serve as many users as possible and thus he can control the users to achieve this goal. However in some of the concepts this is not the case. There may be various actors with only partially overlapping interests. How the trade-off between these various interests should be done is not clear, nor is the methods for reaching this trade-off.

Another underlying assumption of radio resource management is that spectrum is scarce. The DSA concepts may possibly invalidate this assumption and thus the objectives of radio resource management should be revisited.

One of the problems with radio design is that we essentially have reached the limit of what can be done on a single link. Even if more sophisticated signal processing techniques become practically available, the capacity of a single link cannot be improved beyond the Shannon limit. Thus significant capacity gains may only occur if spectrum can be utilised more efficiently. Thus the management of spectrum from a system perspective is important.

5.8 Real-time trading mechanisms

The need of mechanisms for real-time trading with spectrum use rights are of importance at least for one of our sketched DSA concepts and may be useful, if developed, for DSA systems falling under other concept categories. It is well worth noting that it seems quite possible to have such mechanisms if the time to setup a service, running the service, that is, use negotiated spectrum, tear down the service, is well over, say, ten minutes. It may be the case that it can be done in a reliable way for service times in the region of one minute, but can it be done for services demanded, produced and ended in the order of a single second? Can it even be shrunk down to the millisecond order? For different mechanisms suited for such time constants, what are their impacts on quality of services provided, what are their impacts on spectrum usage reliability and how can we ensure such trade in a secure enough way?

There is also a difference, more and more emphasized as the time constant becomes smaller and smaller, between a centralized control and decision making in the trade and a distributed authorization, control and decision making. If the order of the time constant is tens of minutes, then a centralized implementation seems doable. But, could it be done if the order is tenths of a second or shorter? If service setup, produce and consume, and finally tear-down time in total is small, does that imply a distributed implementation?

These challenges would we like to explore for DSA systems having a need for real-time trading mechanisms.

5.9 Interesting areas for further research

Today's radio systems are interference handling wise more or less built on the same principles as the old crystal radio! Our belief is that DSA will be a reality in the future, but it will be introduced evolutionary not as a revolution from one day to another. We have studied three different DSA concepts and we believe that they all three, from a technical point of view, are realistic to implement. Systems derived from these concepts will probably exist together with traditional licensing systems many years ahead. A mixture of the concepts in one single system is also likely to come. The technology developers must also find ways to demonstrate the capabilities of DSA systems in order to gain confidence among the market actors.

The technical core of DSA is spectrum usage efficiency, interference handling and resource management. To a large extent much of the basic technology exists already today. The difficulties in making DSA successful are not the technology development itself, but to make regulatory and business aspects fit together with the technology.

Standardized SDR has the potential to provide not just the needed flexibility, it will also support the evolutionary path that we believe is necessary to follow. Open software and hardware architectures are common building blocks for dynamic spectrum access and heterogeneous/ambient network access. New products, systems and services may be offered with short time to market.

Here we summarize the technical areas that we believe are necessary to study in future research to enable an affordable, efficient and evolutionary path towards DSA:

- Identification and system design of flexible, realistic and scaleable technical DSA system solutions (technology + regimes) based on the concepts. This must be done to be able to analyze the properties of DSA system level wise. It will also make it possible to demonstrate the DSA capabilities.

- Dynamic interference control. In a DSA context, the functions for intersystem-interference handling must be distributed among the users since it is impossible to perform the whole intersystem-interference analysis in advance as being done today. We need to develop methods and metrics for determining the influence of interference. Both the interference caused on incumbent systems on the DSA devices, but also the interference caused by DSA devices on non-DSA devices already using the spectrum. What kind of interference measurements (metrics) is convenient for instant decision making online?

- What overall system performance properties should have most influence on the final decisions in the intersystem-interference analysis given a certain convenient interference metric? Several alternative performance properties could be of interest such as QoS, reliability, capacity etc.

- What metrics are convenient in order to control that given rules/etiquette are followed by the users?

- How high degree of freedom can be given in an etiquette rule without risking interference-caused spectrum “breakdown” (anarchy) among the users?

- Flexible/adaptive waveforms may be needed to use gaps in the spectrum. How do these waveforms look like? How to define these in a technological neutral way? Can they be made rather simple or is there a need for high(er) complexity?

- Flexible terminals; Standardized SDR enhances the flexibility of DSA even further. Still there is critical RF-hardware with large demands on agility and linearity. Analyze and study methods to lower the demands on the RF-parts to make them more affordable.

- DSA using standardized SDR: Critical areas to study are system design/integration methods, cross-layer design/optimization, power efficient higher level software methods, application software, etc.

- Study standardization aspects regarding using standardized SDR. Is it critical if the standards do not involve technical neutral DSA support?

- Power consumption in DSA systems using SDR. Software defined radio promises higher flexibility and potentially lower cost devices. However the current implementation is power-demanding and thus difficult to use in battery powered terminals.

- Measuring spectrum usage. We need to find methods to measure the use of the spectrum. The data is needed to find available spectrum that can be used for communication, to avoid interfering with other devices and to allow the regulator to check that rules for usage are obeyed.

- Technical mechanisms for real time trading. To enable real time trading there is need to design the mechanisms to allow real time trading. Both the legal framework and the technical implementation must be considered.

- Hidden terminal/node and silent receiver handling. Whenever we rely on information that the terminals can measure themselves there are always problems caused by the users that cannot be detected by the measuring terminal. This tends to even more critical using distributed DSA concepts. Investigation of the possibilities to overcome the common pitfalls of already available methods for the decentralized non-cooperative case (tightly coupled to dynamic interference control). Investigation of new methods to support both cooperative as well as non-cooperative scenarios.

- Investigation of advanced detectors for energy detection of low energy signals. This should include achievable processing gain, computational requirements, implementation complexity, measurement reliability including influence of signal characteristics, propagation channel effects and antenna influence.

- Radio resource management with business side information. The traditional radio resource management research has focused on maximizing capacity. However when business agreements between actors or the self interest of the individual players are taken into account a lot of the “common sense” in radio resource has to be revised.

- How to (if it is possible?) provide a certain level of QoS in distributed DSA scenarios?

- Which rules provide good spectrum utilization in the commons case?

- Security and reliability issues. When the spectrum is opened up to more players using distributed solutions it becomes more important to know who one is communicating with. Thus the authentication and authorization issues become more important.

- Radio resource management. In general there is little research done on joint radio resource management for heterogeneous systems. Both centralized and decentralized algorithms need to be investigated.

- Non cooperative Radio Resource management. One of the main changes when introducing DSA is that the various users may not have an interest in cooperating, in fact they may compete for the same resource. Thus there are critical (and interesting) new problems related to how these users will behave if they are not controlled by a central authority.

6 Regulatory possibilities and challenges

In this chapter the different concepts for DSA systems will be assessed from a regulatory viewpoint. Furthermore, an evaluation of the potential changes that will have to be made for each concept is made, along with an assumption of the timeframe needed under the current regulatory framework to make the necessary changes.

The main rationale behind the regulatory analysis is that;

- The regulatory framework and the spectrum management regime of today are not well adapted to evolving and emerging radio communication technologies
- Advanced technical solutions can often not be introduced because of regulatory barriers and thus, possible improvements in spectrum efficiency can not be taken account of
- The main question is, how can flexibility and harmonisation be combined in the regulatory process for the benefit of spectrum users, industry, consumers and society

6.1 Regulatory obstacles

On the whole there is flexibility enough in the regulatory framework to introduce DSA-systems nationally. However, we have not seen an introduction of DSA-systems yet, mainly because of obstacles such as the fact that there are a limited number of suitable bands and that transfer of licenses have only been introduced in some markets and to a limited extent. Furthermore national border coordination is internationally regulated under the radio regulations and there is a need to harmonise the introduction DSA-systems on a wider scale.

In order to enable the introduction of DSA based systems some major and minor changes will have to be made to the regulatory framework for spectrum management.

A few of the most critical regulatory issues that are complicating the introduction of systems based on DSA principles are;

- International and national allocations are made indefinite (normally 20+ years)
    - Older “dumb” technology is protected from interference from new “smart” technology
    - Obsolete technologies are allowed to survive
    - New technology can only be introduced in available vacant bands
    - “Refarming” of frequencies is a strenuous and time consuming process
- Allocations and assignments are based on worst case interference scenarios
    - Excessive use of worst case planning has made the actual use of frequencies
    - With agile and cognitive systems, interference planning according to worst case interference scenarios, have no real meaning
- Licenses are awarded with exclusive rights

- Makes the concepts of underlays and overlays difficult
- Non interference basis is the general concept for most types of licenses

- Licenses are often limited to a system, an application or a service
    - Change of use, or flexible use is not generally possible
    - In licenses, restrictions are often found regarding standards, technology and service
    - In many cases license obligations include non-radio parameters
- Licenses are not generally seen as an asset that can be used for multiple services
- Assignment of licenses have in many cases been closely linked to political goals
    - Many assignments for mobile systems have requirements on rollout and coverage
- Assignment of spectrum is generally made under the paradigm of "spectrum scarcity"
    - The fact that many assignments have been made to a small number of exclusive users, e.g. GSM, under a strict service definition regime has resulted in a notion that the license holders can maintain that level of exclusivity in providing the type of services that the license enables
    - If change of use is introduced in a liberal way, the perceived spectrum scarcity for certain services with high demand will decrease and the scarce resource will to some extent rather be the infrastructure or the customers than spectrum as such
- One of the prevailing cornerstones of current spectrum management is that harmonisation is always the best solution
    - The notion of harmonisation as the ultimate goal is becoming increasingly challenged with the proliferation of new technology and new innovative evolutionary and revolutionary steps in the use of harmonised spectrum
    - However, there is a need for light harmonisation, or what is sometimes referred to as harmonised flexibility, to enable a mass market
- The service definition paradox, most frequency are on an international level allocated to a specific service such as fixed/mobile, broadcasting, radionavigation etc.
    - On the national level the allocation is made on a more detailed level, for example making distinctions between PMR, mobile and fixed allocations. When new agile technology that, depending on how it is used can be seen as both a mobile and a fixed solution, is introduced this leads to a situation where the national allocation tables and frameworks are more detailed than the radio systems themselves
- In radio terms the world is divided in three planning regions, in which the use of spectrum and the allocation of different services are not the same
    - The development over the last decade is pointing in the direction of mobility and global circulation of radio equipment. As a result the ITU-

region model will in the long run cause a problem to the implementation of more flexible and dynamic systems.

6.2 Regulatory aspects for the DSA concepts

When it comes to the regulatory aspects for the proposed DSA concepts it is important to realise that there are more hinders to the introduction than the pure regulatory issues. In many cases the introduction of DSA systems is hindered not only by rules and regulations, but the general policy in spectrum management and the "way things work", such as processes and guidelines that will need to be changed.

As described earlier, there are three distinct levels of the regulatory pyramid. On the global level there is the ITU[3] with the Radio Regulations and the framework of global regulations which have the status of national treaties. On regional level there are different regional organisations such as the CEPT[4] in Europe, CITEL[5] in the Americas, etc. Furthermore, in Europe the European Union has become a key player in the regional regulations in spectrum management. On national level it is the Spectrum Management Authority, SMA, which is responsible for the assignment and management of the spectrum. The national responsibility can in many cases be split between the government and a national regulator.

In this report the EU and the CEPT have been used for the regional level, and Sweden will be used for the national level. However, the evaluation is made so that it will be applicable to any region and to any national market, to the largest extent possible.

The regulatory changes that might be needed to introduce DSA-systems can be mapped into a matrix with the geographic parameter on one axis and the type of change needed on the other axis. In the matrix below some examples of changes have been described.

	Global	Regional	National
Policy	• Active phasing out of old allocations • Move away from the exclusive rights paradigm • Promote liberalisation and innovation • License exempt spectrum is effective • Study the possibility to change policy	• Promote liberalisation, innovation and technology neutrality • Developing a framework for flexibility • Move away from worst case interference scenario planning • Study the possibility to change policy proactively based on technological	• Increase focus on lowering market entry barriers • Make use of the potential flexibility under the current framework • Enable frequencies for scientific use • Study the possibility to change policy proactively based on technological development

3 The International Telecommunication Union - http://www.itu.int

4 The European Conference of Postal and Telecommunications Administrations - http://www.cept.dk

5 La Comisión Interamericana de Telecomunicaciones (The Inter-American Telecommunication Commission) - http://www.citel.oas.org

	proactively based on technological development	development	
Regulation	• Changes to the Radio Regulation	• Technology neutral recommendations and decision	• Changes to laws and regulations to introduce new interference definitions
Processes	• Speed up the WRC process	• Speed up the processes from proposal to decision	• Ex-post approval of trading • Enable quick transfers and change of use

Regarding the timeframes for changes to the regulatory framework under the current regime an indication for the different levels are:

- ITU – global allocation of spectrum 5 – 10 years
- CEPT – recommendations and decisions 1 – 3 years
- EU - harmonisation decisions 1 – 5 years
- National – change of frequency plan 0,5 – 2 years

6.3 License Tenure

Depending on the spectrum management regime the license tenure is of major importance.

Under a command and control regime the tenure gives the license holder the benefit of having the exclusive right to be one of a limited number of players that can provide a specific service in a geographical area, (e.g. a national GSM license). Under a command and control model the tenure can be relatively short, given that it is long enough for economic viability of the system, to avoid that spectrum is left unused.

In a market regime, as has been described in the concept real time spectrum exchange, the tenure is of major importance. In order to enable a transparent and viable market for spectrum the tenure for a license will have to be indefinite, or perceived as indefinite, i.e. more than 20 years. The reason is that a shorter tenure will have negative impact as to the valuation of the license and the incentive to sell underused spectrum.

Under a commons regime, e.g. the open spectrum access concept, the tenure is of less importance, however, if spectrum is assigned to commons use for a limited timeframe that timeframe will have to take into account the difficulties to refarm spectrum that is used for license exempt use.

In summary the tenure is an important factor in any spectrum management regime, and has to be considered in any design of licenses and the management of the limited resource spectrum

6.4 Tradable rights design

In order to make the described scenario (real time license exchange) a reality a large number of major changes will have to be made to the regulatory framework as it is today.

One of the major regulatory challenges on both regional and national level is to define what could be referred to as "tradable rights", i.e. define licenses to make them tradable. This may seem like a trivial task at first glance, but it is not. Many of the license conditions, rights and obligations have been designed for the specific use for which the license was intended.

Furthermore, the challenge of designing these tradable rights in a technology neutral manner to enable a wide variety of services and technologies is a major task.

6.5 Spectrum refarming

In international organisations the topic of more spectrum for license exempt use has been on the agenda for years. The only argument is how much spectrum that should be set aside for license exempt use. One of the threats of allocation spectrum for license exempt use that it is very difficult to refarm such spectrum, if the need would arise in the future.

6.6 Regulator role

The national spectrum management authority (SMA) has throughout history taken the role of managing the spectrum in the sense of assigning both exclusive and non-exclusive licenses subdividing the spectrum and coordinating international harmonisation.

With the introduction of DSA systems, e.g. secondary trading and increased flexibility in license conditions, the role of the SMA will change. Some of the mechanisms that were previously taken care of within the SMA will be left to the market. In this transition new roles will have to be taken by the SMA.

Depending on what concept for DSA that is examined the new roles will have different characteristics;

- In a license exempt scenario the role of the SMA will to some extent be to identify new spectrum for license exempt use and to police the thin rulebook. Furthermore the role will include the proactive identification of new solutions, technologies and concepts and to, in a timely manner, enable their introduction in license exempt bands
- In a market mechanism scenario the role of the SMA will be more focused on enabling the market and removing unnecessary barriers
- In a scenario that combines the different concepts as presented in this report the main role will mainly be shifted towards a more technology neutral management of spectrum, this raises the question how the interplay between legislation in competition in general and radio specific legislation will develop.

6.7 Interesting areas for further research

As has been described in this chapter the current regulatory framework is not very well adapted to evolving radio technologies, however there are initiatives underway to adapt the regulatory framework to accommodate new technologies such as DSA.

Within the regulatory arena there are a number of areas that are interesting for further research.

- Digitalisation and the introduction of intelligent equipment opens up the possibility to work the spectrum harder. In this paradigm shift there are a number of different and incompatible spectrum management regimes emerging, how shall the benefits be taken care of in order to be able to work the spectrum harder, without "picking winners" and excluding others?
    - What kind of balance between different models or concepts can we expect in the future?
    - For example what will be the balancing act between the incompatible models of command and control and commons?
    - Can spectrum once assigned to the commons model be refarmed in any way?
- What aspects of the regulatory regime should be fixed and well defined and what aspects should be flexible?
- Are there methods to achieve both increased flexibility and harmonised regulation without involving regulatory bodies on higher (slower/inflexible) levels?
- Successful design of tradable rights can potentially result in more efficient and profitable spectrum use. How shall such tradable licenses be designed to offer the most benefits to users, consumers, manufacturers etc?
- What will the role of the spectrum management authority be in a DSA environment?
- What changes are needed to adapt the current regulatory arena to the changes in technology, and on what levels are these to be made?
- Are there methods to speed up the current regulatory process towards a regime adapted to DSA, and how could the migration path look like?
- Could regulation be both flexible and globally harmonised (which may be contradictory)?
    - Harmonised flexibility vs. flexible harmonisation
    - Essential requirements vs. standards and service definitions
    - National fragmentation vs. global harmonisation
    - How autonomous can a national market be under the regional and global harmonisation umbrella
    - What are the boundaries of harmonisations
- How could unorthodox sharing models be designed on a regulatory level to achieve a higher use of the spectrum?

7 Market dimensions of DSA

7.1 Introduction

This project is based on the general assumption that a more organic access of frequencies (as opposed to large capacities at long intervals) can unleash new sources of innovation and growth otherwise not available. This assumption is based on previous theoretical and empirical work geared to explain the processes behind crucial innovations in related areas, such as the computer industry.

In this chapter we will briefly review some of the more important previous studies, and discuss why and how they might have a bearing also in the area of wireless communications. Given the complexity of the matter there will be obvious problems to pursue any stringent tests, which can be launched in order to falsify or solidly support the hypothesis. Large-scale phenomena like innovation and growth are clearly affected by a lot of other factors apart from the effects of different policies for frequency access. That said, comparisons with other countries and sectors, can at least can be able to strengthen or weaken the arguments for different frequency access policies and procedures.

7.2 Direct vs. more complex effects

7.2.1 The direct effects

The effectiveness and efficiency of frequency management can be measured on different levels. The most straightforward approach is to focus on Unused Spectrum as a problem in itself as it creates unneeded scarcity and forces new services into higher bands where building for coverage is extra costly A partial remedy is in sight with the introduction of frequency trading, but a lot remains in order to make the processes more responsive to current societal and commercial needs .An important step would be the enabling of "change of use" where alternate technologies and services could be launched - "What about the scope for more short-term flexibility?", where unused frequencies can be (more temporarily) utilized by other actors at a certain price. There are some feasible options as discussed in previous chapters of this DSA-report. But there are also some more radical and visionary approaches, like those presented by Professor Eli Noam at Columbia University [38]. According to this vision each and every packet can literally "pay its way" (like stamps) to a common pool of frequency resources.

Before looking into visions for the future, what can be learnt from the historical experiences gained within other sectors and other countries? As well from the experiences gained from the successful vs. less successful migration through the 1/2/3 "generations" of mobile communications. A clearly more complex issue as the ripple affects the society at large beyond the sector of "pure" telecommunication.

7.2.2 Possible comparisons with other sectors

What is there to be "imported" (or not) from the experiences of other sectors when it comes to swifter, and hence potentially more effective, alignment between supply and demand? There are some candidates most notably within the areas of wire-line telecommunication and electricity. Within the wire-line telecommunications sector capacity swapping (both long-term and short-term) has been common also in between otherwise competing carriers, and there are international bourses explicitly geared to match current supply and demand [39]. Within the Electricity sector there are also bourses (like Nord-El) matching supply and demand on a real-time basis over national borders [40].

How come that similar mechanisms are not present also in e.g. the Mobile Telecom Industry? There are obvious differences between sectors but also some crucial similarities. After all, the mobile carriers are already engaged in some swapping albeit only outside their home-turfs, even if they are swapping capacity rather than frequencies per se. Still, a customer from Sweden in e.g. London can auto select the best available base station irrespective of operator. Why not the same solution back home as the technical solution as well as the clearing mechanism of payments between operators seems to be already in place? There are a number of possible obstacles such as that international visitors have a marginal impact on total load whereas they pay a lot more for roaming compared to domestic users. Back home there is less to gain for the operators, as long as they have a similar customer profile and hence have to cope with the same peak hours.

7.2.3 Possible comparisons with other countries

What is there to be “imported” (or not) from the experiences in other countries? Among the candidate countries are Hong-Kong, Australia, UK, Germany and the US.

One possible comparison is Hong-Kong with respect to its policy of sequential (step-by-step) access of frequencies for 2G. In a first round only limited capacity was granted and only for a two year-period. In the second round only those who had actually invested and won customers were granted more frequencies etc. By this kind of qualification process sheer speculators were discouraged. HK did also pursue a version of its own for the 3G licensing, as the auction was not about paying any large lump sum upfront as in parts of Europe, but instead focused on the highest bid on the percentage of (actual) revenue to be paid to the Government over time. Also in this case hoarding was discouraged and barriers to entry (by any need to pay lump sums in advance) minimized.

Australia with respect to its “privatization” of the access process - within a framework set by the Regulator.

UK and Germany are often cited as warning examples with reference to the staggering amount of money paid for the licenses. The popular interpretation of “sunk cost” is that those having already paid dearly are supposed to be in a rush to invest rapidly and heavily in order to recover their money. However, even in theory quite the opposite might be rational from a “ cynical” business perspective. There is no “ First Mover Advantage” to get into 3 G from 2 G, but rather the opposite. The more of a delay the better. In the meantime the technology will be more stable and cheaper, and the need to pay for any extra subsidies of 3 G handsets vanish. In brief, those paying hefty sums for their licenses actually paid for their privilege NOT to invest “ prematurely”.

In the longer term operators might actually need also the new frequencies allocated for 3 G in Europe, but a consequence of the hoarding is that large chunks of spectrum might be left unused for quite a few years.

The US is bound to be an even more relevant reference case as it has chosen much more pragmatic policies compared to Europe. Partly because out of necessity as the frequencies originally intended for UMTS worldwide were not available. Back in history the concept of UMTS (Universal Mobile Telecom Services) was born in the era of Voice Telephony. Everyone should be able to use the same handset whether in Europe, Asia or the US working on the very same frequency. Later on multiband handsets became available, but also the perceived need to add also non-voice services under the generic label of "3G". Anyhow some operators in US, like AT&T, have (somewhat ironically) chosen to follow the supposedly "European" migration path from GSM to GRPS to EDGE. Others have based their offerings on another technical platform (CDMA) but are likewise only gradually moving from 2G to "near 3G", to full 3 G. From a marketing perspective this gradual (organic) migration path has proved to be successful also in Japan where KDDI has got ~~far~~ more customers to its "near 3G" in comparison to the dominant operator, DoCoMo which "jumpstarted" into fully fledged 3 G from its successful i-mode (2.5 G) service. In fairness, DoCoMo had actually no choice but to jump, as they didn't have the option of backwards compability with its ongoing i-mode services. They were hence bound to be a case in point of what can be labeled as " the tragedy of non-organic migration"-.DoCoMo´s previous success with i-mode has became its worst competitor of its own making .Too few of their customers have proved willing to give up what they already have, at least not unless the price tag is lowered drastically enough to compensate for the unavoidable teething problems stemming from clumsy and battery-hungry handsets, more spotty coverage etc.

European operators are luckily facing less of a drastic situation, compared to DoCoMo in Japan, as 3G handsets are backward compatible to the existing GSM networks, offering nationwide coverage in more than 100 countries. That said, the European economy at large looks bound to lose the competitive edge previously achieved by the successful deployment of GSM Asian and American companies have already taken full advantage of more pragmatic regimes, enabling more customer-oriented and organic growth.

The fact that large parts of the frequency spectrum remain mainly unused is a crucial problem in its own right. Unused spectrum is a clear challenge, and any remedy looks bound to have a positive impact on economic growth. However, there is a need to take also the more complex ("ripple") effects into account. Unused spectrum represents a loss not only to the operators, but also for the ICT-sector and the society at large. In order to assess these ripple effects the next section starts with an historical overview.

7.2.4 Possible comparisons with previous "generations"

Going back to very early developments the NMT-system (now labeled 1G) can be seen as almost handmade, developed and launched under the tight control of the then Televerket and its Nordic counterparts, which made sure that all the pieces fitted together. However, the architecture was sufficiently open to make a Go. Handsets of all makes and nationalities could be used, and they were sold by several independent retailers. (This might sound self-evident, but it is sometimes forgotten that NTT in Japan also were early out. They achieved little due to the overly closed and monopolistic policies of the NTT. On another continent AT&T and its Bell Labs had of course the technology, but it was blocked by anti-trust laws. The first cell networks come not in use in US until four years after Scandinavia and Japan. Perhaps the cake was divided in too small pieces before it was even fully baked?

Anyhow, Comviq was able to launch a US-based solution in Sweden at the same time as the NMT-network.

The GSM-system (now labeled 2G) was also tightly designed once again by Televerket and its counterparts in Europe. However GSM provided a further degree of openness thru the introduction of the SIM-card. In the area of wireless communication GSM is often quoted as a success story due to its (relatively) open architecture, enabling interaction between a great numbers of actors over national borders, also outside Europe. (Even if we tend to forget that it actually took a number of years to fully overcome a number of teething problems). In its more mature stages the industry resembled the PC- industry where open interfaces enable a high degree of cost-effective specialization and outsourcing. The classical value chain where each and every link in the whole process was closely monitored (and often produced in-house) by a few monoliths was replaced with more dynamic web "value constellations" with more free and dynamic inter-action between a host of actors. No need for each and everyone to fully comprehend the full and complex process at large. All any new actor needed to focus on was to achieve the best possible solution in between clearly defined interfaces for input vs. output. This process where success feeds further success could well have continued for yet a number of years with successive and organic deployment of upgrades like GPRS and EDGE in pace with the users demand for new services and the adjacent industries ability to deliver the new software and content required. It is a bit of irony that it has been some operators in US (rather than in Europe) that has adopted this organic step-by-step enhancement of GSM making sure that the full constellations of actors can move in concert to the tunes of actual customer demand. Other operators in US are based on another (CDMA) technology base, like the successful KDDI in Japan. The common feature, irrespective of technology base, is the careful timing of demand and supply taking all actors and contributors into account. No network upgrade until there is a secured supply of cheap enough handsets and attractive content which can motivate the customers for the next upgrade. An outside-in approach and “organic” architecture as opposed to an inside-out strategy.

It is often tempting to repeat a previous success move, so Europe choose to jump-start 3G as "a new generation" rather than consider UMTS as just and upgrade and booster to 2G like GPRS and EDGE. The previous transition to 2G from 1G went rather smoothly, so why not also the transition to 3G from 2G? There are several fundamental reasons to why the two processes are not comparable.

To start from the user’s perspective. The transition to 2G from 1G was far easier for the simple reason that only a few actually had to switch. For a clear majority of GSM-users this was their very first mobile phone, enabling a new degree of freedom compared to the fixed phone line. The difference between having a mobile vs. no mobile was pretty dramatic and positive. Also for those which actually had to switch from NMT to GSM it was pretty straightforward and only a matter of one well-known service, voice telephony. Over time GSM-services were extended to provide roaming also in countries outside Europe, and improved by gradually upgraded data communications capabilities. New features could be added, without any need to sacrifice what was already available. In brief, it was a smooth ride.

By contrast, the transition to 3 G from 2 G is bound to be an uphill battle. Many of the new features are unknown to most users, and necessitates a number of non-trivial settings and acceptance of equally unknown billing methods.(Mbytes rather than plain minutes etc). A perhaps even more crucial obstacle is that the users , at least in the short term, have to give up some advantages they already taken for granted, like convenient size and weight of the handsets, long battery life etc. Even if these obstacles might be resolved over time, the supply side does not look well prepared for any speedy solution.

From the perspective of the suppliers, they are facing a far more complex situation compared to the previous migration from 1 G to 2 G, not only because of the large number of different services to cater for. The successful breaking up of the vertical value chains requires new rounds of coordination of a highly scattered number of potential contributors, including handset and content providers etc. In the absence of any clear “channel captain” (and clear interfaces) this means time-consuming negotiations between potential partners. Who is to pay whom for what? Most of the operators are also badly equipped to handle the unavoidable outburst of questions and complaints from the users. It will no longer be a matter of providing a single and homogenous voice telephony service, where “Same Size Fits All”. The market is bound to be much more differentiated.

Professional users would ask for customized solutions to enable secure access to corporate Intra-nets. Private consumers would be more interested in the lowest possible price, and hence willing to accept “best effort”. The very concept of (any homogeneous level of) QoS is bound to be challenged, and replaced by a more pragmatic set of different trade-offs between price and performance.

Wide geographical coverage has been one of the success factors for GSM, now available in more than 150 countries, as opposed to the long splintered coverage in the US. On the other end of the scale there is also the viral spread of highly localized WiFi hotspots providing quite higher capacities at a lower price per MB. Yet another contrast is the survival of the low-speed Mobitex 20 years after it was launched by the Televerket. Still preferred by some users as it provides better coverage of the whole country than even the classical NMT. Mobitex did also serve as the launching pad for the BlackBerry service in the US, as low capacity was considered less of a problem compared to coverage.There is clearly a trade-off between coverage vs. capacity, which looks bound to be of increasing importance over time, as still other technological options become available (WiMAX, UWB etc).

Selected references to add point to this discussion can be found in Möllerryd [41]who, among other things, discusses the migration paths from 1 G to 2G in Sweden.

In Coase [25], classical study on the importance of transaction costs. Underlines the inhererent difficulties of building a new value web with a host of actors for 3 G rather than to use a more smooth transition along the existing 2 G development path.

In Christensen – one book1[42] and one classical article[43] on how performance overshooting in one aspect of technology (e.g. speed) , can open the door for other ” disruptive” technologies more adapted to present customer demand.

8 Impact on innovation and growth

8.1 Introduction

The mechanisms and technical boundaries and possibilities discussed in previous chapters will affect the Swedish market in several ways. In this chapter we try to look at the Swedish system of market players in a holistic way and wee what impact the introduction of Dynamic Spectrum Access (DSA) regimes have on innovation and growth.

The approach chosen stems from the formulated overall research question for the economical analysis in this project:

How will dynamic spectrum access affect the growth possibilities for radio-related small- and medium-sized companies?

From this general question, theoretical argumentation is used to derive four more specific proposals that can direct further study on the subject. The chapter also includes analysis based on existing empiric research and findings as well as concluding comments on concrete methodological choices for further data collection.

8.2 Theory and existing research

8.2.1 Time lags

The current spectrum access mechanisms used internationally can be roughly divided into auctions and beauty contests, with beauty contests with fees as a special case. The 2000-2001 European auctions of 3G (UMTS) mobile telecommunication licenses were some of the largest in history. These auctions cumulatively raised over $100 billion (or over 2% of GDP) in countries like U.K., Netherlands, Germany, Italy, Austria, Switzerland, Belgium, Greece and Denmark [54]. Other countries like Sweden choose to let the State evaluate what companies that could maximize benefits for society in terms of coverage and quality of service.

Much material has been published on the pros and cons of these mechanisms for spectrum access (see for example [49]; [50]). These mechanisms both, however, have in common a fairly static view upon the access.

First of all the licensing periods are extremely long – up to 20 years in most cases of UMTS-licensing in Europe (see Fig 5).

Country:	Method:	Lic. period
Denmark	Auction	20 years
Finland	Beauty contest	20 years
France	Auction	20 years
Germany	Auction	20 years
Italy	Auction	20 years
Norway	Beauty contest + fees	12 years
Spain	Beauty contest + fees	20 years

Sweden	Beauty contest	15 years
United Kingdom	Auction	20 years

Figure 5. Licensing period for UMTS-licenses in Europe. Selected countries. Source: PTS, with compilation by Thorngren & Gustafsson (2002).

The licensing period have also been extended in some countries even if the European Commission strongly discouraged it. The French and Italian regulators have extended their licence period from 15 to 20 years. A motif for an extension would be that operators could have a better chance to get back the heavy investments in 3G licences that so far have turned out to be quite unfortunate. Against this stand concerns about the competitive landscape in the Telecom industry in Europe.

On top of this license transfer and a European secondary market for spectrum is even prohibited in some countries. Traditionally the only way to exchange spectrum has been through merger or acquisition of the service licensee, or via the regulator. Licence transfer is not explicitly permitted in Austria, Belgium (ownership roved by authority), Finland, France, Germany, Luxembourg, and United Kingdom. Licence transfer is explicitly permitted in Denmark (regulator discretion), Greece (approval by regulator), Ireland (consent of regulator), Italy (only following 4 years and subject to approval), the Netherlands (ministerial consent), Portugal (authorisation of government), and Spain (after 4 years with ministerial consent). [60]

Besides a concern of the overall competitive environment in the European Telecom industry, questions can also be raised around the long-term innovativeness in this current quite rigid regime. Every industry or a sectoral innovation system includes a row of natural and sound time-lags when a new technology goes from invention to commercialization. These time lags include work on standardization, for testing the technologies in large systems and for customers to accepting the new technology. However, besides these “normal” time-lags, the involved actors (telecom operators, broadcasting companies, governmental agencies) treats one of its most important “inputs”, radio spectrum, with great protectionism including large time-lags from that spectrum is released until it can be put under control of the forces of supply and demand.

This argumentation leads to the first proposition stating that:

> Current spectrum access mechanisms result in long time lags between invention and commercialization of new radio technologies.

8.2.2 Entry barriers

"Innovation processes" is a widely used concept, not only in economic theory but also in the general policy debate. The concept is sometimes applied to the (successful) commercialization of a specific technology or even of a specific product. It is however more common to analyze innovation processes on a macro level with reference to the interlocking within a broadly defined sector or within the Society at large. Classical early examples are Erik Dahméns studies of development clusters ("utvecklingsblock") [52] not to speak of Schumpeters statements on "Constructive Destruction" [58]. More recent examples of the consequences of "Disruptive Technologies" have been published by Clayton Christenson at Harvard

Business School, focusing on the (lack of) interaction between established companies vs. newcomers [48].

VINNOVA has chosen to use a wide interpretation of the concept of "Innovation Processes", underlining the importance of a well functioning interaction between different sectors as a precondition for successful innovation – processes in a bounded system.

In VINNOVA's terminology the national context is analyzed as an Innovation System defined as:

> "Actors in research, business and government that in co-operation generate, exchange and use new technology and new knowledge in order to create sustainable growth through new products, services and processes." (www.vinnova.se, free translation from Swedish)

Schumpeter distinguishes between the invention, the innovation and the diffusion. The invention is the generation of new ideas in a society. The innovation is the development of those ideas through to the first marketing or use of the new technology. The diffusion is the later spread of this new technology across its potential market. VINNOVA's concept of Innovation Systems can be said to addresses and include all these stages. The concept is also used on different levels of aggregation, on the nation as a whole, a region or specific industrial sector.

Focus is on the *interchange* between the actors. Very few innovation activities happen in isolated settings. This interchange is illustrated as a Triple Helix where especially three types of actors must function well in order to generate growth: academic institutions, business, and the public sector (for a good review see [47]). In an efficient Innovation System the payback on investments in research and development are high. The whole system should allocate resources where they are needed best, with a minimum level of friction.

As for Information and Communication Technology (ICT), Sweden has a long track record of successful innovations and companies and this part of the economy has grown in importance. When comparing with other countries, the Swedish national innovation system has a high dependence on external markets and the large multinational companies have an unusually strong position in the economy. The academic institutions have been given broad goals including connecting companies and other actors in society.

However, VINNOVA as well as OECD is pointing out that the base for growth must be widened from a few large companies to a more diversified industrial structure. This implies a focus on the working environment for small- and medium sized companies.

Sweden officially applies the EU recommended definition of a small and medium sized enterprise (SME) as:

> "a company over 50 and under 250 employees that has a annual turnover not exceeding EUR 40 million and/or a balance-sheet valuation not exceeding EUR 27 million." (A company under 50 employees is defined as small.) [56]

Swedish industrial policies for a long time focused on large enterprises and individual sectors. In the 1970s and 1980s industry policy was used to level out unemployment or recession in certain sectors, e.g. ship building. Policies aiming at small enterprises have grown only under the last two decades [59].

Several reasons are brought up why SMEs have become a more prioritized target of industrial policy. First, SMEs are an increasingly important source for employment and economic growth not any more created by larger corporations to the same extent as before [55]. Nearly 70% of all new jobs in Sweden are created in the SME sector [56]. Productivity growth and overall economic growth in the whole OECD will continue to be strongly influenced by the dynamics of the SME sector. One driving factor for this is the increasing share of outsourcing among larger firms. So, fascination in growth of SMEs among public decision makers is based on the government's desire to promote opportunities for employment.

Second, in the context of dynamic spectrum access and introduction of new market mechanisms, the smaller enterprises' ability to utilize disruptive technologies can be as important as mere job creation for the growth of the economy (Christensen, 1997). These disruptive technologies, e.g. potentially Software Defined Radio, can in smaller firms faster become a part of the service offering and tried out on the market. High-growth SMEs are viewed as the top 5% or 10% of all growing firms. These fast growers are dominated by young firms proving exceptional performance regarding innovation. SMEs are a major source of innovation in the Swedish economy. Specific government regulations and other markets mechanisms in a sector can naturally influence the overall climate for innovation, diffusion and commercialization of technology. If new regulations or market mechanisms can change an industry sector so that more SMEs can be active, evidence speaks for that this leads to exceptional growth and employment creation [56].

Taken together, active approaches and considerations for the benefit of SME, regardless of industry, seem to be a beneficial also for the Society as a whole.

In this project the focus would be on radio-related SMEs. A working definition of these SMEs is:

> "SMEs using radio technology as a central part of their product or service development and offering."

For these SMEs the future of dynamic spectrum access raises many interesting strategic questions. These companies are all dependent on how the State and market forces handle the potential scarcity of radio spectrum. What will happen if parts of the free spectrum used by broadcasters and others should be opened in a near future? If restrictive licenses sold at auction should be relaxed? If flexible licenses would allow more spectrum to be used where demand is greatest. If radio spectrum becomes freely available to anyone who wants to use it? If well-functioning second markets for spectrum trading can be established?

The term 'entry barrier' has been used in economic theory to explain actors' behaviour on a market [45]. In a setting of spectrum management we would like to argue that at least two factors can seriously affect the possibility for new radio-related SMEs to enter the market as well as for existing ones to continue to grow.

First, the current access regime hinders the possibilities for SMEs to test new radio technologies for a certain spectrum band and then withdraw if the technology proves not to be economically feasible. In an environment where the industry bets explicitly on "technology generations" with maybe 10 year cycles – technologies that will dominate large chunks of available spectrum resources – the element of innovative playfulness and diversity of technologies will be quite low. These tendencies for rigidness are here labelled as 'long time-lags'.

Second, the spectrum resource today is not prices by the market and in many cases most probably is over-priced. Spectrum has an all-or-nothing mentality attached to it where, even if beauty contest is used, the spectrum hardly can be considered "free" because hefty obligations regarding coverage and quality of service must be fulfilled, leading to enormous investments. As have been shown the possibilities to withdraw from an spectrum investment is also minimal or even prohibited by law.

Based on this discussion the second proposition states that:

> *These time lags raise unnecessary high entry barriers for upcoming actors (in reality SME, existing and up-starting) and technologies, as well as barriers to growth for existing SMEs.*

8.2.3 Inefficiencies

A country often develops strengths based on the "natural" or historically path-dependent factors such as resources and problems encountered and solved [45]. This also goes with a specific technology or innovation [44].

On markets with less rigid spectrum access management (e.g. real time spectrum trading) there would be a higher chance of seeing competitive initiatives in the area of new radio technology, e.g. software for spectrum trading, radio technologies that fully utilizes the dynamic possibilities. This also seems to be the case when looking upon recent development in the US.

But Sweden still has a large amount of people highly trained and experienced in radio technology development. The question is whether today these people are fully using their skills in the economy.

Here could be a good place to start distinguishing further among the SME actors. The impact of the introduction of dynamic spectrum access on the SMEs would depend on what products/services they are offering, that is, what types of customers they have. Because this would affect which position on the market they have and how they can use this position to gain from DSA. Does the SME offer a service or product? An application or a new infrastructure? What is its market power for example measured in independence form a market mobile network operator.

It is also important to acknowledge that the current regime not only affect the first tier actors in a negative way, the multiplicator effect (described by Keynes and others) implies that also other parts of the economy is affected. First tier actors would include radio-related SMEs including e.g. WISPs (with radio competence) and clearing houses for roaming and billing. Then second tier actors would be software (not radio) providers, content providers, terminal providers, marketing & consultancy agencies and so on.

It is hard to measure 'competence' but one rough measure is how many people that are employed in the industry. Another measurement would be patents related to radio technologies. It is too early to jump into conclusions whether radio competence in Sweden is "walking away" or simply diffusing out into other industries due to rigid telecom policies. Further research has to look into this issue. For the moment anectodotal evidence makes us formulate the third proposition as:

> *This leads to inefficient usage of the existing competence on the Swedish market.*

8.2.4 New technology and mechanisms

Let us recapitulate the characteristics of some of the DSA concepts more thoroughly described in earlier chapters.

Shared spectrum access could be interesting because of the promising cost savings. If reality, this proposal would implicate an opening of options for spectrum usage probably leading to an increased value of the spectrum. Hopefully spectrum as a resource would be used more efficiently; however coverage may not be fulfilled for the band in question.

Real time spectrum exchange could be driven by continuing deregulation of spectrum access policies. If applied this can lead to more optimal dimensioning but then pricing must also be made flexible. Also here spectrum usage would be more efficient, but questions remain if a "perfect market" can evolve; are there enough actors and can information about pricing be made transparent enough?

Open spectrum access is backed by success stories from activity on deregulated parts of the spectrum. If reality on a larger scale this would imply much lower entry barriers for new actors. Industrial and innovation dynamics would probably increase, but question marks are raised about possible overload and variable quality of service.

License exempt operation (Ref. Case) is driven by large hardware manufacturers with enough market power. This proposal gives incentive for important new promising applications (e.g. in logistics and telematics), but there is a risk to miss the target if standardizing focuses on specific technology and not function.

Compared with *traditional licensing* all these alternative proposals for spectrum access could lead to lowered entry barriers for newcomers, faster implementation of new technologies and positive indirect effects on the innovation system, possibly with the loss of controlled high coverage.

Some system proposals encourage innovative activities while some provides more incentives for coverage. Using combinations of the system proposals presented could be an attractive way to move forward.

The fourth proposal states that:

> *A regulatory regime permitting a dynamic spectrum access regime with applied technologies like multi/broadband radio, software-defined radio, smart antennas, electronic secondary market places for spectrum etc could lower the entry barriers for newcomers and have positive implications for the innovation and growth.*

8.2.5 Summary

This chapter have touched upon some observations around spectrum access linked to possible economical impact on the telecom sector innovation system and existing theory. Key concepts are time-lags, entry barriers, inefficient usage of competence and innovation & growth. This discussion has led down to four propositions, or hypotheses, that should be elaborated and tested in further study. Focus has been on the key actors of radio-related SMEs.

The four propositions are:

I. Current spectrum access mechanisms result in long time lags between invention and commercialization of new radio technologies.

II. These time lags raise unnecessary high entry barriers for upcoming actors (in reality SME, existing and up-starting) and technologies, as well as barriers to growth for existing SMEs.

III. This leads to inefficient usage of the existing competence on the Swedish market.

IV. A regulatory regime permitting a dynamic spectrum access regime with applied technologies like multi/broadband radio, software-defined radio, smart antennas, electronic secondary market places for spectrum etc could lower the entry barriers for newcomers and have positive implications for the innovation and growth.

In the following section recommendations on methodology in order to address these proposals are discussed.

8.3 Discussion on further research and methodology

First some words of caution. It can easily be argued that the long row of complex factors that affect competitiveness, success and growth of SMEs makes it very hard to isolate certain individual factors and claim causality. The factors are both based on situation and context. For example the specific context of a market, with governmental support of SMEs, access to financial support through venture capitalists and so on. The specific situation could be a release of a natural resource like radio spectrum or any other major business opportunity that would change the business opportunities.

We can also divide these factors into internal and external factors. Internal factors can be owner-management problems and financial management of assets. External factors are state of demand of the products/services the SME are selling, as well as governmental support and tax system, employment, and competition. In this project the external factors like regulation have been the centre of attention, but we cannot forget the internal managerial factors, because they can drastically affect the business of the SME.

So, although a multitude of factors are hypothesized to impact business success, there is no consistent pattern to the characteristics of what makes SME grow succeed in an industry [57][53]. The chance of finding causal relationships between introduction of new market mechanisms for spectrum access and the growth of radio-related SMEs will be very slim on a sectorial medium level of analysis.

Having said this we are sure that the problem of assessing how a new spectrum access regime would affect the Swedish innovation system can be successful with a simultaneous top-down and bottom-up attack. A recipe for further research should include macro-economical measurements on GDP-level to show the economical effects in rough ranges, including considerations of multiplicator effects. This has been done with interesting results for other industries. These efforts should be complemented with micro-level case studies with entrepreneurs and other actors in and around the relevant SMEs. Work with the relevant cases of today includes looking on the Swedish national innovation system from the viewpoint of small- and medium- sized companies developing and selling products and services related to radio technology. Introduction of mechanisms for dynamic spectrum access is to be seen as an external variable affecting the working environment of these actors. Together we believe that this research design, with the development of a theoretical framework focusing on economic questions around spectrum as a tradable resource, would lead to fruitful results related to future innovation and growth.

Extensive data collection is outside the resource boundaries of this project phase, but some concrete suggestions for further data collection is relevant. The measurement framework presented in Table 1 is compiled from VINNOVAs work on the Swedish Innovation Systems (Vinnova, 2004:1).

Table 2: Measurement framework. Derived from Vinnova Analysis Report.2004:1

Possible factors:	Possible measurement constructs:
Innovation System Competitiveness	
Long-term economic development	GDP
Economic structure	Share of e.g. producers and consultants
International Trade	Input/output of country
Job creation	Number employed
Value-adding innovation	New innovations
New firm start-ups	Number employed
Growth patterns in SMEs	Employment
Technology & Science Performance	
Technology patenting	Number of patents
Science productivity and quality	International benchmarking
Innovation activities & Interactions	
Government R&D investments	Absolute numbers
Business R&D investments	Absolute numbers
University R&D investments	Absolute numbers
Public-private partnerships	Absolute numbers
R&D Structures & Human resources	
Total R&D expenditures	Absolute numbers
People with higher education	Absolute numbers
Human resource mobility	Job turnover
Financing & Incentive structures	
Type of R&D financing	Shares
Venture capital & seed financing	Absolute numbers
Taxes & regulations	International benchmarking
Labour market incentives	International benchmarking
Innovation investment incentives	International benchmarking

In this framework the major measurement groups are Innovation System Competitiveness, Technology & Science Performance, Innovation activities & Interactions, R&D Structures & Human resources and Financing & Incentive structures. We believe that this framework should be used as a starting ground from where measurements of the impact of dynamic spectrum access regime should be launched.

As seen in the possible measurement construct in Table 1 international benchmarking would be an important ingredient. There are several specific country cases with more dynamic spectrum policies that should be used as reference cases. Hong Kong, USA, Australia and New Zealand are possible candidates especially interesting due to partially more market-oriented approaches.

Figure 1 Method demonstration with framework compiled from Vinnova Analysis Report.2004:1

In Figure 2 a graphic demonstration of how results from such an analysis could look like. The DSA concepts are there compared to the reference case of today's traditional licensing. Every DSA concept receives a unique profile based on measurements and estimations where measurements are not viable.

9 Issues for further research

In the previous sections, we have identified a number of research problems and outlined important areas that need to be further researched to enable the introduction of DSA concepts and technologies. Based mainly on the urgency of the problems and the competence in the project team, a number of these issue have been selected to be addressed in phase two of the project, while other areas are either deemed to be less urgent or fall outside the competence area of the team and are thus not within of the scope of the project. Yet other areas are already adequately researched in other projects and other contexts.

The selected focal points for further research are

- *Spectrum management regimes*
  Here the work will consist of developing some concrete system proposal, i.e. combinations of technologies and policies, that allow a more detailed study. The current concepts are considered to be baseline proposals to be further developed but also completely new concepts are not precluded. Another important task is the systematic analysis and identification of bands where new spectrum management regimes can be used. Also migration aspects when moving from traditional spectrum management to DSA systems need to be investigated carefully.
- *Resource management issues*
  In this area, a number of interesting questions are selected, some which are of more fundamental character. One of these more fundamental issues is non-cooperative radio resource management for flexible terminals and in systems where users and network providers compete for the same spectrum and have selfish objectives. Such settings may involve both more centralized as well as distributed solutions. Various business agreements between actors may also distort the picture. Applications of game theory have shown promise in analyzing these problems. Another fundamental issue is the issue of distributed dynamic interference control. Methods and metrics for determining the influence of interference need to be investigated to assess both the interference caused on incumbent systems on the DSA devices, but also the interference caused by DSA devices on non-DSA devices already using the spectrum.
- *Spectrum trading mechanisms*
  In this research, secondary trading of licenses and spectrum access rights are investigated closer. In particular the feasibility, the mechanisms and the technologies for real-time spectrum trading are interesting subjects. Also the notion of "interference rights", i.e. buying a right to spread interference in a certain band and location is of great interest.
- Impact on the innovation system
  This involves both more general effects as well as a more specific look at the Swedish scene.

10 Summary

The first phase of the project had the aim to provide a qualitative assessment of the potential benefits of dynamic spectrum access regimes. The analysis in the report and other studies in the area, indeed indicate there is a potential to both lower the entry thresholds for new actors as well as provide radical improvement to the efficiency of spectrum usage. The area is definitely of significant issues and the project should be continued studying the DSA concepts in more detail.

Further, using a systematic procedure, we have identified a number of critical areas and bottleneck problems where more research is needed to achieve these benefits. As "side effect" in this procedure, a number of novel and interesting spectrum management concepts were derived, e.g. the "real-time spectrum trading" and "use rights" concepts. Out of this gross list of interest problems, a number of highly important problems were selected, matching the competence of the project team. These problems are proposed to be the focus of the next phase in the project.

Finally, the report provides an overview of the most important ongoing research and policy-making activities in the DSA-area.

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12 Appendix A - Full scenario space analysis

12.1 Transferable spectrum

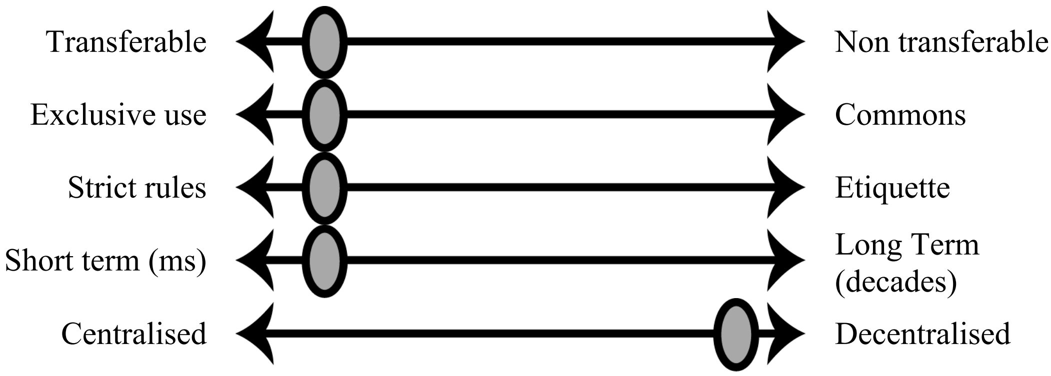
12.1.1 0. Frequency as property – Real-time license exchange

In this system concept conventional exclusive licenses are allocated by the regulator (e.g. in a license auction). The licenses are constrained to a specific service and can be constrained in time. The licenses thus acquired can be resold fast by means of electronic trading mechanisms through the regulator or some central "license exchange" actor or mechanism basis like property without intervention by the regulator.

(Research) problems: Auctions, pricing of spectrum (Economical issues) Frequency adaptive systems, can change operating frequency on a hourly or daily basis.

Example: Telia rents 3G spectrum to 3 during busy hour (on central exchange)…

12.1.2 1. Frequency as property – Real-time license trading



In this system concept conventional exclusive licenses are allocated by the regulator (e.g. in a license auction). The licenses are constrained to a specific service. The licenses thus acquired can be resold fast by means of electronic trading mechanisms on a bilateral basis like property without intervention by the regulator.

Will probably occur anyway. Only operators involved…

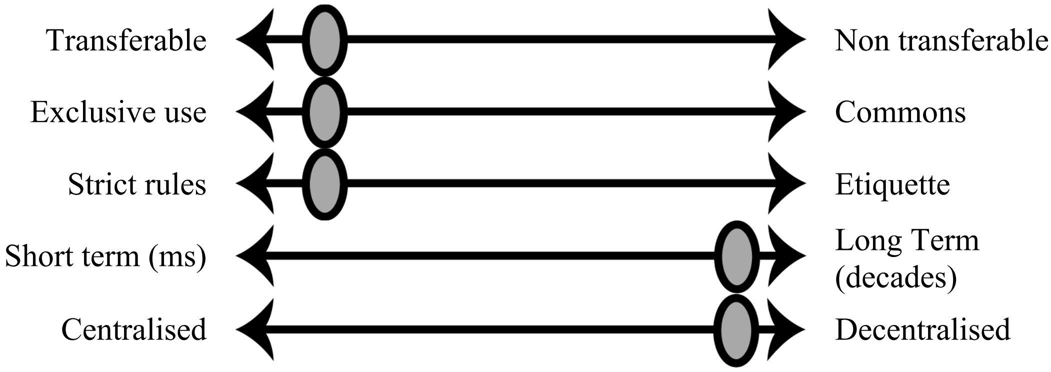
(Research) problems: Auctions, pricing of spectrum (Economical issues) Frequency adaptive systems, can change operating frequency on a daily, weekly basis

12.1.3 2. Frequency as property – License exchange

In this system concept conventional exclusive licenses are allocated by the regulator (e.g. in a license auction). The licenses are constrained to a specific service and can be constrained in time. The licenses thus acquired can be resold by means of conventional trading mechanisms through the regulator or some central exchange mechanism basis like property without intervention by the regulator.

(Research) problems: Auctions, pricing of spectrum (Economical issues) This is ongoing… E.g. Orange moving license to Svenska UMTS nät?

12.1.4 3. Frequency as property – License auction

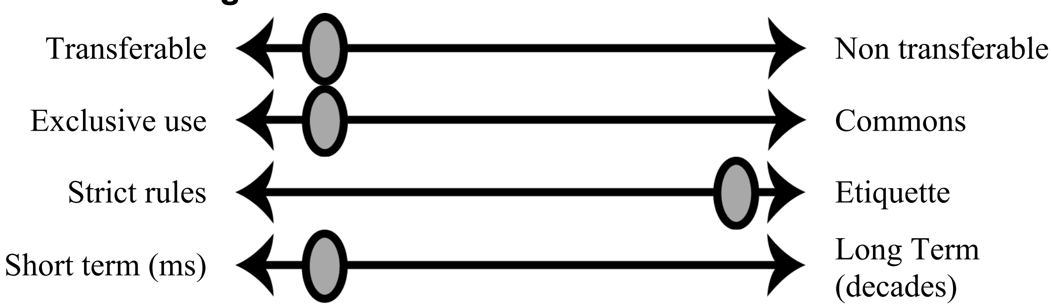


In this system concept conventional exclusive licenses are allocated by the regulator (e.g. in a license auction). . The licenses are constrained to a specific service. The licenses thus acquired can be resold by means of conventional trading mechanisms on a bilateral basis like property without intervention by the regulator.

(Research) problems: Auctions, pricing of spectrum (Economical issues)

Examples: PCS licenses in USA, McCaw buying all licenses…

12.1.5 4. Frequency as property – Real-time spectrum exchange



In this system concept conventional exclusive licenses are allocated by the regulator (e.g. in a license auction). The spectrum usage is not constrained to a specific service but could be used in any fashion by the spectrum owner with no or within some very relaxed etiquette rules. The licenses thus acquired can be resold fast by means of electronic trading mechanisms through the regulator or some central "license exchange" actor or mechanism basis like property without intervention by the regulator.

We will probably see interference rules, but few other rules in the licenses. Exchange may be needed to simplify registering responsible.

(Research) problems: Auctions, pricing of spectrum (Economical issues) Frequency adaptive systems, can change operating frequency on a hourly, daily basis.

12.1.6 5. Frequency as property – Real-time spectrum trading

Transferable – Non transferable

Exclusive use – Shared - Commons

Strict Rules – **Etiquette**

Short term (ms) – Long term (Decades)

Centralized – **Decentralized**

In this system concept conventional exclusive licenses are allocated by the regulator (e.g. in a license auction). The spectrum usage is not constrained to a specific service but could be used in any fashion by the spectrum owner with no or within some very relaxed etiquette rules. The licenses thus acquired can be resold fast by means of electronic trading mechanisms on a bilateral basis like property without intervention by the regulator.

Although the trading is decentralized, a central register for responsibility is probably required. (But difficult to maintain)

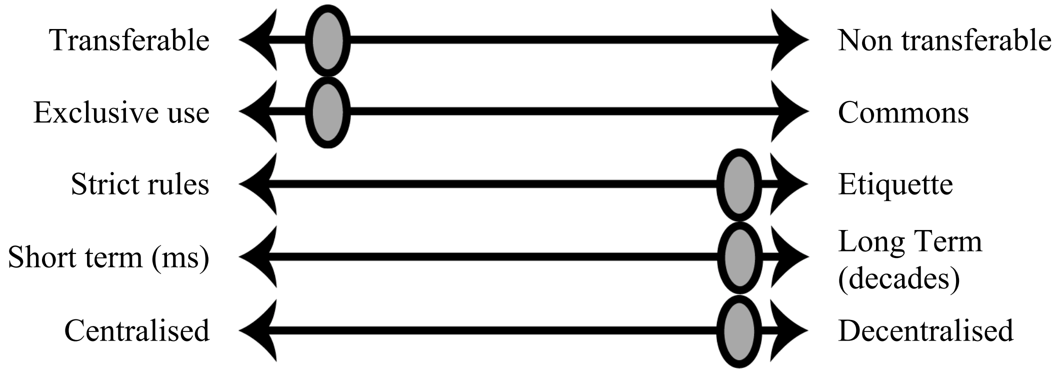
(Research) problems: Auctions, pricing of spectrum (Economical issues) Frequency adaptive systems, can change operating frequency on a daily, weekly basis

12.1.7 6. Frequency as property –Spectrum exchange

In this system concept conventional exclusive spectrum bands are allocated by the regulator (e.g, example today in auctions). The spectrum usage is not constrained to a specific service but could be used in any fashion by the spectrum owner with no or within some very relaxed etiquette rules. The spectrum thus acquired can be resold by means of conventional trading mechanisms through the regulator or some central exchange mechanism basis like property without intervention by the regulator.

(Research) problems: Auctions, pricing of spectrum (Economical issues)

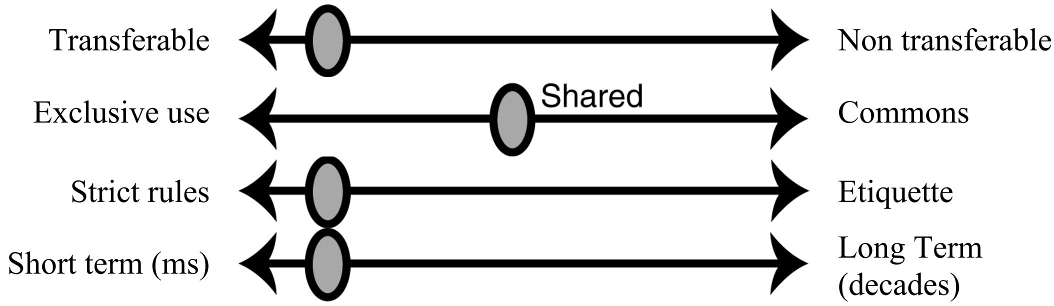
12.1.8 7. Frequency as property – Spectrum auction



In this system concept conventional exclusive spectrum bands are allocated by the regulator (e.g, example today in auctions). The spectrum usage is not constrained to a specific service but could be used in any fashion by the spectrum owner with no or within some very relaxed etiquette rules. The licenses thus acquired can be resold on a bilateral basis like property by means of conventional trading mechanisms without intervention by the regulator.

(Research) problems: Auctions, pricing of spectrum (Economical issues)

12.1.9 8. "Super radio" licensing



Licenses that require certain radio technology, and imperative spectrum sharing, are allocated by the regulator, but only for short term use. Actors may choose to sell its license. Short term use may require many fast spectrum transactions; difficult to do in a centralized manner. If "must share channel and use certain technique", then there is little degree of freedom.

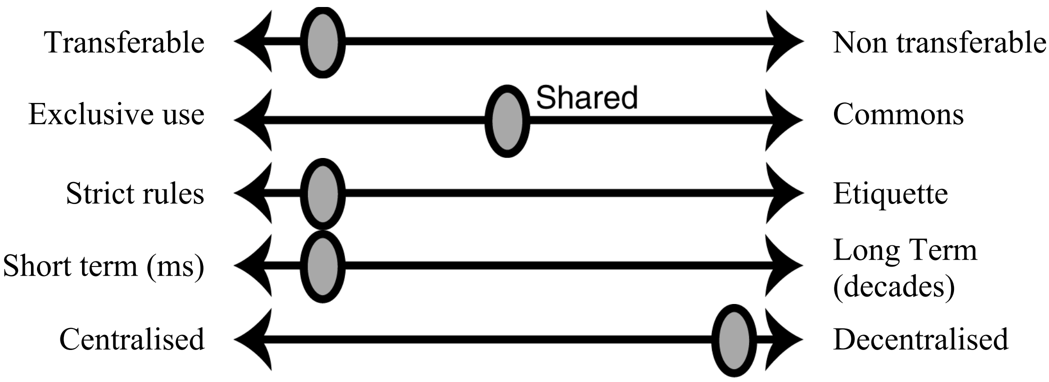
(Research) problems: Could require highly standardized very complicated radios; the super radio.

Relevance: Quite unrealistic.

Analogy: The public swimming pool; you may not use certain lanes, or misbehave.

Note: The shared concept is novel and difficult to understand.

12.1.10 9. "Super radio" licensing

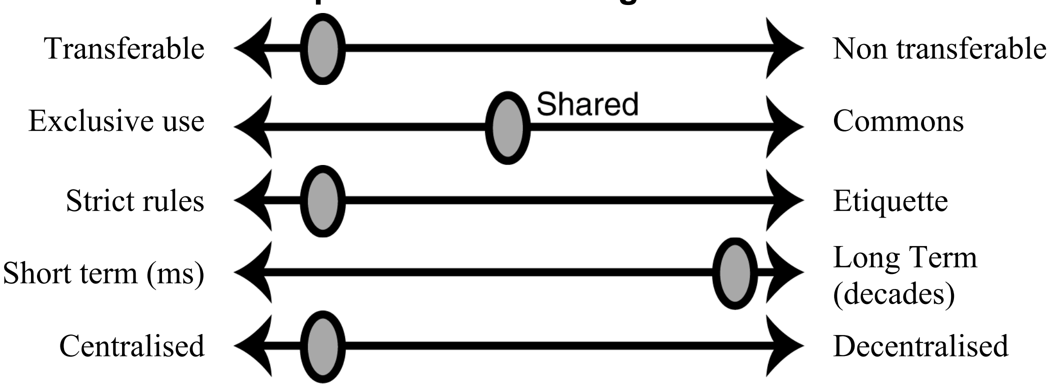


Same as above, but the actors buy/sell from each other directly. Slightly closer to reality than the example above.

(Research) problems:

Relevance: Quite unrealistic.

12.1.11 10. "Super radio" licensing



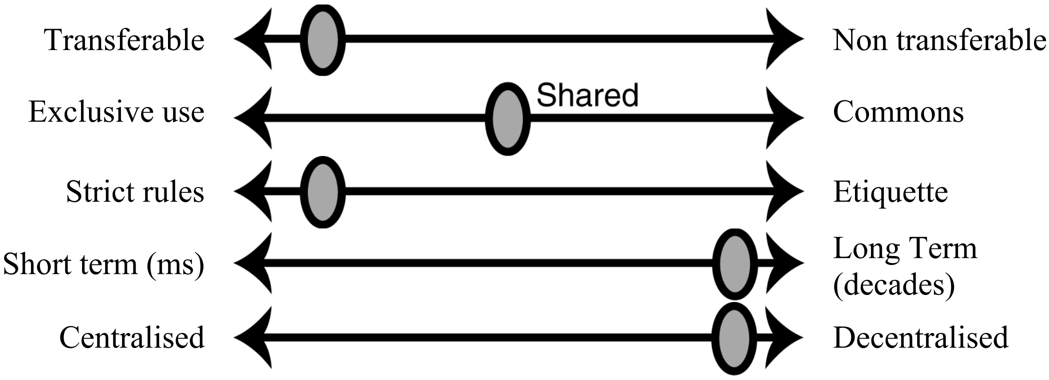
Similar to above, but licenses can be purchased/sold only in a centralized fashion.

Relevance: Quite unrealistic.

Analogy: Again the public swimming pool, but with one-year ticket.

Example: 3 taxi companies get shared access to frequencies

12.1.12 11. “Super radio” licensing

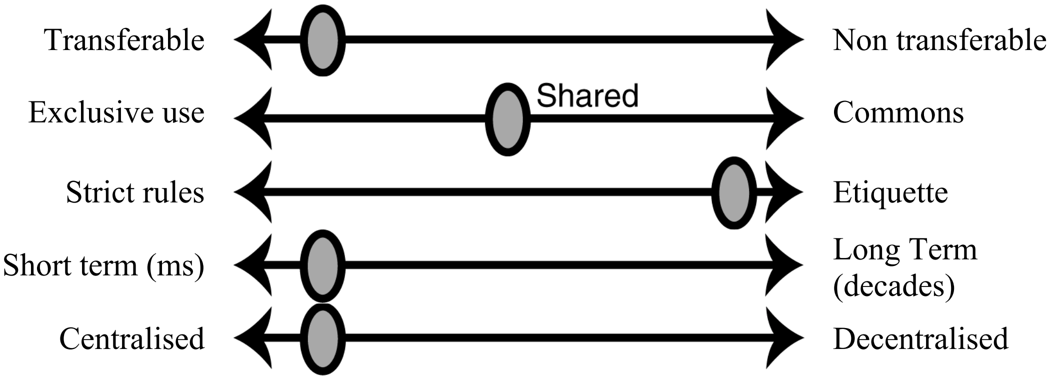


Here the license is allocated on a long term. Strict rules mean expensive system design and validation before such things can be deployed. Hinges much on that the technology will work when deployed.

(Research) problems: Still complicated radio issues. Powerful actors may buy licenses, increasing their market share leading to oligopoly, diminishing the commons aspect and reducing the spectrum efficiency.

Relevance: Quite unrealistic.

12.1.13 12. Flexible licensing



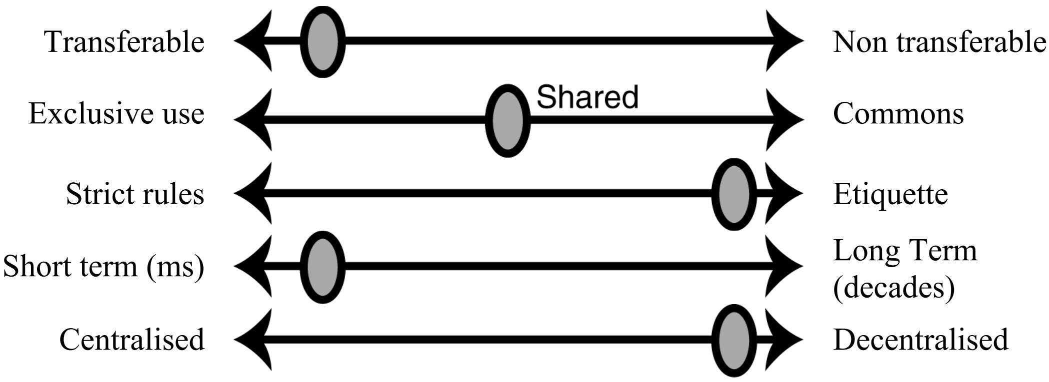
Here the same things apply, but actors may not do direct license trading.

(Research) problems: Relevance of centralized allocations for short term use.

Relevance: Possible.

Analogy: The rock concert, with no seats.

12.1.14 13. Flexible licensing

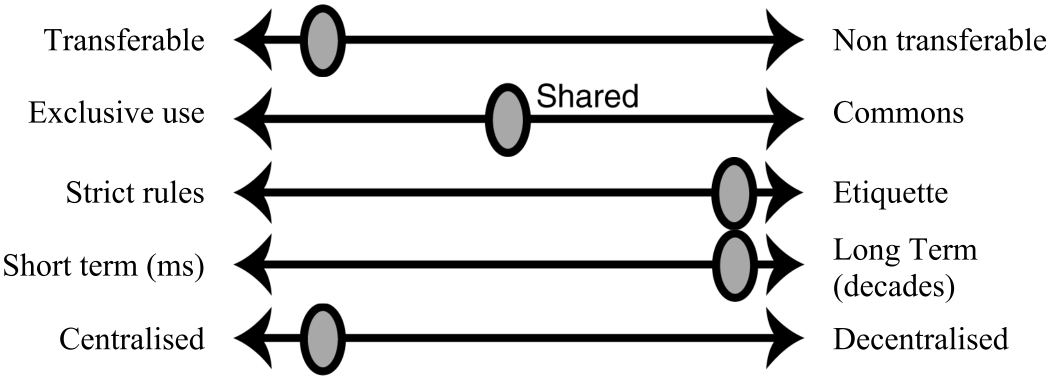


Similar to the above, but on a shorter time scale. Perhaps the most volatile and dynamic scenario.

(Research) problems: Even more functionality has to be put in the terminal if licenses are only short term.

Relevance: Possible.

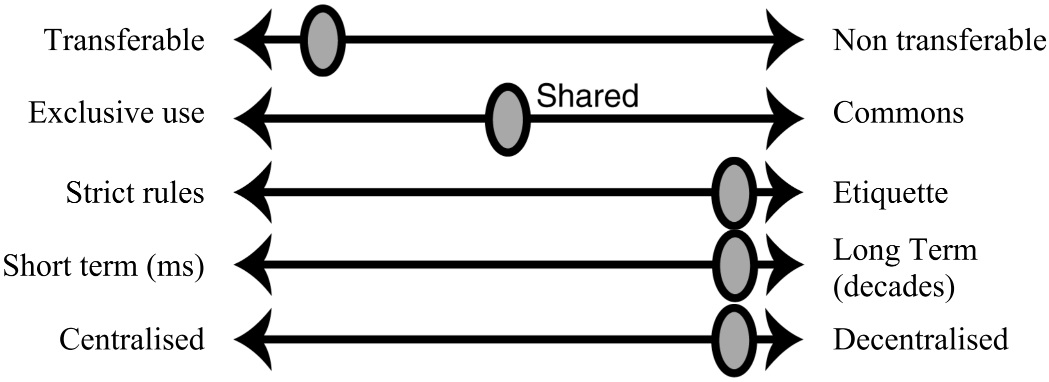
12.1.15 14. Flexible licensing



Same as above, but no direct license trading.

Relevance: Very realistic.

12.1.16 15. Flexible licensing



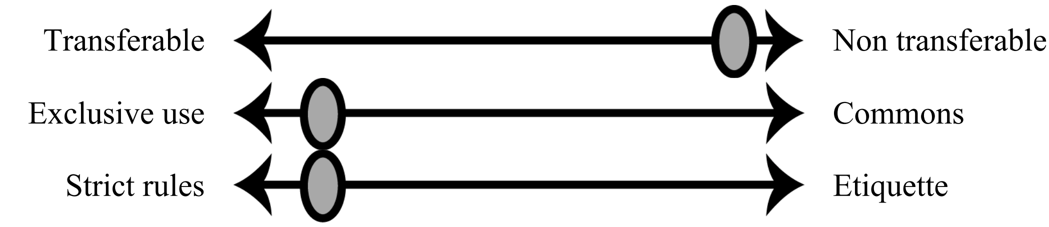
This is a set of combinations that gives very large flexibility in frequency utilization. Actors share the spectrum, which they are granted access to for a long period of time. Actors may choose to purchase/sell their license directly to others.

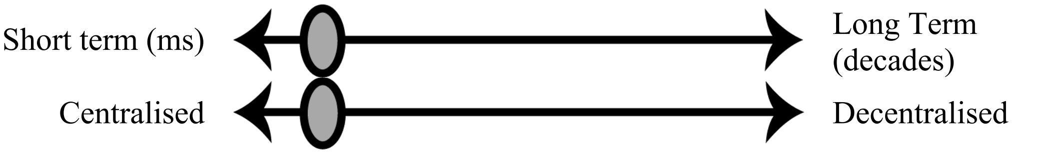
(Research) problems: The traditional issues on unlicensed operation, ad hoc networks, SDRs etc. Large span in technical solutions and innovations.

Relevance: Very realistic.

12.2 Non transferable licenses

12.2.1 16. Instant licensing

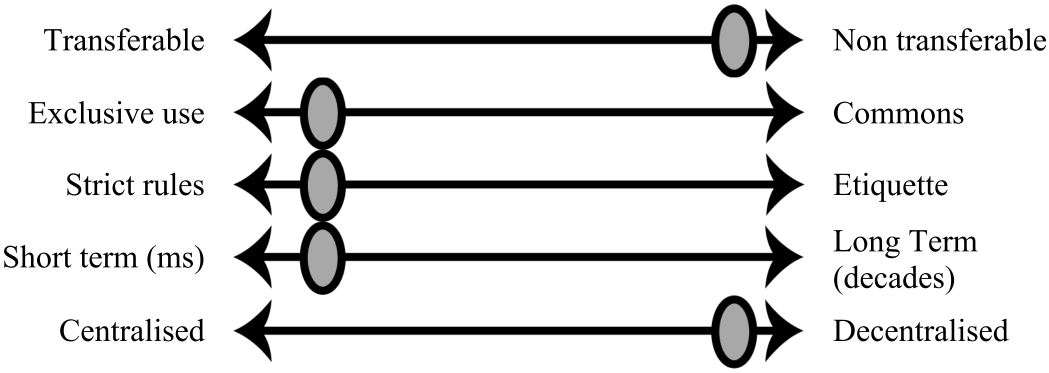




In this system concept licenses are allocated by the regulator on a short term basis. A user applies and is given a license after a short term for. This requires some kind of instant licensing procedure where the procedure is automated. The shorter the license validity the more automated the procedures have to be. The application and license granting is done centrally.

(Research) problems: Granting licensed on an automated basis. Also since the validity time of licenses are short investing in equipment may be risky.

12.2.2 17. Instant licensing



This case is similar to the previous except that the decisions are made in a decentralized manner. This can of course cause some coordination problems, but is probably not a bottleneck issue.

This is a strange combination… Decentralized and Non transferable

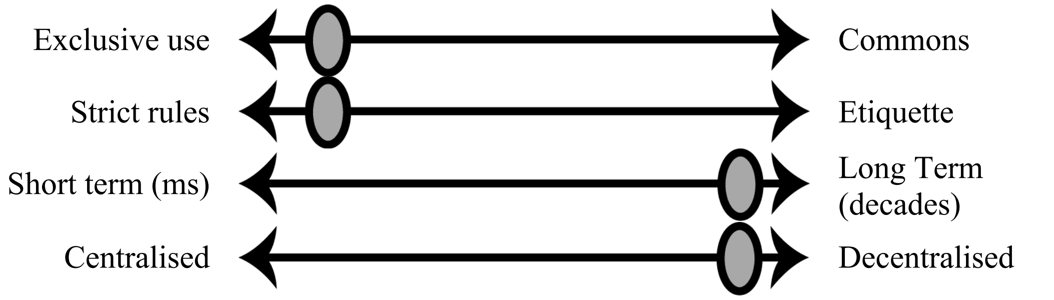
12.2.3 18. Traditional licensing

This is the traditional regime for licensing. An application is made to the regulator who grants exclusive use for an extended period of time.

(Research) problems: The problem is that spectrum is underutilized…

Relevance: Reference case.

12.2.4 19. Traditional licensing



This is similar to the previous case, but the decisions are made in a distributed manner. This can cause coordination problems. HF licensing today for example is one case where the distributed decision-making causes problems.

With decentralized we mean sublicensing, e.g. PTS delegates partial licensing rights.

12.2.5 20. Licensed anarchy

In this case the permit to use spectrum is granted to someone for a short time. Again this could require some kind of instant licenses. There are similar licensing schemes around. One example from real life, although not purely in this corner, is where operators get a piece of spectrum to operate in (and they can select their own strategy. However the ones that do not have customers loose their license after a short time. It is the licensing authority that makes the decisions on a centralized manner.

(Research) problems: Again the possibility to make quick spectrum decisions and the economic risks with short term licenses.

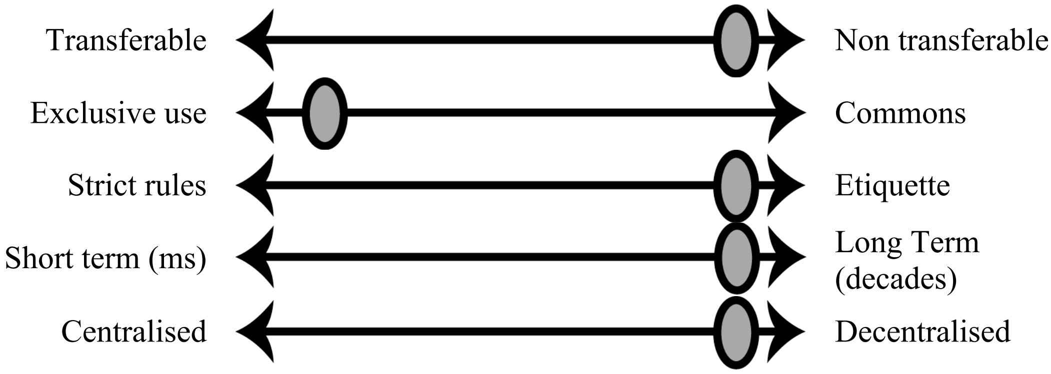
12.2.6 21. Licensed anarchy

This is similar to the previous case, but the decisions are made in a decentralized manner. Again here is the problem of coordination.

12.2.7 22. Traditional licensing

This is probably similar to spectrum policies in the US than in Europe. An operator is granted exclusive us to spectrum for quite some time and can decide to do whatever in that spectrum. Maybe there are examples of broadcasters that have reused their spectrum for other purposes.

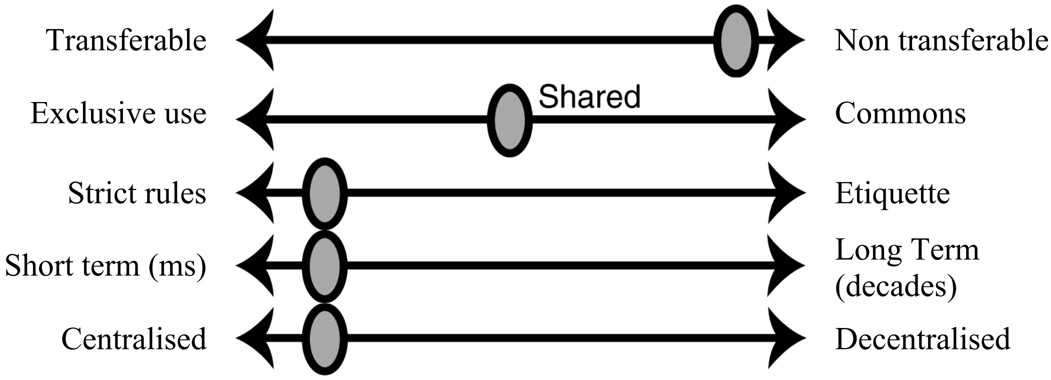
12.2.8 23. Traditional licensing



Here we have regional authorities that give out permissions to use spectrum for a long time for whatever.

Relevance: This is probably a strange case…

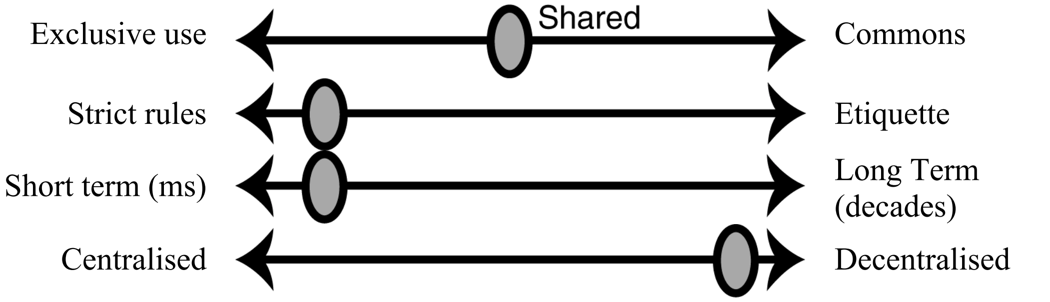
12.2.9 24. Use Rights



Some users are granted use of spectrum. But they have to share the spectrum among them. Is this the category that Ultra Wideband falls into?

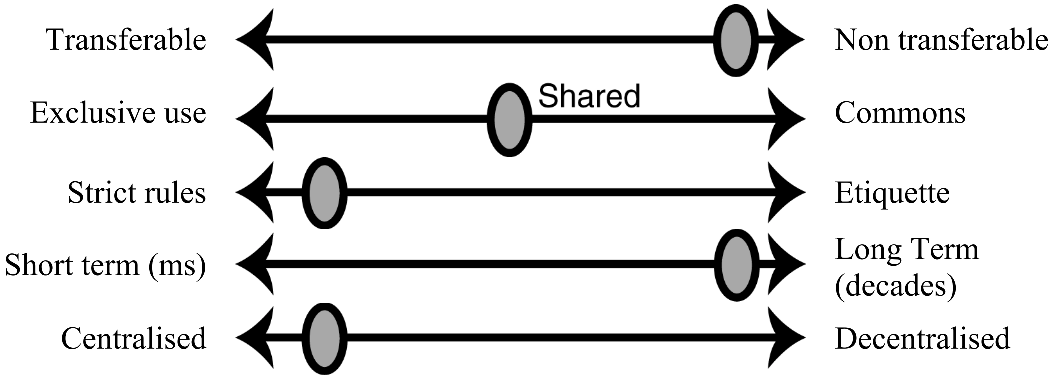
(Research) problems: Can something centralized really be so quick?

12.2.10 25. Use Rights



This case is the same as above, but with the decisions of the regulator made in a decentralized way.

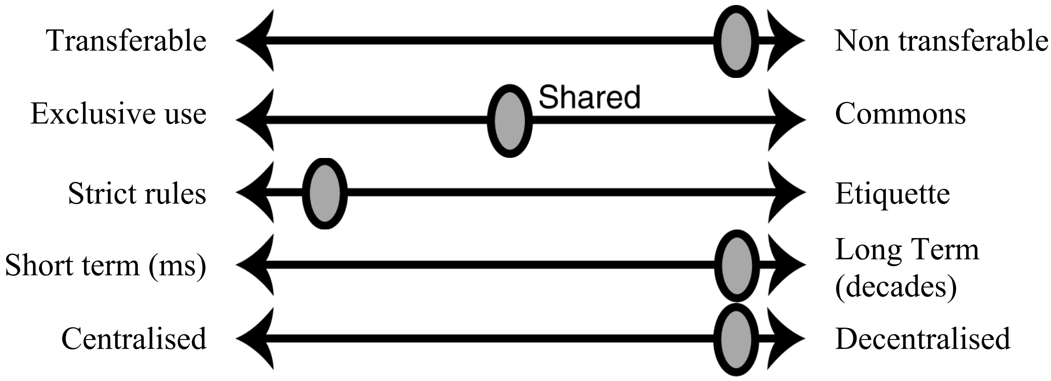
12.2.11 26. Use Rights



This is actually the case of lots of spectrum pieces today. There may be someone who is designated as primary user and others that must tolerate interference and must not interfere. This may be fairly simple to achieve since there are a number of rules that can be set. This case is similar to the case of license exempt operation. By limiting the number of users and designing the algorithms correctly it is possible to achieve good results.

(Research) problems: Algorithm design.

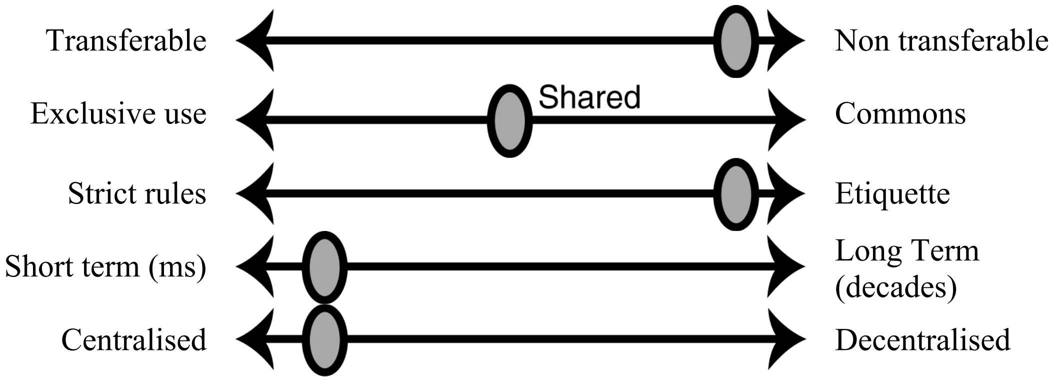
12.2.12 27. Use Rights



In this case the regulator has delegated the spectrum handling to a few actors. One possible example would be to let some broadcasters use a specific band for broadcasting, but the frequency coordination is left to the broadcasters themselves.

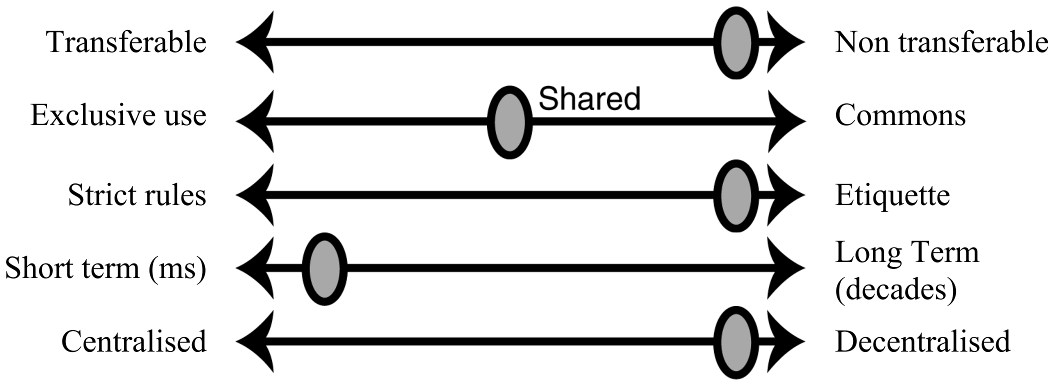
(Research) problems: Again. Cooperation among the permission holders could be interesting to study.

12.2.13 28. Use Rights



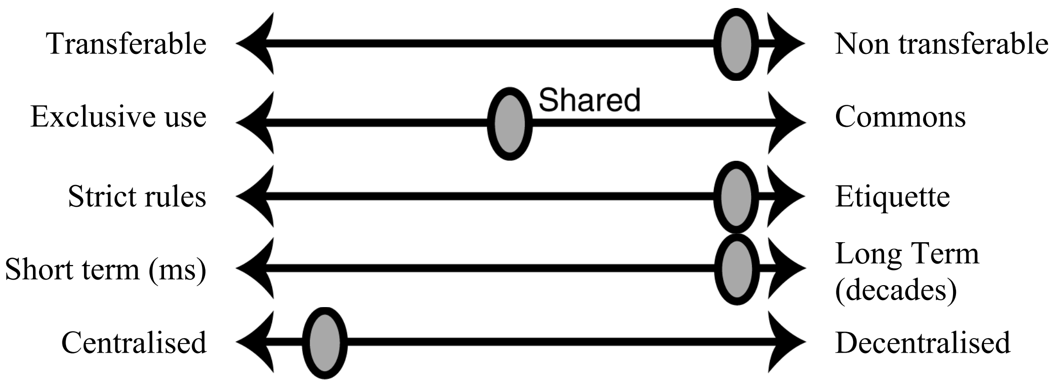
During a short time a number of users can use the spectrum. A number of actors request permission and some are granted the rights. Could there be a "black market" of spectrum where the big players make side agreements when supplying applications?

12.2.14 29. Use Rights



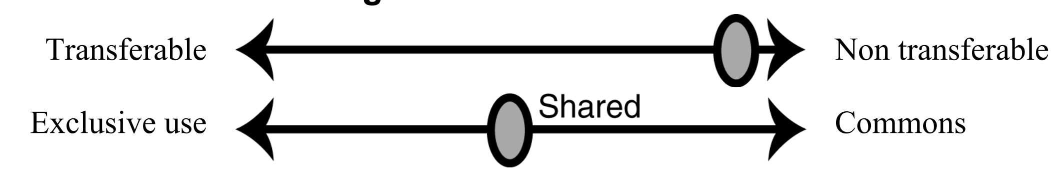
Here we again have the problem that the regulator has to deal with when he has to make distributed decisions.

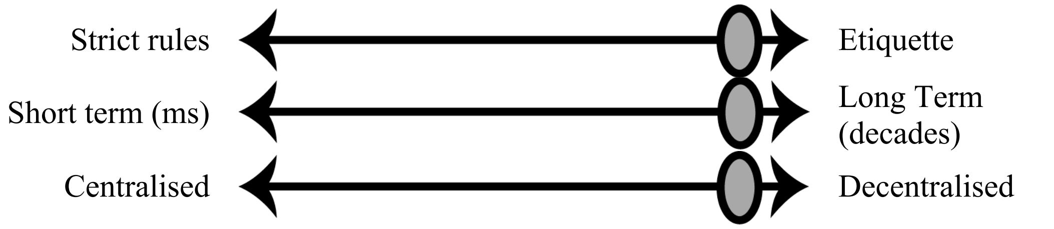
12.2.15 30. Use Rights



Here the regulator lets a few users use the spectrum for whatever purpose for a long time. Probably the license holders cooperate among them to achieve good results.

12.2.16 31. Use Rights





Here the license holders cannot agree and does whatever they think is best.

(Research) problems: How does greedy behaviour affect the system performance?

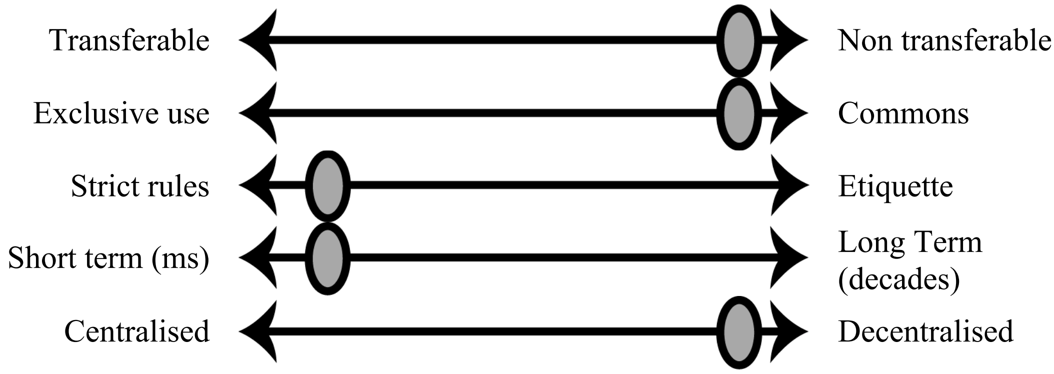
12.2.17 32. License exempt operation (light)

This is similar to what we mean with license exempt operation today. Anybody can use the spectrum, but there are a lot of rules to follow. For example the users must adhere to a specific standard. The interesting thing is that the decisions are made in a centralized manner. It is possible to imagine cases when the users voluntary agree to cooperate and chooses to cooperate through a central forum.

In the commons case the time and de-/centralized is about technology.

(Research) problems: The cooperation is interesting from a research perspective. Questions to be answered are how the various actors are going to respond to rules and conversely how rules are to be designed to achieve good cooperative results.

12.2.18 33. License exempt operation



This is what is commonly known as license exempt operation. Anybody can use the spectrum but has to follow very strict rules, e.g. comply with a standard. The rules are made to achieve good overall results.

(Research) problems: Obviously designing the rules are of interest. Essentially this is about designing algorithms that should be implemented in the radios.

Example: DECT is an example of system design in this case. Strict rules could enforce cooperation.

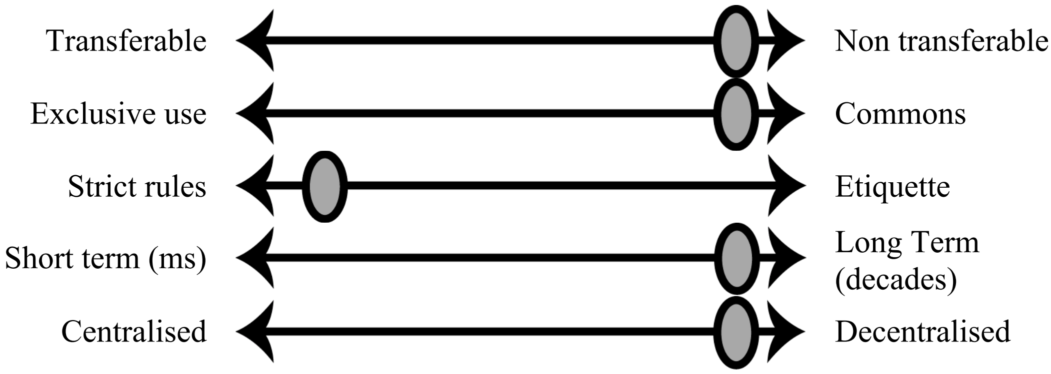
Relevance: This case could be used for illustrating European style frequency management.

12.2.19 34. License exempt

This is a very strange case. Anybody is allowed to use the spectrum for extended periods of time. The decisions are made for long times in a central manner.

Relevance: Probably a degenerate case!

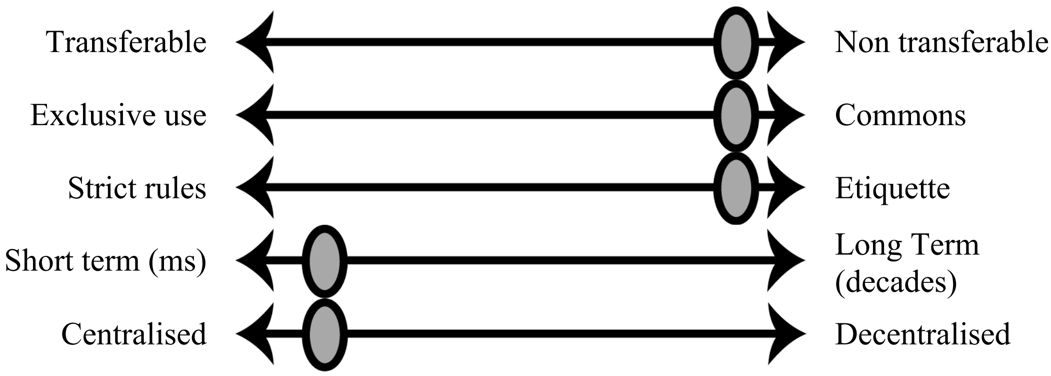
12.2.20 35. License exempt



This is also a strange case. It is like license exempt operation, but the radio resource allocation algorithms run extremely slow. It is like having a bunch of fixed frequency transmitters that should work together. Sometimes it works and sometimes it does not. If the load is not very high it does work however.

Relevance: Is it a degenerate case?

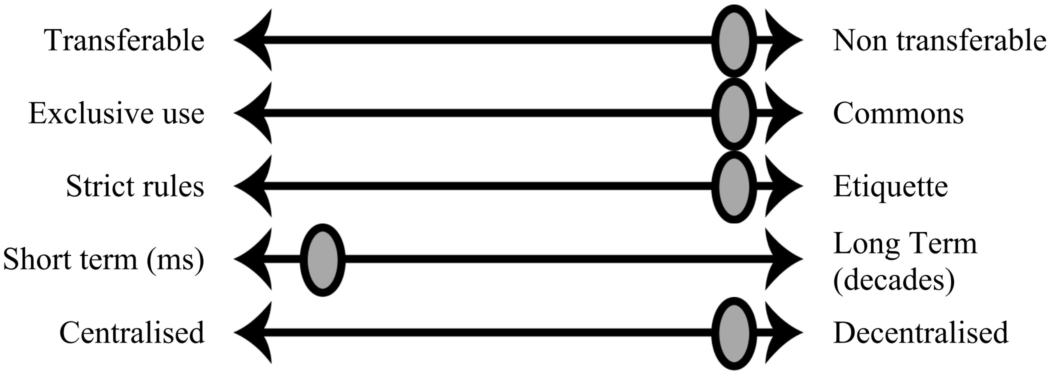
12.2.21 36. Unlicensed operation



This is similar to the unlicensed operation as of today. But here the users have agreed on cooperating in a centralized manner. This central cooperation is must be quick and thus automated. However there are probably incentives for someone to not cooperate as well.

(Research) problems: The cooperation and aspects of that. How do the actors behave if there are almost no rules to follow? Will they voluntarily cooperate?

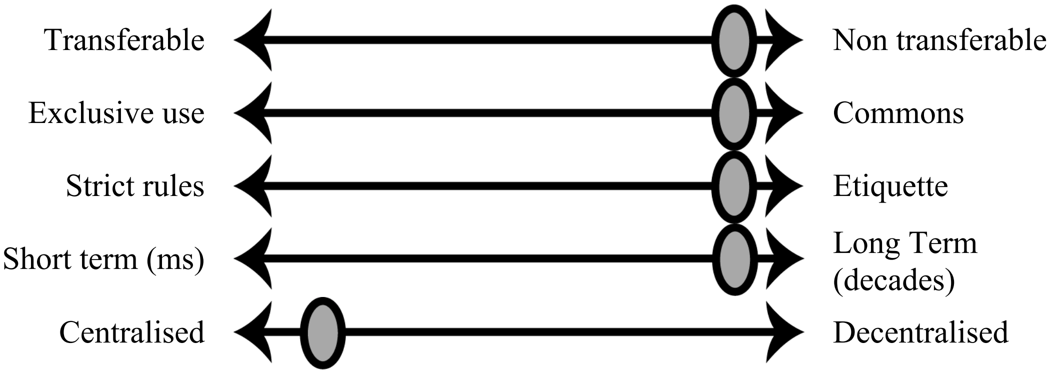
12.2.22 37. Unlicensed operation



This is what is commonly known as unlicensed operation. Anybody can use the spectrum using whatever they want to do. Since there are no rules users behave greedy and thus all user may not get as good throughput as if they had cooperated.

(Research) problems: The question is if overall good results can be achieved through rather simple rules. Also how will user behave when there are no rules? Will there be spontaneous cooperation?

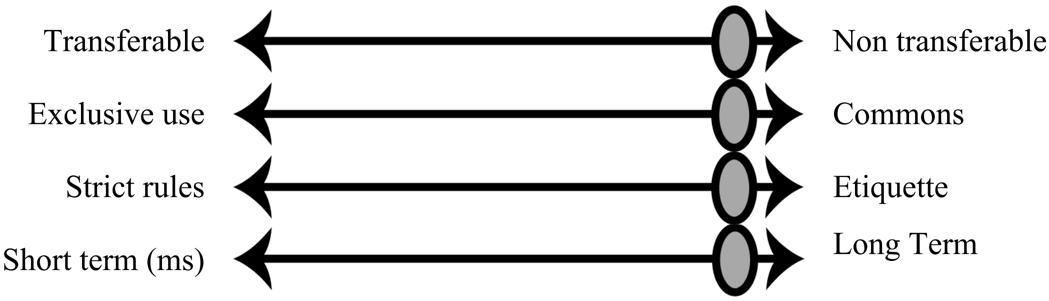
12.2.23 38. Unlicensed operation



This is a strange combination. Can there really be centralized decisions if there is a commons? The very slow spectrum decisions are also strange since there is likely to be changes that are much quicker. After all there is nobody that controls who can enter and who cannot.

Relevance: Degenerate case?

12.2.24 39. Unlicensed operation



This is not as strange as the case above, but still it is strange. Can there really be slow processes in the commons?

Relevance: Strange case.

13 Appendix B

Currently, the assignment of spectrum to different radio systems is based on fixed allocations, where the spectrum is divided into non-overlapping contiguous blocks assigned to different radio standards, separated by guard bands. The overall reason for this kind of spectrum allocation is to handle intersystem-interference in an efficient manner. Existing analysis methods for intersystem-interference control are therefore based on static scenarios both in space and time, i.e., the analyses are performed for a limited amount of interference-victim combinations. Typically, the final result is obtained by worst-case assumptions, where the simultaneous impact from different interference sources is considered. In a DSA scenario, this fixed assignment is no longer an available solution on the intersystem-interference problem why completely new methods for intersystem-interference analyses are needed. The development of such new methods is a necessary condition for interference avoidance in any DSA concept chosen, since all three concepts proposed are based on etiquette rules. However, the real-time spectrum exchange concept contains an amount of centralized functions and will therefore require less new methods for intersystem-interference control than the other proposed concepts. The open spectrum access concept will require the largest amount of new methods for intersystem-interference control.

Existing state-of-the-art analysis methods for intersystem interference in wireless services are often based on algorithms for analogue systems, modified with simplified algorithms to analyse the impact on digital communication receivers. The underlying algorithms for analogue systems require detailed information of the systems being analysed. System parameters not specified in the system specification are assumed to be determined by additional measurements. These kinds of measurements are normally very expensive to perform and, therefore, the needs for new analysis methods that do not need such detailed information have been recognized. Furthermore, existing methods are focused on the single transmission/ receiver link level. The rapid development within the area of digital communications has given an increased variety of system parameters that an analysis tool must be able to handle. The development of analysis tools for intersystem-interference analysis has not been fast enough to handle all new digital systems in another way than with simplified models. Furthermore, existing analysis methods are designed to analyse static scenarios both in space and time, i.e. the analyses are performed for a limited amount of interference-victim combinations. Typically, the final result is obtained by worst-case assumptions where the simultaneous impact from different interference sources is considered. This means a situation that is statistically unlikely to occur.

In a dynamic network scenario, the intersystem-interference analyses cannot be performed in advance for a limited number of static cases. This is because the number of potential intersystem-interference cases will be too large, almost infinite. Furthermore, the necessary intersystem-interference analyses must include the total actual interference environment, i.e., not only the known intentional/unintentional transmitters. The intersystem-interference analyses must be done online for each case. This means that all kinds of background interference will affect the result of these analyses for a certain system. Since the analyses must be done online, no detailed information, such as system specification parameters, of the actual interference signal will be available. The analyses will be based on some kind of more or less simple measured value of the total interference at the moment. Thus, reliable analysis methods based on a reduced number of interference-signal parameters must be available.

13.1 Intersystem Interference Analyses and Control

In the case of Exclusive use, existing methods for intersystem interference analyses are used. The intersystem-interference analyses and control are performed on a centralized level. Existing analysis methods are designed to analyse static scenarios both in space and time, i.e., the analyses are performed for a limited amount of interference-victim combinations. Typically the final result is obtained by worst-case assumptions where the simultaneous impact from different interference sources is considered.

In the case of *Shared spectrum,* the intersystem-interference analyses cannot be performed in advance for a limited number of static cases. This is because the number of potential intersystem-interference cases will be too large, almost infinite. Furthermore, the necessary intersystem-interference analyses must include the total actual interference environment, i.e., not only the known intentional/unintentional transmitters. The intersystem-interference analyses must be done on a decentralized level and more or less online.

13.2 Brief history

The background of intersystem interference analyses may be found in the 1920s, when broadcasting services started to reach the general public. Quite soon it became evident that control of the generation of different man-made radio disturbances was essential in order to guarantee a good quality of the new broadcasting services. However, imposing limitations on electrical equipment and household appliances could cause trading problems if different countries applied significantly different norms. This problem was soon realized on national levels, which led to the foundation of the International Special Committee on Radio Interference (C.I.S.P.R.). The International Electrotechnical Commission (IEC) and the International Telecommunication Union (ITU) were cofounders [29]. The first goal was to reach an agreement on measurement procedures. This work was carried out during the 1930s. After that, the work of developing standard emission limits could start. The first standard produced was at a national level when the BS613 (1935) concerning components for radio disturbance suppression devices was published in England. In 1937, the BS727 concerning characteristics of an apparatus for measuring of radio disturbance was published. This standard had a major impact on the standardization work within C.I.S.P.R. The C.I.S.P.R. Publication No. 1 including the characteristics of a standardized measurement receiver and certain design features was published in 1961. In the practical applications, man-made disturbance sources have up to now been divided into two major categories with its own methods and approaches; intentional and unintentional sources. Intentional sources include other transmitting equipment which typically works with some kind of modulated signals and whose disturbance typically consists of harmonics and intermodulation products. Unintentional sources are other electronic systems that are not intended to produce any radiated electromagnetic energy and whose electromagnetic energy typically consists of different kinds of electromagnetic noise such as Gaussian noise and impulse noise. Historically, the work of analyzing radio-interference problems has been carried out in three separate areas of application:

- Frequency planning
- Intersystem-Interference analyses for intentional sources.
- Intersystem-Interference analyses for unintentional sources

These areas are briefly described in the following sections below.

How is interference defined today? The Interference Protection Working Group of FCC Spectrum Policy Task Force defines four levels of interference [30].

Interference. The effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radio communication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy.

Harmful Interference. Interference which endangers the functioning of a radio navigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radio communication service operating in accordance with International Radio Regulations.

Permissible Interference. Observed or predicted *interference* which complies with quantitative interference and sharing criteria contained in International Regulations or in ITU-R Recommendations or in special agreements as provided for in these Regulations.

Accepted Interference. Interference at a higher level than defined as permissible interference and which has been agreed upon between two or more administrations without prejudice to other administrations.

These definitions of interference, which are decades old, are also found in the international radio regulations. The terms *permissible interference* and *accepted interference* are used in the international coordination of frequency assignments between administrations. Some of these definitions need to be updated to reflect the changes in system performance as they relate to system capabilities in the past and are not suitable for DSA-operation purposes.

13.3 Frequency planning

Frequency planning is today done on a centralized level by the regulation authorities at national and international levels. The methods for frequency planning are typically based on knowledge about frequency characteristics, output power, and sensitivity levels for the systems of interest.

13.4 Intersystem-Interference analyses for intentional sources

Intersystem-interference analyses for intentional sources are the activity of analyzing potential interference problems between two or more co-located intentional transmitters and receivers on a limited area of space. Typically this is carried out for different kinds of vessels such as aircraft, ships and cars. Other applications are different fixed constructions containing wireless systems. Airports and base-stations are typical examples of such fixed constructions. The intersystem-interference analyses are typically performed by the system integrator.

13.5 Intersystem-Interference analyses for unintentional sources

The disturbance from unintentional sources is regulated with standards for radiated emission limits. These standards are defined as maximum levels of the electric field strength at a certain distance from the unintentional electronic unit. In these standards a certain measurement procedure is also defined. Current measurement procedures and detectors are actually based on the work carried out in the standardization organizations during 1930 – 1939. It was during this time period the so-called quasi-peak detector was defined for standard emission measurements. Thus, present commercial emission standards are developed to protect analog communication services. The work of developing measurement procedures considering a digital radio receiver as a disturbance victim started both in CISPR and ITU-R [31] in the middle of the 1990s. The progress in this work has been slow until the behavior of the RMS detector as a possible choice for new standardized measurement was evaluated [32]. This is a very complex problem since there is a large variety of digital modulation and coding schemes to consider as the area of digital communication services undergoes a rapid development. However, to find a solution is necessary in order to protect these services against radiated electromagnetic emission.

13.6 State of the art of Intersystem Interference Analyses

Existing state-of-the-art analysis methods for intersystem interference are based on algorithms for analog systems, modified with simplified algorithms to analyze the impact on digital communication receivers. The underlying algorithms for analog systems require detailed information of the systems analyzed. System parameters not specified in the system specification are assumed to be determined by additional measurements. These kinds of measurements are normally very expensive to perform and therefore the needs for new analysis methods that do not need such detailed information have been recognized. No such methods have yet been published.

In existing algorithms, the intersystem-interference analyses of digital systems are based upon the simplification that all interference signals are treated as if they were additive white Gaussian noise (AWGN). This means that only the power, not the waveform, of the interference signal is considered to estimate the impact on a digital radio receiver. The main reason for this simplified approach is that alternative methods are much more complex and requires more powerful analysis tools and more skilled personnel to use them and interpret the results. One drawback with this simplified approach is that the waveform of an interference signal dramatically affects the impact on a digital system. Unfortunately, for some interference signals, this approach significantly underestimates the impact on a digital communication system [33]. The rapid development within the area of digital communications has given an increased variety of system parameters that an analysis tool must be able to handle.

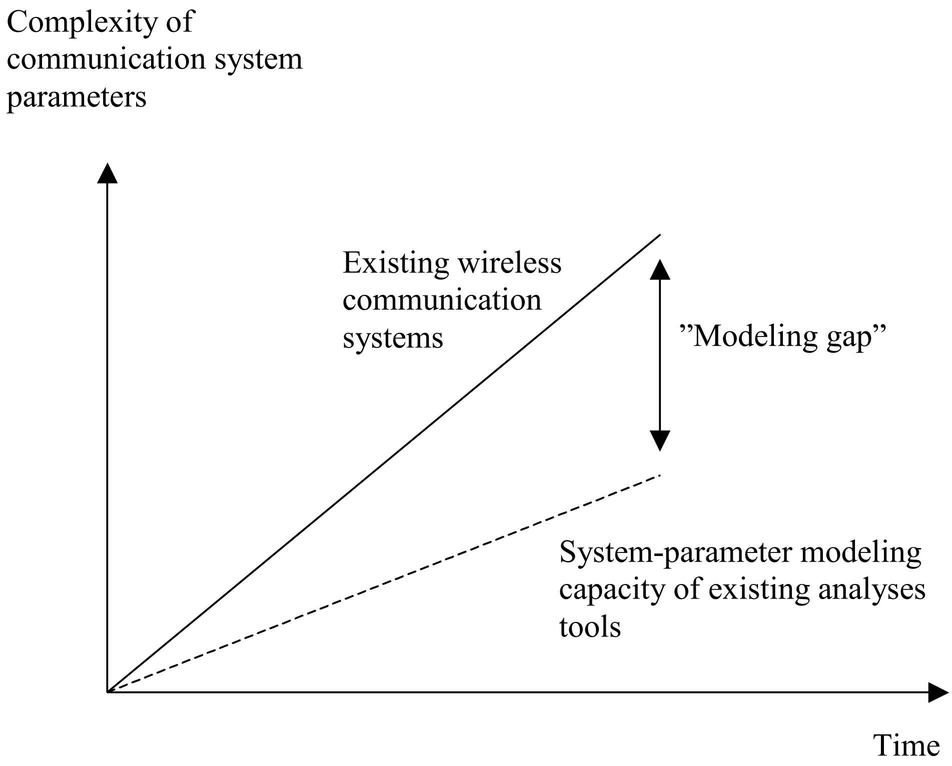


Figure 6. A schematic view showing that the capacity to handle the increasing amount of system parameters is to low in existing analysis tools for intersystem interference.

The development of analysis tools for intersystem-interference analysis has not been fast enough to handle all new digital systems in another way than with simplified models. This phenomenon is schematically illustrated in Fig. 6. Furthermore, existing analysis methods are designed to analyze static scenarios both in space and time, i.e. the analyses are performed for a limited amount of interference-victim combinations. In summary, the state of the art within intersystem interference analyses could be described as follows:

- Present methods/tools for intersystem-interference analyses are based on algorithms for analogue systems, modified with simplified algorithms to analyse the impact on digital communication receivers. These simplified methods that not consider the interference waveform properties are widely used.
- The analyses are done for static scenarios in space for a limited number of transmitters and receivers. The focus is on the transmission/receiver link levels and the final result is obtained by worst-case assumptions where the simultaneous impact from different interference sources is considered.
- In present methods the underlying models for analogue systems require detailed knowledge of system parameters.

13.7 Intrasystem Interference Analyses and Control

This area typically belongs to the area of electromagnetic compatibility (EMC). Intrasystem-interference issues are a natural part of the system development process where it must be verified that the system can work without disturbing itself. In a DSA scenario intrasystem-interference problems can occur that have not been foreseen in the development process. This is due to that a DSA scenario can generate so large amount of system-parameter combinations that is impossible to check in the system development process. Thus, the purpose of the intra-system interference analysis is to verify that the system itself will not suffer from internal interference problems caused by an unfortunate combination of system parameters.