Miia Mustonen

ANALYSIS OF RECENT SPECTRUM SHARING CONCEPTS IN POLICY MAKING
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Abstract

During the last couple of decades a lot of research efforts have been spent on developing different spectrum sharing concepts. As the traditional regulatory methods for spectrum allocation are proving inadequate in responding to a growing need for mobile spectrum in a timely manner and finding spectrum for exclusive use is getting increasingly difficult, the political atmosphere is also becoming more and more receptive to new innovative spectrum sharing concepts that increase the efficiency of spectrum use. These concepts also provide regulatory authorities an opportunity to fundamentally change the current major operator driven mobile market and thereby to allow new players and innovative services to surface. However, there is still a gap between the work done by the research community and the work of the regulatory authorities.

In this thesis, the aim is to clarify the reasons behind this gap by analysing three prevailing regulatory spectrum sharing concepts: Licensed Shared Access, the three-tier model and TV white space concept. As different stakeholders involved in spectrum sharing – the incumbent user, the entrant user and the regulatory authority – have very diverse roles in spectrum sharing, their incentives and key criteria may vary significantly. In order for a spectrum sharing concept to have a chance in a real life deployment, all these perspectives need to be carefully considered. In fact, a feasible spectrum sharing concept is a delicate balance between the viewpoints of different stakeholders, not necessarily the one offering the most efficient spectrum utilization. This thesis analyses spectrum sharing concepts from all these perspectives and as a consequence unveils the common process model for implementing a spectrum sharing concept in real life, highlighting the distinct roles of different stakeholders in its phases.

Keywords: Citizen’s Broadband Radio System, cognitive radio systems, Licensed Shared Access, spectrum regulation, spectrum sharing, TV white spaces
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Acta Univ. Oul. C 624, 2017
Oulun yliopisto, PL 8000, 90014 Oulun yliopisto

Tiivistelmä

Parin viimeisen vuosikymmenen aikana tutkimusyhteisö on kehitänyt valtavasti eri käsitteitä ja tuloksia taajuuksien yhteiskäyttöön. Matkapuhelinoperaattoreiden nopeasti kasvavan tiedonsiirtoto- ja taajuustarpeen myötä myös poliittinen ilmapiiri on muuttunut vastaanottavaisemmaksi uusille jaetuille taajuuksienkäyttömalleille, joilla voidaan sekä lisätä taajuuksien käytön tehokkuutta että mahdollistaa uusien toimijoiden ja innovatiivisten palvelujen kehitys. Taajuuksien yhteiskäyttömalleihin liittyvä tutkimustyö ei kuitenkaan usein palvele suoraan taajuusviranomaisten tarpeita.


Asiasanat: kognitiivinen radiojärjestelmä, kolmitasoinen taajuuksien yhteiskäyttömalli, lisensoi tujuuksien yhteiskäyttömalli, taajuuksien yhteiskäyttömallit, taajuus sääntely, TV kaistojen yhteiskäyttömalli
Preface

The research work reported in this thesis was started in August 2013 and was conducted at the communication systems research area of the VTT Technical Research Centre of Finland. The principal supervisor of this thesis was Professor Jari Iinatti and Dr Marja Matinmikko was the other supervisor. I would like to thank my managers at VTT, Mr Kyösti Rautiola and Dr Jussi Paakkari for providing me with stability and continuity in my research work that enabled concentration on the given topic and also for allowing me to dedicate some time to the finalization of the thesis. The research work of this thesis was conducted in the Cognitive Radio Trial (CORE)+ and CORE++ projects funded by the Finnish Funding Agency for Innovation, Tekes, during 2013-2014 and 2015-2016, respectively. Additionally, financial support received in the form of a personal grant from Riitta ja Jorma Takanen foundation, is gratefully acknowledged.

I would like to thank my supervisor Prof Jari Iinatti at the University of Oulu for his insight and support throughout the thesis work. I am deeply grateful to my other supervisor, Dr Marja Matinmikko, without her persistent encouragement and motivation I most probably would never have pursued my degree in the first place. She has provided me with not only the technical but also the mental support required to finish the work. As the manager of the CORE+ and CORE++ projects she was able create a creative and positive atmosphere and made us feel like the work we were doing was important and meaningful. That I think is quite a gift! I would also like to thank my follow-up group members Prof Marcos Katz and Dr Timo Bräysy, for their valuable guidance.

I am grateful to my great colleagues and fellow researchers who participated in writing the papers that form the basis of this thesis: Dr Marja Matinmikko, Dr Seppo Yrjölä, Mr Marko Palola, Prof Dennis Roberson, Dr Oliver Holland, Mr Teemu Rautio, Mr Kari Horneman, Mr Jan Engelberg, Dr Tao Chen, Dr Marko Höyhtyä, Docent Harri Saarnisaari, Prof Jarkko Paavola, and Mr Arto Kivinen. The work in the CORE+ and CORE++ projects has allowed me to work side by side with many extremely talented and inspiring people with diverse backgrounds on trialling, implementation, and business studies. Without this diversity and the fruitful co-operation in the project consortium, I would not have been able to gain the multidisciplinary expertise that I did on the topic. Therefore I wish to extend my gratitude to each and every member of the CORE+ and CORE++ project teams. Together and with each other’s help it was possible to achieve great things. I would also like to thank Docent Markus Mück and Prof Martin B H Weiss for reviewing
the manuscript and providing me with comments that improved the quality of the thesis. I’m also grateful to Semantix for reviewing the language.

In addition to the academic knowledge, the work on the publications for the thesis, as well as the regulatory work in the CORE+ and CORE++ projects, has required a lot of insight into the regulatory domain. I’m deeply grateful to Mr Pekka Ojanen who initially introduced me to the regulatory world back in 2006 and patiently taught me the right procedures and practices. Since then, I have received a lot of support and would specifically like to thank Mr Jan Engelberg, Mr Tom Wikström, Mr Pasi Toivonen, Mr Petri Lehikoinen, Mrs Eiman Moheyldin, Mr Karsten Buckwitz, and Mr Gernot Rausch who, among others, have supported me and provided guidance on this journey.

What kind of a life would it be, if it revolved purely around work? I would like to express my deepest gratitude to all who have enriched my life and provided me with much needed distraction from work throughout these years: my family, relatives, colleagues, and friends. Regardless of how far away you are, or how long it has been since we talked, memories of times spent together have carried me through all obstacles. My parents Sirpa and Pentti: your unconditional love, support, and encouragement throughout my whole life have made me the person I am today. My husband Giuseppe: thanks to your love and your confidence in me I have arrived to this point in my right mind. My sons Joona and Alessio: you are the core of my soul!
### Abbreviations

<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
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<tr>
<td>AI</td>
<td>Agenda Item</td>
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<td>AAS</td>
<td>Active antenna systems</td>
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<td>ASA</td>
<td>Authorized Shared Access</td>
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<td>APT</td>
<td>Asia-Pacific Telecommunity</td>
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<td>ATU</td>
<td>African Telecommunications Union</td>
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<td>BS</td>
<td>Base station</td>
</tr>
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<td>CA</td>
<td>Carrier aggregation</td>
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<td>CBRs</td>
<td>Citizen’s Broadband Radio Service</td>
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<tr>
<td>CCC</td>
<td>Cognitive control channel</td>
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<tr>
<td>CCR</td>
<td>Cognitive control radio</td>
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<tr>
<td>CEPT</td>
<td>European Conference of Postal and Telecommunications Administrations</td>
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<td>CITEL</td>
<td>Inter-American Telecommunications Commission</td>
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<tr>
<td>CoPSS</td>
<td>Co-primary spectrum sharing</td>
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<td>CORE+</td>
<td>COgnitive Radio trial Environment+ project</td>
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<tr>
<td>CORE++</td>
<td>COgnitive Radio trial Environment++ project</td>
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<tr>
<td>CPC</td>
<td>Cognitive pilot channel</td>
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<tr>
<td>CPM</td>
<td>Conference Preparatory Meeting</td>
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<tr>
<td>CRS</td>
<td>Cognitive radio system</td>
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<td>CUS</td>
<td>Collective Use of Spectrum</td>
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<tr>
<td>DCA</td>
<td>Dynamic channel allocation</td>
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<td>DSA</td>
<td>Dynamic spectrum allocation</td>
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<tr>
<td>DTT</td>
<td>Digital terrestrial television</td>
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<tr>
<td>EC</td>
<td>European Commission</td>
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<td>ECC</td>
<td>Electronic Communications Committee</td>
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<tr>
<td>eNB</td>
<td>enhanced NodeB</td>
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<tr>
<td>ESC</td>
<td>Environmental Sensing Capability</td>
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<td>EU</td>
<td>European Union</td>
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<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
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<td>FCC</td>
<td>Federal Communications Commission</td>
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<td>FDD</td>
<td>Frequency division duplexing</td>
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<td>FS</td>
<td>Fixed service</td>
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<td>FSS</td>
<td>Fixed satellite service</td>
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<td>FSU</td>
<td>Flexible spectrum use</td>
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<td>Acronym</td>
<td>Description</td>
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<tr>
<td>GAA</td>
<td>General Authorized Access</td>
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<tr>
<td>HLG</td>
<td>High Level Group</td>
</tr>
<tr>
<td>IA</td>
<td>Incumbent Access</td>
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<tr>
<td>IMT</td>
<td>International mobile telecommunications</td>
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<tr>
<td>ISM</td>
<td>Industrial, scientific, and medical</td>
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<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
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<tr>
<td>ITU-R</td>
<td>International Telecommunication Union Radiocommunication sector</td>
</tr>
<tr>
<td>LAS</td>
<td>League of Arab States</td>
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<tr>
<td>LC</td>
<td>LSA Controller</td>
</tr>
<tr>
<td>LR</td>
<td>LSA Repository</td>
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<tr>
<td>LRTC</td>
<td>Least restrictive technical conditions</td>
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<td>LSA</td>
<td>Licensed Shared Access</td>
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<tr>
<td>LSRAI</td>
<td>LSA Spectrum Resource Availability Information</td>
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<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
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<tr>
<td>MNO</td>
<td>Mobile network operator</td>
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<tr>
<td>MS</td>
<td>Mobile Service</td>
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<tr>
<td>NPRM</td>
<td>Notice of Proposed Rulemaking</td>
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<tr>
<td>NRA</td>
<td>National Regulatory Authority</td>
</tr>
<tr>
<td>NTFA</td>
<td>National Table of Frequency Allocations</td>
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<tr>
<td>OAM</td>
<td>Operations, administration and management</td>
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<tr>
<td>PAL</td>
<td>Priority Access License</td>
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<tr>
<td>PCAST</td>
<td>President's Council of Advisors on Science and Technology</td>
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<td>PMSE</td>
<td>Programme Making and Special Events</td>
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<tr>
<td>QoS</td>
<td>Quality of service</td>
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<td>RAN</td>
<td>Radio access network</td>
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<tr>
<td>RAT</td>
<td>Radio access technology</td>
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<tr>
<td>RCC</td>
<td>Regional Commonwealth in the field of Communications</td>
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<tr>
<td>RLAN</td>
<td>Radio local access network</td>
</tr>
<tr>
<td>RSPG</td>
<td>Radio Spectrum Policy Group</td>
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<td>RRS</td>
<td>Reconfigurable Radio Systems</td>
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<td>SAS</td>
<td>Spectrum Access System</td>
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<td>SDL</td>
<td>Supplemental downlink</td>
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<tr>
<td>SRD</td>
<td>Short range device</td>
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<tr>
<td>SG</td>
<td>Study Group</td>
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<tr>
<td>SON</td>
<td>Self-organizing networks</td>
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<tr>
<td>TDD</td>
<td>Time division duplexing</td>
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<tr>
<td>TG</td>
<td>Task Group</td>
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>TS</td>
<td>Technical specification</td>
</tr>
<tr>
<td>TV</td>
<td>Television</td>
</tr>
<tr>
<td>UAS</td>
<td>Unmanned Aircraft Systems</td>
</tr>
<tr>
<td>UE</td>
<td>User equipment</td>
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<tr>
<td>UHF</td>
<td>Ultra high frequency</td>
</tr>
<tr>
<td>US</td>
<td>United States</td>
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<tr>
<td>UWB</td>
<td>Ultra-wideband</td>
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<tr>
<td>WP</td>
<td>Working Party</td>
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<tr>
<td>WRC</td>
<td>World Radiocommunication Conference</td>
</tr>
<tr>
<td>WS</td>
<td>White space</td>
</tr>
<tr>
<td>WSD</td>
<td>White space device</td>
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Original publications

This thesis is based on the following publications, which are referred throughout the text by their Roman numerals:


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1 Introduction

At the same time as the mobile industry is faced with the explosion of mobile data caused by the increased use of smartphones, tablets, laptops, and other devices (Cisco 2016), the regulatory authorities are challenged to find adequate spectrum resources to react to this trend. The allocation of additional spectrum for mobile service is currently a very time consuming and complex regulatory process, and finding spectrum that can be allocated and used exclusively for mobile communications in a harmonized manner is getting increasingly difficult. Therefore, regulatory authorities are motivated to consider new approaches and tools to respond to the trend in a timely manner in order to avoid the spectrum crunch that would limit the potential economic benefit that could be achieved from the increased use of mobile data. This has led to consideration of concepts that allow spectrum to be used by multiple systems in a shared manner, instead of exclusivity.

The political pressure to implement spectrum sharing has been increasing all over the world, as high-level statements have been made on behalf of spectrum sharing. In the United States (US), the President’s council of advisors on science and technology (PCAST) already stated several years ago that the norm for spectrum use in the future should be sharing, not exclusivity (PCAST 2012). The proposal was to make additional 100-150 MHz of spectrum available for shared wireless broadband use. In Europe, the Radio Spectrum Policy Group (RSPG) of the European Commission (EC) has identified a need to develop regulatory mechanisms for spectrum sharing, both for the commercial and public sector (RSPG 2012). Additionally, the EC has highlighted the importance of investing in research to develop technologies that enable sharing of radio frequencies (EC 2012). Currently, on the verge of the 5th generation (5G) of the mobile communication systems, forward looking spectrum policies and spectrum sharing are gaining attention as the enablers of the evolution. The 5G Action plan from the EC identifies unlocking spectrum assets for 5G to support innovation and market entry 2016 identifies it as one of the key actions (EC 2016). In the opinion of the RSPG on spectrum aspects for 5G, a target was set to continue analysing spectrum related challenges, such as spectrum sharing, usage and license conditions (RSPG 2016). In the CEPT roadmap for 5G, investigations on new sharing opportunities and the challenges of new technologies are encouraged (ECC 2016).

Even if there currently seems to be a general consensus on the fact that at least some level of sharing is an inevitable part of the way that spectrum is going to be
used in the future, there is still an apparent gap between different views on how this could be implemented. The research domain plays a critical role in the innovation, testing and trials of new spectrum sharing concepts. However, criteria for a feasible spectrum sharing concept for industry or an administration vary from the academic criteria. For industry, there needs to be viable business opportunities and guaranteed spectrum access, with reasonable complexity and implementation cost. For the National Regulatory Authorities (NRAs) the main concerns on spectrum sharing are related to securing equitable access to spectrum for all stakeholders. Therefore, in order to be implemented in real-life applications, a spectrum sharing concept requires co-operation between the regulatory, industry, and research domains.

1.1 Overview of the regulatory spectrum sharing concepts

Regulatory concepts for spectrum sharing are being developed in all parts of the world. Some of these concepts are frequency specific, whereas others aim to provide a general framework that could be applied to different frequency bands. One of the pioneering concepts for frequency specific spectrum sharing has been the television (TV) white space (WS) concept, which aims at higher utilization of the ultra-high frequency (UHF) band. The concept was initially introduced in the US by the domestic regulatory authority, the Federal Communications Committee (FCC), which already defined the rules for unlicensed use of the band in 2010 (FCC 2010). Similar frameworks for TV WS usage have also been introduced in Canada (IC 2012) and Singapore (IDA 2014). In Europe, CEPT has developed guidelines for national implementation of the regulatory framework for TV WS usage (ECC 2015) and currently the regulatory authority of the UK, Ofcom, is moving forward with implementation of this framework (Ofcom 2015a). In addition to unlicensed TV WS usage, a more comprehensive review of different approaches to the use UHF in a shared manner between mobile and broadcasting services was provided in Lamy (2014). A stakeholder analysis of such shared use has been performed in Matinmikko et al. (2017) and business aspects were considered in Yrjölä et al. (2016b). In the US, the current activities on the UHF band aim to allow broadcasting companies to return their usage rights to the FCC to be auctioned in so-called incentive auctions (FCC 2012b).

Another spectrum sharing concept considered in Europe is the Licensed Shared Access (LSA) concept. The LSA concept is an extension of an Authorised Shared Access (ASA) concept, which was initially proposed by industry to European regulators as a solution to ensure a harmonized spectrum for mobile broadband in
the bands identified for mobile (ECC FM 2012). Based on this concept proposed by the industry, the European Commission (EC) developed LSA as a more general sharing framework enabling more efficient use of spectrum by allowing two or more radiocommunication systems of any services to share the same spectrum band in a controlled manner (RSPG 2011). The official definition of LSA according to the EC is: “A regulatory approach aiming to facilitate the introduction of radiocommunication systems operated by a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users. Under the Licensed Shared Access (LSA) approach, the additional users are authorised to use the spectrum (or part of the spectrum) in accordance with sharing rules included in their rights of use of spectrum, thereby allowing all the authorized users, including incumbents, to provide a certain Quality of Service (QoS)” (RSPG 2013). In practice, this means that individual LSA licences with limited duration and/or area will be issued to permit additional usage on spectrum bands that are currently being underutilized by the incumbent users.

In the US, the three-tier model to support the Citizen’s Broadband Radio Service (CBRS) was created on the basis of the PCAST proposal to create a way to enable commercial access to the federal spectrum, while protecting current and future federal usage from harmful interference (PCAST 2012). The CBRS consists of two priority levels of commercial access, licensed and unlicensed (also called opportunistic) usage. The licensed users hold short-term priority operating rights, for a specified geographic area. The licence guarantees users interference protection from opportunistic use at the lowest priority level. Opportunistic access is allowed on those spectrum bands, in those geographical areas, and time periods when they are unoccupied by higher priority users. Opportunistic users will not receive interference protection from higher priority CBRS users and are not allowed to interfere with them.

1.2 Motivation and contributions of the thesis

As the pressure from rapidly increasing mobile traffic places strains on finding additional frequency resources for mobile, frequency bands become more crowded and finding frequency bands that can be cleared for exclusive mobile use is becoming increasingly challenging. Currently, spectrum is allocated to different services by a World Radio Conference (WRC) of the International Telecommunication Union Radiocommunication sector (ITU-R). WRCs are held
every four years and a lot of studies are conducted in ITU-R groups prior to every WRC to identify the amount of spectrum required for different services and to determine compatibility of different services for shared operations. Allocating a band by ITU-R to Mobile Service (MS) means that the mobile operator can use the bands to create a hotspot/coverage around base stations (BSs) to serve users. Identification of a band to international mobile telecommunications (IMT) by ITU-R can be considered as an additional market driver for IMT technologies. However, due to technology neutrality, the identification for IMT does not change the regulatory frameworks. Despite the obvious growing trend for the use of mobile broadband in the world, the latest WRC, held in 2015, encountered difficulties in finding suitable resources for IMT identification below 6 GHz. Only two bands (1427-1518 MHz and 3.4-3.6 GHz) were identified for IMT in a globally (or nearly globally) harmonized manner. In the agenda for the WRC in 2019, there are no considerations for IMT identification to any bands below 24 GHz. Therefore, the next opportunities for identification of additional IMT spectrum below 6 GHz will be in the WRC in 2023. These long cycles of the traditional spectrum regulatory work serve as motivation for the work in this thesis on alternative solutions that can be implemented within the current frameworks.

Another challenge in the current practices is that even the identification to IMT by ITU-R alone does not yet guarantee that a band can be used by mobile in all countries, especially exclusively, since there are no bands below 6 GHz, which do not have existing usage by other services (incumbent usage). Re-farming a spectrum band is again a time consuming process and in some cases it is not even possible to find new suitable bands for existing services. For example the band 2.3-2.4 GHz was already identified to IMT globally at the WRC in 2007, however, the band is currently used in Europe for other services that vary between countries (ECC 2012). Most European countries have indicated that they want to maintain this incumbent usage for the long term. On the other hand, occupancy measurements conducted on the band (Höyhtyä et al. 2014) indicate low levels of average spectrum occupancy. The sporadic low level usage has in part motivated studies to improve the efficiency of the use of these bands through spectrum sharing. Discussion on the reliability of different metrics to calculate network load can be found in de Vries et al. (2014). In addition, a more flexible regulatory framework allowing shared use of spectrum band between different services, would remove the need for re-farming, reduce competition between services, and allow faster access to spectrum bands. In the US, the current practices of clearing and re-allocating bands have been criticized as being too expensive and time consuming.
The ultimate goal in spectrum use in the US is to protect all services only against their usage, not according to ownership (PCAST 2012).

Current practices of granting spectrum access rights with auctions on few high-priced, exclusive, long-term, and nationwide licences with coverage obligations shape the competitive field, limiting access to spectrum to major operators that have an existing customer base to guarantee return of investment. Predictions on the future data explosion together with long mobile licence duration encourage major operators to bid on spectrum resources, far beyond their current need, to safeguard their business and position in the future. Novel regulatory spectrum sharing concepts offer administrations an opportunity to fundamentally change the way that spectrum is licensed for mobile by introducing more tailored and short-term licences that are based on shared usage with other existing services. This will allow new players and new innovative services to surface to the benefit of the public.

A shift from exclusive spectrum use into shared use increases the complexity and risks to the involved stakeholders:

– the incumbent user that currently holds usage rights to the spectrum band,
– the entrant user that wishes to gain access to the band through spectrum sharing, and
– the administration that acts as a facilitator and creates the framework for shared use.

The research question that this thesis aims to answer is: What are the requirements of different stakeholder’s, and from the process point of view, that need to be fulfilled in order for a spectrum sharing concept to achieve regulatory acceptance and eventually to reach practical implementation? Due to their different roles in the process, they also have very different incentives and criteria for a spectrum sharing concept. In order for a spectrum sharing concept to have a chance in reality, all these need to be carefully considered. This thesis carefully analyses criteria from all these perspectives, in order to provide the reader with a comprehensive view on the complex surrounding that a spectrum sharing concept needs to fit into. It also provides an overview of the overall process of implementing a spectrum sharing concept into a band, highlighting different tasks in the different phases of this process. The emphasis in this thesis has been on the mobile network operator (MNO) as the entrant user and existing features of Long Term Evolution (LTE) and LTE-advanced technology, which enable spectrum sharing, are reviewed.

This thesis is based on seven original papers summarized in Section 0. The author has had the main responsibility of writing all the publications I-VII. The
original ideas for the papers came from the author and they were processed together with Dr. Matinmikko. The general process model introduced in publication I is a result of a discussion with all the authors of the paper from diverse backgrounds on the regulatory processes of different spectrum sharing concepts. Supplementary contributions of the author related to the business aspects of LSA include those in Ahokangas et al. (2016), Ahokangas et al. (2014a), Ahokangas et al. (2014b), and Ahokangas et al. (2014c) and for spectrum sharing in more general terms in Matinmikko et al. (2014). The author has also been involved in designing the practical implementation of the LSA concept and related publications (Matinmikko et al. 2015, Palola et al. 2014a, Palola et al. 2014b). In addition to academic publications, the author has been contributing and actively participating in the creation of the European regulatory framework for Licensed Shared Access for the 2.3-2.4 GHz and 3.6-3.8 GHz bands in the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT) (CEPT 2015a, CEPT 2015b, ECC 2014a, ECC 2016).

1.3 Outline of the thesis

This thesis is organized as follows. In Chapter 2, the current spectrum regulatory framework is described. In Chapter 0, an overview of the tools that can be used for enabling access to spectrum is provided. Chapter 0 describes the state-of-the-art of spectrum sharing including concepts from both the regulatory domain and research. Chapter 0 summarizes the contribution of the original papers.
2 Current spectrum regulatory framework

The current spectrum regulatory framework consists of three levels. Firstly, on an international level, the International Telecommunication Union Radiocommunication sector (ITU-R) reviews and revises Radio Regulations (RR) in the WRC every fourth year (ITU-R 2016). The RR define the allocation for frequency bands to different radiocommunication services, and related technical parameters and procedures for coordination of these services. The RR are a binding treaty that is to be obeyed by all countries for the purposes of cross-border coordination. The study cycle leading to the revision of RR is illustrated in Fig. 1. The WRC decides on the Agenda Items (AIs) for the next WRC. These AIs are attributed to different Working Parties (WPs) or Task Groups (TGs) by Study Groups (SGs). There are currently six different SGs in the ITU-R that deal with different radiocommunication services. WPs and TGs are responsible of technical studies, for example sharing and coexistence studies between different radiocommunication services, which are required to provide answers for each AI. The results of these studies are provided to the Conference Preparatory Meeting (CPM) in the form of draft CPM text. The role of the CPM is to then prepare a consolidated report on the ITU-R preparatory studies and possible solutions to the WRC AIs. The allocations in the ITU-R are done on a primary and secondary basis, where the latter ones should not cause or claim protection from harmful interference to stations of primary services to which frequencies are already assigned or to which frequencies may be assigned at a later date (ITU-R 2016). In addition to spectrum allocation, the ITU-R performs a lot of studies on emerging technologies based on study questions issued by the SGs or Radio Assembly (RA) of the ITU-R. One example of such a study question has been the ITU-R Question 241 on cognitive radio systems (CRSs) initially drafted in 2007 and last updated in 2015 (ITU-R 2015a). CRS aims to use a spectrum band on a shared basis with a higher hierarchy user, by using cognitive capabilities and therefore avoiding causing harmful interference. The studies conducted in the ITU-R in response to this question have been reported in multiple ITU-R Reports, for example (ITU-R 2009, ITU-R 2011a, ITU-R 2011b, ITU-R 2014).
Fig. 1. The process towards revision of the RR by the ITU-R.

There are six principal regional spectrum regulatory groups recognized by the ITU, namely the CEPT, the Asia-Pacific Telecommunity (APT), the Inter-American Telecommunications Commission (CITEL), the African Telecommunications Union (ATU), the Council of Arab Ministers of Telecommunication and Information represented by the Secretariat-General of the League of Arab States (LAS) and the Regional Commonwealth in the field of Communications (RCC) (ITU 2015). Regional harmonization plays a critical role in the implementation of the ITU-R spectrum allocations especially in Europe with multiple borders and small internal markets for single countries. Harmonization is required to assure industry of the continuity of spectrum availability and QoS guarantees to enable the profitability of their investment. The regional organization of the ITU in Europe, CEPT, currently has 48 administration members and it covers almost the entire geographical area of Europe. Regional authorities regarding spectrum issues are the ECC of CEPT and the European Commission (EC) (ECC & ETSI 2011). The European Telecommunications Standards Institute (ETSI) is the European standardization organization.

The relationship between European regional authorities – the EC, the ECC of CEPT and the ETSI – is illustrated in Fig. 2 (ECC & ETSI 2011). The EC submits study mandates to both the ECC of CEPT and the ETSI. The ETSI responds to these via harmonized standards. The ECC of CEPT drafts technical implementation
measures aimed at harmonizing the use of the radio spectrum and communicates these to the EC in the form of CEPT Reports and to national administrations, as well as to the ETSI, in the form of ECC Reports, ECC Decisions, and ECC Recommendations. These guidelines are implemented on a voluntary basis. However, those CEPT Reports that are adopted as EC Decisions by the EC become mandatory for all member states of the European Union (EU) (EC 2002). The cooperation agreement between the ECC of CEPT and the ETSI, the so-called Memorandum of Understanding, ensures for example that deliverables from these parties do not contradict each other and the results from sharing studies are mutually acceptable and implemented consistently by both parties.

Fig. 2. The European regulatory environment.

Influencing international decision making through active participation in the activities described above is important for NRAs. However, while the international regulatory framework provides both binding boundary conditions and non-binding guidelines regarding spectrum related issues, the NRA has the sovereign right to authorize spectrum access and use in their country’s territory, as long as binding international agreements are obeyed with regard to interference caused to services in neighbouring countries. Naturally, this also means that the final decision on the implementation of a spectrum sharing concept will be made by the NRA. Regardless of this fact, the research conducted on spectrum sharing concepts often overlooks issues regarding its applicability in national authorization procedures or requirements that the NRA have on spectrum use regarding protection, for example. The authorization process is described in Fig. 3. The National Table of Frequency
Allocations (NTFA) is a tool for national administrations to plan the allocation of frequency bands and provide visibility to policy making, in order to provide certainty for development and investment. It specifies the radio services authorized in frequency bands and the entities, which have access to them (ECC 2014a). The NTFA is influenced by the international table of frequency allocations – Article 5 of the RR (ITU-R 2016) – and harmonization measures adopted at European level. Deviation from these is possible in such way that border co-ordination between neighbouring countries is not impacted. The use of bands in other countries is also taken into account to ensure economies of scale for equipment (ITU-R 2015b).

Similarly to the international table of frequency allocations, the frequency allocation in the NTFA may be on either a secondary or primary basis. National frequency assignments allow the detailed technical management of the frequency bands required, especially for dynamic sharing and coexistence issues. The frequency assignment is an analysis of the most appropriate frequencies for radiocommunication systems and coordination with existing assignments (ITU-R 2015b). The assignment includes the definition of the least restrictive technical conditions (LRTC) for operations on the band. Frequency authorization issued by the NRA may be either with or without individual rights of use (or authorization). Operations with individual right of use or individual authorization are often referred to as licensed operations. Operations without individual rights of use are based on general authorization and are often referred to as unlicensed operations.

Individual rights of use are given for a fixed period and they include both rights and obligations (for example on coverage) for the licence holder. Mechanisms for administrations to deliver individual rights of use include first come/first served, auction, and beauty contest (RSPG 2009). As indicated by the name, first come/first served refers to a method where rights to spectrum blocks are granted in chronological order. An auction is the most commonly used method for granting access rights to mobile operators nowadays, in which bidding can be made either in an open or sealed manner (Cramton 2013). In the basic format, access rights are granted from the highest bid downwards to the next highest bids until all access rights have been granted. There are also several variants to this basic auction procedure (Jilani 2015). In a beauty contest, the access rights are awarded based on both the bidding amount and the bidders’ competence to provide services. Especially in the EU member states, there are binding regulations on the establishment of an open, transparent, and non-discriminatory authorization process. Considering a national procedure, illustrated in Fig. 3, for a mobile band as an example: a frequency allocation defines the band for mobile service; a
frequency assignment defines the LRTC for the mobile network; and the frequency authorization is the licence issued by the NRA to a specific mobile operator. The purpose of defining the LRTC is to avoid harmful interference, which is traditionally calculated based on the worst-case forecasts of interference. In research, a risk-informed interference assessment has been proposed for estimating interference between services (de Vries 2017).

In the case where no individual rights of use are given to a band by an administration, i.e. in the case of unlicensed operations, access to band is based on the compatibility studies conducted by the CEPT to determine a set of regulatory parameters to ensure the protection of radio services (ECC 2014a). Examples of this are short range devices (SRDs) and 5 GHz radio local access networks (RLANs).

Fig. 3. The national regulatory framework.
3 Spectrum sharing in research

Spectrum sharing has already been a popular research topic for several decades and during that time the research community have investigated a lot of different techniques and concepts. In spectrum sharing, two or more radio systems use the same frequency band and the concepts can be divided into horizontal and vertical spectrum sharing concepts (ITU-R 2014). In horizontal spectrum sharing, radio systems sharing the frequency band hold the same level of spectrum usage rights. In vertical spectrum sharing (in research also referred to as spectrum sharing with hierarchical access (Zhao & Sadler 2007)), new radio systems share the band with an existing radio system, which maintains higher priority access rights. New radio systems are allowed to utilize frequencies in such way that the existing spectrum users do not experience harmful interference. Firstly in this section, an overview of different concepts and their basic principles is provided. Secondly, one of the most popular concepts, cognitive radio system (CRS), is introduced. Emphasis is given to the research activities related to the CRS enabling technologies since even if the current regulatory spectrum sharing concepts do not require all the characteristics of CRS, they do utilize at least some of the enabling techniques. The development of those techniques has, to a large extent, led to the acceptance of the sharing concepts in the regulatory domain.

3.1 Research activities on spectrum sharing

In order to clarify the wide variety of different spectrum sharing concepts proposed in research, a fusion of two existing classifications from the literature is used. According to Akyildiz et al. (2008) approaches for spectrum sharing can be classified with regards to four different aspects: the architecture, spectrum allocation behaviour, spectrum access technique, and scope. The considered architecture may be either centralized or distributed. The spectrum allocation behaviour of the sharing nodes may be either cooperative or non-cooperative. These were labelled cooperation or coexistence in Peha (2009). From a regulation point of view, cooperation increases the complexity of a sharing concept and changes in technology, interference, and security may require fast reaction times (Peha 2009). In accordance with Zhao & Sadler (2007), for the division with regard to the spectrum access technique, the concepts may be further divided into dynamic exclusive, open and hierarchical access models. Dynamic exclusive access aims to enhance the use of a spectrum resource, while maintaining the exclusivity of the
usage, whereas open access refers to unlicensed access to a spectrum band, similarly to industrial, scientific, and medical (ISM) band. The hierarchical model refers to multiple priority layers in the spectrum access and it can be further divided into overlay and underlay technologies. In the overlay spectrum access, spectrum is accessed by the node of a lower priority system at a specific spectrum band, time, and geographical area with adequate separation in time, frequency, or space to the nodes of the higher priority system to avoid harmful interference. In underlay spectrum access, transmission of the lower and higher priority users may happen simultaneously at the same band and geographical area, however, transmission power of the users of a lower priority system is so low that it is considered only as noise by the users of higher priority system. The scope in Akyildiz et al. (2008) referred to a single radio access network (RAN) (intra-RAN) or between different RANs (inter-RAN) sharing. The division of spectrum sharing concepts used in this section is done in accordance with the two classifications by Akyildiz et al. (2008) and Zhao & Sadler (2007), and it is illustrated in Fig. 4.

![Classification of spectrum sharing concepts](image)

**Fig. 4. Classification of spectrum sharing concepts.**

Considering first the concepts for dynamic exclusive access, dynamic spectrum allocation (DSA) was developed to facilitate flexible co-existence between different RANs in one spectrum band (Leaves et al. 2004). The concept was based on an assumption that two RANs, having distinct traffic patterns, could lend spectrum from one another to support each other’s peak hours. In DSA, the different RANs were assumed to use different radio access technologies (RATs), whereas in flexible spectrum use (FSU) the RANs were assumed to use the same RAT (Dixit 2008). Both DSA and FSU are implemented using a centralized
architecture. Dynamic channel allocation (DCA) is an intra-RAN concept for
dynamic exclusive access (Katzela & Naghshineh 2000).

The spectrum sharing concepts proposed for open access, unlicensed or
spectrum commons give no priority to any single entity. The devices may merely
coexist, for example like WiFi devices, or the devices may actively communicate
and cooperate with each other (Peha 2009). Concepts may also be divided into fully
distributed (Naparstek & Leshem 2014) or centralized concepts. In centralized
concepts, a spectrum server (Raman et al. 2005) or a database (as is the case for
example in the IEEE 802.11af standard for TV WS usage, see Flores et al. (2013)),
is used to control the access to spectrum. Adding governance to open access
spectrum access will allow, for example, the irreversibility of open access to be
overcome (Lehr & Crowcroft 2005).

Spectrum sharing, which introduces hierarchical access to a spectrum band is
also referred to as vertical spectrum sharing (ITU-R 2014) or as primary-secondary
sharing (Peha 2009). Ultra-wideband (UWB) wireless communication is an
underlay spectrum sharing concept in which a radio uses a spread spectrum
technique and low transmit power to transmit a signal close to noise level (Yang &
Giannakis 2004). For overlay techniques the terms opportunistic access techniques
and spectrum pooling (Weiss & Jondral 2004) are also used. In a spectrum overlay
technique, a new mobile radio system with lower priority is introduced to a band
with existing licensed usage with higher priority. Within this band, a separation is
required in frequency, time, or geographical area to avoid harmful interference.
Policy options for primary and secondary users, depending on the application
requirements, have been discussed in Peha (2005). A new regulatory concept of
pluralistic licensing (Holland et al. 2012) has been proposed for awarding licenses
to primary users under the assumption that secondary spectrum access will be
allowed and interference may occur within predefined parameters and rules known
at the time of licensing. In the concept, the interference characteristics have an
effect on the licence fee. In these research activities the lower priority usage is
assumed to be purely unlicensed. One approach to allow hierarchical spectrum
usage on a licensed basis is so-called spectrum trading (Valletti 2001), also referred
to as spectrum leasing or enabling secondary spectrum markets (FCC 2004). This
refers to the right of a licence-holder to lease their licensed spectrum or parts of it,
in a defined geographical area, for a specified period of time. Including trading
rights into the new mobile licences is becoming increasingly common among
administrations. In this way, it may be possible to support more complex sharing
concepts and increase the efficiency of spectrum use; however, there are currently
no means to ensure fairness, competition, or transparency in a similar way to
is one technology that enables overlay spectrum sharing, and will be discussed in
more detail in the following subsection. One proposed concept that does not fall
within the categorization shown in Fig. 4 is the co-primary spectrum sharing
(CoPSS) (Luoto et al. 2014). CoPSS is often considered as a form of spectrum
pooling; however, instead of introducing multiple levels of hierarchy it allows
multiple mobile operators to share a spectrum band with equal rights.

As shown in Fig. 4, the regulatory spectrum sharing concepts that are analysed
in this thesis (introduced in Chapter 0) are hierarchical overlay spectrum access
concepts. In the three-tier model and in the TV WS concept, the lower priority
access may be allowed on either an unlicensed or a licensed basis, whereas in the
LSA concept the lower priority usage is only introduced on a licensed basis. A
comprehensive survey and analysis of different licensed spectrum sharing concepts
from a mobile operator perspective can be found in Tehrani et al. (2016). In each
of the spectrum sharing concepts, access to spectrum bands is controlled by a
central entity and they all enable sharing between different RANs (inter-RAN).
While the lower priority usage in both LSA and the three-tier model is non-
cooperative, in the TV WS concept the information on spectrum availability may
be passed between devices in a cooperative manner (Karimi 2015).

3.2 Research on the enabling techniques for CRS

The concept of cognitive radio was already introduced in academia in 1999 (Mitola
& Maguire 1999) and the signal-processing and communication theoretical aspects
of cognitive radio were first considered by Haykin (2005). Publication of these
landmark papers initiated a massive amount of research on the topic during the last
12 years. An indication of the research volume spent on the topic is that while the
time-span of spectrum sharing research leads back further into the past than
cognitive radio, there are around 7,000 publications in IEEEExplore on spectrum
sharing and almost 20,000 on cognitive radio.

According to the original definition, cognitive radio was defined as having
three distinct capabilities that enable sharing the band with other systems: obtaining
knowledge, adaptation, and learning. This principle is contained also in the official
ITU-R definition of the cognitive radio system stating that CRS is “a radio system
employing technology that allows the system to obtain knowledge of its
operational and geographical environment, established policies and its internal
state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained” (ITU-R 2009). The CRS principle is illustrated in Fig. 5, together with the enabling technologies.

Fig. 5. Cognitive radio system and enabling technologies.

Tools to obtain knowledge include a database, spectrum sensing and wireless channel. All of the regulatory spectrum sharing concepts introduced and analysed in this thesis utilize, at least partly, a database as the enabler for sharing (ETSI 2013, FCC 2015, Ofcom 2015a). In the case of spectrum sharing, a database is a repository where information on the available spectrum opportunities and boundary conditions for their usage, such as allowed transmission time and power, is maintained. The use of a database as a standalone technique for obtaining knowledge requires that the incumbent user is willing to update and capable of updating the information about its spectrum usage either directly to the database or to the entity maintaining it. This is a reasonable assumption, for example, in the case of the most common incumbent usage on the 2.3-2.4 GHz band, Programme Making and Special Events (PMSE) for wireless cameras (ETSI 2014c). Depending on the amount processing before entering the data to the database or the processing ability of the database itself, the information obtained from the database may be sent directly to the available channels (ETSI 2015a) or merely information
on the incumbent usage (ETSI 2014). The spectrum usage information in the
database may also be based on detected signal levels fed to the database, for
every other users or dedicated sensors (FCC 2015). Storing information in a
database may also cause a risk and therefore be forbidden, especially when
considering particularly sensitive usage information such as governmental usage
(FCC 2015). The feasibility study of databases and sensing (both device and
network) with regards to cost and efficiency for different spatial and temporal
traffic characteristics has been presented in Weiss et al. (2012). In general,
databases are assumed to be more practical for cases where the location of existing
radio users is fixed rather than mobile, due to less frequent updating and less
complexity (RSPG 2010). The database-based spectrum sharing concepts currently
considered in regulation require a centralized unit to guide the spectrum decisions
and therefore fall into the category of the centralized architecture in Fig. 4. However,
research has also been conducted on distributed databases. Such an approach may
depend, for example on multiple distributed secondary access points connected to
the central database, owned either by the same or different MNO and the channel
selection is based on game theory (Chen & Huang 2013). Research on polycentric
governance of databases suggests that local determination of rights, rules, and
enforcement could result in more efficient resource management (Weiss et al. 2015)
(Weiss et al. 2017).

Spectrum sensing refers to a capability to detect other signals around the CRS
nodes and it is especially applicable when the level of detected signal is sufficiently
strong or the signal type is known beforehand (ITU-R 2014). The most commonly
considered spectrum sensing algorithms, listed from the least to most complex, are:
energy detection, waveform based sensing, cyclostationary, radio identification and
match filtering (Yücek & Arslan 2009). One of the major issues debated with
regards to spectrum sensing is whether the reliability of the schemes is adequate to
protect the other users (ITU-R 2014). Hidden node problem refers to the ability of
a CRS node to sense the primary user transmission that is blocked for example by
a building (Letaief & Zhang 2009). Cooperative spectrum sensing is the most
common method proposed to mitigate the issue. In cooperative sensing, all CRS
nodes perform sensing individually and send their observation either as a one bit
hard decision or as a soft decision (with more bits to indicate the reliability of their
sensing information) to a fusion centre (Chaudhari et al. 2012). Based on the
received information the fusion centre will make a decision on the availability of
the channel. Some of the most common algorithms proposed for decision making
between cooperating CRS nodes are AND, OR and majority logic rules (Axell et
The effect of the cooperative sensing on the required receiver sensitivity was studied in Mishra et al. (2006). Performance of the spectrum sensing is often given by the probability of missed detection or the probability of false alarm. In receiver operating characteristic (ROC) curves, these are given as each other’s function (Yücek & Arslan 2009). A missed detection will, in the worst case, lead to interference to the primary user, whereas a high probability of false alarm will lead to a decrease in the efficiency of spectrum use. In general, there is a trade-off between the accuracy of the sensing information and the loss in throughput due to the increased complexity of the sensing algorithms and the time used for spectrum sensing (Liang et al. 2008). Also, a weighted probability of area recovered as a function of fear of harmful interference has been suggested for illustration of the same trade-off (Tandra et al. 2009). Sensing may be conducted by CRS nodes themselves or by a separate sensing system. In the three-tier sharing concept considered in the US, a separate system with Environmental Sensing Capability (ESC) functionality has been introduced to complement the database access for those incumbents that do not want to reveal information about their location or transmission characteristics (FCC 2015).

A third method considered for obtaining knowledge is the use of wireless channels. Two of the developed concepts are the cognitive pilot channel (CPC) and the cognitive control channel (CCC). CPC is a centralized solution in which the BS transmits network information on a fixed channel (Houze et al. 2006). The CPC may be a broadcast channel on a global public frequency band (out-band CPC) or it may be operator specific (in-band CPC) (Feng et al. 2012). The CPC may also be an on demand channel (Perez-Romero et al. 2007). The CCC (also known as cognitive control radio (CCR)) is a channel between different distributed CRS nodes in a specific geographical area targeted to enhance coordination between them (ITU-R 2014). Potential implementation options for the CCC based on different existing protocols and systems have been listed in Stavroulaki et al. (2012).

The decision making or reasoning refers to the ability of a CRS node to find an appropriate action in response to a specific situation, in line with a specific system target. It involves three main functions: spectrum characterization, spectrum selection and CRS node reconfiguration (Akyildiz et al. 2006). Decision making in cognitive radio refers to choosing the most suitable modulation and coding scheme, transmission power, operating frequency, channel bandwidth and communication technology (Masona et al. 2013). Of these, most CRS related research has been conducted on the decision making and dynamic adaptation of power (Xu et al. 2015) and frequency/channel (Höyhtyä et al. 2011). On the network management level
different adaptation methods can be considered to reduce the interference caused to the incumbent as well as to optimize the amount of users that can be served by the network.

In real-life implementation of a CRS, the boundary conditions for the adaptation – such as interference levels and timescales – would be defined by the regulatory authority. In accordance with the technology neutrality principle, technology used for decision making and adaptation can be chosen freely by the CRS within those limitations. Decision making and network adaptation are required in all regulatory concepts analysed in this thesis, as there is a need to make decisions and adapt the lower priority usage to the existing higher priority usage. In all of them, the actual decision making on the available spectrum opportunities is done centrally in a database, even in the case that a distributed ESC system is used for obtaining the availability information. In LSA, the adaptation of the network is relatively straightforward as it only consists of power (and possibly antenna) reconfiguration. In both the three-tier model and the TV WS concept, the complexity of adaptation is slightly increased as there may also be changes in the centre frequency. Existing and emerging technologies that can aid in the network adaptation, for example by maintaining a reasonable service level to users, and their applicability to the spectrum sharing concepts has not been properly analysed in the research literature.

Learning can be defined as the process of accumulating knowledge. The learning paradigms in CRS can be classified into unsupervised and supervised learning (Bkassiny et al. 2013). In unsupervised learning, the CRS node has no a priori knowledge about its environment and it learns by instruction. Methods for unsupervised learning include game theoretical models (see surveys for research on game theory models, e.g. in Wang et al. (2010) and in Charilas & Panagopoulos (2010)), Bayesian non-parametric approaches (Han et al. 2011) and reinforcement learning (see survey e.g. in Jiang et al. (2011)). In supervised learning, the CRS node is able to exploit a priori information about the environment and learns by reinforcement (Bkassiny et al. 2013). Methods for supervised learning include artificial neural networks (see survey, for example, in He et al. (2010)).
4 Regulatory concepts for spectrum sharing

Following years of extensive research efforts on spectrum sharing, in recent years the regulatory community has also become receptive to concepts that allow spectrum to be used by multiple systems in a shared manner, instead of exclusivity. This chapter introduces three widely accepted regulatory concepts for spectrum sharing: LSA, the three-tier model and TV white spaces (WS), in sections 4.1, 4.2, and 4.3, respectively. Afterwards, a short description of other concepts under investigation or introduced in the regulatory domain, and national variations of the first three ones, is given.

4.1 Licensed Shared Access

LSA was introduced by the EC as a general concept to facilitate controlled sharing between any two systems in such way that predictable QoS is provided (RSPG 2011). The work in the EC was inspired by an industry initiative aiming to introduce a similar licensed shared use between mobile service and existing services, also referred to as incumbent services. The LSA concept, as introduced by the EC, may be applied between any two services, even if the first use cases considered have also involved mobile service. In LSA, the incumbent user will maintain higher spectrum usage rights. Access to the shared band is based on a licence regime and a sharing framework, which is a set of conditions for shared access negotiated between the incumbent user, the entrant user, and the NRA. These conditions should make LSA sufficiently attractive and predictable for the entrant user, the so-called LSA licensee, to invest in equipment and network.

The first use case of LSA considered, in the standardization and regulation in Europe, has been the application to the 2.3-2.4 GHz band to enable mobile operations on the band (CEPT 2015a, CEPT 2015b, ETSI 2013, ETSI 2014c, ETSI 2015c). This band has been allocated to MS and identified for IMT by the WRC-2007 of the ITU-R in a globally harmonized manner; however, due to the incumbent usage on the band it is not available for mobile use on an exclusive basis globally, or even in all European countries. The incumbent use varies between different countries in Europe, therefore tools developed for sharing need to adapt to differences in the incumbent use characteristics. Both regulatory and standardization activities on LSA aim to ensure interoperability and harmonization of these solutions in order to create a European internal market for devices and to provide economies of scale for the industry.
The first regulatory report from the CEPT on LSA provided an overall description of the LSA concept as a general regulatory framework and its applicability to the current regulatory practices regarding spectrum use (ECC 2014a). Regarding the 2.3-2.4 GHz band, the EC sent a Mandate to the CEPT to study harmonized conditions for mobile use on the band (EC 2014). As a response, the CEPT developed guidelines for the sharing framework for LSA for this band. First, technological and regulatory options for sharing between mobile broadband and the relevant incumbent services were identified. This included an overview of different incumbent services on the band in all European countries and options for sharing for each of these services (CEPT 2015a). The incumbent services are PMSE (both commercial and governmental video links), telemetry, fixed links, and Unmanned Aircraft Systems (UAS). Additionally, there is an amateur service on a secondary basis but it does not need to be protected in the same way as other incumbent services. Second, a more detailed study was performed on the technical sharing solutions between the mobile broadband and PMSE, as the most common incumbent usage on the band (CEPT 2015b). In this study, a step-by-step approach for the implementation of an LSA sharing framework was introduced with the following steps: determining the extent and type of incumbent use, calculating the protection criteria for the incumbent, and identifying operational conditions for sharing, such as implications for the mobile network.

In the ETSI RRS, the scope of the LSA work has been to provide MNO additional bandwidth for mobile broadband either for macro or small cell deployment. The first system reference document from the ETSI provided an overview of the concept, including aspects such as operational features, performance requirements, and high level functions (ETSI 2013). The first technical specification (TS) provided a list of functional and performance requirements for the LSA system that would enable mobile broadband access to the band (ETSI 2014c). The effect of these requirements to the required functionalities of the LSA Controller (LC) and the LSA Repository (LR) has not been discussed in the research literature. The second TS defined high level functions and mapped them to the architecture elements, the LR and the LC (ETSI 2015c). It also defined high level procedures, messaging, and information exchange between these elements. The last TS defined the application protocol between the LC and the LR, and the content of the LSA Spectrum Resource Availability Information (LSRAI) conveyed by this protocol (ETSI 2017). Additionally, a report on LSA from 3rd Generation Partnership Project (3GPP) aims to identify a global solution supported by the 3GPP network management architecture and internal interfaces (3GPP 2016).
The major benefit of LSA, when applied to the mobile network, is that in its basic form it requires no changes to internal procedures or air interfaces of the mobile network. Therefore, there is no need to change the existing 3GPP standardization and implementation can be done in a fast and simple manner. Beyond the support of a new spectrum band, LSA requires no changes to the existing network or user equipment. The applicability of the existing LTE/LTE-Advanced technologies and features for the implementation of LSA has received very little attention in the research literature. The inclusion of the shared bands with variable availability and access conditions does require changes to the network management. This is foreseen as being implemented with two additional functional blocks on top of the cellular architecture, namely the LC and LR (ETSI 2014c, ETSI 2015c, 3GPP 2016). This is illustrated in Fig. 6.

The LR is a database that takes care of the co-ordination of spectrum use between possibly multiple incumbents and LSA licensees in such way that interference is avoided. In the LR, information on the incumbent spectrum usage and protection requirements can be stored and updated (ETSI 2014c). The incumbent location may be provided by the incumbent itself, an NRA, or an estimation algorithm may be used (Jayawickrama et al. 2016). The LR provides the LC information regarding
sharing conditions as necessary and ensures that the information is only available to the intended recipient. The LR ensures that conditions of the sharing framework and LSA license are met. The LR is a central element that has real-time information about usage and conditions on the LSA band, therefore it can be used by the NRA for monitoring the operation.

The LC is the control unit, which ensures that the protection requirement of the incumbent user is met. It translates the information received from the LR into permitted transmission powers of the BSs in the network and commands the operations, administration and management (OAM) unit of the mobile network accordingly. The LC requires full knowledge of the mobile network layout to be able to calculate the total interference caused to the incumbent user by the mobile network. Therefore it is generally acknowledged that this unit should be fully under the purview of the MNO (ETSI 2015c). Algorithms for calculating which BSs to power down may be based on a simple minimum distance calculation between the BS of the mobile network and the incumbent user (Jokinen M. et al. 2016) or more advanced, taking into account the sum of all BS powers (Perez E. et al. 2016). Simple algorithms are usually based on the worst case scenario, inherently accounting for multiple BSs, and therefore may lead to suboptimum performance. In fact, a field measurement campaign conducted on the interference caused by an LTE transmission to a PMSE receiver indicated that interference is avoided with shorter distances than theoretical minimum separation distances (Kalliovaara et al. 2015). However, the processing speed allows tracking of a mobile incumbent.

LSA, as any spectrum sharing concept, complicates the business environment and model for all stakeholders. Easier access to spectrum to new players, introduced by shared use, presents potential risks in terms of increased competition and new service innovation to current service providers. Therefore, it is of utmost importance to also consider incentives for all of the stakeholders. Potential incentives for the incumbent user include flexibility and scalability in spectrum use, sharing the infrastructure, maintaining spectrum access in the long term or getting compensation for sharing (Ahokangas et al. 2014a). Business scenarios for the incumbent users in LSA depend on their business focus and mode of change (Ahokangas et al. 2014b). An aggressive and interactive scenario was found to improve the possibilities for an incumbent user to find new business opportunities arising from the introduction of LSA. In addition to business considerations, there are also more specific technical requirements arising from the incumbent – for example regarding handling of confidential information – that have not been analysed in research literature even if they may have a significant impact on the
practical implementation and architecture of LSA. For the MNO, LSA may offer an opportunity to gain access to additional spectrum bands in a timely manner (Ahokangas et al. 2014c). Business models for MNOs differ based on the current position of the MNO. An existing dominating MNO may use LSA resources as a cost-efficient solution to grow their customer base, whereas for a small challenger MNO LSA could offer an opportunity to expand their business and challenge the dominating MNOs.

The LSA concept has been trialled in the 2.3-2.4 GHz band using a live LTE/LTE-Advanced network in Finland (Matinmikko et al. 2013) and in Italy (Guiducci et al. 2017). In Finland, the incumbent usage in the band is PMSE wireless cameras. The first LSA trial was already presented in Finland in 2013 and the trial environment was further developed and advanced features were added to showcase consecutive trials between 2014 and 2015 for academic, regulatory, and standardization audiences. In 2014, features such as an LSA Repository, an incumbent manager, TD-FDD handovers and emergency evacuation were added (Palola et al. 2014a, Palola et al. 2014b). In 2015, additional functionalities included small cells, tracking of mobile incumbents, an LSA Controller as an integrated SON solution as well as an enhanced protection algorithm (Matinmikko et al. 2015). The trial in Italy is a pilot in which interference to FS links, governmental use, PMSE wireless cameras, and Wi-Fi at the band above 2.4 GHz are measured with the equipment from the Italian ministry (Guiducci et al. 2017).

4.2 Three-tier model for a Citizen’s Broadband Radio Service

The three-tier model for a Citizen’s Broadband Radio Service (CBRS) is a spectrum sharing concept currently under consideration in the US. The initial application of it is considered for the 3550-3700 MHz band. The Federal Communications Commission (FCC) released a Notice of Proposed Rulemaking (NPRM) in December 2012 on making 100 MHz (or up to 150 MHz) of spectrum available for shared wireless broadband use (PCAST 2012). The proposal was to create a way to enable commercial access to the federal spectrum while ensuring the primary federal operations are protected from interference and allowed to develop their technology and spectrum use in the future. The President subsequently endorsed this concept in an Executive Memorandum dated June 2013 (President Barak Obama 2013). Technical specifications for CBRS are produced in the WinnForum. On April 17, 2015, the FCC released the Report and Order (FCC 2015) for establishing a three-tier framework for making the federal 3.5 GHz band available
for shared commercial use for CBRS. Most recently, the FCC completed the regulatory framework and finalized the rules governing the use of this band (FCC 2016), including the finalized specific licensing, technical, and service rules for dynamic sharing between three tiers of users.

In CBRS, three levels of hierarchy in spectrum usage are supported (PCAST 2012). The Incumbent Access (IA) users represent the highest tier and are guaranteed protection from harmful interference from all CBRS users when and where they deploy their networks or systems (FCC 2016). IA includes federal shipborne and ground-based radar operations as well as fixed satellite service (FSS) earth stations. For a finite period of time there are also grandfathered terrestrial wireless operations in the 3650-3700 MHz band.

The entrant usage introduced by the CBRS consists of two tiers: Priority Access and General Authorized Access (GAA). Priority Access operations are based on a Priority Access License (PAL) and users receive protection from GAA operations. A PAL is an authorization to use a 10 megahertz channel in a single census tract for three years. A census tract that defines the geographical area for a PAL varies significantly depending on the population density, covering on average an area with 4000 inhabitants. PALs will be assigned via competitive bidding in up to 70 MHz of the band, 80 MHz is excluded from PAL usage. The spectral location for operations may change in accordance with the IA usage. GAA use will be licensed by rule and is permitted on any frequencies not assigned to PALs. Licensed by rule refers to the fact that any entity qualifying as an FCC licensee may use equipment authorized by the FCC without having to obtain an individual spectrum license (FCC 1996). GAA users will receive no interference protection from other CBRS users, and are not allowed to interfere with higher tier users.

The non-federal incumbents need to register their operational parameters with the FCC or a Spectrum Access System (SAS) and are protected according to this information. The SAS will perform the coordination functions and assign the spectrum access rights to the CBRS users. It is also capable of receiving and responding to interference complaints. An ESC may be used to detect transmissions from radar systems and transmit that information to an SAS for incumbent protection. Accounting for institutional and economic factors through the introduction of polycentric governance in the design of SAS has been proposed by Weiss et al. 2015. In accordance with their considerations the SAS decision process could be affected for example by public and non-governmental organizations, spectrum entrants, and regional coordination, while accounting for local circumstances. Use case studies of such polycentric governance model accounting
are given in Weiss et al. (2017). Results of the studies indicate that model has potential to reduce interference and enable a wider variety of enforcement methods, in comparison to traditional regulatory methods.

The CBRS extends business model design from mobile operator centred connectivity into other internet business models (Yrjölä et al. 2015). The CBRS aims to expand the ecosystem with new roles and increased dynamics, which on the one hand increase innovation potential but on the other hand increase complexity. For MNOs the CBRS may offer additional value by improving the support of asymmetric media data traffic, high quality connection and personalization of services (Yrjölä 2016a, Yrjölä et al. 2017a). Additionally, as the required investment in spectrum decreases, new business opportunities may be opened for vertical segments, for alternative operator types as well as for the internet domain. As the area for single PAL, census tract, is quite small and GAA service providers may offer their services in the same geographical area, the CBRS is most likely to consist of several small CBRS networks and standalone radios with different technologies in the same geographical area. One technology suggested for managing such a complex and heterogeneous environment in a distributed manner is blockchain (Yrjölä 2017b).

Some research trials for the three-tier model with commercial LTE technology components have been performed in Finland to showcase real life behaviour of the network (Aho P. et al. 2016, Palola M. et al. 2017). These trials were conducted in accordance with the work on technical specifications of the CBRS. Evaluation performed on the achievable evacuation times indicated that the 60 second maximum period for the evacuation time set by the FCC is not achievable with existing procedures and technology (Palola M. et al. 2017). Investigations on the evacuation time revealed that the most time consuming phase of the evacuation is the reconfiguration of the BSs by the network management system. In order to reduce the time required for this phase, the BSs should be optimized to support fast on-air frequency changes. Google is leading the industrial trials on the CBRS in the US and has recently announced a series of tests to be conducted on the equipment including LTE technology of the hardware vendors (FierceWireless 2017).

4.3 European TV white spaces

White space refers to a part of the spectrum, which is available for a radiocommunication application (service, system) at a given time in a given geographical area on a non-interfering/non-protected basis with regard to primary
services and other services with a higher priority on a national basis (CEPT 2008). In bands used for TV broadcasting (TV bands), there are localised gaps in the usage of the radio frequency spectrum in between the assigned TV channels. In fact, these WSs are already used by several other services such as radio navigation, fixed or mobile services for military applications, radio astronomy and PMSE services (wireless microphones in the case of this band). Coordination with these services needs to be taken into account when considering additional WS usage.

Similar to LSA, the European approach to TV WS uses geolocation databases to determine which parts of the spectrum band are available in which locations. But unlike with LSA, spectrum can be used on a licence-exempt basis as long as the requirements for database communication and reservation are met, for example. One of the differentiating factors to other TV WS approaches considered in the European TV WS approach is that the database may return a variable permitted maximum transmission power in each channel in such a way that harmful interference to any incumbent receiver is not caused, allowing WS usage in more locations than in the case of a fixed maximum transmission power. This requires knowledge of the locations of incumbent receivers, both digital terrestrial television (DTT) and PMSE.

The European regulatory activities on TV WSs were initiated in the ECC of CEPT by addressing technical and operational requirements for the possible operation of cognitive radio systems in the WSs needed to ensure the protection of the incumbent radio services (ECC 2011). A range of possible deployment scenarios, some key working assumptions and protection criteria for sharing studies were identified. The work was continued with technical investigations for the development of the regulation for white space devices (WSDs) (ECC 2013a). This work included, for example, a description of the protection of incumbents on the band and adjacent bands as well as a classification and technical characteristics of WSDs. Next, the use of centralized geo-location databases for protection of the incumbent services, including framework proposals and feasibility assessment was provided (ECC 2013b). Finally, the overall framework for TV WSD using geo-location databases and for providing guidance for national implementation, including options for database policy and provision, was introduced (ECC 2015).

The standardization activities for TV WS have been taking place in the ETSI RRS, where extensive standardization efforts were taken by defining and publishing technical specifications for use cases (ETSI 2010), information exchange between geo-location databases (ETSI 2015a), system architecture and high level procedures for the use of WS (ETSI 2015b) as well as on the
requirements for WSDs (ETSI 2014b). The implementation of TV WS in Europe should be done in accordance with the three harmonized European standards that cover WSDs (ETSI 2014a): parameters and procedures for information exchange between different geo-location databases (ETSI 2015d) and signalling protocols and information exchange for coordinated use of TV WSs (ETSI 2015e).

The UK has been active in proposing the framework for TV WS operation. The UK regulator Ofcom has completed a series of trials of its TV WS framework (Holland et al. 2015). Based on the trials, Ofcom proposed some minor changes to the framework and is moving ahead towards commercial operation (Ofcom 2015a). Ofcom is also allowing licensed operations of WSDs in cases where the geolocation information of the devices must be manually entered (Ofcom 2015b).

4.4 Other concepts

4.4.1 Examples of TV white space concepts globally

The UHF band has also been heavily under investigation for shared usage in parts of the world other than Europe. The purpose of this section is to name some of the regulatory activities around the world in a non-exhaustive manner. In the US, the FCC introduced the regulatory and standardization framework for the TV WS concept (FCC 2010, FCC 2012a). Regardless of the considerable amount of effort put into the development and finalization of the concept, it never reached the stage of commercial deployment. Currently in the US, the licence holders on this band from the broadcasting community have been granted the rights to re-sell their licences in so-called incentive auctions (FCC 2012b). Also in Canada, a regulatory framework for using TV bands by non-broadcasting devices, has been developed (IC 2012). The Canadian administration has also published specifications that include technical and operational requirements for WSDs (IC 2015a) and databases (IC 2015b). In Asia, for example the regulatory authority of Singapore has developed a regulatory framework for TV WS operations (IDA 2014), as well as technical standard for white space devices (IMDA 2016). In developing countries, great interest has been shown towards TV WS implementation as a solution to provide broadband connectivity in an affordable and efficient manner to deliver government services, education and telemedicine, for example (Kennedy et al. 2015). TV WS trials have been launched for example in South Africa, Kenya, Malawi, Tanzania, Namibia and Ghana. An analysis of the key issues within the
policy, technology and business domains with regard to TV WS access in the Southern Africa Development Community is provided in Masonta et al. (2017).

4.4.2 Flexible use of UHF

In addition to the TV WS research, other more controlled approaches for the flexible use of the UHF band have also been discussed. In Europe, a High Level Group (HLG) comprised of both the mobile and broadcasting sectors, was convened by the EC to deliver strategic advice for a European strategy on the future use of the UHF band. The group never reached a consensus, however, the results were reported by one of the group members (Lamy 2014). In this report, introducing additional downlink only mobile broadband was envisioned as a solution to allow the continuation of TV broadcasting while allowing more efficient utilization of the spectrum. In parallel, a report was prepared in the ECC of CEPT on a long term vision for the UHF broadcasting band, including analysis of possible scenarios (ECC 2014b). These included scenarios with only broadcasting usage, hybrid usage between broadcasting and LTE (both downlink only and bi-directional), as well as usage by future communication technologies only. Currently it is considered by the RSPG of the EC that the frequency band 470-694 MHz should remain available for broadcasting in the future. However, member states should also have flexibility to use the band for wireless broadband in accordance with national circumstances without causing interference to or claiming protection from broadcasting in the neighbouring countries (EC 2017). Stakeholder analysis on the hybrid usage of the lower UHF band between mobile and broadcasting reveals that the highest power and legitimacy with regards to the usage of the band is possessed by the NRA (Matinmikko et al. 2017). Research on the service and business opportunities, as well as on LTE technology enablers for flexible use of the lower UHF band, indicate that several envisaged services scale by leveraging key existing technological assets and capabilities while extending current MNO business models beyond connectivity (Yrjölä et al. 2016b).

4.4.3 Collective Use of Spectrum

Collective Use of Spectrum (CUS) has been defined by the EC as a concept that “allows an unlimited number of independent users and/or devices to access spectrum in the same range of designated CUS frequencies at the same time and in a particular geographic area under a well-defined set of conditions” (RSPG
CUS is an uncontrolled concept based on general authorization, similar to RLANs. A device uses its own capabilities to determine the parts of spectrum that are unused. This increases the risk for interference in comparison to controlled schemes; however, the risk can be mitigated through power limits, duty cycle limits, coordination or introduction to higher frequency ranges. As the number of CUS users is not controlled, the QoS offered to users depends on the amount of congestion. Similar to any uncontrolled concepts, the introduction to a spectrum band is irreversible, limiting the future usage of the band.

4.4.4 Light licensing

A light licensing regime refers to licence-exempt usage, where a certain level of protection is provided to the spectrum users by controlling the access to the band by a database (ECC 2006). In a light licensing regime, the user informs the regulator about the position and characteristics of the stations and if they can be installed without affecting already registered stations, the new station is added in the database. The model follows a “first come first served” principle, however, a mechanism to challenge whether a station already in the database is really used or not should be implemented to make sure that only active users are protected.
5 Summary of the original papers

Until recently the regulatory environment for an MNO has remained stable and mobile operations have always been based on exclusive licenses. As the challenges in finding suitable spectrum resources for exclusive use increase, competition for resources has started to create tension between the mobile industry and other industry fields, such as satellite and broadcasting. Spectrum sharing introduces a shift in the paradigm for spectrum regulation, by allowing different industry fields to co-operate instead of compete for resources and by doing so enabling more efficient use of spectrum. This chapter provides a summary of the original papers of the thesis, by first providing a short overview of the papers and their relation to each other. Second, an analysis of the overall process for introduction of a spectrum sharing concept is provided. Third, the role and critical factors for the national regulatory authority are given. Fourth, characteristics and critical factors for the incumbent user are discussed. Fifth, enabling techniques and critical factors from the perspective of an MNO, in the role of an entrant user, are introduced. Lastly, requirements for the LSA system and their effect on the implementation are discussed.

5.1 Overview of the papers

A shift from exclusive spectrum use into shared use increases the complexity and risks to the involved stakeholders. In order for the new way of co-operation to be successful, it is necessary that the criteria for spectrum sharing are considered from the viewpoints of all the key stakeholders: the incumbent spectrum user, the entrant spectrum user and the NRA. Fig. 7 illustrates how the perspectives of different stakeholders have been considered in the original publications. A general process model and roles of all the stakeholders in different phases of the process were discussed in Paper I. The NRA is the facilitator of a spectrum sharing concept and therefore it is crucial to consider how a concept fits into the current regulatory processes. This aspect was discussed in Paper II. The incumbent spectrum user owns the current spectrum usage rights and therefore has a significant impact on the successful roll out of a spectrum sharing concept. The role of the incumbent user was considered in Papers III and IV, of which the latter concentrated on the specificity of a satellite system as an incumbent user. The entrant spectrum user has to implement the technical solutions that facilitate spectrum sharing in such
way that sharing conditions are fulfilled and harmful interference is avoided. Papers V, VI and VII provided the viewpoint of an MNO as the entrant spectrum user.

![General process model](image)

**Fig. 7. Aspects of spectrum sharing considered in the original papers.**

In the original papers, a theoretical analysis of the prevailing spectrum conditions, existing regulation, merging spectrum sharing concepts and key stakeholders with the associated enabling technologies was used to extract the pre-requisites for feasible spectrum sharing concepts. Three different topical regulatory spectrum sharing concepts were considered in the original papers: LSA, CBRS, and European TV WS, as shown in Table 1. The most comprehensive analysis was made on the LSA concept for which a significant amount of content was created and delivered to regulation and standardization. Application of LSA to enable mobile access to a spectrum band, was considered from the perspectives of the NRA (Paper II), an incumbent user (Papers III and IV), and an MNO (Paper V, VI and VII), as shown in Table 1. The CBRS has been analysed from the NRA (Paper II) and the incumbent user (Paper IV) perspectives. A more general analysis of all three concepts, highlighting the roles of each stakeholder in the process was provided in Paper I.

**Table 1. Sharing concepts considered in the original papers.**

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>LSA</th>
<th>CBRS</th>
<th>TV WS</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRA</td>
<td>Papers I &amp; II</td>
<td>Papers I &amp; II</td>
<td>Paper I</td>
</tr>
<tr>
<td>Incumbent spectrum user</td>
<td>Papers I, III &amp; IV</td>
<td>Papers I &amp; IV</td>
<td>Paper I</td>
</tr>
<tr>
<td>Entrant spectrum user</td>
<td>Papers I, V, VI &amp; VII</td>
<td>Paper I</td>
<td>Paper I</td>
</tr>
</tbody>
</table>
5.2 The regulatory process for spectrum sharing

Phases for the implementation of any spectrum sharing concept can be presented as a general process model, as has been illustrated in Paper I and is shown in Fig. 8. The process consists of five phases: regulatory preparations, access rights, deployment, operations, and release. In reality, phases of the process may be very complex and occur in an overlapping or even reversed fashion, however, in the following, activities related to each of the phases are summarized. The implementation of a new sharing concept may be initiated due to a need to find spectrum resources for a certain service or for political reasons, such as promoting efficient use of spectrum or enabling introduction of new innovative services. A new spectrum sharing concept can be developed nationally or an existing concept can be adopted, and possibly tailored, from an international regulatory framework or another country. In all cases, the NRA has the right to authorize the spectrum use in their country and decide on the implementation of a spectrum sharing concept.

During national regulatory preparations the NRA needs to evaluate the suitability of a service or application for shared operations and identify appropriate bands for sharing. The NRA also needs to identify the potential stakeholders and arrange negotiations between them, possibly also with public interest groups and other government entities. For the entrant user it is especially important to prove technical feasibility via testing, trials, and experimental deployment. Position papers may be needed, e.g. to make the political atmosphere more receptive to sharing. The outcome of the national regulatory framework is a set of boundary conditions, also denoted as the sharing framework. These conditions include operational requirements, for example on information exchange and its security. They may also include protection requirements and restrictions on the entrant system deployment. Additional tools required for shared access can be defined, including their requirements, for example certified database providers. The boundary conditions should contain enough details for the entrant user to be able to evaluate the required investment against the spectrum opportunity. The international and regional regulatory framework aims to create a common market for equipment and to ensure interoperability between countries, as discussed in Chapter 2. In addition to regulatory activities, international standardization activities take place on functionalities, interfaces, protocols and high level architecture.

The rights of use granted by the NRA are based either on an individual licence for operations on the band or general authorization (without individual rights of use)
verified by compatibility studies by the CEPT resulting in type standardization for the devices, as discussed in Chapter 2 (RSPG 2009). The process itself is carried out nationally, usually alongside a consultation process. Traditionally mobile licenses have been granted on an exclusive basis with certain obligations, for example on coverage. This has restricted the number of licenses and raised their prices, making them available only to operators with an existing infrastructure and customer base. Recent regulatory spectrum sharing concepts aim to solve this issue by introducing more local licenses of possibly shorter duration. Databases can be used as a part of the authorization process to provide regular real-time updates on the authorization. On the unlicensed bands, there has traditionally been no means to control the amount of devices or guarantee QoS for users on these bands. Designating a band for unlicensed use has also been considered to be irreversible. These issues can be solved by introducing control on the devices through the use of databases (Lehr & Crowcroft 2005), which are used in some cases in conjunction with specific sensing systems. For databases and sensing systems similar standardization activities are needed as for devices, defining requirements on the maximum delay and minimum sensitivity for example.

Shared operations require either modifications to the existing deployment of the entrant user or completely new deployment. The entrant system needs to be planned in such way that no harmful interference is caused to the incumbent user, using either frequency, spatial, time, or signal separation. For this, incumbent users may need to give information about their system and usage characteristics. In the case of spatial separation, there may be areas where the entrant system deployment is not allowed, or has limitations, for example on transmission power. These areas are referred to as exclusion and restriction zones, respectively (ETSI 2014c, ECC 2016). Also, specific tools to facilitate sharing, database or sensing systems, need to be deployed. These tools become more critical when dynamic sharing, either in terms of incumbent spectrum use or entrant user access rights, is considered.

Operations on the bands shared with users with higher priority may require the entrant user to implement tools to get real-time information on the spectrum usage as well as tools to adapt the network accordingly, for example to power down affected BSs or to change centre frequency. Spectrum availability evaluation is done by databases either based on direct input received from the incumbent user itself or detection information from a sensing system. The entrant user may be authorized to use the shared resource until the incumbent arrival, or access rights may be revisited periodically. In order to avoid the risk of interference, standardization needs to define procedures to check the connectivity to the database.
The entrant user may also need to evaluate the aggregate interference caused by its network to the incumbent user. In some cases, this may have to be done at a fast pace and even a mobile incumbent may need to be tracked and protected. Alternatively, the NRA may convert protection requirements into restrictions to the network deployment of the entrant user, to protect details of the incumbent usage (ECC 2016). Either the entrant user or the incumbent user needs to conduct interference monitoring and report lowered QoS to the NRA. The enforcement actions of the NRA are decided nationally and should be defined in the sharing framework.

After the spectrum user rights of the entrant user expire, the shared band is released. If the spectrum usage of the incumbent user has changed or the protection criteria need to be reconsidered, the regulatory framework and boundary conditions are re-evaluated and modified. Alternatively, the access rights based on the same sharing framework and boundary conditions may be offered to all prospective entrant users in-line with the transparency and fairness requirements of the licensing process. The NRA may account for the existing entrant system deployment on the band and related investments made in the process. With control over the devices and deployment of the entrant user, the release of the shared band is straightforward. In addition to the general process model, Paper I maps the activities in different phases into different stakeholders and analyses the differences of these phases in three prevailing regulatory spectrum sharing concepts: LSA, the three-tier model and European TV WS.
5.3 Role of National Regulatory Authority

Implementing a spectrum sharing framework on a frequency band is a complex process facilitated by the NRA and requiring co-operation from all stakeholders. An NRA needs to provide a feasible regulatory framework to support new sharing concepts. The criteria for a feasible spectrum sharing concept from an NRA perspective are discussed in detail in Paper II and summarized in Fig. 9. Constantly increasing spectrum demand for various radiocommunication services creates pressure to make the use of spectrum resources efficient. Increased efficiency of spectrum use should lead to measurable gains, such as enhancement of existing services, better coverage, or new services. Protection of all spectrum users is one of the primary goals of an NRA, therefore technical measures to prevent harmful interference are of the utmost importance.

The NRA needs to obey technological neutrality, defining technical parameters and limitations arising from the existing usage as the only boundaries to the entrant systems. A sharing framework created by the NRA should provide predictable access and usage conditions and contain enough information for business model
development for all users, therefore co-operation with both the incumbent user and the entrant user in developing of the sharing framework is encouraged. The enforcement of spectrum sharing regulations by the NRA is vital in broad implementation of a spectrum sharing system. The NRA needs to define measures that allow direct implementation (such as monitoring) and enforcement in accordance to the national framework. Enforceability is based on the national authorization process, whereas implementation may also be aided by predetermination of international standards for the networks or devices.

The NRA needs to ensure that a sharing concept does not provide special advantage to any particular entity. Pro-competition and fairness can be guaranteed for example by awarding procedures as was discussed in Chapter 2 (RSPG 2009). The principle of transparent and non-discriminatory access to the bands must be respected. In order to support investment planning, the sharing framework needs to guarantee basic legal certainty requirements. This includes security of the information exchange between users and additional entities included in the sharing process, such as databases.

The NRA needs to foster innovation obtained by the introduction of a new technology that provides new services and encourages new investment. With spectrum sharing, the required time to gain access to spectrum can be shortened, and less stringent coverage obligations may lead to shorter technology life cycles and new business models, based on localized services. In the field of optimizing spectrum sharing between systems, innovations can also arise for example from novel interference mitigation techniques. With the NRA allowing more services to utilize the available spectrum, introduction of novel services and investigation of new business models in real world deployment is enabled.
5.4 The incumbent user

The incumbent user, as the current holder of spectrum rights, is vital for the successful introduction of any sharing scheme to a frequency band. The type of incumbent usage has a great influence on the implementation of a sharing framework, as will be discussed in Section 5.4.1. As discussed in Section 0, in vertical spectrum sharing concepts the incumbent user maintains higher rights in comparison to the entrant use. This is the case in all the regulatory concepts considered in this thesis. Therefore, it is important to take into account all possible concerns of the incumbent user, as discussed in Section 5.4.2.

5.4.1 Characteristics of the incumbent usage

The three-tier model and LSA are general regulatory frameworks that can be implemented in various bands with variable incumbent usage. The practical implementation details of the framework depend highly on the considered frequency band and usage scenarios of the incumbent user. As was discussed in Paper III, the incumbents can be classified as either governmental or commercial
based on their spectrum use rights, and as static or dynamic depending on their spectrum usage patterns.

Governmental incumbents – covering fields such as defence, public safety, or science – do not possess individual rights of spectrum use but their access to frequency bands is usually on a shared basis and regularly reviewed by the administration. A commercial incumbent is a private entity, which holds spectrum usage rights granted by the administration. These rights can be either individual or general, as discussed in Chapter 2. Individual rights of spectrum use protect the commercial incumbent from additional obligations, such as sharing the band, until the end of their license period. Dynamic spectrum usage is not tied to a particular geographical area or time and it is not predictable. Sharing with an incumbent with dynamic spectrum usage requires dynamic management functionalities. Static spectrum usage occurs most of time in a certain geographical area or at pre-defined time instants. Interference to a static incumbent can be mostly prevented with traditional methods such as exclusion zones and times.

The first use case for the LSA was the 2.3-2.4 GHz band (ETSI 2014c, ETSI 2015, CEPT 2015a, CEPT 2015b) and the second use case is the 3.6-3.8 GHz band (ECC 2016). The first use case for the three-tier model, the so-called innovation band, is the 3.55-3.7 GHz (FCC 2015, FCC 2016). The TV WS concept is a UHF band specific implementation. In Table 2, the incumbent usage for the bands considered for different sharing frameworks (Paper I) is shown. In the table, (F) denotes fixed spectrum usage and (D) refers to dynamic spectrum usage.

PMSE usage, both in the case of wireless cameras (2.3-2.4 GHz band) (ECC 2012) and microphones (UHF band) (CEPT 2009), is dynamic. Even if some use cases of the PMSE devices are tied to a certain location (such as a theatre, a media house or a stadium), there is still usage that does not follow predictable patterns. Ground stations for aeronautical telemetry, including both manned and unmanned aircraft systems, are normally fixed to certain locations (CEPT 2015a). Their usage is also predictable, as the flight path of an airplane is usually known well in advance. However, as the service is critical, reliable protection methods are needed. A Fixed Service (FS) is a fixed radio link, an infrastructure or backhaul link, between stations in a telecommunications or broadcast network (ECC 2016). In the case of FS, the short length and directivity of the links makes protection easy, however, the exact location of the link may be confidential. Characteristics of Fixed Satellite Service (FSS) as an incumbent were discussed in Paper IV. FSS Earth stations are fixed to certain locations. The received radio signal is very low and satellite receivers typically use highly directional parabolic antennas. The beam coverage
of a satellite is by several orders of magnitude larger than a terrestrial cell, therefore the aggregate interference from terrestrial sources needs to be controlled. Latencies caused by long satellite links set a limit on the dynamism of the spectrum management. Radiolocation services, in the case of the band for the three-tier model, denote naval radars owned by the Department of Defence. In this case, the limitations on spectrum use occur occasionally in coastal areas. However, due to confidentiality issues, the arrival of a vessel cannot be stored beforehand in a database; protection has to be based on environmental sensing. This requires relatively short response times and dynamic solutions for spectrum management. The wireless broadband service, in the case of CBRS, will be considered as having the same level of access rights as the entrant system, thus specific protection mechanisms are not required. Terrestrial broadcasting or terrestrial TV is fixed to certain UHF channels. There are locations within a country where some of these channels are not used for TV broadcasting in order to avoid interference to TV service in adjacent areas.

### Table 2. Incumbent usage on the spectrum bands considered for sharing.

<table>
<thead>
<tr>
<th>Sharing concept</th>
<th>The incumbent user</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSA 2.3-2.4 GHz band</td>
<td>PMSE (wireless cameras) (D)</td>
</tr>
<tr>
<td></td>
<td>Telemetry (F)</td>
</tr>
<tr>
<td></td>
<td>Fixed Service (F)</td>
</tr>
<tr>
<td>LSA 3.6-3.8 GHz band</td>
<td>Fixed Satellite Service (F)</td>
</tr>
<tr>
<td></td>
<td>Fixed Service (F)</td>
</tr>
<tr>
<td>Three-tier model</td>
<td>Radiolocation (D)</td>
</tr>
<tr>
<td></td>
<td>Fixed Satellite Service (F)</td>
</tr>
<tr>
<td>TV WS</td>
<td>Terrestrial Broadcasting (F)</td>
</tr>
<tr>
<td></td>
<td>PMSE (microphones) (D)</td>
</tr>
</tbody>
</table>

#### 5.4.2 Critical factors for an incumbent user

The incumbent has to adapt its functionalities to the new, shared operation, therefore the roll out of a sharing scheme should be made as straightforward as possible for the incumbent user and any possible concerns should be taken into account. The critical factors for the incumbent user were discussed in Paper III and are summarized in Fig. 10. In vertical spectrum sharing, the incumbent user maintains higher spectrum usage rights and is therefore also allowed to reclaim the spectrum band or part of it, within the license duration. If the spectrum usage of the incumbent user is dynamic, the reclaim or evacuation request from an incumbent
user is part of the normal shared operation. In this case, simple tools for an incumbent user to provide information about its spectrum usage should be developed. For example in the LSA, the evacuation is initiated as the incumbent user informs on the change in the availability of the shared band. The time limit for the completed evacuation, as well as the size of the area to be evacuated, varies according to the protection criteria defined by the incumbent user.

The incumbent user should be able to maintain its normal operation, including provision of predictable QoS and mobility, regardless of the sharing. In some cases, the incumbent user may need to provide information about changed conditions for the shared band, whereas in other cases the entrant system is responsible for getting this information. Technical requirements for the entrant user should be defined by the incumbent user. Information on the network of the incumbent user and actual spectrum usage in the LSA band or any other bands should be considered as classified information and protected. In all cases, the information required from the incumbent user should be limited to the minimum necessary to facilitate sharing. In some cases, it may even be necessary to use a protection mask to hide the actual spectrum use (for example defence) or location (for example FS) of the incumbent user. Measures need to be taken to secure both the data transmitted by the incumbent user and data stored, for example in databases, and to make sure it is only available to the intended recipient. In some cases, the incumbent user may request information or monitor where, when, and by whom the shared band is used, for example for security reasons. Such information includes an acknowledgement that the evacuation of a spectrum band is complete.
5.5 The entrant user

An entrant user refers to a new user attempting to gain access to a spectrum band with existing usage through spectrum sharing. The analysis provided in this thesis is limited to the case of an LSA and even further to an MNO as the entrant system in accordance with the first use cases in European spectrum regulation, while acknowledging that the LSA is a general regulatory framework without any limitations on the type of entrant user. With LSA, an MNO can use spectrum resources in the geographical areas and time periods when the incumbent user is not using them. Moving from exclusive into shared operations will require careful consideration from the MNO side, therefore design criteria for adopting LSA are considered in Section 5.5.1. Spatially and temporally varying availability of the resources will further complicate mobile networks, which are already deployed in multiple frequency and hierarchy layers. Fortunately, there are multiple existing LTE/LTE-Advanced features and techniques that can be utilized in the implementation of LSA, as shown in Section 5.5.2. The ability of the MNO to respond to varying resource availability is foreseen as being based on the implementation of an additional management system, the LSA system, on top of the cellular architecture, as also discussed in Section 4.1. The standardization requirements from the ETSI RRS and their effect on the implementation of the LSA
system are discussed in Section 5.6 (ETSI 2013, ETSI 2014c, ETSI 2015c, ETSI 2017).

5.5.1 Critical factors for the MNO

LSA is a tool for an MNO to access spectrum bands that are not otherwise available to it. However, shared operations also pose some risks that need to be carefully considered. Design criteria to minimize these risks were considered in Paper V and are illustrated in Fig. 11. Data and interfaces of the MNO network need to be secured. This applies also to information transmitted to and from the LSA system, as well as information stored in its database. The MNO should be able to provide a predictable QoS to its users using the LSA band when it is available. In practice this means, that the MNO should be able to operate in interference-free conditions and have a sufficient level of spectrum availability, without competition between multiple MNOs. Since the MNO should implement mechanisms to provide QoS for its users by using alternative networks or resources when the LSA resource is not available, the MNO needs to have full control over the management unit that contains a list of available resources and does network planning for them. Early notice on an upcoming evacuation request would help network planning. The information that the MNO needs to share about its network should be limited to minimum necessary, information such as eNB positions or transmit powers does not need to be shared with other stakeholders. The long term availability of the LSA spectrum, preferably in a harmonized manner, globally, or at least in Europe, would guarantee a return of investment for the MNO on the eNBs supporting the new bands and the development of new management functions. On the other hand, the MNO should also be allowed to deploy LSA locally, based on market demand (without requirements on nationwide coverage).
5.5.2 Enabling techniques for spectrum sharing

There are several LTE/LTE-Advanced technology features standardized by the 3GPP that can facilitate the introduction of LSA bands into the heterogeneous network environment of an MNO. How these enabling techniques can be associated with different phases of using the LSA resources was discussed for the first time in Paper V. The results of the paper are summarized in Table 3. Using cell re-selection procedures (Kazmi 2011), user equipment (UE) can select the serving cell from different RATs and frequencies based on its own signal strength measurements. When the LSA cell is powered off or down by an MNO due to an evacuation request from an incumbent, UEs will automatically start a cell re-selection procedure. Alternatively, the MNO can clear the LSA cell by gradually lowering the transmit power of the eNB before locking it. This graceful shutdown will allow UEs to conduct inter-frequency handover (Kazmi 2011) in a controlled manner and without causing connection breaks to the user. The risk of connection break can also be removed by pairing a carrier on the LSA band with a carrier on a licensed band by using carrier aggregation (CA) (Ghosh et al. 2010). By using CA, the user can benefit from higher data rates when the LSA resource is available. Using supplemental downlink (SDL) (considered for example for 1452-1492 MHz in 3GPP (2014)), the downlink of a frequency division duplexing (FDD) channel is
paired with a time division duplexing (TDD) channel to boost the downlink capacity.

For LSA cell activation and deactivation, self-configuration (Aliu et al. 2013) can be used for configuring key radio configuration parameters of the new cell and its neighbours on the fly without manual intervention. Load balancing, as one of the self-optimization features (Aliu et al. 2013), can be used to even out the load generated across the network by handing over users from one cell to another. The procedures may need to be reconsidered due to the variable availability of LSA resources. Active antenna systems (AAS), vertical sectorization, and beamforming (Astely et al. 2013) can be utilized to optimize network coverage and capacity by changing antenna parameters (such as tilt, azimuth, or beam shape) to enable more accurate exclusion zones and more efficient utilization of the non-static LSA resource. Dual connectivity (Astely et al. 2013) allows a UE to be connected to two cells (for example an existing LTE FDD cell and the TD-LTE LSA cell) at the same time. Traffic steering can be used for directing traffic to the most suitable cell layer, frequency, and RAT within any network governed by the MNO (Aliu et al. 2013). The use of LSA resources needs to be supported by traffic steering functions, however, extensions to the existing procedures are needed due to the varying availability of these resources, as was discussed in Paper VI.

Table 3. LTE/LTE-A features for different phases of operation using LSA (Paper V).

<table>
<thead>
<tr>
<th>LSA phase</th>
<th>LTE/LTE-Advanced enabling technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network planning and configuration</td>
<td>Self-configuration</td>
</tr>
<tr>
<td>Activation and de-activation of the cells on the LSA band</td>
<td>Cell re-selection</td>
</tr>
<tr>
<td></td>
<td>Frequency handover</td>
</tr>
<tr>
<td></td>
<td>Traffic steering</td>
</tr>
<tr>
<td></td>
<td>Self-configuration</td>
</tr>
<tr>
<td></td>
<td>Active Antenna Systems</td>
</tr>
<tr>
<td>Use of the LSA resources</td>
<td>Cell re-selection</td>
</tr>
<tr>
<td></td>
<td>Frequency handover</td>
</tr>
<tr>
<td></td>
<td>Traffic steering</td>
</tr>
<tr>
<td></td>
<td>Carrier aggregation</td>
</tr>
<tr>
<td></td>
<td>Supplemental downlink</td>
</tr>
<tr>
<td></td>
<td>Load balancing</td>
</tr>
<tr>
<td></td>
<td>Active Antenna Systems</td>
</tr>
<tr>
<td></td>
<td>Carrier Aggregation</td>
</tr>
<tr>
<td></td>
<td>Dual connectivity</td>
</tr>
</tbody>
</table>

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5.6 Requirements for the implementation of the LSA system

In order for a new spectrum sharing concept to be technically feasible and to provide legal certainty, its introduction requires participation from all key stakeholders and a coherent framework needs to be developed in spectrum regulation and standardization. Even if the detailed implementation solutions depend on national decisions, the framework developed in regional regulation and standardization forums allows for a harmonized market within European countries. Therefore, the ETSI standardization has derived the system requirements for mobile broadband operating in the 2.3-2.4 GHz band using LSA (ETSI 2014c). As discussed in Section 4.1, the implementation of LSA is foreseen as being based on an LSA system, which comprises of two logical units: an LSA Repository and an LSA Controller. The LR is a database that stores and updates information required for sharing and delivers the information to the intended recipient. The LC protects the incumbent by translating this information, together with the information of its network layout, into LSA resource availability information and configuring the mobile network on the LSA band accordingly. In Paper V the high level functionalities of the LC were summarized as:

- obtain, store and report information on the sharing framework and licence conditions,
- identify and configure cells for the LSA band,
- activate and de-activate cells on the LSA band,
- estimate interference conditions,
- maximize or maintain QoS,
- optimize network use for the LSA band and
- report on the LSA resource usage.

In the Paper VII, the 36 requirements from ETSI standardization (ETSI 2014c) were re-grouped in order to highlight the implications of these requirements to the required functionalities and implementation of the LSA system. The original mapping from the ETSI vs. the mapping proposed in the paper is shown in Fig. 12. The general system operation requirements were divided into sharing framework, robustness, information exchange, and operations to better highlight their implications for the implementation. Additionally, protection and security related requirements of the general operation requirements were added to those groups. The evacuation was separated as its own group. Resource grant requirements were
renamed as MNO protection. Additionally, those resource grant requirements related to evacuation and security were moved to those groups.

Fig. 12. Mapping of the LSA system requirements from ETSI (ETSI 2014c) in Paper VII.

The LR receives and provides information via interfaces to the incumbent user, the NRA, and the LC. Input and output information to the LR as well as its required functionalities are shown in Fig. 13. The LC receives and provides information via interfaces to the LR and OAM of the mobile network. Input and output information to the LC as well as its required functionalities are shown in Fig. 14. The mapping between the information shown in Fig. 13 and Fig. 14 and the ETSI RRS requirements for the LSA System can be found from Paper VII.
Fig. 13. Input, output, and tasks of the LSA Repository.

Fig. 14. Input, output, and tasks of the LSA Controller.
6 Discussion and conclusion

The rapid increase in mobile data usage in the last few years has caused regulatory authorities to struggle to find solutions that guarantee spectrum resources to support this trend. While the regulatory process for traditional spectrum allocation is proving too time consuming and complex, even allocated bands remain unusable for mobile exclusively due to existing usage; this has motivated regulatory authorities globally to look for new sharing solutions that enable more efficient spectrum usage, by allowing multiple systems to use the same spectrum bands. Considering the wide range of sharing concepts that have been studied and proposed by academia and industry in the past, only a small subset of them has entered the regulatory domain. Understanding the administrative process and factors that contribute to the regulatory acceptance of a sharing concept, will help academic and industry research to develop spectrum sharing concepts with a higher probability of practical implementation.

6.1 Key findings

There are three key stakeholders involved in the development and implementation of a spectrum sharing concept: the NRA, the incumbent user, and the entrant user. The aim of this thesis was to answer a research question: *What are the requirements of different stakeholder’s, and from the process point of view, that need to be fulfilled in order for a spectrum sharing concept to achieve regulatory acceptance and eventually to reach practical implementation?* The first contribution of the thesis was an analysis of the critical factors for different stakeholders. The role and criteria for the NRA were analysed in Section 5.3. The NRA, and administration in more general, is in a key position to decide on the adoption and implementation of a spectrum sharing concept. In order for a sharing concept to be feasible from the NRA point of view, it needs to fulfil certain requirements on, for example, interference protection and enforcement. The impact on the incumbent user characteristics and the critical factors of the sharing concept were analysed in Section 5.4. The incumbent user has a great influence on the implementation of the sharing concept. The regulatory sharing concepts considered in this thesis are aimed at different spectrum bands, on which the characteristics of incumbent usage vary significantly. These characteristics, such as mobility and security requirements, largely dictate the tools and framework for sharing, as discussed in this thesis. Additionally, a more general analysis of the issues that need
to be taken into account to preserve the rights of the incumbent user was presented. Analysis from the entrant user perspective, presented in Section 5.5, concentrated on the critical factors, as well as on the suitability, of the existing technologies to the sharing framework. From the entrant user perspective one of the key issues is the right balance between the required investment and the amount of spectrum opportunities. As the entrant user has the responsibility to implement the required technical solutions for obeying protection requirements defined in the sharing framework, the ability to utilize existing features to support sharing is of utmost importance. Usability of the existing technologies was analysed only from the perspective of an MNO accessing a spectrum band using LSA. General design criteria as well as enabling features of the LTE/LTE-Advanced technology have been discussed.

Analysis of the perspectives of individual stakeholders culminated in an understanding of key criteria for the whole process of introducing a spectrum sharing concept into a band. It was found that while all three regulatory spectrum sharing concepts discussed in this thesis – LSA, the three-tier model, and TVWS – have several dissimilarities and specificities, they all follow a common process model, which was presented in Section 5.2. This process model has five distinguishable phases where all of the stakeholders involved have very different roles and tasks. The five phases of the process and the key outcome of each phase to enable successful roll out of a sharing concept are illustrated in Table 4 (in accordance with Paper I).

The most challenging and diverse phase of the process is the regulatory preparations, which consist of both national and international preparations. In this phase, all stakeholders have their own distinct role and the desired outcome usually varies significantly. The NRA, as the facilitator for the regulatory preparations, is in a key role in this phase, striving to create such a sharing framework that offers incentives for both the incumbent and the entrant user, while still being compatible with regulatory frameworks. The process is typically initiated at the request of the entrant user, which needs to prove technical feasibility of the sharing concept and required tools through development, testing, and trial activities. Participation in international standardization activities is needed to make sure that these tools are harmonized. The sharing concept also needs to create enough straightforward spectrum opportunity for an entrant user to attract investment. On the other hand, the sharing concept also needs to fulfil possibly quite strict protection criteria defined by the incumbent user trying to maintain its rights. Therefore, the incumbent user needs to define the available resources and conditions for sharing,
such as terms for evacuation and maximum interference levels. To guarantee adequate protection, all circumstances that could lead to harmful interference situations need to be identified. In order to create a sharing framework that is able to balance between these sometimes highly conflicting viewpoints, close cooperation between all stakeholders is vital. Negotiations required for such cooperation are unique for spectrum sharing, requiring renewal of internal processes of the NRA.

Awarding access rights is a national process facilitated by the NRA. Depending on the dynamicity of the spectrum sharing concept, traditional means for awarding access rights, discussed in Chapter 2, may become inadequate. The key criterion for an NRA is to find flexible enough awarding mechanisms that still promote competition and respect transparent and non-discriminatory access. Especially in the case of licence based sharing concepts, careful consideration is needed on the pricing of the licences for shared operations. The shared resource may not always be available and predicting the availability beyond statistical probability may not be possible in all cases.

The most critical groundwork for the deployment phase is already done in the preparations phase where requirements for the implementation are negotiated and possible limitations to both entrant user and incumbent user network sites are determined. The actual deployment phase mainly concerns the entrant user, which needs to ensure that both its network sites and tools to facilitate sharing, for example the database and ESC system are developed and deployed in accordance with the agreed sharing framework. The dynamicity of the sharing concept, as well as the protection requirements from the incumbent user, has a direct impact on the complexity and cost of the tools for sharing.

During the shared operations, information between all stakeholders needs to flow seamlessly and securely only to the intended recipients. Actions should be taken in accordance with this information within the timeframe defined in the sharing framework. The entrant user needs to manage the configuration and reconfiguration of its network as well as sharing tools in such a way that the requirements set in the sharing framework for time scales and maximum interference levels are respected. On the other hand, the entrant user also needs to maximize the quality of experience to its users. The operations phase is critical for the incumbent system as well, since any shortcomings in the preparations phase may come to light at this point, possibly having detrimental effect on the incumbent user operations. The release phase, starting from when the spectrum usage rights of
the entrant user expire, allows all stakeholders to reflect on the sharing and re-
define the framework if necessary.

Table 4. Phases of the general process model and key criteria in each phase (in accordance to Paper I).

<table>
<thead>
<tr>
<th>Phase</th>
<th>Key criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulatory preparations</td>
<td>Definition of framework and protection requirements that attract entrants to invest, while protecting incumbents from harmful interference.</td>
</tr>
<tr>
<td>Access rights to the shared spectrum</td>
<td>Creating mechanisms for awarding of access rights in a flexible manner, while promoting competition and considering specificities of the sharing concept.</td>
</tr>
<tr>
<td>Deployment</td>
<td>Planning of entrant and incumbent system deployment in accordance to sharing requirements.</td>
</tr>
<tr>
<td>Operations</td>
<td>Seamless flow of information between stakeholders and tools for network adaptation of the entrant user in accordance to spectrum availability.</td>
</tr>
<tr>
<td>Release</td>
<td>Lessons learned from the sharing process.</td>
</tr>
</tbody>
</table>

6.2 Main shortcomings

In this thesis, the most thorough analysis has been conducted on an MNO as the entrant user accessing a spectrum band using LSA. This case is actually quite straightforward as the architecture of the MNO does not need to be modified and access to a shared band can be implemented with additional functional blocks on top of the existing cellular architecture. This is one of the key reasons why LSA is an attractive solution, especially in Europe where the incumbent usage varies between countries. In such a fragmented field where a single country has only a limited market, it is vital to have a sharing solution that allows the use of the same network and end user equipment, regardless of the incumbent usage, to achieve economies of scale. Using LSA, equipment operating on a band with LSA and equipment operating without LSA (in case there is no incumbent usage) are fully interoperable. In the case of the three-tier model and TV WS, more complex end devices are required. Some discussion of how incumbent usage will affect the entrant user and tools required for sharing, in the case of the three-tier model and TV WS, can be found in Section 5.4.1, however, a thorough analysis from the entrant user perspective has not been conducted in the case of the three-tier model or TV white spaces.
Stakeholder analysis is a multidisciplinary research area, which can be analysed from various perspectives such as those of social sciences, economics, and policy, for example. In reality, decisions and actions of stakeholders are highly dependent on the competitive, social, political, institutional, and economic environment in which they operate. Such analysis has intentionally been left out of the scope of this thesis, which instead concentrated on what stakeholders should be doing and the criteria they should consider in order to accomplish a viable sharing concept from a technical point of view. Looking at the feasibility of a spectrum sharing concept as a whole and especially the political debate around it, various additional stakeholders could be identified, such as public interest groups. However, in this thesis a choice was made to limit the stakeholder analysis to the primary stakeholders that have a direct impact on the sharing concept from the technical and spectrum use point of view in order to keep the scope tractable.

6.3 Future work

The author had the privilege of following and contributing to the development of the LSA concept from the first trials all the way into the development of the international regulatory and standardization framework. Currently, the concept is ready for the first NRA to start the national process for awarding access rights on a spectrum band using the developed framework. However, currently there has been no interest from the entrant user side for a framework, which would allow them limited and lower access rights to a spectrum band in comparison to the incumbent user. In particular, major mobile operators have protested against such a framework. In order to gain from the full innovation potential of the LSA concept, the framework could be applied to allow new players to enter the business. This could be applied either to provide a service that would not require 100 per cent availability, or to a band where the availability is highly predictable. One such band in Europe is the 3.6-3.8 GHz band, where the static nature of FSS usage would guarantee the LSA band availability in the licence area for a known period of time. In addition, this would require the related tools and authorization process to be developed for distributed operations, including investigations on topics related to distributed databases, such as blockchains. Support from the network side would include concepts like network slicing and cloud core. From the NRA perspective, methods and procedures to enable local licensing should be developed, for example the concept of the micro-operator. Future research on these topics would without a doubt also benefit – or even become a prerequisite to – the commercialization
process of the other sharing concepts considered in this thesis, namely, TV white spaces and the three-tier model.
List of references


CEPT (2015a) Report 56: Technological and regulatory options facilitating sharing between Wireless broadband applications (WBB) and the relevant incumbent services/applications in the 2.3 GHz band. European Conference of Postal and Telecommunications Administrations.


EC (2014) DG CONNECT/B4: Mandate to CEPT to develop harmonised technical conditions for the 2300-2400 MHz (‘2.3GHz’) frequency band in the EU for the provision of wireless broadband electronic communication services. European Commission.


ECC (2016) Report 254: Operational guidelines for spectrum sharing to support the implementation of the current ECC framework in the 3.6-3.8 GHz range. European Conference of Postal and Telecommunications Administrations, Electronic Communications Committee.


ETSI (2014a) EN 301 598: White Space Devices (WSD); Wireless Access Systems operating in the 470 MHz to 790 MHz frequency band; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive. European Telecommunications Standards Institute.


ETSI (2015a) TS 103 143: System architecture for information Exchange between different Geo-Location databases (GLDB’s) enabling the operation of White Space Devices (WSDs). European Telecommunications Standards Institute.


ETSI (2015d) EN 303 144: Parameters and procedures for information exchange between different GLDBs. European Telecommunications Standards Institute.


ETSI (2017) TS 103 379: Information elements and protocols for the interface between LSA Controller (LC) and LSA Repository (LR) for operation of Licensed Shared Access (LSA) in the 2300 MHz-2400 MHz band. European Telecommunications Standards Institute.


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