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FIELD MEASUREMENTS IN DETERMINING INCUMBENT SPECTRUM UTILIZATION AND PROTECTION CRITERIA IN WIRELESS CO-EXISTENCE STUDIES

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Abstract

Studies of spectrum sharing and co-existence between different wireless communication systems are important, as the current aim is to optimize their spectrum utilization and shift from static exclusive spectrum allocation to more dynamic co-existence of different systems within same frequency bands. The main goal of this thesis is to provide measurement methodologies for obtaining realistic results in modeling incumbent spectrum utilization and in determining incumbent protection criteria.

The following research questions are considered in this thesis: Q1) How should field measurements be conducted and used to model incumbent spectrum utilization? Q2) How should field measurements be conducted and used to determine protection criteria for incumbents in a co-existence scenario with mobile broadband? and Q3) Which licensing methods and technological solutions are feasible to enable spectrum sharing in frequency bands with incumbents?

To answer to Q1, this thesis describes the development of a spectrum observatory network concept created through international collaboration and presents measurement methodologies, which allow to obtain realistic spectrum occupancy data over geographical areas using interference map concept. A cautious approach should be taken in making strong conclusions from previous single fixed location spectrum occupancy studies, and measurements covering larger geographical areas might be needed if the measurement results are to be used in making spectrum management decisions.

The field interference measurements considered in Q2 are not covered well in the current research literature. The measurements are expensive to conduct as they require substantial human resources, test network infrastructure, professional level measurement devices and radio licenses. However, field measurements are needed to study and verify hypotheses from computer simulations or theoretical analyses in realistic operating conditions, as field measurement conditions can not or are not practical to be adequately modeled in simulations. This thesis proposes measurement methodologies to obtain realistic results from field interference measurements, taking into account the propagation environments and external sources of interference. Less expensive simulations and laboratory measurements should be

used both to aid in the planning of field measurements and to complement the results obtained from field measurements.

Q3 is investigated through several field interference measurement campaigns to determine incumbent protection criteria and by analyzing the spectrum observatory data to determine the occupancy and trends in incumbent spectrum utilization. The field interference measurement campaigns have been conducted in real TV White Space, LTE Supplemental Downlink and Licensed Shared Access test network environments, and the obtained measurement results have been contributed to the development of the European spectrum regulation. In addition, field measurements have been conducted to contribute to the development and technical validation of the spectrum sharing frameworks.

This thesis also presents an overview of the current status and possible directions in spectrum sharing. In conclusion, no single spectrum sharing method can provide universally optimal efficiency in spectrum utilization. Thus, an appropriate spectrum sharing framework should be chosen taking into account both the spectrum utilization of the current incumbents and the future needs in wireless communications.

Tiivistelmä

Langattomien tietoliikennejärjestelmien taajuuksien jakamisen ja yhteiskäytön tutkiminen on tärkeää, koska taajuushallinnan tämänhetkinen tavoite on taajuuksien käytön tehostaminen sekä siirtyminen staattisesta eksklusiivisesta taajuusallokoinnista dynaamiseen eri järjestelmien yhteiskäyttöön samoilla taajuuskaistoilla. Tämän väitöstyön päätavoitteena on kehittää kenttämittauksiin menetelmiä, joita hyödyntämällä saataisiin todenmukaisia tuloksia vakiintuneiden käyttäjien taajuuskäytön mallintamisessa ja suojauksen kriteerien määrittelyssä.

Tämä työ pyrkii vastaamaan seuraaviin tutkimuskysymyksiin: K1) Miten kenttämittaukset vakiintuneiden käyttäjien taajuuskäytön mallintamiseksi tulisi tehdä ja miten mittaustuloksia voidaan hyödyntää? K2) Miten kenttämittaukset vakiintuneiden käyttäjien suojauskriteerien määrittämiseksi tulisi tehdä ja miten mittaustuloksia voidaan hyödyntää? K3) Mitä lisensointimenetelmiä ja teknisiä ratkaisuja voidaan käyttää mahdollistamaan taajuuksien yhteiskäyttö taajuuskaistoilla, joilla on jo ennestään vakiintuneita käyttäjiä?

Työ vastaa ensimmäiseen tutkimuskysymykseen esittelemällä kansainvälisenä yhteistyönä kehitetyn taajuusobservatoriokonseptin ja mittausmenetelmiä, joiden avulla voidaan esittää häiriökarttoja käyttämällä vakiintuneiden käyttäjien taajuuksien käyttöastetta maantieteellisillä alueilla. Aiempiin yhden kiinteän mittauspaikan taajuuksien käyttöasteen tutkimuksien tuloksiin tulisi suhtautua varauksella, ja suurempia maantieteellisiä alueita kattavia mittauksia saatetaan tarvita mikäli mittaustuloksia käytetään taajuushallinnan päätöksissä.

Toisen tutkimuskysymyksen häiriömittauksia kenttäolosuhteissa ei ole käsitelty kattavasti nykyisessä tutkimuskirjallisuudessa. Häiriömittausten tekeminen on kallista, koska ne vaativat huomattavia henkilöresursseja, testiverkkoinfrastruktuuria, ammattilaistason mittalaitteita ja radiolupia. Kenttämittauksia kuitenkin tarvitaan tietokonesimulaatioiden ja teoreettisten analyysien hypoteesien tutkimiseen ja oikeaksi osoittamiseen todenmukaisissa käyttöolosuhteissa, koska kenttäolosuhteita ei voida tai ei ole käytännöllistä mallintaa riittävän tarkasti simulaatioissa. Tämä työ ehdottaa mittausmenetelmiä, joilla voidaan saada todenmukaisia tuloksia kenttäolosuhteissa

ja jotka ottavat huomioon radiosignaalin etenemisympäristöt sekä ulkoiset häiriölähteet. Edullisempia simulaatioita ja laboratoriomittauksia tulisi käyttää sekä kenttämittausten suunnittelun apuna että täydentämään kenttämittauksista saatuja tuloksia.

Kolmatta tutkimuskysymystä tutkitaan useiden kenttämittauskampanjoiden avulla sekä tutkimalla taajuusobservatorioiden mittausdataa vakiintuneiden käyttäjien taajuuksien käyttöasteen ja taajuuskäytön kehityssuuntien määrittämiseksi. Kenttämittauskampanjat on tehty oikeissa TV White Space, LTE Supplemental Downlink ja Licensed Shared Access -testiverkkoympäristöissä ja mittausten tuloksia on käytetty edesauttamaan Euroopan taajuussääntelyn kehitystä. Kenttämittaustuloksia on käytetty lisäksi taajuuksien jakamisen järjestelmien kehittämisessä ja validoinnissa.

Työ esittää myös yleiskatsauksen taajuuksien jakamisen tämänhetkisestä tilasta ja mahdollisista tulevaisuuden suuntauksista. Tiivistettynä voidaan todeta, että mikään yksittäinen taajuuksien jakamisen menetelmä ei voi tarjota yleisesti mahdollisimman tehokasta taajuuksien käyttöastetta. Sopiva taajuuksien jakamisen menetelmä tulisi valita ottaen huomioon sekä nykyisten vakiintuneiden käyttäjien että tulevaisuuden langattoman viestinnän tarpeet.

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Back in 2008, I had a Bachelor of Science degree from *Multimedia and DVD technology* and was working in a travel company as a Sports and SuperKids leader on the island of Crete in Greece. For some reason, I applied and was accepted to study for a Master's degree in wireless communications at University of Turku. At that moment, I hadn't given the slightest thought to doctoral studies, but here we are.

The research leading to this dissertation was funded by University of Turku, University of Turku Graduate School and Tekes - the Finnish Funding Agency for Technology and Innovation.

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At one point in time, none of my supervisors were at University of Turku. That was far from ideal, but I'm glad that we still managed to pull through!

I also want to express my deep gratitude to Dr. Marko Höyhtyä. In addition to authoring two of the publications included in this dissertation, he has in practice been a supervisor for me in the final stages of my dissertation. Thank you for the help and the significant contribution in improving and clarifying this dissertation and the last journal submission.

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I am very honored to have Dr. David Gómez-Barquero as my opponent. I still have warm memories from our brief encounter in Valencia in 2010 and I'm hoping that future will bring more good memories.

I am very grateful to Pekka Talmola, whose expertise in DTT receivers, participation in the regulatory work in the EU and in planning and conducting the field measurements has been the absolute foundation of this dissertation.

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Janne Penttilä, Jussi Penttilä and Maria Tikka, I constantly admire how genuine, unfaltering and honest you are. You represent all the qualities in a person which I value the most. I would consider myself unbelievably lucky having even one of you as my friend, and I'm at a loss of words what it means to me to be friends with the three of you.

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I want to warmly thank my parents Merja and Jouko and my sisters Siru and Katja for always being there for me and for their unquestioned love and support.

Turku, April 18, 2017,
Juha Kalliovaara

Contents

Acronyms

1G 1st generation mobile networks. 18

2G 2nd generation mobile networks. 18

3G 3rd generation mobile networks. 18

3GPP the 3rd Generation Partnership Project. 18, 89

4G 4th generation mobile networks. 18

5G 5th generation mobile networks. 3, 18, 19, 75, 79, 95

ACIR adjacent channel interference power ratio. 49, 50

ACLR adjacent channel leakage ratio. 48, 49, 48, 49, 50, 59, 70

ACS adjacent channel selectivity. 47, 48, 49, 50, 59

AGC automatic gain control. 33, 45, 47, 50

ASA Authorized Shared Access. 82

AVMS audiovisual media Services. 76, 78

BBC British Broadcasting Corporation. 68

BEM block edge mask. 50, 53, 58, 78

BER bit error rate. 43, 44

BRAN Broadband Radio Access Networks. 70

BS base station. 43, 48, 50, 57, 58, 59, 76, 78, 86, 87

CA carrier aggregation. 19, 20, 74, 84

CBRS Citizens Broadband Radio Service. 88

CEPT European Conference of Postal and Telecommunications Administrations. 8, 17, 21, 23, 24, 50, 53, 64, 65, 66, 69, 72, 74, 81, 83, 84, 85, 86, 88

CK Cokriging. 36

CMOS complementary metal oxide semiconductor. 46

CR cognitive radio. 65, 66, 67

CSV comma-separated value. 34

CULT Committee on Culture and Education. 76

CUS Collective Use of Spectrum. 20

dBd decibels relative to a reference dipole antenna. 38

dBm decibel-milliwatt. 77

DSM Digital Single Market. 4, 23

DTT digital terrestrial television. 1, 4, 6, 8, 10, 12, 15, 29, 36, 38, 39, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 52, 53, 54, 55, 57, 58, 57, 58, 59, 60, 64, 65, 66, 67, 68, 69, 70, 75, 76, 77, 78, 79, 80, 94, 95

DVB-H Digital Video Broadcasting - Handheld. 64

DVB-T Digital Video Broadcasting - Terrestrial. 43, 44, 64, 86

DVB-T2 Digital Video Broadcasting - Second Generation Terrestrial. 43, 64, 80

EC European Commission. 21, 22, 23, 24, 74, 76, 83

ECC Electronic Communications Committee. 8, 21, 23, 24, 47, 57, 64, 65, 66, 67, 69, 72, 73, 76, 84, 85, 86, 87, 88

ECP European Common Proposal. 23

EHF extremely high frequency. 19

eMBMS evolved Multimedia Broadcast Multicast Service. 80

ESC Environmental Sensing Capability. 88

ESR_5 Erroneous Second Ratio 5. 43, 44, 45, 50

ETSI European Telecommunications Standards Institute. 8, 21, 23, 24, 64, 66, 70, 72, 73, 79, 88, 89

EU European Union. 4, 20, 22, 23, 24, 47, 48, 64, 69, 78, 94

FBMC filter bank multicarrier. 95

FCC Federal Communications Commission. 73

FDD frequency-division duplex. 74

FEF Future Extension Frame. 80

FICORA the Finnish Communications Regulatory Authority. 66

FM frequency modulation. 15, 33

FSPL free-space path loss. 58

FUHF the Future of UHF Frequency Band. 75, 76, 80

GAA General Authorized Access. 88

GE06 Geneva 2006 frequency plan. 63, 64, 78, 79

GMM Gaussian mixture model. 34

GPS Global Positioning System. 38, 39

GSM Global System for Mobile Communications. 18, 33

GSMA the GSM Association. 18

IC integrated circuit. 46

ICT information and communications technology. 16, 24

IDW inverse distance weighted. 36

IEEE Institute of Electrical and Electronics Engineers. 73

IF intermediate frequency. 45, 46

IMT International Mobile Telecommunications. 15, 17, 18, 19, 20, 82, 89

IMT-Advanced International Mobile Telecommunications-Advanced. 18

IMT-2000 International Mobile Telecommunications-2000. 18

IoT Internet of Things. 1, 95

ISM industrial, scientific and medical. 20

ITU International Telecommunication Union. 16, 18, 74

ITU-R International Telecommunication Union Radiocommunication sector. 16, 17, 19, 28, 30, 41, 50, 52, 58, 79, 81, 88, 89

LAA License Assisted Access. 20

LDM Layer Division Multiplexing. 79

LNA low-noise amplifier. 33, 45

LSA Licensed Shared Access. 2, 4, 9, 12, 21, 81, 82, 83, 84, 85, 86, 87, 88, 89

LTE Long Term Evolution. 9, 12, 18, 20, 43, 48, 50, 58, 64, 75, 76, 78, 79, 80, 86, 88, 95

LTE-A+ LTE-Advanced+. 80

LTE-A LTE-Advanced. 18

M2M machine-to-machine. 75

MAE mean absolute error. 36

MBB mobile broadband. 1, 3, 9, 12, 15, 17, 23, 27, 41, 48, 50, 57, 58, 60, 64, 68, 69, 73, 74, 75, 76, 78, 79, 81, 82, 84, 85, 86, 94

Mbps Megabits per second. 27

MCD measurement-capable device. 87

MCL minimum coupling loss. 58, 67, 69

MMSD minimum mean shortest distance. 36

MNO mobile network operator. 20, 21, 74, 78, 82, 83, 84, 88, 89

MoU memorandum of understanding. 24

MPEG-2 Motion Picture Experts Group 2. 44

MSD minimum separation distance. 85, 86, 87

MUKV mean universal Kriging variance. 36

NICT National Institute of Information and Communications Technology. 73

NRMSE normalized root mean square error. 36

NSF National Science Foundation. 32

OA&M operations, administration and maintenance. 84

OB outside broadcasting. 81, 86

Ofcom the Office of Communications. 68, 72

OFDMA orthogonal frequency-division multiple access. 50

OJEU Official Journal of European Union. 24

OK ordinary Kriging. 36

OOB out-of-band. 47, 49, 50, 53

OSA opportunistic spectrum access. 2

PAL Priority Access License. 88

PMSE Programme Making and Special Events. 4, 10, 29, 65, 66, 69, 70, 72, 75, 81, 84, 85, 86

PPDR Public Protection and Disaster Relief. 75

PR protection ratio. 41, 42, 43, 44, 45, 46, 47, 48, 50, 52, 53, 58, 67, 68, 70, 86

PSD power spectral density. 50

QEF quasi error free. 43, 44

QoS quality of service. 20, 21, 73, 81, 83

R&TTE Radio and Telecommunication Terminal Equipment. 24, 70

RB resource block. 50

RBW resolution bandwidth. 30

RED Radio Equipment Directive. 24, 48

REM radio environment mapping. 28, 29, 30, 35, 36, 38, 87

RF radio frequency. 7, 29, 32, 33, 45, 47, 70

RMS root mean square. 41, 50

RR Radio Regulations. 16, 17, 88

RRC-06 Regional Radiocommunication Conference 2006. 63

RRS Reconfigurable Radio Systems. 83

RSC Radio Spectrum Committee. 22

RSPG Radio Spectrum Policy Group. 23, 76, 82, 83

RSPP Radio Spectrum Policy Programme. 23

RSSI received signal strength indicator. 38, 39, 92

SAS Spectrum Access System. 12, 21, 81, 88, 89

SC-FDMA single-carrier frequency-division multiple access. 50

SDL Supplemental Downlink. 12, 74, 75, 76, 78, 79, 80, 95

SDR software-defined radio. 65

SE43 Spectrum Engineering 43. 8, 65, 66, 67, 69, 70

SFP subjective failure point. 43, 44, 45

SINR signal-to-interference-plus-noise ratio. 46, 47, 49, 57, 76, 87

SOM the Self-Organizing Map. 34

SRD Short Range Device. 20

SSA spatial simulated annealing. 36

ST61 the Stockholm 1961 Agreement. 63

TB terabyte. 32

TDD time-division duplex. 75

TOoL+ Tower Overlay over LTE-Advanced+. 80

TVWS TV White Space. 6, 8, 10, 12, 21, 29, 57, 58, 63, 64, 65, 66, 67, 70, 72, 73

UE User Equipment. 9, 12, 58, 86

UHF ultra high frequency. 4, 12, 54, 58, 63, 64, 65, 66, 70, 73, 74, 75, 76, 78, 79, 80, 95

UK United Kingdom. 67, 72, 73

UN United Nations. 16

US the United States. 4, 21, 32, 34, 73, 88

WBB wireless broadband. 17, 84, 85

WG FM Working Group Frequency Management. 83

WG SE Working Group Spectrum Engineering. 65

WiFiUS Wireless Innovation between Finland and the US. 32

WISE White Space Test Environment for Broadcast Frequencies. 38, 63, 66, 67, 70, 72

WRAN wireless regional area network. 73

WRC World Radiocommunication Conference. 16, 17, 23, 78

WRC-23 World Radiocommunication Conference 2023. 76

WRC-15 World Radiocommunication Conference 2015. 74, 76

WRC-12 World Radiocommunication Conference 2012. 74

WRC-07 World Radiocommunication Conference 2007. 64, 81

WRC-19 World Radiocommunication Conference 2019. 19, 76

WSD white space device. 8, 12, 66, 67, 68, 69, 70, 72, 73

Chapter 1

Introduction

The radio spectrum is a limited natural resource, which covers the frequency range of electromagnetic radiation from 9 kHz up to 3000 GHz [1]. Radio frequencies can be used to send and receive information over radio waves without a physical contact. A radio transmitter uses an antenna to convert electricity into information-transmitting radio waves, which are received and converted back to electricity by radio receivers and their antennas. This communication over radio waves is hence called wireless communications. Different wireless communication systems, such as voice radio, digital terrestrial television (DTT), mobile telephony, and mobile broadband (MBB) are ubiquitous in our daily lives.

Demand for radio spectrum is constantly increasing as wireless services, especially video streaming and emerging Internet of Things (IoT), are being adopted at an accelerating pace. Mobile phones, laptops and tablets are becoming more and more common, and the quality of available content and services is also increasing. This has resulted in rapid increases in the amount of traffic in mobile networks, and the increases are predicted to continue [2–4]. This presents extreme challenges for mobile communication systems, as there is a lack of new spectrum resources to be allocated for the growing number of connected devices, services and users.

The wireless communication technologies themselves are approaching the fundamental theoretical limits of bandwidth efficiency, but simultaneously the frequency bands are exclusively licensed to different services which might not utilize all of their spectrum resources. Valuable spectrum resources can be left unexploited at different frequencies if the license owner does not use them at all times or at all locations. For example, several spectrum measurement campaigns covering frequencies up to 3 GHz state that the spectrum utilization rate is on the scale of 10 to 20% [5–7], and thus most of the spectrum resources remain unused. It is necessary to utilize the existing frequency resources more efficiently to satisfy the growing demand for spectrum, but the current exclusive licensing methods do not allow this. Recent international studies have concluded that spectrum sharing will play a major role in maximizing the amount of available spectrum for wireless communications systems [8, 9].

The current exclusive spectrum licensing needs to be updated or replaced to enable spectrum sharing. In spectrum sharing, the users who currently hold an exclusive license to use a frequency band are called incumbents, and are the primary users of the band. If the incumbents are using their spectrum resources inefficiently, their spectrum resources could potentially be shared with other users who could use the vacant spectrum resources at certain times or at certain locations where the license holder does not have any transmissions. Spectrum occupancy measurements have been proposed to find candidate frequency bands for spectrum sharing [5]. The vacant spectrum resources could be utilized through dynamic spectrum access methods, such as opportunistic spectrum access (OSA) [10] or Licensed Shared Access (LSA) [11]. In OSA, the shared spectrum user chooses the best available vacant transmission channel in an opportunistic and dynamic manner as an unlicensed secondary user of the spectrum, who does not need a license, but does not have any guarantees on the amount and quality of available spectrum and has no protection from any harmful interference. In LSA, vacant spectrum resources can be leased to shared spectrum users, known as LSA licensees, who are guaranteed an exclusive access to the leased spectrum resources and are protected from harmful interference. The incumbents are also protected from interference and might receive economic benefits from leasing their underutilized spectrum resources. The terminology and definitions for shared spectrum access methods is diverse, but OSA and LSA could be considered as the two main categories in frequency bands with existing incumbents.

Regardless of the used shared spectrum access method, it is essential to guarantee that the incumbents currently present in the band are protected from any harmful interference that could be induced by the newly introduced shared spectrum users. Studies on incumbent spectrum utilization and on the protection of incumbents are needed to validate the feasibility of shared spectrum access methods and to define which frequency resources are available for spectrum sharing and at what power levels the shared spectrum users could operate without causing harmful interference to the incumbents. Based on the results of these studies, regulations and radio equipment standards need to be created or updated to enable spectrum sharing in different frequency bands.

1.1 Motivation and goals

Traditionally new spectrum has been repurposed to mobile networks, but the spectrum resources below 6 GHz have already been allocated to different services on a dedicated basis. Studies on the operation of the future 5th generation mobile networks (5G) are currently active in frequencies between 24 and 86 GHz [12,13], which can provide the large bandwidths and high data rates required by the increasing amount of MBB traffic. However, the radio waves do not travel over long distances in frequencies this high. Building mobile networks operating solely on these higher frequencies would require a lot of base stations and be extremely costly.

As the frequencies below 6 GHz are able to provide the needed coverage and to reduce the costs of building mobile networks due to their better propagation characteristics, spectrum resources below 6 GHz are expected to play a key role in 5G [14]. Spectrum sharing is needed to improve the efficiency of spectrum utilization in these frequencies, and especially spectrum below 1 GHz will be essential in providing nationwide and indoor coverage for 5G [15].

This thesis studies shared spectrum access from the incumbent point-of-view. The focus is on using field measurements in studies evaluating incumbent spectrum utilization to find underutilized candidate frequency bands for spectrum sharing and determining protection criteria to allow spectrum sharing implementations which guarantee that the incumbents are protected from any harmful interference. The term field measurement refers to any radio signal measurement conducted outside of a controlled laboratory environment.

The research questions are:

Q1 How should field measurements be conducted and used to model incumbent spectrum utilization?

Q2 How should field measurements be conducted and used to determine protection criteria for incumbents in a co-existence scenario with mobile broadband?

Q3 Which licensing methods and technological solutions are feasible to enable spectrum sharing in frequency bands with incumbents?

In addition to answering these questions, an objective of this thesis is to present an overview of the current status and possible directions of spectrum sharing. The main goal of this thesis is to provide measurement methodologies for obtaining realistic results in modeling incumbent spectrum utilization and in determining incumbent protection criteria. These methodologies can and have been used to conduct field measurements in real test network environments to study the feasibility of different spectrum sharing methods.

To answer Q1, a long-term spectrum observatory measurement system network in Finland and the United States (US) is collaboratively developed to study the measurement methodologies to determine the spectrum utilization of the incumbents and to determine the optimal measurement system architecture. Field measurements are also conducted to build radio environment maps modeling the signal levels of the incumbent transmissions.

To answer Q2, the protection of the incumbents from harmful interference is investigated in realistic operating conditions through interference measurements in field conditions in real test network environments. Such test network environments are rare in the academia and the incumbent protection is usually studied through laboratory measurements or theoretical simulations. Based on reviewing existing literature and on the experience gained from conducting field interference measurements, this thesis proposes methodologies to conduct interference measurements in field conditions and analyzes the role of field measurements in studies of incumbent protection.

To investigate Q3, field measurement campaigns are conducted in two case studies on unlicensed and licensed spectrum sharing in ultra high frequency (UHF) TV band and on licensed sharing in 2.3-2.4 GHz frequency band. The incumbents operating in these bands are DTT receivers and Programme Making and Special Events (PMSE) equipment, such as wireless microphones and wireless cameras. The European level regulation and standardization work to enable spectrum sharing is very active, and the European Union (EU) is working on breaking the existing barriers and creating policies for Digital Single Market (DSM) [16] to enable access to digital services for the citizens throughout the whole union. Thus, the field measurement campaigns aim to contribute to the studies on topical matters in European spectrum harmonization. The measurements have been conducted in collaboration with Turku University of Applied Sciences, Illinois Institute of Technology, Aalto University, VTT and Centria.

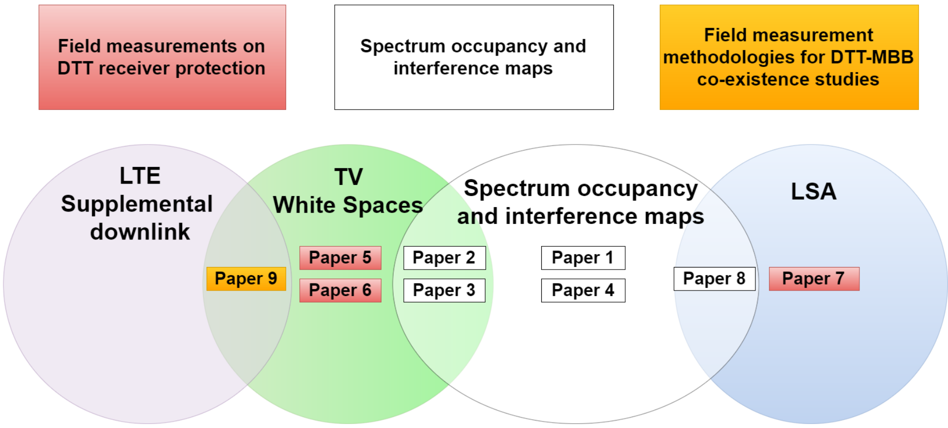

Figure 1.1: The relation between the publications and the topics of this thesis.

1.2 Publications and author's contributions

The author is the first or co-first author in papers 4, 5, 6, 7 and 9. In papers 2 and 3, the author is the second author and has independently conducted the field measurement campaigns and validated the data which was used to create the radio environment maps. The author's contributions in Paper 8 are minor, but the paper is included to demonstrate how the spectrum occupancy measurements were used in the LSA feasibility studies in 2.3 GHz band, which were later complemented by the field interference measurements in Paper 7. The author's contributions in Paper 1 are also minor, but it is included as it comprehensively surveys the methodologies for spectrum occupancy measurements and interpolation methods, to which the author has contributed in papers 2, 3, 4, 8 and related publications [17, 18]. Figure 1.1 illustrates the relation of each included publication to the topics within this thesis.

- **Paper 1** [19] Marko Höyhtyä, Aarne Mämmelä, Marina Eskola, Marja Matinmikko, Juha Kalliovaara, Jaakko Ojaniemi, Jaakko Suutala, Reijo Ekman, Roger Bacchus, and Dennis Roberson: Spectrum occupancy measurements: A survey and use of interference maps. IEEE Communications Surveys & Tutorials. 2016, volume 8, number 4.

  This article surveys measurement campaigns and associated interference maps, introducing the latter as a tool for spectrum analysis and management based on the measurement data. Comprehensive methodology for the measurement and analysis of spectrum occupancy is presented. The different phases of the spectrum occupancy measurement and analysis process are described and a thorough discussion of interpolation methods is provided. Means to improve the measurement accuracy are discussed, especially regarding spatial domain considerations and the impact of the sampling interval on the results. A practical example of an improved measurement system design covering all the phases of the measurement process and used at the Turku, Finland, Blacksburg, VA and Chicago, IL spectrum observatories is given. Using the improved design, more realistic spectrum occupancy data can be obtained to lay the foundation for spectrum management decisions.

Author's contributions: The author has contributed to the interference map concept through the work originally conducted in papers 2 and 3, where interpolation methods were used to create signal level maps for DTT broadcasting networks to be used in TV White Space (TVWS) geo-location databases. This work produced measurement data and important example figures to this survey article. The author has also contributed to the spectrum observatory measurement system design, spectrum data analysis in papers 4, 8 and [17, 18], provided references and reviewed the article. The concept of creating interference maps using the spectrum occupancy data was created by the first author of the article together with the second author.

- **Paper 2** [20] Jaakko Ojaniemi, Juha Kalliovaara, Ahmad Alam, Jussi Poikonen, and Risto Wichman: Optimal field measurement design for radio environment mapping. CISS 2013, Baltimore, Maryland, USA, March 2013.

  TVWS geo-location database is fundamentally based on field strength estimates of the primary service obtained using radio propagation models. Even with the most sophisticated propagation models currently available, the predicted values always contain errors due to the limited geographical information. To overcome this, a geostatistical approach for estimating the radio environment based on universal Kriging interpolation is proposed in this paper. The samples collected from the measurement locations are used to interpolate the signal strength values for locations where no measurements have been conducted.

  Author's contributions: The author has built the measurement setup, planned and conducted an extensive field measurement campaign to provide the measurement samples needed for the interpolation process and to verify the proposed modeling procedure, and validated and analyzed the measurement data.

- **Paper 3** [21] Jaakko Ojaniemi, Juha Kalliovaara, Jussi Poikonen, and

Risto Wichman: A practical method for combining multivariate data in radio environment mapping. PIMRC 2013, London, UK, September 2013.

This paper proposes a multivariate Kriging method which utilizes correlated secondary information obtained from a terrain based propagation prediction model to complement the measurement data. A considerable improvement in prediction accuracy is achieved compared to univariate interpolation methods. The proposed method is especially practical in scenarios where relatively small numbers of measurement samples are available or the sampling locations are distant, and additional accuracy in the boundaries of the prediction surface is needed.

Author's contributions: The author has built the measurement setup, planned and conducted an extensive field measurement campaign to provide the samples needed for the interpolation process and to verify proposed modeling procedure, and validated and analyzed the measurement data.

- **Paper 4** [22] Ryan Attard, Juha Kalliovaara, Tanim Taher, Jesse Taylor, Jarkko Paavola, Reijo Ekman, Dennis Roberson: A high-performance tiered storage system for a global spectrum observatory network. CROWNCOM 2014, Oulu, Finland, June 2014.

  This paper describes the measurement band plan, storage and database architecture for long-term continuously measuring radio frequency (RF) spectrum observatories in Finland and the US. The collaborative creation of an improved measurement band plan is described in detail. The new band plan for the spectrum measurement system allows collection of spectrum data with higher sensitivity through careful use of band-pass filters to attenuate strong out-of-band transmissions, and by using an amplifier for the weaker signals in the 3-6 GHz band. The developed band plan eliminates the noise floor fluctuation present in the earlier implementation and eliminates distortions caused by the strong signals. The measurement system is covered in more detail in Paper 1.

  Author's contributions: This paper combines two aspects: database design and the spectrum measurement system and its band plan. The author has written parts related to wireless communications and can thus be considered as a co-first author. The author has contributed to the development of the improved measurement band plan by analyzing the spectrum data to determine the limitations of the measurement equipment and to determine the strong signals needing to be attenuated to improve the sensitivity of the measurement system. The author also participated in developing centralized on-server analysis of the spectrum data and in improving the data processing methods.

- **Paper 5** [23] Pekka Talmola, Juha Kalliovaara, Jarkko Paavola, Reijo Ekman, Heikki Kokkinen, Kari Heiska, Risto Wichman, Jussi Poikonen: Field measurements of WSD-DTT protection ratios over outdoor and indoor reference geometries. CROWNCOM 2012, Stockholm, Sweden, June 2012.

  This paper presents field measurement campaigns conducted in a DTT test network to determine protection criteria for DTT reception against interference from a white space device (WSD). The campaigns are based on reference scenarios created in the European Conference of Postal and Telecommunications Administrations (CEPT)/Electronic Communications Committee (ECC) group Spectrum Engineering 43 (SE43), where technical work to define European-wide WSD protection ratio proposals has been performed. The measurement results provide realistic numerical estimates on the maximum possible transmitted power of a WSD without visible errors in DTT reception in the reference scenarios.

  Author's contributions: The paper is written by the author. The author took part in planning and conducting the measurements and analyzing the results. The original motivation for the conducted measurements is from Mr. Pekka Talmola, who was active in the CEPT/ECC SE43 working group and has reported and contributed the measurement results to the group.

- **Paper 6** [24] Juha Kalliovaara, Jarkko Paavola, Reijo Ekman, Arto Kivinen, Pekka Talmola. Book chapter: TV White Space network trials. Book editors: Robert Stewart, David Crawford, Andrew Stirling, and Sarah Lynch. TV White Space Communications and Networks, Elsevier, 2017. (Reviewed final submission)

  This book chapter describes TVWS field interference measurements and application pilot trials performed in Finland during 2011-2014. A TVWS test network environment was developed and built in Turku, Finland, along with a geo-location database to control the frequency use. The environment was built to conduct interference measurements, which were part of the work in the CEPT/ECC SE43 group and have contributed to the creation of harmonized technical conditions for TVWS and to a European Telecommunications Standards Institute (ETSI) standard for WSDs. Two application pilot trials to demonstrate the feasibility of TVWS networks are also presented: Helsinki area public transport ticket sales and transit information screens trial and a video surveillance trial.

Author's contributions: The author has written the paper and participated in the described work apart from the geo-location database design.

- **Paper 7** [25] Juha Kalliovaara, Tero Jokela, Reijo Ekman, Juhani Hallio, Mikko Jakobsson, Tero Kippola, and Marja Matinmikko. Interference Measurements for Licensed Shared Access (LSA) between LTE and Wireless Cameras in 2.3 GHz Band. IEEE DySPAN 2015, Stockholm, Sweden, September 2015.

  This paper presents a field measurement campaign investigating the protection of an incumbent professional level wireless camera in the 2.3 GHz band from interference originating from a Long Term Evolution (LTE) User Equipment (UE). The band had been identified as a possible candidate for the introduction of LTE MBB services in Europe with LSA concept, and thus studies on the incumbent protection were needed. These results can be considered as the first practical studies in determining the critical geographical separation between the incumbent wireless cameras and interfering LTE UE transmissions.

  Author's contributions: The paper is written by the author, who participated in planning and conducting the measurements and analyzing the results.

- **Paper 8** [26] Marko Höyhtyä, Marja Matinmikko, Xianfu Chen, Juhani Hallio, Jani Auranen, Reijo Ekman, Juha Röning, Jan Engelberg, Juha Kalliovaara, Tanim Taher, Ali Riaz, and Dennis Roberson: Spectrum Occupancy Measurements in the 2.3-2.4 GHz band: Guidelines for Licensed Shared Access in Finland. EAI Endorsed Transactions on Cognitive Communications, Volume 1, Issue 2, May 2015.

  This paper presents results from spectrum occupancy measurements in the 2.3-2.4 GHz band in Turku, Finland. The recently introduced LSA concept is reviewed as a potential means for making the 2.3-2.4 GHz band available for mobile communications on a shared basis while protecting the rights of the incumbent spectrum users. The spectrum occupancy measurements conducted in one location in Finland show that the use of this band is rather low indicating that there might be potential for mobile communication systems to share this band with the incumbents under the LSA approach.

  Author's contributions: The author has contributed to processing and analyzing the spectrum data from Turku observatory to determine the spectrum occupancy in the band and participated in conducting and analyzing a demonstrative measurement to determine how wireless camera moving in a given terrain profile can be seen from the spectrum observatory data.

- **Paper 9** [27] Juha Kalliovaara, Reijo Ekman, Pekka Talmola, Marko Höyhtyä, Tero Jokela, Jussi Poikonen, Jarkko Paavola and Mikko Jakobsson: Co-Existence of DTT and Mobile Broadband: a Survey and Guidelines for Field Measurements. Wireless Communications and Mobile Computing (accepted with minor revisions).

  This article provides a survey and a general methodology for co-existence studies between digital terrestrial television (DTT) and mobile broadband (MBB) systems in the ultra high frequency (UHF) broadcasting band. The methodology includes characterization of relevant field measurement scenarios and gives a step-by-step guideline on how to obtain reliable field measurement results to be used in conjunction with link budget analyses, laboratory measurements and simulations. A survey of potential European co-existence scenarios and regulatory status is given to determine feasible future use scenarios for the UHF TV broadcasting band. The DTT reception system behavior and performance are also described as they greatly affect the amount of spectrum potentially available for MBB use and determine the relevant co-existence field measurement scenarios. Simulation methods used in determining broadcast protection criteria and in co-existence studies are briefly described to demonstrate how the information obtained from field measurements can be used to improve their accuracy. The presented field measurement guidelines can be applied to any DTT-MBB co-existence scenarios and to a wide range of spectrum sharing and cognitive radio system co-existence measurements.

  Author's contributions: The paper is written by the author. The text and proposed methodologies are based on reviewing existing literature, experience gained from conducting field interference measurements and discussions with other authors.

Related publications

- Jarkko Paavola, Juha Kalliovaara, and Jussi Poikonen. Book chapter *TVWS coexistence with incumbents* in *Cognitive Radio Policy and Regulation: Techno-Economic Studies to Facilitate Dynamic Spectrum Access* [28]. The author participated in writing this book chapter, which explores the field measurement campaigns related to protecting DTT and PMSE wireless microphones in TVWS concept. The content is largely overlapping with papers 5 [23] and 6 [24], and thus this publication is not included in this thesis.

- Juha Kalliovaara, Reijo Ekman, Tero Jokela, Mikko Jakobsson, Pekka Talmola, Jarkko Paavola, Esko Huuhka, Matti Jokisalo and Mikko Meriläinen. *Suitability of ITU-R P.1546 propagation predictions for* *allocating LTE SDL with GE06* [29], accepted for publication in *2017 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting*. This paper presents a comparison and an analysis between signal strengths obtained using ITU-R P.1546 propagation prediction method, field measurements and a professional level network planning tool. This analysis is used to determine if ITU-R P.1546 propagation predictions are suitable for allocating LTE SDL with GE06.

- Marko Höyhtyä, Marja Matinmikko, Xianfu Chen, Juhani Hallio, Jani Auranen, Reijo Ekman, Juha Röning, Jan Engelberg, Juha Kalliovaara, Tanim Taher, Ali Riaz, and Dennis Roberson. *Measurements and analysis of spectrum occupancy in the 2.3-2.4 GHz band in Finland and Chicago* [17], *CROWNCOM 2014*. The author has contributed to processing and analyzing the spectrum observatory data to determine the spectrum occupancy in both locations. Paper 8 [26] is an extended journal article of this paper.

- Abdallah Abdallah, Allen MacKenzie, Vuk Marojevic, Juha Kalliovaara, Roger Bacchus, Ali Riaz, Dennis Roberson, Juhani Hallio, and Reijo Ekman. *Detecting the impact of human mega-events on spectrum usage* [18], *IEEE Annual Consumer Communications Networking Conference 2016*. This publication studies the correlation between human activities and spectrum occupancy in large events. The author has contributed to processing and analyzing the spectrum measurement data.

1.3 Structure and contributions of the thesis

The introduction of this thesis provides a tutorial-type introduction to spectrum sharing to put in context the relevance of the subjects studied in the included papers. As it is not trivial to differentiate the contributions of a specific paper and the author's contributions to that paper without interrupting the smooth flow of the text, one should refer to the previous section for precisely defined list of author's contributions to each of the included papers.

The thesis is organized into seven chapters. This first chapter gives an introduction to the research topic along with the motivation and goals, list of publications and author's contributions, and structure and contributions of the thesis. Below is a chapter-by-chapter description of the rest of the chapters and the main original contributions in them.

Chapter 2 briefly overviews spectrum management, regulation and licensing to clarify why spectrum sharing is needed. Mobile telecommunications and European spectrum harmonization are described in more detail to put in context the case studies of this thesis.

Chapter 3 investigates methods to model incumbent spectrum utilization. The measurement methodologies to obtain realistic spectrum occupancy data are described in Paper 1 [19], which extends the previous state-of-the-art by providing meaningful data about the spectrum utilization over geographical areas instead of a single location. The development of a spectrum observatory network to measure spectrum occupancy data and the improvements made to the spectrum observatory measurement band plan and signal filtering in order to provide more realistic measurement data are described in Paper 4 [22]. Interference maps can be built using measurements at some locations of the map and an algorithm to interpolate the signal levels for the remainder of the map. Papers 2 and 3 [20, 21] describe how interference maps were built using field measurements and Kriging interpolation methods.

Chapter 4 considers field measurements to determine the level of interference a DTT receiver can tolerate from an interfering MBB transmission while still meeting a chosen quality criterion. As field measurements are poorly covered in literature or considered too expensive and time-consuming to be conducted [30], Paper 9 [27] proposes a step-by-step guideline and methodologies to obtain realistic results from field interference measurements, taking into account the propagation environments and external sources of interference. The presented methodologies have been applied to the field interference measurement campaigns conducted in chapters 5 and 6. Paper 9 [27] also analyses the significance and role of field measurements in DTT-MBB co-existence studies, which is a novel contribution to the knowledge.

Chapter 5 describes a chronologically organized case study considering spectrum sharing in the UHF TV band. The chapter begins by describing research conducted to study unlicensed TVWS operation in the band, where Paper 5 [23] presents results from field interference measurement campaigns of WSD-DTT co-existence and Paper 6 [24] introduces the TVWS test network environment built for the field interference measurements and describes the conducted field interference measurements and application pilot trials. The chapter concludes by considering potential regulatory and technological developments in the future use of the UHF TV band. Paper 9 [27] discusses the potential co-existence scenarios within the band, while recent LTE Supplemental Downlink (SDL) field measurement results will be published in [29].

Chapter 6 describes a case study of licensed spectrum sharing in 2.3-2.4 GHz band through LSA concept, whose architecture and development in European regulation are described. The spectrum occupancy studies in Paper 8 [26] and [17] concluded that the wireless camera incumbents occupy only a very small amount of the spectrum resources, which indicates potential for spectrum sharing in this band. The studies on the feasibility of LSA concept and incumbent protection have been active in Europe, and the field interference measurement campaign in Paper 7 [25] provided the first practical results of the geographical separation needed between LTE UE interferer and wireless camera incumbents. The chapter concludes with a comparison between LSA and the US licensed spectrum sharing concept called Spectrum Access System (SAS).

Chapter 7 concludes the introduction of this thesis.

Chapter 2

Spectrum management

This chapter briefly overviews spectrum management, regulation and licensing methods to clarify why spectrum sharing is needed to enable more efficient utilization of radio spectrum. The recent developments and trends in International Mobile Telecommunications (IMT) are described as mobile broadband (MBB) is the main service for which shared spectrum access is considered in this thesis. As the aim of the work conducted in this thesis is to contribute to the European level spectrum harmonization, it is described in more detail.

2.1 International spectrum management

Everyday commodities, such as mobile telephones, frequency modulation (FM) radio and television broadcasting, satellites and even microwave ovens use radio waves and need spectrum resources for their operation. National defence, air-traffic control, disaster warnings, public safety and many other crucial services also need access to spectrum resources for their operation [31]. All of these services operate on a certain frequency, where a signal is sent from the antenna of a transmitter to the antenna of a receiver. If there is another service sending a strong signal on the same or a nearby frequency, the reception of the wanted signal might get distorted and it might not be received correctly. This phenomenon is called harmful interference. As some interference is always inevitable, acceptable levels of interference which do not cause harm to other transmissions need to be defined [32], and a set of rules and regulations need to be followed to avoid harmful interference. Chapter 4 describes mechanisms by which the harmful interference distorts the reception of the wanted signal in digital terrestrial television (DTT).

Different frequency bands are assigned to different services, which each need to follow a specific set of rules and regulations to transmit in that band. This coordination of spectrum use is called spectrum management. The governments have generally taken the control in managing the use of spectrum and assigning frequency bands to be used by different services. This traditional model where all the decisions are made by a spectrum management authority is referred to as command & control [33], and it is commonly used around the world.

Efficient spectrum management needs to address three interrelated problems [34]:

- Allocation of correct amount of spectrum to different uses or classes of use.
- Assignment of usage rights to different users or groups of users.
- Adjustment of already established policies when technology and markets evolve.

Bandwidth of a transmission channel is the difference between the highest frequency and the lowest frequency of a channel. The higher the bandwidth of a channel, the more information can be transmitted on it [35]. The frequency of a transmission is usually declared as the center frequency of a channel. For example, a channel with a bandwidth of 8 MHz and a center frequency of 610 MHz has its highest frequency at 614 MHz and lowest frequency at 606 MHz (614 MHz-606 MHz = 8 MHz). The lower the frequency is, the lower is the potentially available bandwidth. However, the longer radiowaves at lower frequencies can propagate over longer distances and cover larger geographical areas.

Figure 2.1 conceptually illustrates the kilohertz (kHz), megahertz (MHz), gigahertz (GHz), and terahertz (THz) frequency ranges and their properties. The lower the frequency range is, the less the signal attenuates as it propagates through space, and the higher the achievable coverage is. The higher frequency ranges in turn provide larger amounts of available bandwidth, and thus can offer more capacity to transmit data. Figure 2.1 illustrates how the transmit power is usually chosen on the system design level: less power is used in the short-range transmissions in the high frequencies than in the long-range transmissions in the low frequencies.

As radio waves propagate over borders of the nations, it is essential that spectrum management also takes place on an international level. The International Telecommunication Union (ITU) is a specialized agency of the United Nations (UN), which is responsible for information and communications technology (ICT) issues throughout the world [36]. International Telecommunication Union Radiocommunication sector (ITU-R) develops and adopts the Radio Regulations

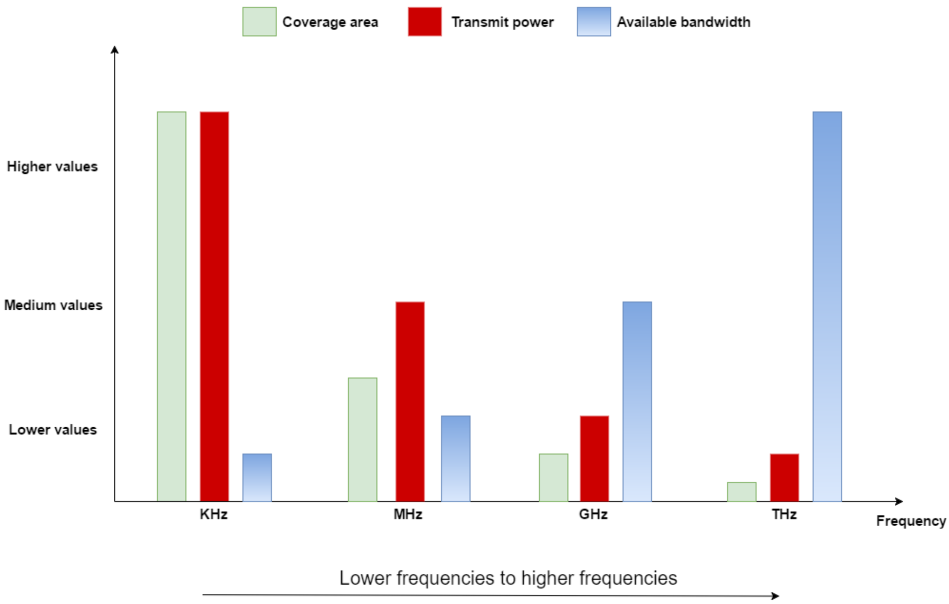

Figure 2.1: Conceptual illustration showing typical values for coverage area, transmit power and available bandwidth for wireless communications systems in different frequency ranges.

(RR) [37], which is a binding international treaty defining a set of rules, recommendations, and procedures for the global regulation of radiocommunications. The RR are revised according to changes in the need and demand for spectrum at World Radiocommunication Conferences (WRCs), which are held every 3-4 years [31]. ITU has divided the world into three regions for international allocation of frequencies. Europe, Africa, Russian Federation and the Middle-East belong to Region 1, North America and South America to Region 2, and South-East Asia and Oceania to Region 3.

As the use of spectrum varies greatly between nations and regions, there are six regional groups recognized by ITU-R. These groups work together to prepare and coordinate common positions for the harmonization of spectrum use when the RR are revised in a WRC. The collaboration in the harmonization of spectrum use is probably most active in the European Conference of Postal and Telecommunications Administrations (CEPT) [38]. The WRC meetings involve thousands of delegates and last four weeks. Their agenda is decided at the previous WRC to allow proper preparation of the items in the agenda [39].

2.2 Mobile telecommunications

The rapid adoption of smartphones, tablets, and video streaming has resulted in a significant increase in the volume of wireless broadband (WBB) data traffic. About 70% of this traffic is offloaded to fixed networks over Wi-Fi, and the remainder is carried over MBB in IMT networks [40]. For clarification, this thesis uses the term WBB to cover both MBB and Wi-Fi technologies. The amount of MBB traffic in Q1 2016 was over tenfold compared to Q1 2011 and 60% more than in Q1 2015 [3], and the increases are predicted to continue [2].

ITU contributes to the standardization and harmonization of IMT, which aims to enable global roaming, reduce the equipment design complexity, preserve battery life, improve spectrum efficiency and reduce cross-border interference [41]. Harmonization also guarantees the availability of equipment in smaller markets, as it would not be financially reasonable to develop different equipment for the small markets if they would use different standards or frequencies. If same services are used at different frequencies in different countries, the devices may even need to use different physical designs.

In the evolution of mobile telecommunications, a new generation is introduced roughly every 10 years [42]. The 1st generation mobile networks (1G) were analog with no data services. The digital data services were introduced in the 2nd generation mobile networks (2G) in Global System for Mobile Communications (GSM) [43] technology, and the data rates have since increased in every succeeding generation. The generations are terms used by the mobile telecommunications industry and are not official standards or requirements. ITU has created a set of requirements for International Mobile Telecommunications-2000 (IMT-2000) [44], which corresponds to what is perceived as 3rd generation mobile networks (3G). The most recent generation is the 4th generation mobile networks (4G), generally defined by the requirements of International Mobile Telecommunications-Advanced (IMT-Advanced) [45]. The de facto standard for IMT-Advanced is the 3rd Generation Partnership Project (3GPP) [46] Release 10 & beyond, known as LTE-Advanced (LTE-A).

The current global usage and trends in 2G, 3G and 4G systems can be found from the GSM Association (GSMA) Mobile Economy report [47]. In Finland, the significance of GSM has decreased, and the shutdown of the networks is expected commence after 2020. The 3G networks are expected to be updated to 4G Long Term Evolution (LTE) or a succeeding generation in the beginning of 2020s. The current 4G LTE networks will also be updated in the coming years to 3GPP Releases 13 and 14, known as LTE-Advanced Pro or 4.5G, which include some features from the upcoming 5th generation mobile networks (5G) mobile networks [48]. 3GPP Release 15 will be the first technology to meet the requirements for 5G, and is scheduled for publication in late 2018. Europe is very active in the development of 5G and encourages preliminary trials in 2017, pre-commercial trials from 2018 and fully commercial launch of 5G services by the end of 2020 [13]. The first 5G trials will be made in frequency bands which are already allocated to IMT. 3.4-3.8 GHz is identified as a potential common pioneer 5G band in Europe for implementations as early as in 2018 [13]. There is no additional spectrum below 6 GHz left to be allocated for 5G, but the networks in current IMT frequency bands will eventually be updated to 5G and additional spectrum resources can be obtained through spectrum sharing.

Different frequency ranges between 24 and 86 GHz will be considered in World Radiocommunication Conference 2019 (WRC-19) for 5G use to provide high contiguous bandwidths and high capacity. As the IMT systems have not been previously deployed in these frequencies, the technical development of 5G has been active to solve the new problematics the higher frequencies present and some have been concerned that 5G is focusing too much on the higher frequencies and becoming an urban system [49]. However, IMT spectrum below 6 GHz will be essential for 5G to provide the needed coverage.

The higher frequencies introduce higher path losses and higher atmospheric attenuation, and especially the extremely high frequency (EHF) range between 30 and 300 GHz requires a different design in the transmission antennas when compared to the antennas in frequencies below 6 GHz. The signal wavelengths in EHF range from 10 mm to 1 mm, and are hence called *millimeter waves*. The range of operation on millimeter wave frequencies is short, typically from a few meters up to a few hundred meters. As the wavelengths in these higher frequencies are shorter, the antennas are proportionally smaller. Hundreds of extremely small antennas can form an array in a device, and the signals from each antenna can be combined through digital signal processing to achieve the higher gains needed due to the higher path losses. The technical feasibility of IMT in frequencies above 6 GHz has been studied by ITU-R in [50].

Thus, the 5G in higher frequencies present complex technical challenges in antenna and algorithm design, while in frequencies below 6 GHz the problem is the lack of available spectrum resources. The focus in this thesis is on spectrum sharing and in the frequencies below 6 GHz. Radio equipment can use the coverage-providing lower frequencies simultaneously with high-capacity-providing higher frequencies through carrier aggregation (CA) [51] methods.

2.3 Licensing methods to access radio spectrum

Radio spectrum is typically licensed to its users with individual licensing, where the spectrum is divided into frequency bands exclusively assigned to a certain use or a range of compatible uses and separated by guard bands to mitigate interference from adjacent frequency bands. Individual licenses ensure that there is no harmful interference [32] from other services and give an exclusive right to use a specific frequency range in a specific area under certain conditions, such as power levels, antenna heights and locations. Licenses might also include obligations for the services, such as requirements to build a certain network coverage.

The licenses have usually been granted on a first come, first served basis when the demand for spectrum within the band is considered to be less than the supply. When the demand exceeds the supply, other mechanisms, such as typically used comparative hearings (also known as beauty contests) and spectrum auctions are used [52]. The mobile network operators (MNOs) need licenses for their IMT networks, but the individual users do not need to acquire licenses for their mobile devices.

Some frequency bands can be used with general authorization. Individual licenses are not needed in these unlicensed bands. However, there are strict rules and regulations on the equipment and their operation in the band. In unlicensed operation, the devices must tolerate any interference from other devices in the band. Thus, in unlicensed spectrum the users have non-exclusive access to spectrum resources and the quality of service (QoS) is unpredictable as the amount and quality (in terms of interference from other users) of available spectrum is uncertain.

Most popular unlicensed services are Wi-Fi and Bluetooth, which operate in the industrial, scientific and medical (ISM) frequency bands. Another typical application in unlicensed spectrum is Short Range Devices (SRDs), which operate at low power levels (usually up top 100 mW [53]) and typically have ranges from few centimeters to up to 100 meters [54]. LTE can also use a combination of licensed and unlicensed spectrum through CA and License Assisted Access (LAA), while LTE technologies such as MulteFire [55] can operate solely in the unlicensed spectrum. The efficient use of unlicensed frequency bands is difficult because of the lack of their global harmonization [56].

The following are the main parameters defining what type of licensing a spectrum user should consider: degree of guaranteed QoS, amount of guaranteed spectrum to access, and the spectrum license fee. The spectrum licensing terminologies and their interpretation differ from country to country. For example, in the European Union (EU), the general authorization is also known as Collective Use of Spectrum (CUS) [57]. In addition to individual licensing and general authorization, there are intermediate forms between them, known as light-licensing [58]. Light-licensing might include either simplified procedures to individual authorization, or additional registration measures to general authorization to aid in the interference management.

The efficiency in the use of spectrum resources could be further improved by allowing shared spectrum access. The operation in unlicensed frequency bands can also be considered as a form of spectrum sharing, but this thesis only considers spectrum sharing in bands with existing licensed users, known as incumbents. The spectrum sharing in frequency bands with incumbents can be both licensed or unlicensed. If all of the spectrum defined in a license is not needed for the transmissions of the license holder at all times or at all locations, the unused spectrum could be licensed temporarily to another user. This partial transfer of incumbents' rights to spectrum to another user is called Licensed Shared Access (LSA), and is especially useful when the other user has only small or temporary needs. The arrangement can be beneficial for both parties, as the license holder can for example benefit economically from leasing its underutilized spectrum resources and the LSA licensee can get additional capacity without the need to obtain an exclusive license [11]. Different methods to access shared licensed spectrum from a perspective of an MNO are surveyed in [59], while chapter 6 describes the European LSA concept and compares it to the similar Spectrum Access System (SAS) method developed in the United States (US).

In unlicensed spectrum sharing, the incumbents are the primary users of the band, and the unlicensed shared spectrum users the secondary users of the band. The secondary users need to operate in a manner which ensures that no harmful interference is caused to the incumbents. The secondary users are not protected from any interference from each other or from the incumbents and have no guarantees on the availability of spectrum for their transmissions. This has diminished the interest in unlicensed spectrum sharing in developed countries. Unlicensed spectrum sharing is active in the TV White Space (TVWS) of the developing countries in Africa and India, as described in section 5.3. Figure 2.2 illustrates how shared licensed spectrum access is categorized to individual licensing as it ensures exclusive access to the shared spectrum resources and a certain QoS, while unlicensed shared spectrum is accessed with general authorization. Shared licensed spectrum has all the benefits of normal licensed spectrum apart from the long-term predictability.

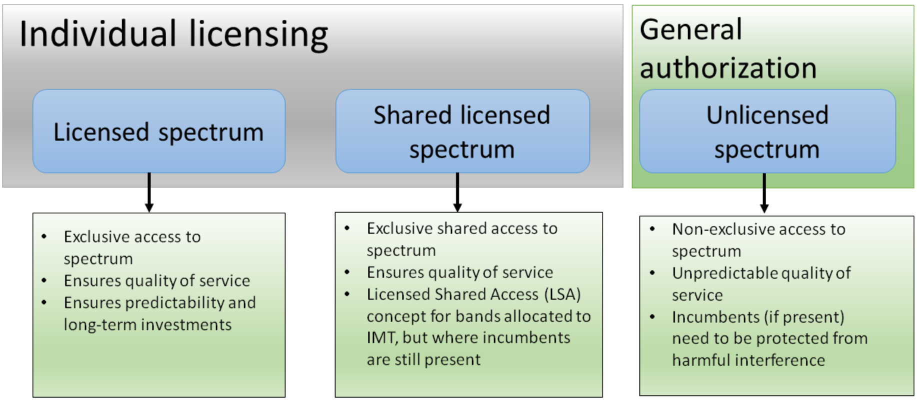

Figure 2.2: Spectrum licensing methods in frequency bands with incumbents.

2.4 Spectrum harmonization in Europe

The European Commission (EC), the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT) and European Telecommunications Standards Institute (ETSI) are the key players cooperating in matters related to the regulation and harmonization of radio frequencies and standardization of radio equipment in Europe. The strong interplay between them is the foundation in the development of regulation and standards to enable spectrum sharing in Europe.

The EC began to increase its involvement in radio spectrum issues in the 1990s, as the spectrum matters began to increasingly affect the European Single Market. A new regulatory framework aiming at further liberalization, harmonization, and simplification of the regulation was created in 2002. The Framework Directive [60] sets the main principles, objectives and policies in EU regulatory policy of electronic communications to achieve the above-mentioned objectives. The related Authorization Directive [61] introduced the concept of general authorization, which facilitates the entry in the market and reduces administrative burden on the operators.

The implementation of these Directives was defined in Radio Spectrum Decision (2002/676/EC) [62], which established a policy and a legal framework in the EU "in order to ensure the coordination of policy approaches and, where appropriate, harmonized conditions with regard to the availability and efficient use of the radio spectrum necessary for the establishment and functioning of the internal market in EU policy areas such as electronic communications, transport and research and development". Radio Spectrum Committee (RSC) [63] was formed from the experts from the Members States to assist the EC in the implementation of this Decision.

The European National Regulatory Authorities manage and allocate radio spectrum for different services within their countries. The Framework Directive [60] allows an EU Member State to set conditions on the use of spectrum within the State. The conditions can be harmonized on European level through mandatory EC Decisions, or ECC Decisions or Recommendations. A regulatory deliverable can also be developed on a national basis if no mandatory or voluntary harmonization measures are available.

In 2011, the EC initiated studies on spectrum sharing and the value of shared spectrum access [64] and began to promote shared use of spectrum. The European Parliament and Council approved the first Radio Spectrum Policy Programme (RSPP) [65] in March 2012. It was prepared by the Radio Spectrum Policy Group (RSPG)) [66], which is a group of high level experts in spectrum matters in the EU. The RSPP created a comprehensive roadmap for the internal market for wireless communications, taking into account the *Europe 2020 growth strategy* [67] and the Digital Single Market (DSM) [16] agenda for Europe. The Programme sets general regulatory principles and policy objectives for the spectrum use and defines concrete actions to enhance efficiency and flexibility in spectrum use. The Programme will be applied to all types of radio spectrum use and to all spectrum related decisions within the European internal market. One of the concrete actions in the strategy is to ensure that 1200 MHz of spectrum will be addressed to the growing demands of MBB.

2.4.1 CEPT/ECC

The CEPT [68] comprises of 48 national regulators in the field of posts and telecommunications. CEPT creates European Common Proposals (ECPs) representing European interests at the international level in the WRCs. The ECC is an expert group within CEPT. The objective of ECC is to develop policies and regulations to harmonize the use of radio frequencies in Europe. Mainly four types of deliverables are produced by the ECC:

- CEPT Reports present final results from studies conducted in response to an EC mandate to develop technical harmonization measures. As illustrated in Figure 2.3a, EC can make mandates to ECC under the Radio Spectrum Decision [62]. The EC uses CEPT Reports in the development of Commission Decisions on the harmonized technical conditions of spectrum use.

- ECC Reports are results of studies usually conducted in support of a harmonization measure. They can be used as a basis for future Decisions in the EC and in development of standards in ETSI.

- ECC Decisions are regulatory texts, which provide measures on significant harmonization matters. The Decisions are non-binding, but CEPT member administrations are strongly urged to implement them.

- ECC Recommendations provide harmonization measures, which the CEPT member administrations are encouraged to apply. Typically they concern matters where ECC Decisions are not yet available, or provide other guidance to the administrations.

2.4.2 European Telecommunications Standards Institute

ETSI [70] develops standards for radiocommunication systems and equipment. ETSI was established by CEPT in 1988, and is an officially recognized European standards organization responsible for the development of ICT standards for fixed, mobile, radio, broadcast, Internet and aeronautical services. The standards are globally applicable, and together with other deliverables [71] produced by ETSI, they form Europe's contribution to the global ICT standardization and harmonization. ECC is an officially recognized partner of ETSI. A bilateral agreement called memorandum of understanding (MoU) [72] defines the close relationship between, as illustrated in Figure 2.3b. The deliverables produced in ECC are used as a base material in the development of Harmonized Standards in ETSI.

The RED 2014/53/EU [73] came in force in June 2016 and covers most of the equipment using radio spectrum. The Directive states that all equipment placed on the European market must comply with requirements related to electromagnetic emissions and interference, protection of health and safety, and effective use of radio spectrum. Equipment manufactured according to a Harmonized Standard [74] may be placed in the market in the whole EU. The RED replaced the previous Radio and Telecommunication Terminal Equipment (R&TTE) Directive 1999/5/EC [75] from 1999.

Before placing the product on the market, the manufacturer of the equipment has to perform a set of specific radio tests and make a declaration of conformity (self-declaration) stating that the product meets the requirements of the Harmonized Standard. The self-declaration in RED has to be made for both the radio equipment hardware and its software, while R&TTE only covered the hardware.

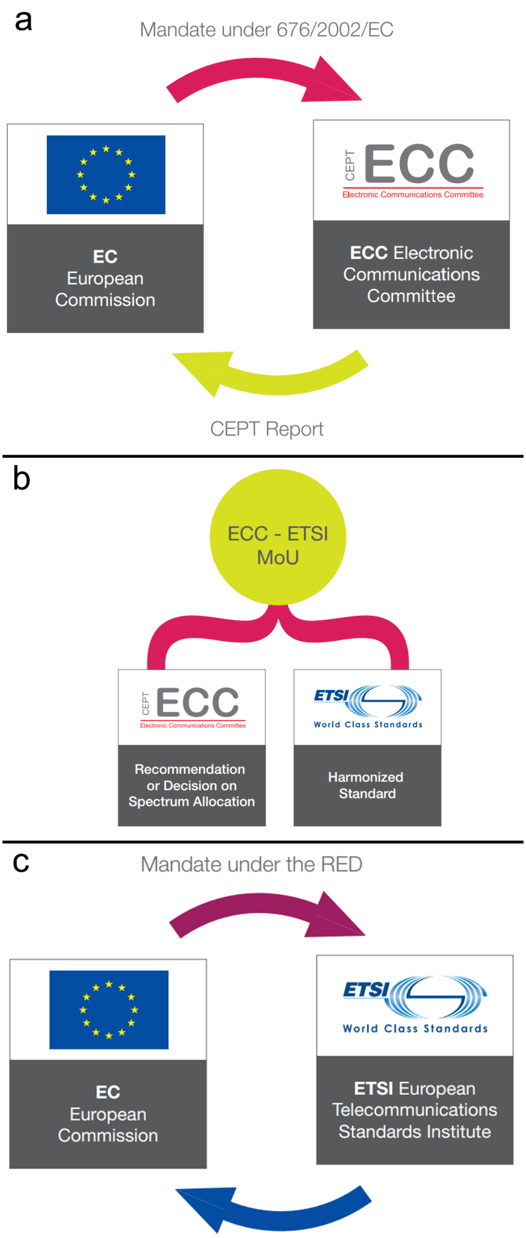

Figure 2.3: A: European Commission (EC) can mandate Electronic Communications Committee (ECC) to create studies on harmonization measures under the Radio Spectrum Decision 676/2002/EC [62]. B: Memorandum of understanding (MoU) between ECC and ETSI. The results of ECC studies are used in the development of ETSI Harmonized Standards. C: EC can mandate European Telecommunications Standards Institute (ETSI) to create Harmonized Standards under RED. Modified from [69].

ETSI produces the Harmonized Standards in response to EC mandates issued under the RED, as illustrated in Figure 2.3c. The Harmonized Standards provide the necessary technical details to achieve essential requirements for the equipment, and thus function as the key enablers of the Single Market in Europe. The references of Harmonized Standards have to be published in the Official Journal of European Union (OJEU) [76]. RED puts an emphasis on improving the radio equipment performance to enable more efficient use of spectrum, and the Harmonized Standards previously released under R&TTE are being updated accordingly [77].

Chapter 3

Spectrum occupancy measurements and interference maps

Accurate modeling of incumbent spectrum utilization provides information which can be used to make spectrum management decisions and to improve the efficiency of shared spectrum access methods. A useful metric in finding candidate frequency bands for spectrum sharing is spectrum occupancy, which expresses the spectrum utilization rate as a percentage. This chapter describes how incumbent spectrum utilization can be determined using spectrum occupancy measurements and interference maps. The proposed methodologies for conducting spectrum occupancy measurements and creating interference maps are described in Paper 1 [19] and can be used to extend spectrum occupancy measurements from previous single location measurements to cover geographical areas. The development of a spectrum observatory network to measure spectrum occupancy data in Paper 4 [22] and the Kriging interpolation methods to create interference maps in papers 2 and 3 [20, 21] were used as a base material for the survey in Paper 1 [19] and are also described in this chapter.

3.1 Metrics to determine spectrum utilization

There is no radio spectrum left for new allocations in frequencies below 6 GHz, and thus the existing spectrum allocations need to be used more efficiently to respond to the needs of growing amount of mobile broadband (MBB) traffic. If the spectrum utilization in a frequency band is very low, the band could be a potential candidate for spectrum sharing. Thus, a metric is needed to determine spectrum utilization and to find potential candidates for spectrum sharing. The efficiency in spectrum utilization can be measured with several different metrics. Spectral efficiency has long been an important metric [78], and in the current communications systems it is expressed as the data rate per second per bandwidth: bits/s/Hz. For example, a system with a spectral efficiency of 2 bits/s/Hz and a bandwidth of 8 MHz can achieve a data rate of 16 Megabits per second (Mbps), calculated with a simple multiplication: 2 bits/s/Hz $\cdot$ 8 MHz.

However, the spectral efficiency of the current wireless communications technologies is already close to the theoretical limits presented in Claude Shannon's *A mathematical theory in communication* from 1948 [35], which states that the theoretical limit to the capacity of a communication channel can be calculated using the signal power, the noise power and the available bandwidth. Spectral efficiency is a metric which only defines the data rate a communications system can achieve with a given bandwidth. A frequency band can be allocated to a spectrally efficient system, but the frequency band could still be completely or partially unutilized if the system does not transmit at all times or at all locations.

Spectrum occupancy is a metric which expresses the utilization rate of a channel as a percentage. The channel is defined as occupied at times when the measured power level in the channel exceeds a set threshold, and at other times the channel is defined as free. Thus, spectrum occupancy can be used to determine the current utilization and to analyze the suitability of a frequency band for spectrum sharing [5]. International Telecommunication Union Radiocommunication sector (ITU-R) has published extensive guidelines to conduct and analyze spectrum occupancy measurements in [79, 80].

Measurement campaigns covering frequencies up to 3 GHz have reported low spectrum occupancy values, in the scale of 10 to 20% [5,6,81]. However, these spectrum occupancy measurements can not be used to fully characterize the spectrum utilization and should not be used to draw definite conclusions [19]. The obtained values depend greatly on the measurement parameters and thresholds [82], but the main problem is that these measurements are conducted at a single location with a single device. Measurements focusing only on the time and frequency dimensions and completely omitting the spatial dimension (i.e. the spectrum is measured only at one location and the location information is dismissed) can not be used to determine the spectrum utilization outside the measurement range of the measurement device.

3.2 Interference maps

To provide meaningful information about spectrum utilization, the spectrum occupancy measurements should be conducted over a certain geographical area instead of a single location. Different wireless communications systems also need to be measured using dedicated measurement parameters, antennas and locations to reliably detect their transmissions. To assess spectrum utilization over a certain geographical area, spectrum data from multiple devices at multiple locations in that area needs to be measured, processed and combined into a presentation of the area. The concept of radio environment mapping (REM) was proposed for this purpose in [83].

A REM contains the relevant information about the radio signal levels, physical locations of the devices, services available, and related regulations and policies. Interference maps are a subclass of REMs. They describe the level of interference (i.e. the distribution of radio frequency (RF) power) on a specific frequency band and a geographical area. For example, an interference map could be built to describe the digital terrestrial television (DTT) broadcasting network signal levels, i.e. the interference from the primary DTT service to the potential secondary service. These signal levels from fixed DTT transmitters are somewhat static, and could be used for example in a TV White Space (TVWS) geo-location database [84] as the base information when calculating the secondary service power levels which guarantee that the reception of the primary DTT service is protected.

Interference maps can also be built to describe the signal levels of mobile users, such as Programme Making and Special Events (PMSE) wireless microphones. However, the mobility of the users increases the complexity of conducting the measurements. To create up-to-date interference maps, the measurement samples need to be obtained at the same time from several locations with large geographical separation. In case of transmissions from fixed transmitters, the time dependency is small as the signal level variance is low due to transmitters not moving. In practice, collecting samples from several measurement locations at the same time would result in the need to use lower quality measurement devices, such as low-cost independent sensing devices or sensing-capable mobile phones. This would greatly deteriorate the accuracy of the interference maps.

To create an interference map, spectrum data from multiple measurement devices in the area of interest is needed, along with the measurement locations. The measurement data from each measurement location and device can then be combined into an interference map presentation of the area using interpolation methods, as described in section 3.4. The created interference maps can aid in making spectrum management decisions and in finding frequency bands with low spectrum utilization. Interference maps can also be used to avoid intrasystem interference (interference from different signals transmitted by the same system) and intersystem interference (interference from signals transmitted by other systems) by using the map information for environment-aware planning, optimization and resource management of wireless communication networks.

Paper 1 [19] extends the state-of-the-art in spectrum measurement guidelines presented in previous research articles and ITU-R recommendations by proposing how the spectrum measurements should be conducted over a geographical area to create interference maps. The paper divides the creation of an interference map into five different phases, which need to be designed and implemented properly to obtain meaningful information, and to be able to use and visualize that information. The phases are extended and slightly modified from [85], which considered the issues in the creation of REMs with an emphasis on sampling and interpolation. The phases are briefly described below and followed by more detailed descriptions of the main original contributions of the author to phases 1, 3 and 4 in Section 3.3 and to phase 2 in Section 3.4.

1. Filtering and sampling

   Signal filtering is performed to increase sensitivity of the system and to prevent overload. Sensitivity describes the signal level the measurement system is able to detect reliably. Frequency-selective attenuators are used to remove or attenuate unwanted signals causing distortion to the measured signals and decreasing sensibility, and preamplifiers can be used to amplify the low-level signals usually present in the higher frequencies to allow their detection. Filtering is performed before sampling.

   One measurement at a specific frequency, time and location is called a sample. Choosing the correct parameters for sampling in each domain is not trivial, and often involves trade-offs. The scanning speed of the measurement device is a trade-off between *revisit time* (time between two consequent measurements on the same channel), which defines the time resolution of the measurement, and *observation time*, which is the measurement time on one channel. Both times should be as short as possible, but still allow the detection of the signals present in the band.

   The sampling interval in frequency dimension is defined by frequency resolution, while resolution bandwidth (RBW) is the bandwidth of a single sample. Narrow RBW increases the system's ability to distinguish signals in frequency and decreases the noise floor, which allows the detection of weaker signals, but the narrower the RBW is the longer the measurement time is [82]. Careful planning is needed to collect information with sufficient resolution to detect the transmissions, but still keeping the scanning speed and the amount of collected data at an acceptable level.

2. Interpolation

   It is not practical to perform resource-consuming measurements in every single location of an interference map. Interpolation methods use measured values at some locations to estimate values at locations where no measurements have been conducted. Section 3.4 describes the process in more detail with an example, where measurements were conducted at 50 locations to create a map of a 2 km $\times$ 2 km area with a pixel size of 5 m $\times$ 5 m. Substantial measurement resources are needed to construct maps covering large geographical areas as the number of required measurements and their geographical separation grows large.

3. Reduction of data using metrics

   Long-term spectrum measurements produce large amounts of data, which can be reduced by using different metrics. One of the most useful metrics is spectrum occupancy, as it reduces a huge set of energy measurements into an estimate of whether the channel is occupied at a specific moment in time. If the detected power of the received signal exceeds a certain decision threshold, that part of spectrum is occupied, and if not, it is potentially available for sharing. The selection of the threshold is a trade-off between false negatives (missed detection of the signal) and false positives (detection of the signal when it is not present). Setting the threshold to decrease the probability of false negatives increases the probability of false positives, and vice versa.

4. Data storage and management

   The decline in cost of storage allows to store more accurate data from larger number of sensors than before, but storage and management of large amounts of data still needs careful planning. The storage, accessibility and processing of data needs to be fast and simple to allow the researchers, spectrum management authorities and network operators to easily use the spectrum data for their purposes.

5. Visualization

   It is important to be able to visualize the gathered spectrum measurements to provide meaningful information for different audiences and purposes. A visualization of spectrum occupancy allows to easily see

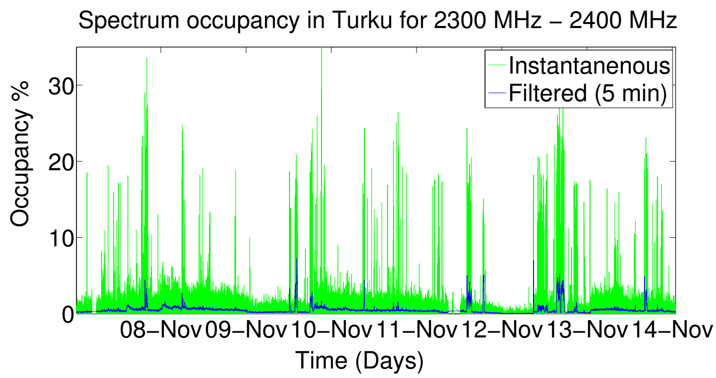

Figure 3.1: Spectrum occupancy in Turku for 2300-2400 MHz frequency band during a week in November 2013.

if there is potential for spectrum sharing. Figure 3.1 shows an example of an occupancy visualization of 2300-2400 MHz frequency band over a period of one week in Turku, Finland. The measurements are conducted with a 3 s scan interval, and the green line shows the instantaneous occupancy over the whole 100 MHz frequency band, and can go as high as 35 %. The blue line shows the occupancy values averaged over a 5-minute time period. These remain at relatively small percentages, indicating that transmissions of short duration dominate spectrum occupancy within the band. The frequency band in question shows very low spectrum occupancy values in this single location, and thus the frequency band shows potential for spectrum sharing in this location. Interference maps are usually visualized using different colors to represent the level of interference in each pixel/location of the map.

3.3 Spectrum observatory network

A spectrum observatory network was built in a GlobalRF Spectrum Opportunity Assessment project [86] in Wireless Innovation between Finland and the US (WiFiUS) program [87], which was jointly funded by the National Science Foundation (NSF) [88] and Tekes, the Finnish Funding Agency for Innovation [89]. The project aimed to build a global network of RF spectrum observatories continuously collecting long-term spectrum data to study the trends in spectrum utilization and to identify frequency bands where spectrum sharing could be feasible.

Currently the three spectrum observatories in Chicago, US, Virginia, US, and Turku, Finland, produce a total of 4.5 terabytes (TBs) of spectrum data per year. The oldest spectrum observatory in Chicago has continuously collected spectrum measurement data since 2007 until present day, and thus the amount of gathered spectrum data is substantial. Turku spectrum observatory was set up in 2013, and Virginia spectrum observatory in 2014. The measurement data from the spectrum observatories in Finland and the United States (US) is collected and stored into a single location at Illinois Institute of Technology [90] in Chicago.

The RFeye node manufactured by CRFS [91] measures the whole frequency band from 30 MHz to 6 GHz in each of the locations. General measurements covering every frequency band up to 6 GHz are not sufficient to comprehensively analyze the multitude of different radio systems operating within these bands, but they provide a good overview on the spectrum utilization. When a specific band is studied, the measurement parameters need to be adjusted according to the transmissions under study. Spectrum occupancy can well be studied from the data without the need to create an interference map, but the data then represents the state of the spectrum utilization only in the area surrounding the fixed spectrum observatory installation.

A band plan describes the revisit time and the frequency resolution used to measure a certain frequency range. The whole 30 MHz to 6 GHz measurement range is split up into several measurement bands with their own revisit times and frequency resolutions, which are chosen according to the characteristics of the transmissions present in the measurement band. The initial band plan for the spectrum observatory network is described in [86]. Strong frequency modulation (FM) radio and Global System for Mobile Communications (GSM) 900/1800 MHz signals caused the RFeye automatic gain control (AGC) to reduce gain or use maximum attenuation to prevent overload, which resulted in a decrease in the sensitivity and the ability to detect weak signals. Strong signals can also create intermodulation distortions, which could be mistakenly interpreted as real signals.

External signal filtering and attenuators were used to overcome the problems introduced by the strong signals in Paper 4 [22], where the initial band plan and spectrum measurement system was updated. The CRFS RFeye node has 4 external RF inputs, which allows to build a different filtering design for each of the RF inputs. A specific frequency range can then be measured from a RF input which has a dedicated signal filtering implemented for that frequency range. A low-noise amplifier (LNA) was also installed to one RF input to improve the system sensitivity in the frequency range between 3 and 6 GHz. The spectrum data from the RFeye nodes was analyzed in MATLAB [92] environment to design the external filtering required to filter out undesired frequency components. The updated band plan and external filtering decreased noise levels and intermodulation distortions in the spectrum measurement data. As the comparisons to the initial band plan in Paper 1 [19] and Paper 4 [22] show, the accuracy of the measurement results was improved considerably.

Paper 4 [22] also describes a high-performance tiered storage system, which significantly improves the storage space, speed and usability for researchers when compared to the earlier implementation described in [93]. The author did not take part in the actual implementation of the database, but contributed to designing the database to enable fast access and easy processing of the spectrum data in MATLAB environment. The data was stored in the previous database in such a way that it first needed to be downloaded to a personal computer, extracted into comma-separated value (CSV) files, and then the batch of CSV files had to be read with MATLAB script before the data could be used and stored in MATLAB format allowing the analysis of the data. The new database design allows the spectrum data to be directly obtained in MATLAB format and to perform analysis of the spectrum data on the server.

As already noted, spectrum occupancy is an important and useful metric when dealing with spectrum data, and it has been the main metric used with the spectrum observatory network data during the first few years of operation. The spectrum data collected from the spectrum observatory network has been used to identify potential candidates for spectrum sharing, and the author has participated in studying the spectrum occupancy of 2.3-2.4 GHz band in Europe in Paper 8 [26] and in [17].

The RFeye measurement device used in the spectrum observatories can also be used with a non-fixed installation and moved to different locations of interest to measure the spectrum. A mobile RFeye device has been used to record the spectrum usage in several events in the US and Finland. An example of the methods that can be used to study the impact of different events to the spectrum utilization was published in [18], where a systematic approach based on two clustering techniques, Gaussian mixture models (GMMs) and the Self-Organizing Map (SOM), were used to detect the impact of human mega-events on spectrum usage. The author took part in analysing the spectrum data for this study.

The mobile RFeye device is also used to further analyze the results of field interference measurement campaigns described in chapters 4, 5 and 6, as it allows to record spectrum data during the measurements for later analysis. This data can be used to confirm that the measured devices have been functioning correctly, and to analyze which external signals have been present. For example, the nearby cellular base stations and other sources of strong harmful interference may have a significant influence on the measurement results.

3.4 Interpolation methods for interference map creation

In a shared spectrum scenario, the calculation of accurate maximum power limits for the secondary users is essential, as they maximize the throughput of the secondary system and guarantee that the interference towards the primary system remains at an acceptable level [94]. To calculate such limits, information on the signal levels of the primary system in different locations is needed.

The suitability of 30 different propagation models, spanning 65 years of publications, to predict the path loss in urban environments is surveyed in [95]. The signal strength in these models is calculated with empirical mathematical formulas and their parameters simulating the effects of different types of wireless channels to the radio signal. Okumura-Hata [96] is one of the most popular models and still widely used in many planning and simulation tools for wireless communication systems. However, the error in the signal levels predicted with these propagation models is significant, and could cause serious interference problems for secondary users if they base their transmission parameters on these predictions. Some of the propagation models presented in [95] are able to create more realistic predictions, but require a substantial amount of data about the environment, such as precise vector models of all three-dimensional structures and topographic data. Thus, using them is very impractical.

REM concept relies on geostatistics and can create more accurate and informative signal level maps than path loss prediction models [85]. REM and its subclass interference map thus are better suited to more accurately determine the power levels in spectrum sharing scenarios, and can aid in improving the efficiency in spectrum utilization. The basic idea is that measurements are conducted at some locations, and interpolation methods are used to estimate the signal level at locations which have not been measured. As the measurements are expensive and resource-consuming, ideally their number should be as small as possible, but still adequate to allow the creation of an accurate signal level map.

Kriging interpolation techniques produce accurate results and an indication of the estimation error for each prediction. The drawback of Kriging interpolation is the computational complexity. Paper 1 [19] presents a survey and comparison of different types of interpolation methods, which all have their own benefits and drawbacks. The selection of the locations where the measurement samples are collected from can be optimized to provide accurate results with a minimum number of measurements. Usually the measurement locations are chosen according to a systematic grid [97], but an appropriately designed sampling scheme further reduces the amount of measurement locations, or improves the accuracy of the interpolation if same number of measurement locations is used.

Paper 2 [20] proposes an improved geostatistical modeling procedure, where the selection of measurement locations is optimized by using spatial simulated annealing (SSA) algorithm instead of a systematic grid. SSA is an iterative search algorithm, which is used to find a global minimum for an objective function and to determine the measurement locations. In this paper, two objective functions were considered. The samples from optimal locations chosen with minimum mean shortest distance (MMSD) function were interpolated using inverse distance weighted (IDW) and ordinary Kriging (OK). These two previously available interpolation methods were then compared to the proposed method of Paper 2 [20], which uses universal Kriging for the interpolation and selects the measurement locations by minimizing the related mean universal Kriging variance (MUKV) variable.

Figure 3.2 illustrates signal level maps produced by a propagation prediction model, IDW method, OK method and the proposed universal Kriging method. Mean absolute error (MAE), normalized root mean square error (NRMSE) and Pearson correlation coefficient were used as the metrics to calculate the average magnitude of error in the predictions. The proposed universal Kriging method signal level map is shown in part d) of Figure 3.2, while the propagation prediction is in part a) and previous geostatistical models in b) and c). The proposed universal Kriging method achieved an average improvement of around 3-6% in accuracy (MAE) compared to the best previously proposed geostatistical approach for REM.

Paper 3 [21] considers a method to combine multivariate data to perform signal strength estimations. Previous techniques have focused only on univariate interpolation, which limits the accuracy of the signal strength estimation in unmeasured locations. The paper proposes a multivariate Kriging method called Cokriging (CK), which uses correlated secondary information from a terrain based propagation prediction model to complement the data from the measurements. The target variable estimated with CK is the signal strength, and the covariable aiding in the estimation is provided by the propagation prediction model. The CK method provides an improvement of 2.6% - 6% in accuracy over univariate methods, and was found to be especially suitable for estima-

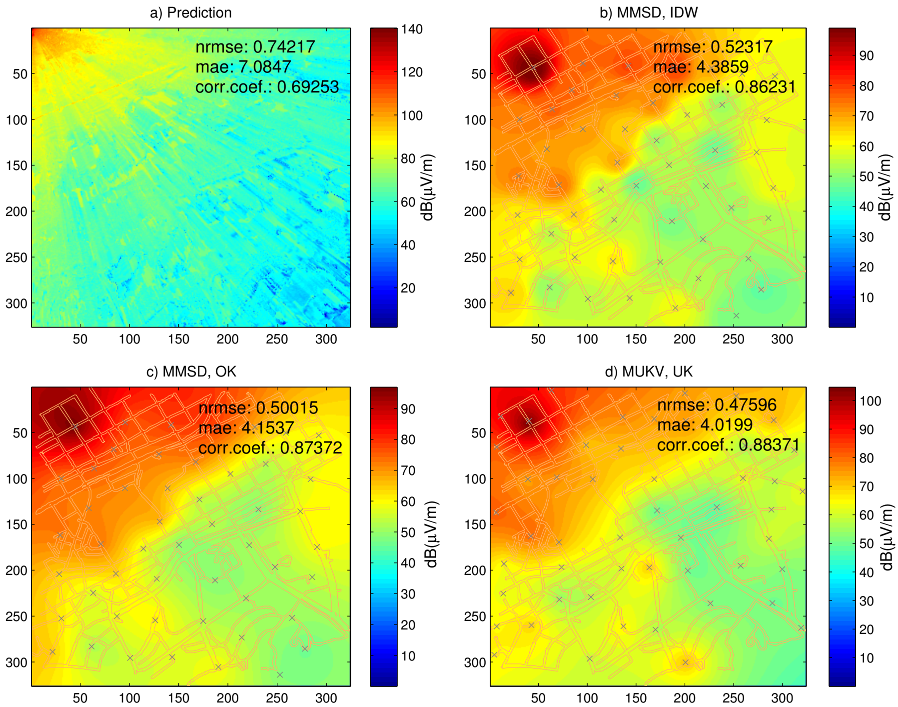

Figure 3.2: Estimated signal strength values for Turku DTT test network area with the methods used in Paper 2 [20]. a) is a propagation model prediction. In b) and c), the signal strength is estimated by interpolating the samples obtained from locations chosen with MMSD by using IDW and OK methods. The sampling locations in d) are selected by minimizing the MUKV, and the signal strengths are estimated with universal Kriging interpolation. Gray crosses indicate the locations where the field measurements have been conducted.

tion in boundary parts of a prediction surface, where the measurement locations are distant or unavailable. If more accurate topographic data were available, it would further increase the accuracy of CK method.

The author has built the measurement setup, planned and conducted extensive field measurement campaigns to provide the samples needed for the interpolation process and to verify proposed modeling procedures, and validated and analyzed the measurement data in both papers 2 and 3 [20, 21]. These papers have demonstrated how field measurements can be used to build realistic signal level maps for incumbent DTT broadcast networks.

The measurement locations in papers 2 and 3 [20,21] were limited to the locations belonging to the street network within the test area. The modeling procedures were verified with extensive measurement campaigns conducted in an operational DTT test network in Turku, Finland. The DTT test network was part of the White Space Test Environment for Broadcast Frequencies (WISE), which is described in more detail in Paper 6 [24]. Pixel size of 5 m $\times$ 5 m was used for the 2 km $\times$ 2 km area in the test network for which the REMs were modeled.

All of the measurement campaigns were conducted with a setup where a measurement antenna at a height of 1.5 m, a measurement device, a Global Positioning System (GPS) device and its antenna, a laptop, and a power source were built into a mobile unit which could be transported using a bicycle, as shown in Figure 3.3. Professional level Completech CA610T-N antenna uses two phased elements to obtain omnidirectional reception with antenna gain of 0 decibels relative to a reference dipole antenna (dBd). The received signal strength indicator (RSSI) values from the R&S TSM-DVB test receiver and the location information from the GPS device were input to a laptop running a LabVIEW-based application, which both controlled the devices and saved the measurement results into a text file.

The accuracy of the R&S TSM-DVB test receiver is calibrated to be within 1 dB. The calibration was performed in Turku University of Applied Sciences radio laboratory using a professional level R&S SFU broadcast test system signal generator and a calibrated R&S ETL TV analyzer. A minimum of 1000 samples were collected from each measurement location and the median value from the collected RSSI samples was used in the interpolation algorithms. If less samples were collected, the reliability of the results might suffer from rapidly changing signal multipath conditions. Extensive amount of measurement data from 6800 pixels outside the sampling locations for the interpolation methods was collected during the transitions between different measurement locations and used to verify the accuracy of different prediction methods. Mobility is present in the transition measurement results as the bicycle is

Figure 3.3: The bike and the measurement setup consisting of a controlling laptop, GPS unit to store locations, Rohde&Schwarz TSM-DVB unit to measure signal strength, and a battery pack.

moving, but the movement is so slow that its effect to the DTT signal multipath and reception conditions is not very significant. Still, the effect of the mobility to the RSSI values can not be quantified without making static measurements from the same locations.

The test receiver can not synchronize and lock to signals with RSSI below -90 dBm, and thus can not provide accurate measurement results for very weak signals. These signal levels are already below the specified field strength for DTT reception and thus are not relevant. The occasional measurement results where the test receiver was not able to lock to the signal resulted in unreliable RSSI values, which have been removed from the measurement data set. Other sources of error in measurements are typically systematic due to equipment failures or erroneous installations. Thus, all of the measured data needs to be carefully analyzed for such errors. A typical error in these measurements was the failure of GPS, which made all the measurement data after the failure useless as the RSSI values did not contain the related location information.

Chapter 4

Field measurements in determining DTT incumbent protection criteria against interference from mobile broadband

The aim of the field measurements described in this chapter is to determine the level of interference a digital terrestrial television (DTT) receiver can tolerate from an interfering mobile broadband (MBB) transmission while still meeting a chosen quality criterion. Protection ratio (PR) defines the maximum level of interference with the chosen DTT reception quality criterion. The properties of DTT receivers and MBB transmitters greatly affect their co-existence performance and by which mechanisms interference is caused to DTT reception.

The current literature and International Telecommunication Union Radiocommunication sector (ITU-R) documentation only describe methodologies for interference measurements in controlled laboratory environments. Radio propagation environments, antennas and sources of external interference in field measurements create a need for additional measures to obtain reliable measurement results. Paper 9 [27] proposes a step-by-step guideline for conducting field interference measurements and states that the field measurements should be used in conjunction with laboratory measurements and simulations to provide more realistic results on DTT-MBB co-existence compatibility. In addition, the paper considers European DTT co-existence scenarios and the effect of DTT reception installations to the DTT reception co-existence performance.

4.1 Definition of protection ratio

The PR is the minimum value of wanted-to-unwanted signal ratio at the DTT receiver input required to obtain a specified reception quality [98]. The specified reception quality is discussed in section 4.2. The wanted DTT signal power is measured over the band of the DTT signal, while the unwanted interfering MBB signal is measured over its assigned band. The power levels are root mean square (RMS) values of the emitted signal power within the respective channel bandwidth [98] and expressed in dB. No data is communicated from the DTT receivers to the DTT transmitters in DTT broadcasting, and thus only the reception of DTT needs to be considered in their protection. The PR methodology evaluates only the DTT receiver performance and does not include the receiving antenna system performance. Especially use of mast amplifiers makes the system more susceptible to overloading effect and can significantly deteriorate the overall reception system performance.

Figure 4.1 shows the incumbent DTT signal on the left and the interferer on an adjacent channel on the right. The interference level in this picture is equal to the maximum allowed level, and thus the PR is the ratio between the DTT incumbent and interfering signal powers. The resulting PR value in this illustration is negative, as the interfering signal power level is higher than the incumbent signal level. When the interference level is equal to or less than the maximum limit defined by the PR, the probability of errors is so small that the reception quality criterion is fulfilled. The probability of errors increases with higher levels of interference, and the reception quality criterion is no longer fulfilled.

Protection ratio is defined on the channel raster of the incumbent service. In the notation used in this thesis, channel N is the 8 MHz channel of the incumbent DTT signal. Other channels are defined in relation to channel N by using a plus or minus sign and the number of channels moved in frequency. For example, if the incumbent DTT channel center frequency is at 610 MHz, channel N-1 is at 602 MHz (610 MHz - $1 \cdot 8$ MHz) and channel N+9 at 682 MHz (610 MHz + $9 \cdot 8$ MHz).

PR for channel N thus means co-channel operation, where typical PRs are in the scale of 20 dB [99–101], which means that to achieve the specified reception quality the incumbent signal has to be at least 20 dB stronger than the total power from interfering signals plus noise. This would lead to very low power levels for the shared spectrum users, and thus co-channel operation is usually not desirable or relevant spectrum sharing scenario. The strong incumbent DTT signals would also cause interference to the shared spectrum user transmissions. The channels adjacent to the incumbent and channels with larger frequency separation

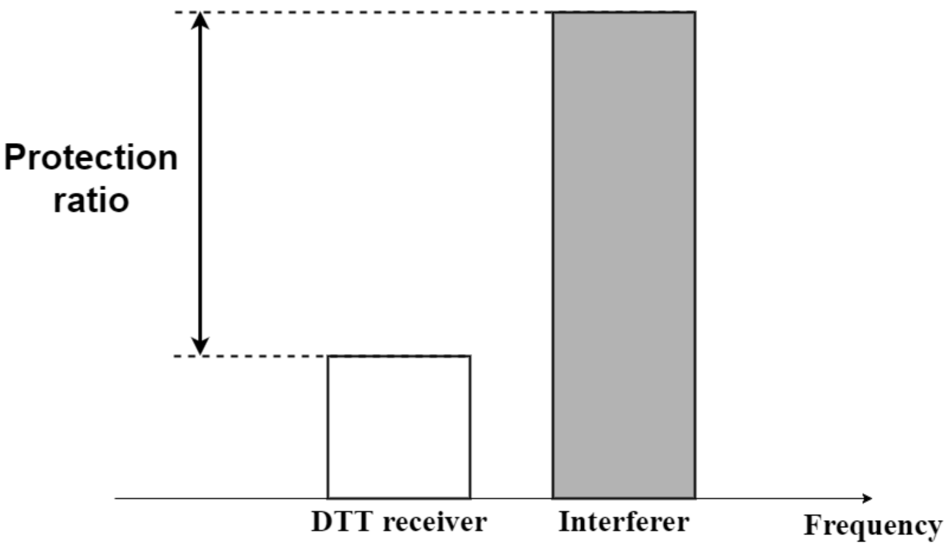

Figure 4.1: Definition of protection ratio (PR).

provide negative PR values, which means that the operation of shared spectrum users is more feasible as their signal levels can be higher than the incumbent DTT signal level.

Figure 4.2 illustrates the PR as a function of the frequency offset between the incumbent and interfering signal. This creates a “PR curve”, which shows how the receiver performs in discriminating against interfering signals on different frequencies [102]. The example PRs in Figure 4.2 show that on co-channel N the incumbent signal has to be 20 to 30 dB stronger than the interfering signal, and that on the adjacent channels N-1 and N+1 the interfering signal can be 15 to 40 dB stronger than the incumbent signal. The curves with different colors represent different signal levels of incumbent DTT transmission, which result in different PRs, as described in section 4.3.

When the frequency separation from the incumbent signal gets larger than approximately 3 or 4 channels, the PR almost reaches a plateau. This is due to both better selectivity of the receiver against interference with larger frequency separation and lower levels of interference from the interferer at larger frequency separations, as described in sections 4.3 and 4.4.

4.2 Definition of DTT reception quality criteria

The DTT system PR studies were initially based on achieving a target bit error rate (BER) of $2 \cdot 10^{-4}$ measured between the inner and

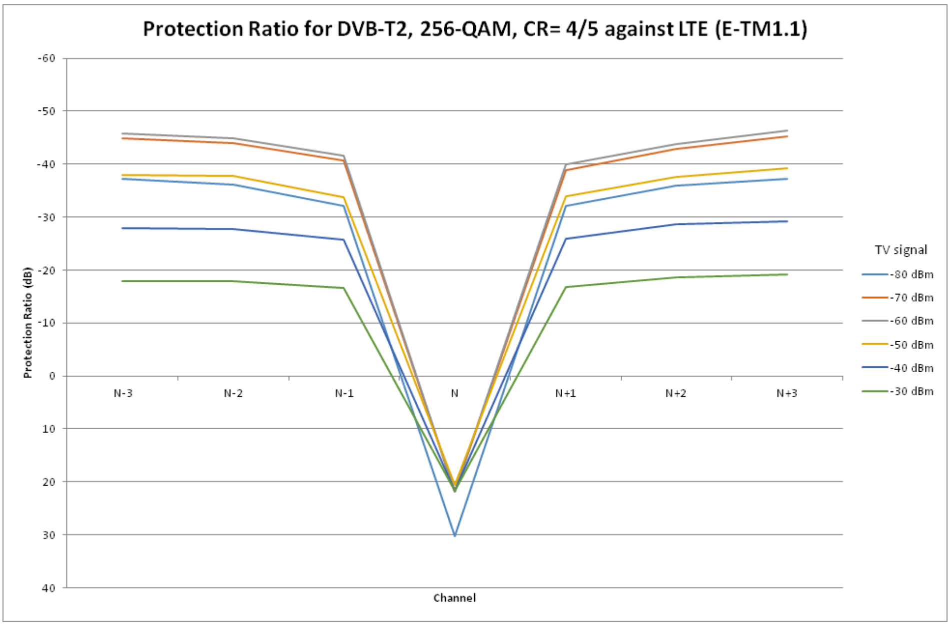

Figure 4.2: PR curves from laboratory measurements between DVB-T2 and LTE BS interferer to demonstrate PRs at different DTT incumbent signal levels. ESR_5 reception quality criterion was used.

outer coding in Digital Video Broadcasting - Terrestrial (DVB-T) receiver [103], responding to quasi error free (QEF) picture quality. The commercial devices often do not allow the measurement of BER, and the QEF criterion is not suitable for portable or mobile reception where BER fluctuations are very large [103]. Thus, a new method called subjective failure point (SFP) was proposed [98].

The quality criterion in SFP is just error-free picture at the TV screen, which corresponds to a picture quality where a maximum of one error can be visible in the picture during an observation time of 20 s. The PR of the incumbent signal to the interfering signal is measured at the receiver input at signal levels producing just-error-free picture and rounded to the next higher integer. The SFP PRs for DVB-T are 1.3-2 dB lower than is needed to obtain BER of $2 \cdot 10^{-4}$ to provide QEF picture quality [104]. The drawback in SFP measurements is that they cannot be conducted automatically, but require a person permanently monitoring the picture quality for errors.

Another very similar and commonly used criterion is ESR_5 [103]. The ESR_5 criterion is fulfilled if the ratio of seconds with packet uncorrectable errors to all seconds in a 20 second interval does not exceed 5% (1 s), as the index in the name states. The packet uncorrectable errors in Motion Picture Experts Group 2 (MPEG-2) stream generate visible failures in the picture, and the Viterbi decoder signals them by setting a flag. Measurements where ESR_5 criterion is used can be automated if the DTT receivers allows access to these flags.

Thus, the ESR_5 and SFP quality criteria are somewhat equivalent with each other, and also with the criterion used in DTT receiver Harmonized Standard EN 303 340 [105], where the minimum time between successive errors in the video is 15 seconds. The PR criterion used in the measurements presented in this thesis corresponds to ESR_5 criterion. Different interference criteria need to be used to protect the whole DTT broadcast system [106] rather than a single DTT receiver, as discussed in Paper 9 [27].

4.3 DTT receiver performance in presence of interference from mobile broadband

The radio frequency (RF) front-end part of a DTT receiver contains the components affecting the receiver performance in DTT signal reception. A tuner and a demodulator are DTT receiver RF front-end parts responsible for converting the received analog RF signal into digital video and audio streams, while the rest of the receiver circuitry processes these streams to be played on a TV or a home theater system. The RF front-end includes analog and digital filters to filter out undesired frequency components, low-noise amplifiers (LNAs) to amplify weak signals, automatic gain control (AGC) to cope with different signal levels, and analog-to-digital converter to convert the received analogue signal into a digital signal at the demodulator. The quality of these components largely determines the DTT receiver performance.

Two main types of tuners exist, both having their own advantages and disadvantages. The classical superheterodyne tuner, also known as can tuner, first shifts the received signal to a lower intermediate frequency (IF) of 36.167 MHz [107], where the signal processing is more convenient. The fixed frequency makes the filtering easier to build and tune, and at lower frequencies the filters can be more selective and transistors can have higher gains. However, a superheterodyne receiver produces an undesired distortion at the mixer stage when it shifts the received channel frequency range to the intermediate frequency range. This distortion appears at an image frequency, which is at the DTT signal frequency plus twice the IF. With the 36.167 MHz IF used in DTT receivers, the image frequency appears approximately 72 MHz above the incumbent transmission, which is where channel N+9 lies in the 8 MHz DTT channel raster. This results in worse PRs on channel

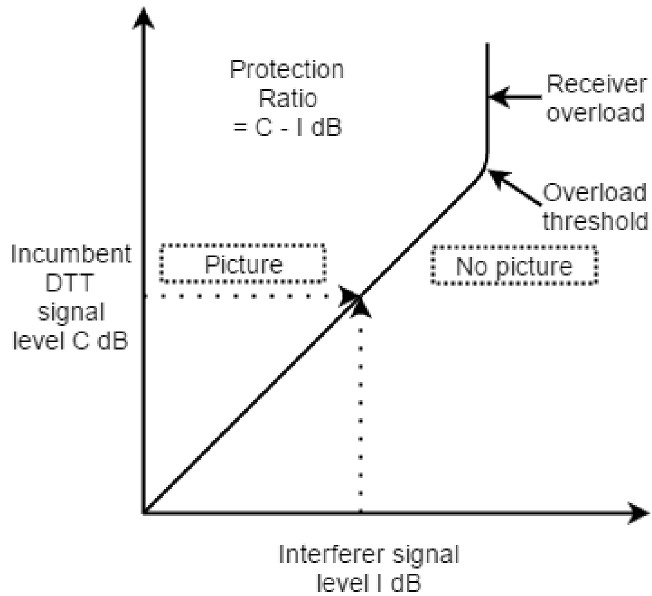

Figure 4.3: Receiver PR behavior below and above overload threshold (Modified from [109])

N+9 with superheterodyne tuners [108].

The second type of tuner is a complementary metal oxide semiconductor (CMOS) integrated circuit (IC), commonly known as silicon tuner. In the past years, the can tuners have been largely replaced by silicon tuners [110, 111]. Silicon tuners use direct-conversion reception, where the signal is not shifted to an IF and the image frequency problem does not exist. However, tuners of this design are more prone to overloading effect [108]. Overloading is a nonlinear feature of the receiver, where the receiver starts to lose its ability to distinguish the received DTT signal from other signals at different frequencies when the signal level is at or over the overload threshold. Figure 4.3 illustrates how the PR behaves linearly until it reaches the overload threshold. At this threshold, the receiver ceases to behave linearly, but does not necessarily fail immediately [109]. When the receiver is in overload state, the PRs no longer apply and the receiver cannot display the DTT transmissions no matter how high the received DTT signal level is. Overloading with different receivers has been widely studied in [98, 103].

The PRs in general are considered to be independent from the signal level of the incumbent transmission, but this would only be true if the receivers behaved linearly under all circumstances. In practice, the PRs of DTT receivers vary as a function of the level of the received DTT signal, and the receivers become more susceptible to interference when the DTT signal level is higher [103]. High signal levels decrease the receiver non-linear performance and sensitivity (the minimum signal-to-interference-plus-noise ratio (SINR) required for the DTT signal reception) [112]. The nonlinearity in the signal processing at the receiver components and amplifiers can also create intermodulation distortions, which may negatively affect the DTT reception. Silicon tuners are more prone to second-order intermodulation distortion and can tuners to third-order intermodulation distortion [113].

If a strong out-of-band (OOB) interfering signal cannot be rejected at the DTT receiver, it negatively affects the receiver's ability to detect the incumbent DTT signal on its assigned channel. This phenomenon is known as receiver blocking. The blocking performance in adjacent channel is defined by adjacent channel selectivity (ACS), which is the ratio of the receiver's filter attenuation over its assigned channel divided by the receiver's filter attenuation over the adjacent channel and is expressed in dB, i.e. ACS defines the power received from the interference on adjacent channel to the incumbent channel after DTT receiver input filter. The ACS is mainly defined by the filter performance if the interference is continuous, but it also depends on all the receiver components, and especially in case of bursty time-varying interference the AGC implementation contributes largely to the ACS performance [114]. In Figure 4.4 the DTT receiver ACS is sufficient to reject the interference from the transmission on the adjacent channel. If the interferer power level would be any higher, it would cause interference to the DTT reception. The higher the ACS value is, the better the receiver can reject interference from a strong signal on an adjacent channel.

Noise figure defines the degradation in the receiver SINR caused by the receiver RF front-end signal chain. It is expressed in dB, and lower values indicate better performance, i.e. smaller degradation. The overall design and quality of components in the DTT receiver RF front-end determines the noise figure. As the components used in the RF front-end vary in different receiver implementations, their behavior in an interference scenario is different from each other. Thus, averaging PR measurement results containing several receivers and tuner types should be avoided. The receiver performance spread can be better illustrated by grouping the receivers into different percentile groups, such as 10^{th}, 50^{th}, and 90^{th} percentile of all measured receivers. This method is typically used in Electronic Communications Committee (ECC) reports, for example in [102].

Good ACS performance in a DTT receiver is beneficial in spectrum sharing scenarios, as it allows other services on adjacent channels to use higher power levels without causing harmful interference to the DTT

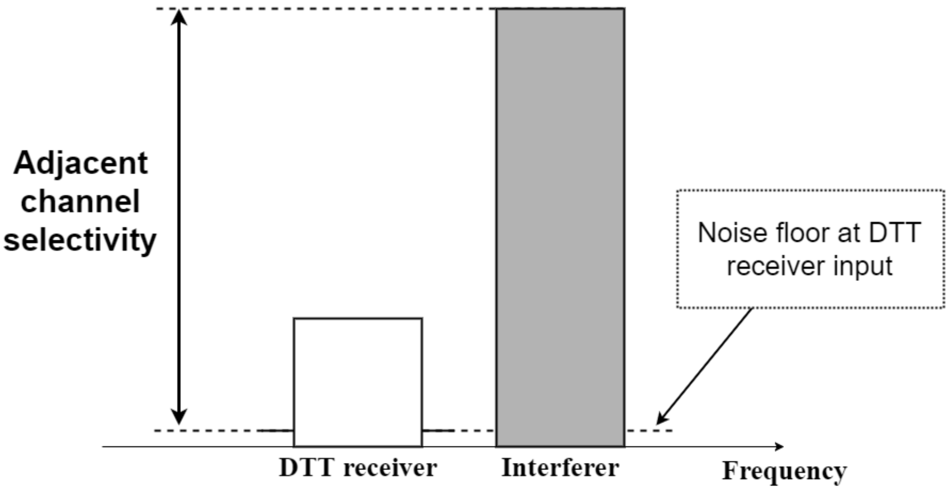

Figure 4.4: Definition of adjacent channel selectivity (ACS).

reception. Previously receivers with low ACS performance could enter the European Union (EU) internal market, as there were no binding requirements for receiver performance. The technical methods to improve ACS in the DTT receiver implementation were known [115], but there were no real incentives for the equipment manufacturers to invest in receiver performance.

The Radio Equipment Directive (RED) [73] defines that requirements for receiver performance need to be created to enable more efficient use of spectrum in the EU. The RED came in force in June 2016, and the Harmonized Standards need to be updated to meet the requirements of RED. Final draft version of *Harmonized Standard for Digital Terrestrial TV Broadcast Receivers to cover the essential requirements defined in the RED* [105] was released in March 2016, and it defines requirements for DTT receiver performance against interference particularly from LTE in 700 and 800 MHz frequency bands. To enter the EU internal market, the DTT receivers need to comply with the requirements set in the Harmonized Standard from June 2017 onwards.

4.4 Characterization of the interfering transmission

An interfering MBB transmission can originate either from a BS or a terminal. The PRs and overload thresholds of the incumbent DTT receiver strongly depend on the time and frequency domain characteristics of the interfering transmission and the adjacent channel leakage ratio

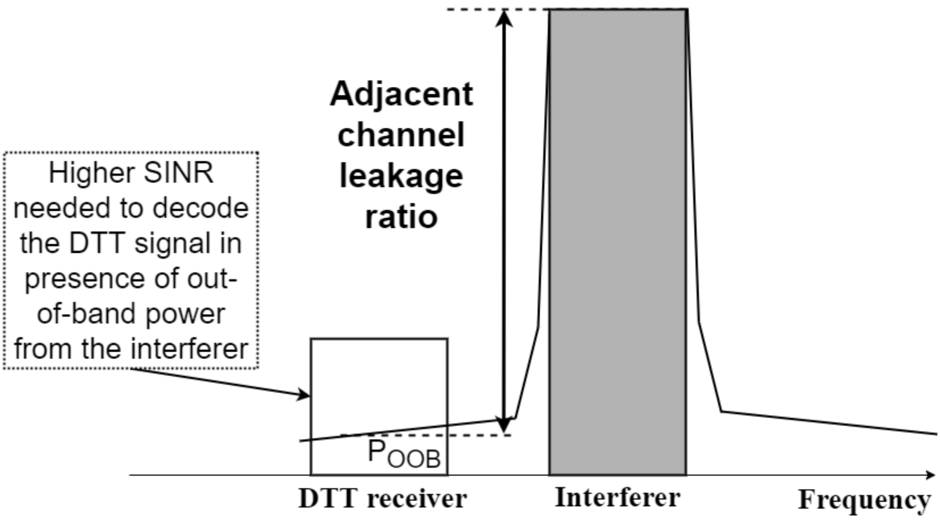

Figure 4.5: Definition of adjacent channel leakage ratio (ACLR).

(ACLR) of the interfering transmitter. There are two mechanisms in adjacent channel operation by which the interferer's emissions can affect the incumbent DTT reception. The interferer's emissions in its assigned channel can be received by the incumbent in its adjacent channel, or the interferer's emissions in its adjacent channel can be received by the incumbent in its assigned channel. In the former case, the incumbent's susceptibility to interference is defined by its ACS, and the amount of interfering power in the latter is defined by the interferer's ACLR.

ACLR is the ratio of the transmitted power on the transmission channel of the interfering transmitter to the power the interfering transmitter leaks into an adjacent channel. This is illustrated in Figure 4.5, where the leaked OOB power P_{OOB} from the interfering signal on the right interferes with the incumbent DTT signal on the adjacent channel. The leaked P_{OOB} can result in a lower SINR value at the DTT receiver input, and thus potentially in a need to raise the DTT signal power level to achieve error-free reception. The higher the ACLR value is, the less interference is leaked into the adjacent channels.

Adjacent channel interference power ratio (ACIR) is the ratio of the total transmission power of the interferer to the total interference power affecting the DTT incumbent. The ACIR takes into account the transmitter and receiver imperfections, and depends solely on the interferer ACLR and incumbent ACS performance. The relation between these power ratio values is defined by equation 4.1 [116].

$$ACIR \cong \frac{1}{\frac{1}{ACLR} + \frac{1}{ACS}} \quad (4.1)$$

Thus, high values in both interferer ACLR and incumbent ACS result in high ACIR values, which means that the interfering transmissions can use higher power levels without causing harmful interference to DTT reception. When the frequency separation from the interferer's assigned channel increases, the P_{OOB} level decreases significantly. P_{OOB} limits are set in standards of LTE and other MBB technologies, but European Conference of Postal and Telecommunications Administrations (CEPT) has also developed a block edge mask (BEM) approach to define least restrictive technical conditions of operation and to maximize the technology neutrality. BEM defines in-block and OOB power limits depending on the frequency offset from the interferer's assigned channel [117]. The larger the frequency separation is, the more stringent the limit is.

Time-variability of an interfering signal can significantly degrade the PRs and overloading performance of DTT receivers, as their channel estimation algorithms and AGC suffer from the rapid variance of the signal [114]. The effects caused by the time-variability differ between different types of DTT receiver implementations. In general, the receiver performance against an interferer in idle mode is worse than against an interferer in fully loaded mode [103], as Figure 4.6 illustrates. PRs for different DTT receivers were measured in laboratory, and their performance in idle mode (the dotted lines) was always worse than the performance of the same DTT receiver in fully loaded mode.

LTE downlink power, i.e. the power from a base station, can vary over time depending on the amount of resource blocks (RBs) used to carry the data in each orthogonal frequency-division multiple access (OFDMA) symbol. ITU-R Report BT.2215 [103] recommends to carry out the PR measurements with LTE interferer with different network traffic loadings of 0% (idle mode), 50% and 100%. The idle mode presents largest fluctuations and thus greatest challenges for the AGC and channel estimation algorithms. Fixing the RMS power or power spectral density (PSD) of the active portions of the idle LTE signal relative to the RMS power or PSD of the LTE signal with 100% traffic loading allows to study the degradations caused by the time variation. Figure 4.7 illustrates how the light purple RMS power peaks from the active portions of the idle mode are set relative to the 100% traffic loading RMS power. Now the amount of traffic loading in the idle mode can be changed to the wanted configuration, as the RMS power of the active portions of the transmissions is the same as in fully loaded mode.

LTE uplink signal from the terminal can vary considerably in both

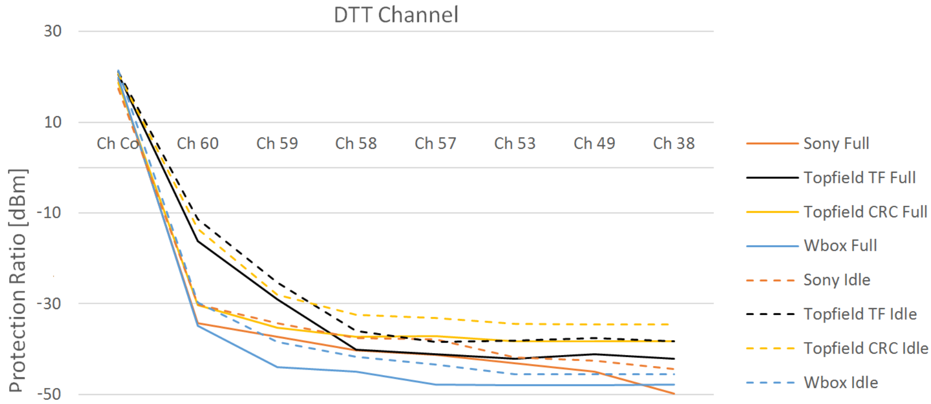

Figure 4.6: Comparison between fully loaded and idle mode PRs (ESR$_5$ criterion) between DTT and LTE BS with four different DTT receivers and -50 dBm DTT signal level.

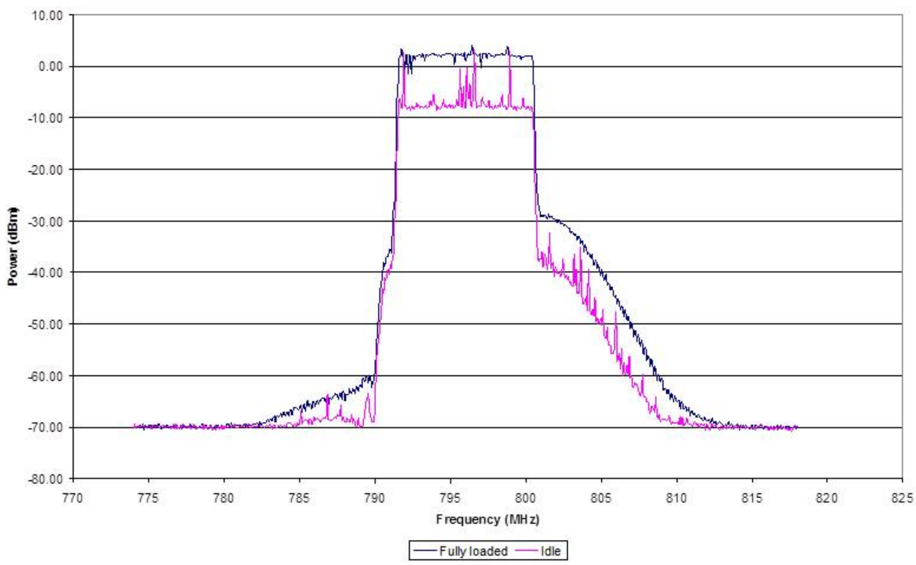

Figure 4.7: Demonstration of setting the RMS power of active portions of an idle mode signal relative to the RMS power of a signal in fully loaded mode. Adapted from annex 1G of [103].

time and frequency domains. The varying number of RBs allocated for each single-carrier frequency-division multiple access (SC-FDMA) symbol can cause rapid variations in frequency domain, while the pauses in the user transmissions lead to an irregular behavior in time domain. When the interferer is an LTE uplink, the measurements are recommended to be conducted with different data rates and traffic loadings on the uplink [103]. Recording the interfering signal PSD and level as a function of time allows to make comparisons and further analysis between results of different field measurement campaigns [103].

4.5 Laboratory measurements to determine incumbent protection criteria

The measurement devices and setups used in laboratory are similar to field measurements, but the test networks for interfering and incumbent signals are replaced with signal generators and the antennas with cabling. Before conducting field interference measurements, the measurement setup can be built and tested in controlled laboratory conditions to verify its operation. ITU-R Report BT.2215 [103] provides a good overview on conducting laboratory measurements to determine PRs for DTT receivers. A general PR measurement setup presented in the report has been applied to the measurements in this thesis, and is illustrated in Figure 4.8.

The measurement setup combines the outputs from the signal generators of the incumbent DTT and interfering signals, and splits the resulting signal and inputs it to the receiver of the incumbent signal and a spectrum analyzer. The filters, attenuators, amplifiers and combiners are all connected with cabling, and their operation and the cable attenuations are frequency-dependent [118]. Their properties thus need to be measured and verified before conducting PR measurements.

An additional isolator between the DTT signal generator and the combiner to keep the power from interfering signal generator returning to the DTT signal generator output may be needed if the combiner itself does not isolate the signal enough. Power amplifier, in conjunction with an adjustable attenuator, allows to increase and control the level of the signal from the interfering signal generator.

The combiner output is connected to a step attenuator, which allows to control the signal level and to study if the distortions in the DTT reception are caused by the overloading effect. If overloading causes the errors in reception, attenuating the level of incoming signals improves the DTT reception quality even though the DTT signal level is lower. The attenuator is then connected to a splitter or a switch, which is

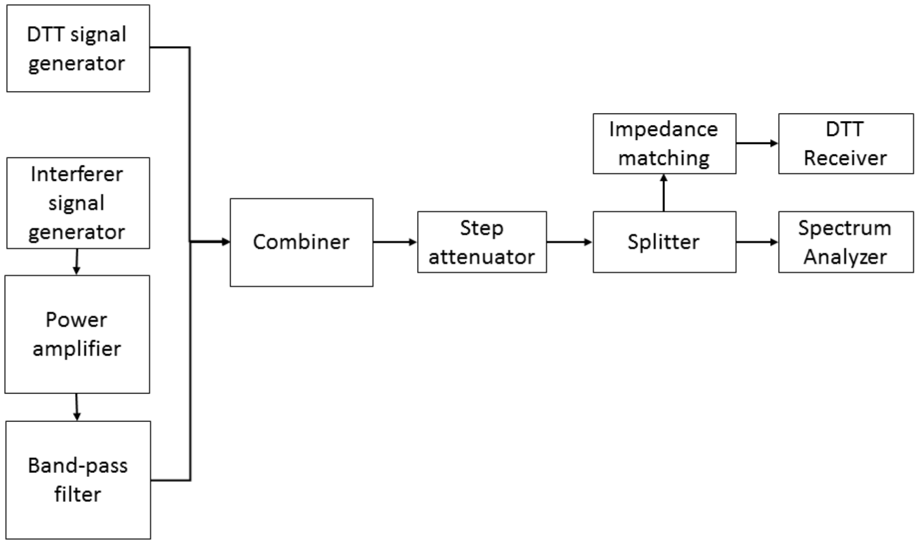

Figure 4.8: A general setup for measuring PRs in laboratory environment.

connected to the DTT receiver input with impedance matching and to a spectrum analyzer. Typically, the impedance of the measurement cabling connectors is 50 Ohm and the receiver input impedance 75 Ohm, which means that a converter for impedance matching is needed. The spectrum analyzer inputs have 50 Ohm inputs, where the measurement cabling connectors can be connected directly. The spectrum analyzer can be used to measure the power levels and visualize the spectrum.

Power amplifiers are needed if the level of the interfering signal is not high enough to cause errors in the reception of the incumbent DTT signal. This happens especially with large frequency separations to the incumbent signal. Depending on the quality of the power amplifier, its use can significantly increase the OOB noise level. Thus, measurements made using a power amplifier cannot be directly compared to measurements made without a power amplifier. The high noise levels caused by the amplifier can cause errors in the reception by different mechanisms than without an amplifier even when the interfering signal level appears to be the same.

The OOB noise components can be filtered out from the interfering signal using an adjustable band-pass filter between the power amplifier and the combiner. This guarantees that the measured PRs of the receiver under test are mainly affected by the interfering power on the interferer's assigned channel rather than some other phenomena caused by the excessive OOB noise levels. It is important to verify that the interfering transmission spectrum mask meets the requirements set for the interfering signals in their standards and CEPT BEMs when using power amplifiers and band-pass filters. The amplified and filtered signal is in practice always different from the original signal even if the spectrum mask requirements are met, so it must be emphasized that measurements conducted using a power amplifier cannot be directly compared to measurements conducted without a power amplifier.

4.6 Field measurements to determine incumbent protection criteria

In laboratory measurements, the environment and interference is controlled, and the signals only travel through cables and possibly a simulated wireless channel. In field measurements, the signals are transmitted with antennas in real operating conditions. The propagation of the radio waves is now determined by the properties of the used antennas, different propagation environments and their obstacles, human activity, weather, and other factors which cannot be controlled as strictly as in laboratory environment. Other sources of interference than the interfering signal are also present and make the analysis of the measurement results more complicated. Field measurements are expensive to conduct as they require substantial human resources, test network infrastructure, professional level measurement devices and radio licenses. Still, the field measurements provide practical and realistic information which can be used to validate results from theoretical analyses, simulations and laboratory measurements. Observations from field might also reveal phenomena omitted from previous studies.

4.6.1 Antennas

In field interference measurements, the signals from both DTT incumbent and the interfering transmitter are transmitted wirelessly with their own antennas, and the DTT receiver receives both the incumbent DTT and interfering signals with its own antenna. The antennas introduce a new degree of complexity to the measurements. The distance between the receiving antenna of the incumbent signal and the interfering transmitter antenna largely determines the level of interference. The antennas have directional qualities, which means that they do not radiate or receive power equally from all directions. The received power changes as a function of the angle and the direction of an antenna.

Omnidirectional antennas ideally radiate equally to every direction, but directional antennas are built so that they concentrate the power in

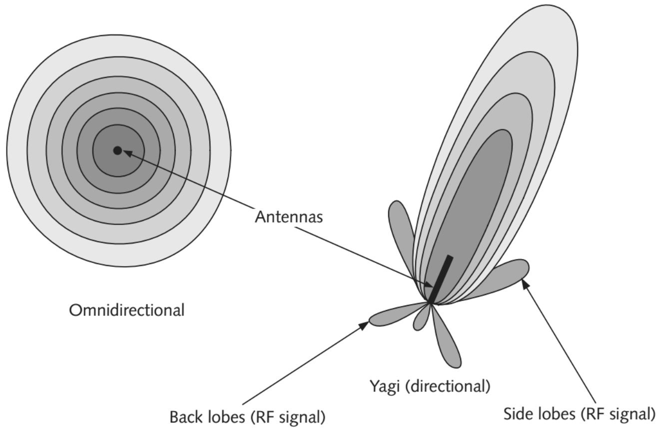

Figure 4.9: Vertical antenna radiation patterns for omnidirectional and directional antennas [119].

one direction to obtain directional gain. Higher gain results in higher received or transmitted power, which is often a desirable property resulting in longer transmission distances. Figure 4.9 illustrates horizontal (viewed from the top) antenna radiation patterns for omnidirectional and directional antenna types. The directional antenna radiation pattern is for a Yagi antenna, which is a common reception antenna type for terrestrial television reception in the ultra high frequency (UHF) band. The main lobe provides the largest directional gain. The antennas also have vertical radiation patterns, and for a Yagi antenna it is very similar to the horizontal radiation pattern.

Three-dimensional antenna radiation patterns can be built using vertical and horizontal radiation patterns. The antennas are polarized either horizontally (radio waves travel from side to side) or vertically (radio waves travel up and down). To achieve optimal signal transmission, both the receiving and the transmitting antenna should use the same polarization. Equally, if the interfering transmission uses the same polarization as the receiving antenna, it causes more interference than if different polarization would be used. Using a different polarization on the incumbent and interfering transmissions is an effective method to mitigate interference. Directional antennas can also be oriented to mitigate interference if the antenna direction with least directional gain is pointing towards the source of interference.

The Finnish Communications Regulatory Authority has created a regulation for the reception antenna system installations to ensure DTT coverage and interference-free operation [120]. Regulation 65 B/2016 [121] and its explanations and applications [122] are only available in

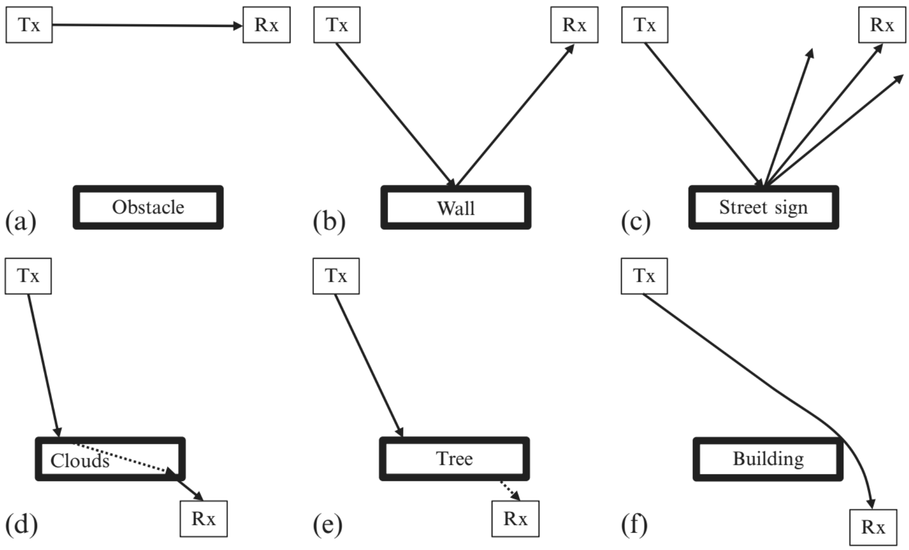

Figure 4.10: Different propagation mechanisms of radio waves: a) line-of-sight, b) reflection, c) scattering, d) refraction, e) absorption f) diffraction. Adapted from [125].

Finnish, and at the moment only the previous version Regulation 65/2013 M is available in English [123]. Regulation 65 defines minimum requirements for reception antenna system installations, and for example, it is expected that the reception antennas at the edge of the coverage area are installed at a height of 10 m and have a gain of 17 dBi. The impulse response of the used power amplifiers needs to fulfill the selectivity requirements set in SFS-EN 50083-2 [124] and the use of integrated amplifiers is prohibited. It is also required that the reception antenna is directed towards the transmitter with the strongest signal level, even if there are other transmitters offering a larger number of programs. Many reception antenna system installations in Finland do not fulfill these minimum requirements and are thus more susceptible to interference [120].

4.6.2 Propagation environment

The various mechanisms through which obstacles in the field environment affect the propagation of radio waves are illustrated in Figure 4.10. Ideally the radio waves could propagate between the transmitter and the receiver in a direct line without obstacles. This is called line-of-sight propagation and is illustrated in Figure 4.10 a). In b), the radio wave is met by an object larger than its wavelength and is reflected from the surface of the obstacle. In c), the radio wave meets an irregularly shaped object and is scattered into several different directions. In d), the radio waves meet an object with different density than its current transmission medium and refraction changes the direction of the propagation. In e), a portion of the signal strength is absorbed when the radio waves propagate through an object. In f), the radio waves are diffracted and bent around the corners and sharp irregular edges of an object they meet.

As a result of terrain, buildings, different transmission mediums, and other obstacles, the original signal arrives at the receiver via several paths. Different signal components arriving through different paths have different delays, creating a signal multipath. This phenomenon is called multipath propagation. The wireless transmissions and the signal multipath are affected by the changes in the propagation environment, such as the weather, activity from humans and the growing leaves of a tree. Thus, the factors affecting the interfering and incumbent signal propagation need to be considered in field interference measurements.

4.6.3 Reference geometries

The scenarios for field measurements are usually chosen to represent the worst cases in terms of interference from MBB to the DTT reception. Reference geometries are used to represent geometries where the antenna installation heights and horizontal and vertical separation distances between the MBB and DTT antennas cause maximal amount of interference to the DTT reception. If the DTT reception is protected in such worst-case reference geometry, it can be assumed that all other possible scenarios are also protected. Reference geometries can be created for interference originating from a mobile terminal or from a mobile BS. The ECC studies on co-existence between DTT and TV White Space (TVWS) [84, 126, 127] provide extensive amount of different reference geometries and considerations on determining the protection of DTT broadcasting. Simulations, theoretical analyses, laboratory measurements and existing research should be used in determining the relevant measurement scenario and reference geometry in different types of DTT-MBB co-existence.

Paper 9 [27] provides general methodologies to determine the relevant scenarios and geometries for field interference measurements and presents example scenarios for interference originating from a mobile terminal and from a BS of the mobile network. This type of interference affects only a portion of the users who are located within certain distance from the BS. The overloading effect occurs in the close vicinity of the MBB BS, while the interference from an MBB BS degrades the

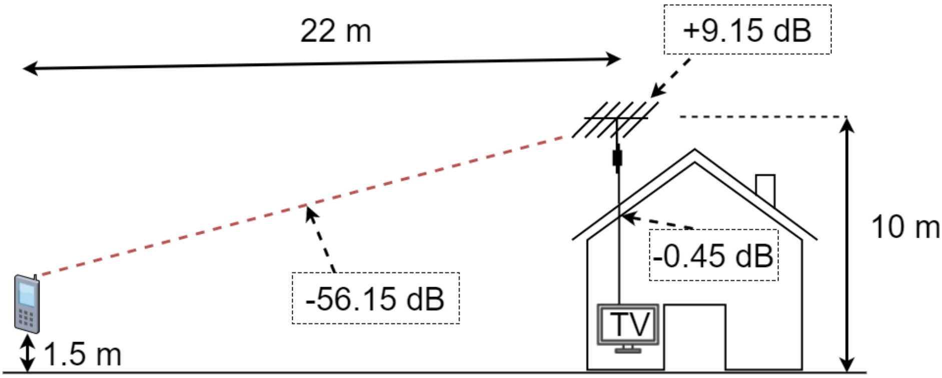

Figure 4.11: A reference geometry to determine PRs between fixed DTT reception and mobile terminal.

DTT reception SINR over a larger geographical area around the BS. The use of power amplifiers degrades the DTT reception system performance in presence of interference and thus increases the size of the area around the MBB BS where the DTT reception SINR degradation and overloading occurs.

The interference from a BS generally affects only the users located within a certain distance from the BS. The location of the BS in relation to the DTT transmitter is also an important factor, as directional antennas with directivity discrimination 16 dB are used for DTT reception in the UHF band [128]. The DTT reception antennas pointing towards MBB BSs are thus subject to more interference. Such scenarios occur when the MBB BS is directly between the DTT broadcast transmitter and the DTT reception location. When the source of interference is a terminal, it can also be simulated with a signal generator possibly connected to a power amplifier and a step attenuator and an antenna. In case of a simulated terminal, it has to be verified that its signal meets the relevant BEM requirements. If real terminals are to be used in measurements, they need to allow to change their operational parameters. Otherwise it is not possible to properly study the effect of different transmission modes and traffic loads.

Figure 4.11 illustrates a reference geometry used in the interference studies against interference from TVWS terminals in Paper 5 [23] and interference from LTE User Equipments (UEs) in 700 and 800 MHz band in [127, 129]. The coupling gain value between the interferer and the incumbent causing maximum amount of interference to arrive at an incumbent DTT receiver input is called minimum coupling loss (MCL). The horizontal and vertical separation in the reference geometry are chosen to achieve lowest possible MCL, and thus maximum interference

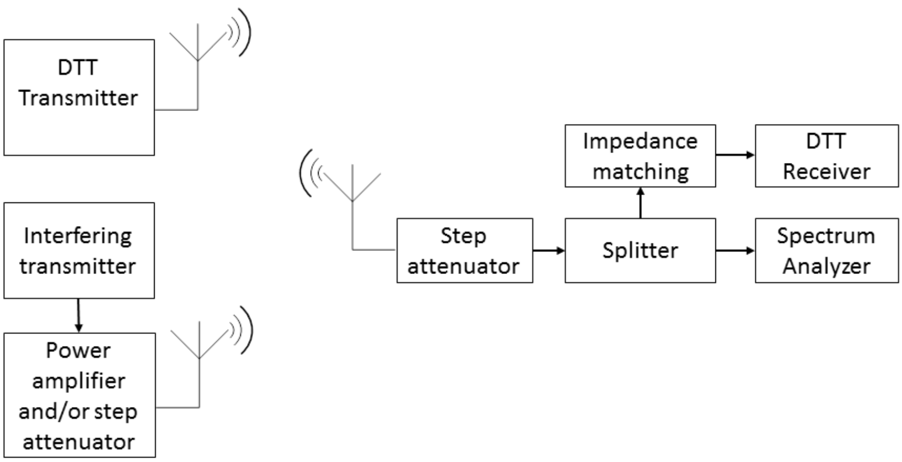

Figure 4.12: A general setup for field interference measurements.

towards the incumbent. The -56.15 dB value represents the free-space path loss (FSPL) at 650 MHz, the +9.15 dBi represents the antenna gain A_G for an antenna compliant with ITU-R BT.419-3 Recommendation [128] and the -0.45 dB the antenna angular discrimination D_A. The formula to calculate the MCL is FSPL + A_G + D_A, and thus in this case MCL = -56.15 dB + 9.15 dBi + -0.45 dB = -47.45 dB.

4.6.4 Conducting field measurements

A general field interference measurement setup in Figure 4.12 is very similar to the laboratory setup in Figure 4.8. The main difference is that the combiner and its cabling are replaced by the reception and transmission antennas of DTT incumbent and interfering transmissions, and that a reference geometry needs to be used to define the separation distances and the alignment of the antennas.

To conduct field interference measurements, radio licenses are needed for the incumbent and interferer transmissions, and they need to allow to cause interference to them. Interference to licensed commercial users is not allowed in the field measurements under any circumstances. Before field measurements, the properties of transmitters and receivers, such as sensitivity, ACS, overloading performance, and ACLR should be measured in a controlled environment to understand their behavior in field conditions. Measurement methodologies for DTT receiver performance are defined in their Harmonized Standard [105].

Finding suitable field measurement locations is problematic especially when the interference from a BS to DTT reception is studied.

Both the DTT signal and the BS signal need to be on a specific level where interference events can occur. Field strength predictions for both DTT and the interfering BS should be used to preselect possible measurement locations, after which their suitability needs to be confirmed in the field measurements. Professional level network planning tools have been found to provide quite accurate predictions [29], but finding measurement locations with suitable power levels for interference measurements is still a time-consuming process.

To allow further analysis of the field measurement results, the RF-eye node introduced in section 3.3 is used to record the incumbent and interfering signal levels as a function of time in the field interference measurements, and also to record the signal levels in other frequency ranges. This measurement data can be used to identify sources of interference other than the intended interferer, as they might cause additional distortions to the reception of the incumbent DTT signal. The data can also be used to validate the incumbent and interfering signal operation, as it can be compared to the measurement diary to which all the events and results during the field measurements are recorded with time stamps. The field measurements introduce variables impossible to reproduce, as the human activity and the signal propagation environment are never perfectly identical. The measurements should be conducted on consequent days to further validate the measurement results in very similar conditions.

Paper 9 [27] proposes a step-by-step methodology to obtain reliable field measurement results to be used in conjunction with laboratory measurements and simulations to provide more realistic results on DTT-MBB co-existence compatibility. The methodology is based on the information presented in this chapter and on the experience obtained from the conducted field measurement campaigns. The methodology consists of the following steps:

1. Determine relevant field measurement scenarios and geometries using existing research, simulations and laboratory measurements.

2. Obtain radio licenses for the measurements and build the required test network infrastructure.

3. Determine field measurement locations with suitable signal levels for the field measurement by using propagation prediction models, network planning tools or preparatory signal level field measurements.

4. Build and verify the operation of the measurement setup in laboratory environment.

5. Conduct signal level measurements at the preselected field measurement locations to determine the suitability of the location. Verify the DTT reception quality and measure impulse response of the DTT signal.

6. Conduct co-existence field measurements.

7. Perform initial analysis of the measurement results.

Chapter 5

Case study: Spectrum sharing in the European UHF TV broadcast band

This chapter describes a case study investigating spectrum sharing in the ultra high frequency (UHF) TV broadcast band in Finland and is organized in a chronological order. The chapter begins by describing a historical perspective on terrestrial UHF TV broadcasting in Europe and the research in Finnish White Space Test Environment for Broadcast Frequencies (WISE) projects, which investigated the exploitation of vacant spectrum resources within the band through unlicensed TV White Space (TVWS) concept. After reviewing the current status of TVWS, the chapter concludes with considerations on potential developments in the use of UHF TV band in Europe.

5.1 TV broadcasting and White Spaces

Traditionally the UHF TV frequencies between 470 and 862 MHz have been used for broadcasting terrestrial TV. Previously analog TV transmissions were broadcasted in the whole 470-862 MHz band, but in the 1990s the European countries started to plan the digitalization of their TV broadcasting networks. An agreement on the use of broadcast frequencies for the analog TV transmissions made in the Stockholm 1961 Agreement (ST61) needed to be updated. New frequency plans for the transition period to the digital television (when both the old analog and the new digital TV transmissions were operational at the same time) and the time after the transition (only digital TV transmissions are operational) were made for Europe, Africa and Middle East at the Regional Radiocommunication Conference 2006 (RRC-06), where a new agreement, the Geneva 2006 frequency plan (GE06) was created [130].

European Telecommunications Standards Institute (ETSI) Digital Video Broadcasting - Terrestrial (DVB-T) standard [99] was chosen as the digital terrestrial television (DTT) broadcasting technology to be used, but GE06 was simultaneously made flexible for future applications. Digital Video Broadcasting - Handheld (DVB-H) [131] was also created for handheld terrestrial reception, but the commercialization of the concept failed and it is now practically obsolete [132]. In 2009, Digital Video Broadcasting - Second Generation Terrestrial (DVB-T2) [133] introduced over 40 percent increase in the maximum data rate, and the advanced error correction and interleaving properties result in a much more robust transmission when compared to DVB-T with same data rate and bandwidth [134, 135]. The 2011 update to DVB-T2 added a T2-Lite subset for mobile and portable reception [134]. The transition from DVB-T to DVB-T2 is being made gradually as the users need to update their receivers to receive DVB-T2. In Finland, the transition to DVB-T2 will be completed in 2020 [136]. The 800 MHz band (790-862 MHz) was allocated for mobile broadband (MBB) at World Radiocommunication Conference 2007 (WRC-07) [137], which led the European Union (EU) to allow MBB within the 800 MHz band in 2010 [138, 139]. In Finland, the 800 MHz band was auctioned for Long Term Evolution (LTE) MBB, whose transmissions began in 2014. The DTT transmissions from the 800 MHz band were reorganized into the 470-790 MHz band. The transition period from analog to digital terrestrial television was completed in Europe in 2015 [140], and after the analog switch-off only DTT transmissions have remained. The spectral efficiency of DTT is higher than in analog TV, and approximately 8 standard DTT channels can be transmitted in the same amount of spectrum previously required by one analog terrestrial TV channel [141]. Thus, spectrum resources were left unutilized in the UHF TV band after the transition to DTT. The amount of spectrum made available by the transition to DTT broadcasting is called the *digital dividend* [137].

Studies on opportunistic unlicensed secondary utilization of the spectrum holes between the DTT transmissions within the UHF TV spectrum, referred to as TVWS, were commenced in European Conference of Postal and Telecommunications Administrations (CEPT)/Electronic Communications Committee (ECC) in 2009. CEPT defines white space as "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" [142]. DTT broadcasting topology uses mainly high power high tower transmitters, which leave local opportunities to reuse the spectrum with low power communications systems which do not cause harmful interference to the DTT reception. The availability of TVWS over large geographical areas has been studied using propagation prediction models in [143–146]. The amount of TVWS depends on which propagation prediction model is used, and as described in section 3.4, the propagation models in general are not very accurate without precise environment data. The interpolation methods presented in papers 2 and 3 [20, 21] can provide more accurate results compared to the prediction models, but require expensive and time-consuming field measurements.

Studies on the protection of the incumbents in the band, DTT and Programme Making and Special Events (PMSE) wireless microphones, are essential in building a framework which allows opportunistic operation of TVWS systems within the band. The DTT transmission are of a static nature, but their amount and channels vary country by country. The PMSE wireless microphones are mobile, and they need to declare their location information to obtain protection from TVWS users. The presence of a PMSE wireless microphone thus reduces the amount of available TVWS in its surrounding area. The amount of available TVWS also depends greatly on how conservative the protection levels for the incumbents are. A high level of incumbent protection translates directly to a reduced amount of spectrum for TVWS users. This highlights the importance of conducting field interference measurements to study the protection criteria for DTT incumbents.

5.2 White Space Test Environment for Broadcast Frequencies (WISE) projects

After a request from ECC, CEPT Working Group Spectrum Engineering (WG SE) established a new project team CEPT/ECC Spectrum Engineering 43 (SE43) at its 53rd meeting in May 2009. SE43 began its work in defining *Technical and operational requirements for the possible operation of cognitive radio systems in the White Space of the frequency band 470-790 MHz* [147]. The term cognitive radio (CR) and closely related software-defined radio (SDR) [148, 149] refer to technologies that could learn about their radio environment and transmit in such frequencies and with such power levels that they would not cause interference to the incumbents.

SE43 was mandated [150] to:

- Define technical and operational requirements for the operation of cognitive radio systems in the white spaces of the UHF broadcasting band (470-790 MHz) to ensure the protection of incumbent radio services/systems and investigate the consequential amount of spectrum potentially available as white space.

- Provide, if required, technical assistance on further issues related to white spaces and cognitive radio systems that ECC may identify in the future.

- Liaise directly with relevant groups within ECC and ETSI as necessary.

First SE43 meeting was held in June 2009, and the group completed its work in its 16th meeting in December 2012. All stakeholders relevant to TVWS were involved in the SE43 work: administrations, industry, operators, PMSE wireless microphone users, and DTT broadcasters. The outcome of the first phase of the work was ECC report 159: Technical and operational requirements for the possible operation of cognitive radio systems in the white spaces of the frequency band 470-790 MHz [127] in January 2011. The report still had several technical and regulatory issues which needed further consideration. However, it was decided that instead of updating the report, two complementary reports would be released.

A White Space Test Environment for Broadcast Frequencies (WISE) was built in 2011 in Turku, Finland, to aid in the work of CEPT/ECC SE43, and to demonstrate technological capabilities of TVWS systems for industry. The Finnish Communications Regulatory Authority (FICORA) [151] issued a test radio license for CR devices operating in the whole 470-790 MHz TVWS frequency range on a 40 km $\times$ 40 km area with 300 000 inhabitants. The license was the first in Europe with a geolocation database controlling the frequency use. A project consortium began its work in WISE project [152] in 2011, and included all the key stakeholders in Finland: universities, geo-location database provider, regulator, DTT broadcaster and user equipment manufacturer.

The project followed closely the topics of CEPT/ECC SE43 working group and contributed its results to the group. The first phase of WISE project (2011-2013) concentrated especially on the field measurement campaigns related to incumbent protection, while the second phase (2013-2015) concentrated on application pilot trials with realistic use cases and on developing and validating the geo-location database functionalities. Additional industrial partners accompanied the original consortium in the second phase. Paper 6 [24] includes a more detailed description of the TVWS test network environment.

WISE project results were contributed to the SE43 work, which produced two ECC Reports [84, 126] in January 2013. ECC Report 185: *Complementary Report to ECC Report 159. Further definition of technical and operational requirements for the operation of white space devices* *in the band 470-790 MHz* [126] describes the protection of incumbent DTT broadcasting and PMSE wireless microphones, protection of services on the bands adjacent to UHF TV band, and the classification and technical characteristics of white space devices (WSDs).

ECC Report 186: *Technical and operational requirements for the operation of white space devices under geo-location approach* [84] describes one of the key issues requiring further consideration in ECC Report 159; the use of information in a centralized manner from a geo-location database to guarantee the protection of the incumbents. In this approach the WSDs determine their location and communicate it along with their technical characteristics to a geo-location database, which responds with information on the available frequencies and associated transmit powers for that location. Geo-location database approach was chosen to be used in TVWS instead of the initially considered CRs, as their sensing technologies were considered too unreliable to protect the incumbents [153].

5.2.1 Phase 1: Field measurements to determine incumbent protection

The main contributions from the first phase of WISE project (2011-2013) were to the studies in interference between the DTT incumbents and secondary opportunistic TVWS users. The measurements were conducted in field conditions in the indoor and outdoor reference geometries defined in ECC report 159, and contributed to the SE43 [154–157]. ECC report 159 [127] defined the reference geometries as one of the technical issues to need further investigation. Field measurements were needed for the reference geometry studies as such geometries are difficult to reproduce in a laboratory environment. For example, the outdoor reference geometry requires a reception antenna at a height of 10 m with a horizontal separation of 22 m to the WSD.

The Turku TVWS test network environment was built to offer an opportunity to conduct these measurements in real operating conditions and in a real test network. Incumbent DTT test network transmission at 610 MHz was used with a TV reception antenna at 10 m in locations with signal strengths of -80, -70 and -60 dBm. Interference from a WSD was introduced to study the protection ratios (PRs) in the reference geometries with the methodologies described in chapter 4 and Paper 9 [27]. The results can be considered as the first practical results from the proposed theoretical reference WSD scenarios of ECC report 159 and first realistic numerical estimates for the minimum PRs between WSD transmitters and primary TV receivers.

Further measurements were conducted to study the effect of different

Table 5.1: Comparison of Ofcom protection ratio recommendations [160] and worst obtained protection ratios from the outdoor reference geometry measurements in Paper 5 [23].

Channel	Ofcom Recomm. [160] (dB)	Outdoor (dB) [23]
N	20	19.7
N-1	-30	-33.4
N-2	-47	-44.1
N-3	-49	-47.5
N-4	-65	-51.9

separation distances and to confirm that the reference geometry scenarios actually are the worst possible cases in terms of interference towards the incumbent. This was actually not the case, and lower minimum coupling loss (MCL) values were measured with separation distances differing from the reference geometry. This is a key finding, as lower MCL values (higher coupling gain) result in more interference to the DTT reception. This result demonstrates that theoretical calculations do not always apply in field conditions, where the signal multipath and its reflections can potentially result in lower MCL than the calculated MCL. This phenomenon has been confirmed in later measurements [158, 159] and is further discussed in Paper 9 [27]. In [158], the lower MCL and lower DTT signal strength values than predicted resulted in negative margins in PRs of DTT for some locations in the United Kingdom (UK) TVWS framework. It is worth noting that only a small number of DTT receivers operate in these worst-case scenarios defined by the reference geometries. Statistics should be used to determine the number of users operating in such scenarios.

Paper 5 [23] combines all the field measurement campaigns conducted to study the co-existence between a WSD (an MBB terminal) and DTT reception in indoor and outdoor reference geometries. Field interference measurements in these reference geometries have not been conducted elsewhere. Table 5.1 compares the results from the worst case outdoor reference geometry measurements to the initial DTT PR recommendations made by the Office of Communications (Ofcom) [160]. The recommendations generally compare well to the worst results from Paper 5 [23], as shown in Table 5.1. On channel $N-1$, the field measurement PR would allow a little higher WSD signal level than Ofcom recommendations. However, especially on channel $N-4$ the situation is completely opposite, as the Ofcom recommendation would allow 13.1 dB higher WSD powers than the worst field measurements.

The major weakness in the results of Paper 5 [23] was that time-varying interfering signals were not used in the field measurement campaign. The later laboratory measurements [103, 110, 114, 161] confirm that the time-variance of the interfering signal can cause a significant degradation in the PR of a DTT receiver. British Broadcasting Corporation (BBC) laboratory measurements were conducted with the same incumbent DTT operating parameters as in Paper 5 [23] and 14 different DTT receivers with several types of interfering signals and time-variability [161], and their results indicate that the Ofcom PR values should be increased by 30-40 dB to guarantee the protection for all measured DTT receivers. The increase in PRs is considerably smaller if the worst-performing DTT receivers are omitted. Typically, a DTT receiver performed well against most types of interference, but performed very poorly against some specific type of time-variance.

The indoor reference geometry measurements in Paper 5 [23] indicate great variations in MCLs between different rooms in the building. To the author's knowledge, other measurement results in this specific indoor reference geometry do not exist. Indoor DTT reception seems to be very susceptible to an interfering terminal in the same or adjacent room, or even in adjacent building if there are only glass windows between the interferer and the DTT incumbent [158]. The geometries and scenarios to represent worst case conditions for indoor reception against interference from an MBB terminal or a WSD are diverse and difficult to determine, as they depend greatly on the materials used in the walls and windows, and because the terminals can move inside the building in an uncontrolled manner. The DTT broadcasting networks are not always implemented to provide indoor coverage, and in such cases the DTT indoor reception is not protected but can still be used opportunistically.

One of the most relevant observations from co-existence studies of DTT receivers is the effect the DTT receiver performance has on spectrum sharing opportunities. If the DTT receiver performance is very poor, the reception gets distorted easily when interference is introduced, and the spectrum sharing opportunities are reduced as the secondary users need to use lower power levels. The results from the studies conducted in CEPT/ECC and in SE43 have probably contributed to the fact that the EU addressed this issue by setting minimum levels for receiver performance, as described in section 4.3.

The protection of incumbent PMSE wireless microphones was also studied in field measurement campaigns in Helsinki City Theatre and Arena Theatre. A WSD signal was used to cause interference to the wireless microphone receivers. The key finding was that the way the microphones are used plays a major role in the signal quality. A belt pack attached to a moving person could perform 30 dB worse than the same equipment in line-of-sight conditions between the belt pack and the receiver and no movement. A contribution from the measurement campaigns was made to SE43 [162] together with the full measurement report [163], which was later published as an annex in ECC report 185 [126].

ETSI Broadband Radio Access Networks (BRAN) has developed a *"Harmonised European Standard EN 301 598: White Space Devices (WSD); Wireless Access Systems operating in the 470 MHz to 790 MHz TV broadcast band; Harmonized EN covering the essential requirements of article 3.2 of the Radio and Telecommunication Terminal Equipment (R&TTE) Directive"* [164], which includes WSD radio frequency (RF) requirements to prevent harmful interference to DTT incumbents by setting specific limits for the radiated power in the assigned and adjacent channels of the WSD. As illustrated in Figure 5.1, the work of SE43, including the WISE project phase 1 contributions, has been used as a basis in the creation of the EN 301 598 Harmonized Standard.

5.2.2 Phase 2: Application pilot trials

WISE phase 2 (2013-2015) focused on application pilot trials to demonstrate the feasibility and technical capabilities of TVWS to the industry. The work in SE43 was completed and had been used to create the technical and operational requirements for TVWS operation and aided in the development of ETSI Harmonized Standard for WSDs [164]. Figure 5.1 illustrates how the contributes created from the field measurements in phase 1 of WISE and the work of SE43 were used in the European regulation to create the technical and operational requirements and the Harmonized Standard for WSD, which made it possible to conduct the application pilot trials of WISE2 using the TVWS framework.

The Harmonized Standard for WSDs [164] defines requirements for devices which can be used in the TVWS of UHF TV band. The WSDs are divided into 5 different device emission classes according to how good their adjacent channel leakage ratio (ACLR) performance is (how much power is leaked into adjacent channels, as explained in section 4.4), and this information is used when the geo-location database calculates the power level a WSD can use. The devices with better classification can use more transmission power without causing harmful interference to the incumbents. Device emission class measurements were conducted for all of the WSD prototypes used in the application pilot trials of WISE2 to verify their device emission classification and enable proper geo-location database operation. The measurement methodology is described in Paper 6 [24].

The geo-location database of the test network environment contains

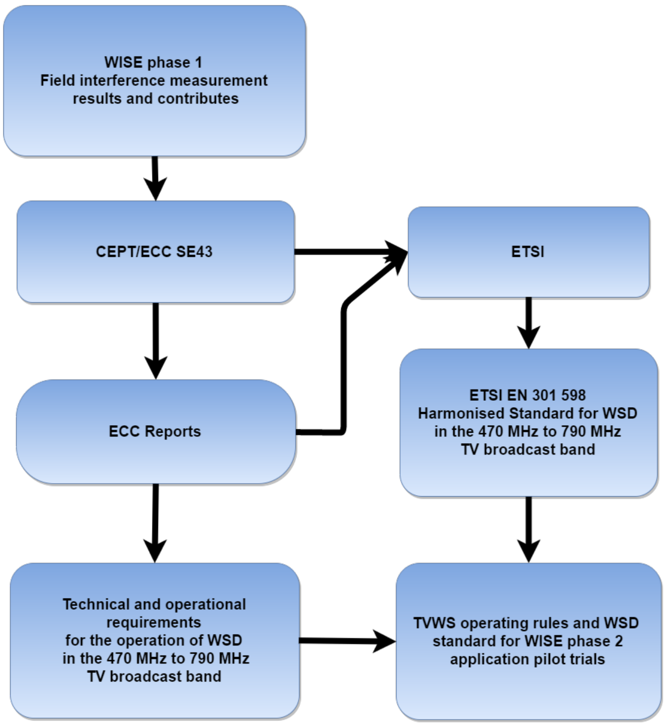

Figure 5.1: The role of contributes from WISE phase 1 in the creation of TVWS operating rules and a WSD Harmonized Standard.

the information needed to protect the DTT and PMSE wireless microphone incumbents operating in the UHF TV band. The geo-location database contains signal level maps of the incumbent DTT network to determine the power levels the unlicensed WSD users could use without causing harmful interference. When the DTT incumbent signal strength, WSD emission class, and the required PRs are known, the geo-location database can calculate the maximum power levels the WSD users can use without causing harmful interference to the DTT incumbents.

Turku University of Applied Sciences has developed a management system for PMSE wireless microphone incumbents. The system allows a PMSE user to register his microphone and communicate its location and related operational information to the geo-location database, which creates exclusion zones around the locations with wireless microphones to protect them from harmful interference. The WSDs are not allowed to operate inside these exclusion zones. The geo-location database incumbent protection algorithms were validated throughout the second phase of WISE project in the practical field measurements and trials, and the technological capabilities of the WSDs used were studied through public transport information, ticket sales, and video surveillance application pilot trials in Paper 6 [24].

The prototype equipment used in the application pilot trials in Paper 6 [24] was more suitable for rural use than urban city environments. The equipment used a proprietary transmission scheme, for which no information on the transmission parameters were available. For example, the system parameters or the equalization algorithms may have been optimized for rural use and negatively affect the performance in an urban environment. The performance was significantly better in rural use scenarios. Still, the application pilot trials have shown that with accurately defined use cases and appropriate equipment, commercial TVWS deployments are possible from technological viewpoint. The results from the conducted measurement campaigns and application pilot trials have been useful in further TVWS system development, geo-location database operation validation, performance evaluation, and in advancing the technical and regulatory progress towards enabling spectrum sharing.

5.3 Global status of TV White Space

The required functionalities for TVWS operation in Europe and the protection of incumbents are described in ECC reports [84, 126, 127], and in ETSI standards [164, 165], but it is up to the National Regulatory

Authority of each country to decide if and how a TVWS framework is actually implemented. A further ECC Report 236: *Guidance for national implementation of a regulatory framework for TV WSD using geo-location databases* [166] was created in CEPT/ECC Frequency Management project team 53 [167] to aid in the national implementation of geo-location databases and published in May 2016. An example and a high-level description of one national implementation is available in Annex 2 of [166], which describes Ofcom implementation of TVWS framework and calculation of operational parameters in the UK.

The complexity of TVWS system and incumbent protection, regulatory uncertainty, and the non-exclusive access to spectrum discourage investments in TVWS [168]. Unlicensed TVWS operation does not provide mechanisms for protection from any harmful interference between the WSDs or from the incumbents, and thus cannot provide any set level of quality of service (QoS) or guarantee access to spectrum resources.

There have been some initial trials for unlicensed TVWS operation, but in Europe large commercial investments are still absent. The European TVWS activities are focused on the UK, where extensive trials and experimentations have been performed [169, 170]. As of January 2017, there are two qualified TVWS database operators providing geo-location database services for TVWS operation in the UK [171]. In the United States (US), Federal Communications Commission (FCC) has created its own set of rules for TVWS operation. They are less complex, but the more rigid and conservative approach results in lower power levels and throughput for TVWS users. ETSI and ECC rule comparisons can be found from [38, 172]. American Institute of Electrical and Electronics Engineers (IEEE) has also created two global TVWS standards: IEEE 802.11af [172] (also known as White-Fi, describing the use of Wi-Fi technology within TVWS) and IEEE 802.22-2011 wireless regional area network (WRAN) to provide MBB to rural areas [173].

Outside Europe and the US, the interest in TVWS is especially high in rural areas of Africa where the Internet penetration is low. Some recent TVWS activities in Africa are presented in [174, 175]. Providing robust and affordable backhaul is problematic in semi-urban and rural India, but as the amount of TVWS is large in India, the use of TVWS to provide this backhaul for a billion plus population of India could be a feasible and cost-effective solution [176]. In Japan, National Institute of Information and Communications Technology (NICT) has also been very active in prototyping and experimenting TVWS in field conditions [38]. Philippines have adopted NICT TVWS database for their Free Wi-Fi project [177].

The propagation characteristics in this frequency range are extremely good when compared to systems operating on higher frequencies [178], and the signal attenuation is significantly smaller when the signal passes through different materials [172]. As these lower frequencies require a lower amount of base stations to provide a certain coverage, they offer a good platform to build mobile networks. However, exclusive access to spectrum, long-term security for the investments in infrastructure, and more manageable QoS and interference are essential for mobile operators if only limited amount of spectrum is available. Unlicensed TVWS spectrum cannot provide these. The interest in TVWS operation In Finland has been low, and investigations on other methods to exploit the UHF TV band more efficiently have been commenced.

5.4 Potential developments in the use of UHF TV band in Europe

In Europe, a High Level Group on the future of the UHF spectrum was set up to deliver strategic advice to the European Commission (EC) to develop a political strategy for the use of UHF band in the coming decades. The group included top executives from Europe's broadcasters, mobile network operators (MNOs), and technology associations [179]. The final report, known as Lamy report [180], was published in September 2014.

The report proposes the following:

- 700 MHz band (694-790 MHz) should be dedicated to MBB across Europe by 2020 (plus/minus 2 years).
- Regulatory security and stability should be ensured for terrestrial broadcasting in the remaining UHF TV spectrum 470-694 MHz until 2030. The spectrum could also be utilized to provide Supplemental Downlink (SDL) or other flexible types of downlink use.
- The technology and market developments should be re-evaluated by 2025.

5.4.1 700 MHz band

The 700 MHz band (694-790 MHz) was allocated to MBB at World Radiocommunication Conference 2012 (WRC-12) [181] with immediate effect after World Radiocommunication Conference 2015 (WRC-15). The technical and regulatory parameters for the use of 700 MHz band for MBB were finalized at WRC-15 in November 2015. The coherent situation in 700 MHz band in all International Telecommunication Union (ITU) regions allows a rare opportunity of near-global harmonization for this frequency band [182].

The EC mandated CEPT to develop the harmonized technical conditions for the introduction of MBB to 700 MHz band [183]. No such mandate was made for 800 MHz band, which made freeing up 800 MHz band a difficult and time consuming process resulting in several temporary agreements [184] and derogations [185]. The frequency arrangement for MBB in the 700 MHz band is harmonized as a paired frequency arrangement of 2 × 30 MHz frequency-division duplex (FDD) and an optional unpaired frequency arrangement of up to four blocks of 5 MHz for SDL [186]. SDL uses the unpaired spectrum to provide additional downlink capacity to an MBB system through carrier aggregation (CA) [187].

The paired spectrum blocks carry only uplink or downlink traffic within one block, while unpaired spectrum allows to use time-division duplex (TDD), where both uplink and downlink traffic are carried in the same frequency block. TDD allows asymmetric uplink/downlink ratio, and thus allows to dedicate frequency blocks for downlink, i.e. SDL. According to national needs, the frequency blocks for optional SDL in 700 MHz band can also be used for alternative options such as PMSE, Public Protection and Disaster Relief (PPDR), and machine-to-machine (M2M) [188–190].

Finland is an early adopter of the 700 MHz LTE MBB, whose operation commences in the band in 2017. The PMSE are no longer allowed in the band [191] and the DTT broadcast transmissions were regrouped into 470-694 MHz frequency band during 2016. The methods to use the remaining sub-700 MHz UHF TV band are investigated in Finnish the Future of UHF Frequency Band (FUHF) project (2015-2018) [192], which is part of Tekes's 5thGear programme [193] for future 5th generation mobile networks (5G) systems and 5G Test Network Finland ecosystem [194].

5.4.2 LTE SDL in 470-694 MHz band

As the media consumption is shifting from traditional broadcasted content (linear TV, where a certain program has to be viewed at a certain time when it is offered) towards personalized content, the whole future of the DTT broadcasting as a delivery method is in turmoil. The current media consumption differs largely between different demographical groups [195], a conspicuous feature being that the amount of consumed broadcasted content increases with age. Thus, the younger generations consume more personalized content and less broadcasted linear content. The Finnish Ministry of Transport and Communications states that the distribution of television programs via mobile networks becomes relevant in the 2020s, and that the change is not only technological, as the content, business models, user expectations, and usage patterns are changing [196].

One of the items on the agenda of the WRC-15 was to introduce a co-primary MBB allocation to the 470-694 MHz band in Region 1. Such an allocation would allow the nations to flexibly choose if they want to use the band for DTT broadcasting or MBB. Even though Finland strongly favored the co-primary allocation, no changes to the current allocation in the UHF band in Region 1 were made. Additionally, an agreement was made that the allocation would not be changed at World Radiocommunication Conference 2019 (WRC-19). This means that the remaining broadcasting in the lower UHF TV band of Region 1 is safeguarded until the World Radiocommunication Conference 2023 (WRC-23). A decision was made that a review of the spectrum use in the entire 470-960 MHz UHF band is to be made at WRC-23.

In November 2014, ECC published a long-term vision for the UHF band in Report 224 [197], which identifies and analyzes possible future scenarios for sub-700 MHz UHF TV band utilization, but does not make any recommendations for the future use of the band. The Radio Spectrum Policy Group (RSPG) long-term strategy for the use of UHF TV band in February 2015 [198] stated that the priority in the sub-700 MHz UHF TV band will still be on distribution of audiovisual media Services (AVMS), but a flexible approach on the use of the band should be taken as the market significance of DTT services in different Member States varies.

In February 2016, the EC proposed that the lower UHF TV band could be used for other services than television broadcasting networks as long as they do not cause harmful interference to the broadcasting services in neighboring Member States [182]. Again, the use would be limited to downlink only (transmission from the network to a receiving terminal) to mitigate interference. However, this proposal needs to be approved by the European Parliament Committee on Culture and Education (CULT) [199], which considered that the band should only be used for broadcasting at least until the end of 2030 [200].

The UHF TV band future scenarios of [197] are discussed in Paper 9 [27], which identifies co-existence of downlink-only MBB (such as LTE SDL) and DTT broadcasting as the most feasible co-existence scenario in sub-700 MHz UHF TV band in the near future. Potential use cases for LTE SDL are discussed in [201], but in general the main use would be to provide additional capacity for video streaming, both with linear and personalized content. The world's first demonstration of LTE SDL in UHF TV band was performed in September 2016 by FUHF consortium partners YLE and Nokia together with Qualcomm [202].

In downlink-only SDL operation, only the interference from the base

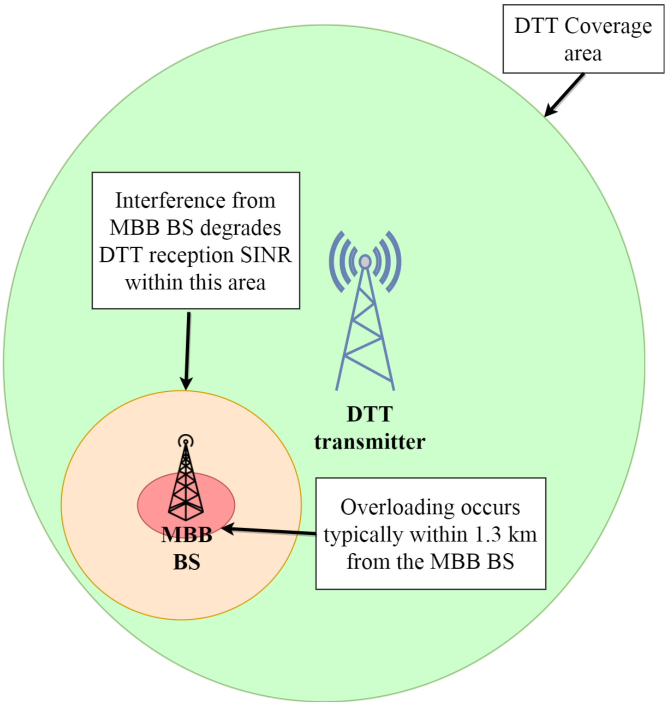

Figure 5.2: Interference from an MBB base station within the DTT coverage area can either degrade DTT reception SINR or cause overloading in the DTT receiver.

stations (BSs) needs to be considered. The interference from a BS generally affects only a portion of users located within a certain distance from the BS. Figure 5.2 illustrates the area where the interference from an MBB BS affects the DTT reception within the DTT coverage area. The overloading effect occurs in the close vicinity of the MBB BS, while the interference from an MBB BS degrades the DTT reception signal-to-interference-plus-noise ratio (SINR) over a larger geographical area around the BS. The use of power amplifiers degrades the DTT reception system performance in presence of interference and thus increases the size of the area around the MBB BS where the DTT receiver SINR degradation and overloading occurs. Large geographical separations are needed for co-channel operation, but the initial field measurements and the experience from co-existence between DTT and LTE BSs in 800 MHz band have shown that adjacent-channel interference events rarely occur with distances larger than 1.3 km from a BS [203, 204].

The requirements for the DTT reception system installation, including antenna, feeder cable and amplifiers have not been addressed in EN 303 340 Harmonized Standard [105]. According to observations from field measurements [158], especially a Harmonized Standard for amplifiers could improve the co-existence performance of a DTT reception system. As no performance requirements or Harmonized Standard for amplifiers exist, devices with inferior performance are still available on the market. The non-linear characteristics of an amplifier can generate intermodulation distortions and significantly worsen the DTT receiver susceptibility to overloading. The DTT receiver Harmonized Standard [105] improves the receiver overloading performance as it requires that the receivers need to tolerate a signal level of -4 decibel-milliwatt (dBm) without going to an overloading state. However, a majority of the DTT receivers released prior to the Harmonized Standard does not comply with this performance requirement [205].

The introduction of 800 MHz band for LTE MBB has resulted in thousands of reported interference cases in Finland, and the MNOs operating in the band are obliged to solve these cases [48]. These LTE transmissions operate on the channels above the highest DTT transmission, and cause overloading and blocking effects similar to what a BS in LTE SDL scenario would cause. Data from these interference events could be very useful in determining typical interference scenarios. The most important method to mitigate interference from LTE is an anti-LTE filter between the reception antenna and the DTT receiver [206]. Such low-pass filters can be used against LTE-700/800 to attenuate the LTE transmissions on frequencies above the highest DTT channel, but in the LTE SDL scenario attenuating the LTE transmissions is more complicated as LTE is transmitted at frequencies interleaved between the DTT channels. Programmable filters could be used to attenuate the LTE transmissions, but such filters are more expensive than low-pass filters. Less expensive option could be to have location-specific fixed filters to attenuate the relevant LTE SDL transmissions in each location where interference occurs.

If the LTE SDL is used to deliver AVMS, it can be perceived that it can already operate in the band if it is coordinated with GE06. LTE SDL concept is also in accordance with the EU objectives to prioritize the use of 470-694 MHz band for AVMS [182] and with the technology neutrality supported in the EU [207,208]. If the LTE SDL deployments do not comply with the GE06 agreement, a World Radiocommunication Conference (WRC) decision or approval of the proposition for flexible UHF TV spectrum utilization in Europe [182] is needed before LTE SDL can be deployed in the frequency band. The GE06 agreement [130] designates the use of UHF TV frequencies for broadcasting in Europe, is technology neutral and uses block edge mask (BEM) to constrain the out-of-band emissions. Using GE06 to allocate LTE SDL would mean interference coordination between each LTE SDL base station and the existing allocations in the GE06 plan. The GE06 agreement defines binding agreements with respect to incoming and outgoing interference. A simulation study using the information on DTT deployments in Finland [209] concludes that there would be broadcasting spectrum available for LTE SDL deployments complying with GE06 agreement.

In practice, using GE06 for allocating LTE SDL raises some questions regarding the co-existence compatibility between LTE SDL and DTT broadcasting, which require further clarifications. For example, the compatibility of GE06 allocations is determined through International Telecommunication Union Radiocommunication sector (ITU-R) P.1546 propagation prediction method [210]. The author has written a conference paper (accepted for publication in June 2017) describing a recent field measurement campaign to study the accuracy of P.1546 predictions with LTE signals in the proximity of the LTE base station [29]. The paper concluded that the predicted signal strength was higher than the measured field strength in all locations. The mean difference between predictions and measured values was 6.8 dB. Thus, using ITU-R P.1546 propagation predictions seems to overestimate the LTE signal strength and the probability of interference events to DTT reception in the proximity of an LTE base station. ITU-R P.1546 is not intended for distances less than 1 km, but such distances are the most relevant for LTE SDL as interference events occur almost exclusively within 1 km from the base station. More sophisticated prediction methods using accurate information on terrain profile and buildings would provide more accurate results in the proximity of an LTE SDL base station than ITU-R P.1546.

5.4.3 Novel candidate technologies to improve the efficiency in spectrum utilization

This section introduces recent technical solutions, which could be potentially used to improve the efficiency in UHF TV band spectrum utilization in the future. ETSI Mobile and Broadcast convergence specification group [211] studies the convergence of MBB and DTT networks, and the aim is to integrate broadcasting and MBB into one technological solution and eliminate the need for separate DTT receivers. This would allow to dynamically use the networks to deliver linear or personalized content. However, delivering the linear content through other solutions than the high power high tower broadcast transmitters would impose huge requirements for the core network. As all the transmitters and receivers would need to be replaced, an adoption to a completely new technology is unlikely to happen in the time frame of next 10 years or so.

A new converged system concept for DTT called WiB [212] was introduced in September 2016 at IBC conference, where it won the best conference paper award [213]. WiB can use the whole UHF TV band for its wideband transmission, and by using robust transmission mode and intelligent interference cancellation it can achieve significant reduction in the transmission power when compared to current DTT systems. This translates directly to reduced capital and operating expenditures. The used Layer Division Multiplexing (LDM) [214] technology also allows to add a second layer, WiB-mobile, to the same spectrum. This layer could be used by the future 5G MBB transmissions. The required receiver complexity is relatively high, but an implementation of this interesting system concept is expected to be feasible in the 2020s.

From a technical viewpoint, the LTE already provides an alternative method for the current DTT broadcasting with its evolved Multimedia Broadcast Multicast Service (eMBMS) (or simply LTE Broadcast) [215–217]. However, the current revisions of eMBMS in practice are a tool to optimize the cell capacity rather than a real dedicated broadcasting channel [218]. eMBMS could be used in the sub-700 MHz frequency band in conjunction with LTE SDL. eMBMS trials are planned to be conducted in the FUHF project.

Another possible technical solution for future UHF use could be a hybrid network approach, where LTE is delivered through DTT network [219]. The LTE would be transmitted in the Future Extension Frames (FEFs) of DVB-T2. This hybrid approach could exploit the synergies between existing DTT networks and mobile networks, resulting in decreases in network deployment costs. The concept, Tower Overlay over LTE-Advanced+ (TOoL+), has been demonstrated to be technically feasible through field trials [219]. The delivery of LTE from high towers requires minor changes to the LTE standard, and thus the authors of the concept have named their version as LTE-Advanced+ (LTE-A+). If the proposed minor modifications make it into the LTE standard, the hybrid approach would still require that the DVB-T2 FEF functionality is implemented in the DTT receivers and the LTE receivers are capable of receiving in the 470-694 MHz band.

Chapter 6

Case study: Licensed Shared Access (LSA) in 2.3-2.4 GHz band

This chapter describes a case study considering the use of vacant spectrum resources in 2.3-2.4 GHz band for mobile broadband through Licensed Shared Access (LSA) method, which provides a predictable quality of service (QoS) and exclusive access to shared spectrum resources. Initial spectrum occupancy studies concluded that the band might be potential candidate for licensed spectrum sharing due to the low spectrum occupancy of the current wireless camera incumbents in the band. The chapter describes the development and architecture of LSA and investigates the incumbent protection methods before concluding with considerations on the current status of LSA and a brief comparison to the Spectrum Access System (SAS) concept developed in the US.

6.1 2.3-2.4 GHz band

International Telecommunication Union Radiocommunication sector (ITU-R) has globally allocated the 2.3-2.4 GHz band for mobile broadband (MBB) systems at the World Radiocommunication Conference 2007 (WRC-07) [220]. However, the frequency band in European Conference of Postal and Telecommunications Administrations (CEPT) countries is currently used by different incumbents [221]. The main users are Programme Making and Special Events (PMSE) applications, such as wireless camera links [222]. They are typically used to transmit video and audio wirelessly from a camera to an outside broadcasting (OB) van, and the typical users thus are broadcasting companies.

Paper 8 [26] and [17] study the spectrum occupancy of the 2.3 GHz band in a single location in Finland for several weeks using the spectrum measurement data from Turku spectrum observatory (described in section 3.3). The spectrum occupancy was very low and sporadic, and the detected busy periods were only 3 to 9 seconds long. The wireless camera transmissions occupy a bandwidth of 20 MHz, meaning a 20% occupancy per transmission over the whole 100 MHz frequency band. The instantaneous channel occupancy values were between 0% and 30 %, but when the occupancy was filtered with a 5-minute moving average filter, the occupancy was between 0% and 5%. The filtered values confirm that the periods when the spectrum is occupied are very short in time. In addition to the signals interpreted as wireless cameras, only a small number of higher power peaks, probably from narrowband amateur radio services, was detected. The wireless camera transmissions are very low-power and difficult to detect, and the studies conducted with a professional level wireless camera in Paper 8 [26] demonstrate that the spectrum observatories are able to detect the wireless cameras only from distances smaller than 250 m. Thus, single-location spectrum occupancy measurements cannot be used to draw strong conclusions on the spectrum occupancy trends over large geographical areas.

One reason why allocating the 2.3 GHz band for MBB in Europe is important is that the frequency band is already in MBB use in other regions. Thus, the transmitter hardware already exists and can be easily implemented in mobile receivers for European market. An economic analysis [223] also indicates that the impact of making 2.3 GHz band available for MBB in Europe could be worth 6.5-22 billion euros. However, the national administrations are unwilling to move the current incumbents to other frequency bands. Such an operation would result in expenses to the incumbents who would need to update their equipment, and in addition, there is a lack of suitable unallocated frequency bands. As the utilization of the 2.3 GHz frequency band appears to be very low, an optimal solution would be to let the current incumbents stay in the frequency band and to allow the MBB operation by exploiting the vacant spectrum resources. Again, the protection of the current incumbents is essential. LSA is needed in the 2.3 GHz band to provide exclusive shared spectrum access to the MBB and to protect the current incumbents.

6.2 Development and architecture of LSA

The development of LSA concept began in European regulation and standardization to create a method for the mobile network operators (MNOs) to deploy their networks into bands allocated for MBB, but which currently have incumbents operating in the band. The concept allows spectrum sharing between an MNO and the incumbents with licensing conditions and rules that benefit both stakeholders. Radio Spectrum Policy Group (RSPG) proposed LSA concept [57] as an extension to an earlier proposal by an industry consortium, called Authorized Shared Access (ASA) [224]. ASA is limited to International Mobile Telecommunications (IMT) use, while LSA can also be applied to other types of spectrum sharing. The 2.3 GHz band was chosen as the first frequency band for which to develop the operating conditions for LSA.

Working Group Frequency Management (WG FM) established Frequency Management 53 (FM53) - Reconfigurable Radio Systems (RRS) & LSA project team in September 2012. The aim of FM53 was to provide generic guidelines to CEPT administrations for the implementation of the LSA. The European Commission (EC) requested an opinion from RSPG on regulatory and economic aspects of LSA in November 2012 [225], and their final opinion from November 2013 [226] defined that LSA 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 LSA approach, the additional users are authorized 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 QoS".

Thus, LSA gives the MNOs a predictable QoS through individual licensing and exclusive shared access to the spectrum resources. The MNO accessing shared spectrum through temporary leasing is called LSA Licensee. The functionalities of LSA are enabled mainly by two additional units on top of the existing mobile networks: The LSA Repository and the LSA Controller. LSA Repository is a database containing information on incumbent spectrum utilization, while the task of the LSA Controller is to guarantee protection and interference-free operation for both types of users by using the data from the LSA Repository.

The LSA Repository can be managed by the National Regulatory Authority, the incumbents, or a trusted third party. The LSA Repository contains information on the spectrum availability for LSA Licensees and spectrum sharing rules. This information is communicated to the LSA Controller through a secure and reliable communication path. Based on the information from the LSA Repository, the LSA Controller controls the spectrum use of LSA Licensee(s). There may be several LSA Repositories from which the LSA Controller gets the information on spectrum availability, and also several LSA Licensees'

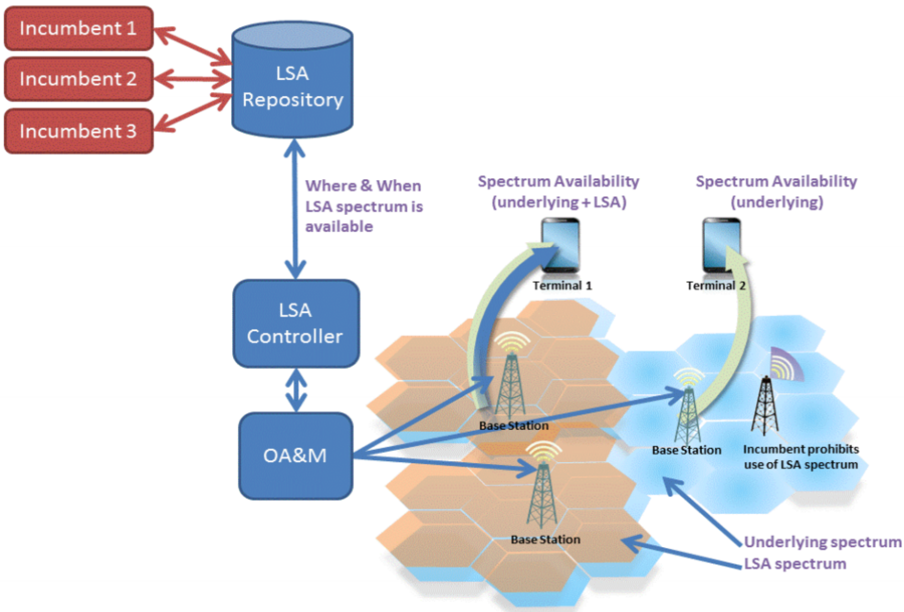

Figure 6.1: LSA architecture. Adapted from [227].

networks.

Figure 6.1 illustrates the LSA architecture. Several incumbents provide information on their spectrum utilization to the LSA Repository, which communicates it to the LSA Controller. The LSA Controller provides this information to the MNO operations, administration and maintenance (OA&M), which instructs that the relevant base stations of the MBB network can use the spectrum resources which are not used by the incumbents in the band. These newly available spectrum resources are taken into use to provide additional capacity through carrier aggregation (CA). The underlying spectrum in other frequency bands (blue cells in the figure) are exclusively licensed for MBB transmissions, while the orange cells can provide additional capacity using the LSA spectrum resources in the 2.3 GHz band. On the right side of the figure the incumbent operation prevents the use of LSA spectrum and only the underlying MBB spectrum resources can be used. This is illustrated through the absence of orange LSA cells.

6.3 Field measurements to determine LSA feasibility and incumbent protection

Electronic Communications Committee (ECC) FM52 was established to develop a harmonized band plan for MBB in 2.3-2.4 GHz band and to establish a regulation allowing implementations of LSA. FM52 created three CEPT reports in response to the EC mandate issued in April 2014 [228]: CEPT Report 55: *"Technical conditions for wireless broadband usage of the 2300-2400 MHz frequency band"* [229] (November 2014), CEPT Report 56: *"Technological and regulatory options facilitating sharing between wireless broadband (WBB) and the relevant incumbent services/applications in the 2.3 GHz band"* [230] (March 2015) and CEPT Report 58: *"Technical sharing solutions for the shared use of the 2300-2400 MHz band for WBB and PMSE"* [231] (July 2015).

CEPT Report 58 [231] concludes that the technical conditions and implementation details of the LSA sharing framework should be defined at a national level, as the type and extent of incumbent usage differs largely between the CEPT countries. The following step-by-step procedure to determine the spectrum sharing conditions is recommended:

1. Determine the type and extent of PMSE use at the national level.
2. Develop technical conditions for the sharing framework, taking into account the relevant technical characteristics of PMSE. The approach is to define protection zones for the PMSE devices.
3. Define operational conditions for the sharing framework and the implication on the MBB network in order to fulfill the PMSE protection requirements.

The PMSE wireless cameras are the most common incumbent users in the band in Finland and across CEPT, and their technical characteristics are similar from one country to another [231]. ECC report 172 [232] describes that PMSE wireless camera links can coexist with MBB at the same time through the use of either geographic separation if the systems operate on the same channel, or a combination of separation distance and frequency separation if they operate in the same location.

Thus, the protection of incumbents can be guaranteed by defining a minimum separation distance (MSD) between the wireless camera incumbents and the LSA Licensees (MBB). MSD defines the minimum geographical distance between the interferer and the incumbent which guarantees the protection of the incumbent. An exclusion zone can be created by using an MSD as a radius of a circle drawn around the incumbent. The LSA Licensees are not allowed to transmit within this exclusion zone. MSDs have been theoretically calculated for PMSE wireless cameras (as defined in [233]) and WBB in ECC report 172 [232].

CEPT Report 58 [231] declares that additional field experimentations to assess feasible implementation solutions may be required. Paper 7 [25] describes a field interference measurement campaign to assess the critical MSDs between the incumbent wireless cameras and interfering Long Term Evolution (LTE) User Equipment (UE) transmissions in the 2.3 GHz band. A typical professional level wireless camera used by the Finnish public broadcasting company was used in the measurement campaign, as it is the most common incumbent user in the band in Finland. The measurements were conducted in the Finnish LSA/LTE trial environment in Ylivieska. As in [231], only the interference from MBB towards PMSE incumbents was considered. The MSDs presented in Paper 7 [25] are from a cordless camera scenario defined in [232], which again is the most common use scenario in Finland. In this scenario, a camera transmits video and audio over a Digital Video Broadcasting - Terrestrial (DVB-T) wireless camera link to an OB van over distances of up to 500 meters. The measurement methodologies presented in chapter 4 were applied to determine protection ratios (PRs) and MSDs for the wireless camera receiver.

The measurement results were compared to the theoretical values in ECC Report 172 [232], and to the PR values between DVB-T receivers and LTE presented in ECC Report 148 [102]. As PMSE wireless cameras use DVB-T, their PRs can be compared to the DVB-T receiver PRs. The wireless camera PR results were in line with the worst 10^{th} percentile of the 81 DVB-T receivers measured in [102]. This poor performance could have been improved by using a channel filter, which is often used with the wireless cameras to block interference from adjacent frequency bands. In some locations, the camera link did not work even without the LTE UE interference. The probable cause for this was the geographical proximity of mobile network base stations (BSs).

The MSDs obtained from the field measurements of Paper 7 [25] are very similar to the theoretically calculated values in [232], which in general seem to slightly overestimate the MSDs. On the adjacent channels, the calculated MSD value is 213 m, while the measured values on channels $N + 1$ and $N - 1$ were 165 m and 190 m. The channels further with larger separation from N are covered with one theoretical value for an alternate channel, which is 106 m. On channels $N + 2$ and $N + 3$ the measured MSD was still on a very similar level, 80 m in both scenarios, but for channels further away, $N + 5$ and $N + 7$, the measured MSD was significantly smaller, 23 m for both. The difference is significant, as the theoretical MSDs are almost 5 times longer than the measured. This overestimation in the theoretical MSDs would result in less efficient use of spectrum resources.

The theoretical formulas of [232] have been slightly revised in [234] to provide more realistic MSDs specifically for operation in the Finnish LSA trial environment, where the field measurements were conducted. The values are only slightly different from the values provided by the original formulas, and the relation in the magnitude between measured and theoretical MSDs is still on a similar level. The field measurement campaign in Paper 7 [25] further validates the feasibility of the theoretical formulas of ECC Report 172 [232] to protect incumbents in LSA concept, but also indicates that the MSDs calculated with the theoretical formulas may be slightly overestimated.

In general, the MSDs and exclusion zones are a very coarse method to protect incumbents, and using them can result in abrupt changes in power levels as the transmissions need to be turned off or on when moving in or out of an exclusion zone. Also, the mutual interference from several LSA Licensees is not considered. The allowed interference from LSA Licensee is defined with a fixed value of -6 dB below the noise floor [231]), and as [235] demonstrates, this may create a situation where the total aggregated interference from several Licensees exceeds the interference limits, even though MSD requirements for each individual Licensee are fulfilled.

Restriction and protection zones allow to create more sophisticated and efficient methods to exploit the vacant spectrum resources within the band than exclusion zones. A restriction zone is an area, where the LSA Licensee is allowed to operate under certain restrictive restrictions, for example on the used power levels and antenna parameters. Such zones are usually defined for certain frequency ranges and time periods. A protection zone is an area, where the incumbent receivers will not be subject to harmful interference caused by the LSA Licensees' transmissions, and is defined as an area, where the interference towards an incumbent at a certain height cannot exceed a certain threshold. This allows the LSA Licensee to create sophisticated algorithms to optimize the spectrum utilization and to benefit from accurately modeling the interference caused towards the incumbent system.

The author has participated in field measurements to validate the operation of enhanced protection zone power control algorithms, which consider aggregate interference, active BS optimization, and transmit power level optimization [236]. Further optimization algorithms for protection zones through signal-to-interference-plus-noise ratio (SINR), antenna tilt, and transmit power optimization were introduced in [235]. These power control algorithms do not have information on the spectrum utilization of other LSA Licensees. A concept proposed in [237] uses measurement-capable devices (MCDs) as nodes of a distributed network to sense spectrum and create dynamic and up-to-date radio environment mapping (REM) considering both the incumbents and the LSA Licensees. This concept could potentially be used in the future to enable more dynamic spectrum sharing on a shorter time basis in LSA.

6.4 Current status of LSA and competing Spectrum Access Systems (SAS) concept

This section considers the feasibility and current status of LSA and briefly compares it to the United States (US) concept for licensed shared spectrum access, SAS. The work on LSA has been very active in regulation and standardization: CEPT Reports [229–231], ECC harmonized conditions for the use of the 2.3 GHz band in [221, 238–240], and European Telecommunications Standards Institute (ETSI) standardization in [227, 241, 242] provide all the measures needed for a National Regulatory Authority in a CEPT country to create an implementation of LSA. A regulatory evaluation in [243] concluded that LSA implementations are feasible. The use of LSA is a national matter, which does not require modifications to the ITU-R Radio Regulations (RR).

A study on the feasibility of LSA from business perspective [244] concluded that LSA implementations could be profitable for MNOs in Finland if they have a reasonably good customer base and well defined network launch and management. The Finnish LSA trial environment is operated in Ylivieska [245, 246], but no commercial deployments of LSA in 2.3 GHz band are available yet. A service pilot with LSA radio licenses to commercial end-users operating with incumbent wireless cameras in the 2.3 GHz band was announced in the Netherlands in May 2016 [247], and more pilots are expected in the near future. The LTE MNOs are expected to make multi-year spectrum sharing contracts with the incumbents to justify investments in building mobile network infrastructure for LSA operation [14]. LSA could also provide mechanisms to mitigate intra-MNO-system interference [14].

A concept called SAS is in development in the US. It is very similar to LSA, as both of them include incumbent users and licensed shared users who have exclusive shared access to the spectrum. The licensed shared access in SAS is known as Priority Access License (PAL). LSA excludes opportunistic access where no protection from incumbents is provided, but SAS adds an additional third tier for unlicensed opportunistic spectrum access with General Authorized Access (GAA), as shown in Figure 6.2. PAL users are protected from interference from GAA tier, but not from the incumbents.

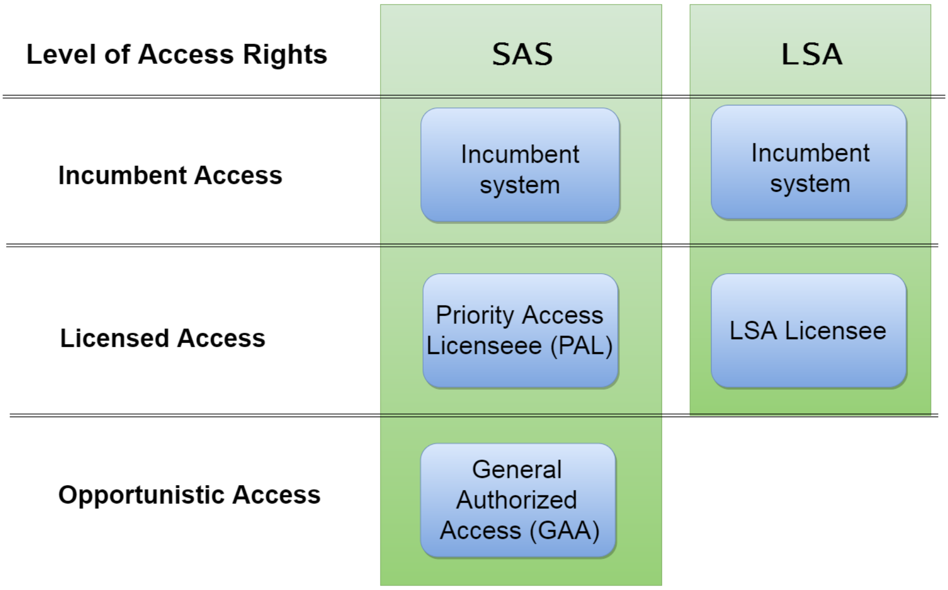

Figure 6.2: Overview of the level of access rights in different tiers of SAS and LSA sharing models

The SAS design ensures protection also for the incumbents who cannot provide a priori information to a central database. This is a major difference to LSA, where this information has to be communicated to a central database (LSA Repository) in order to protect the incumbents. The incumbents operating in the Citizens Broadband Radio Service (CBRS) band include military services whose information is too sensitive to be stored in a database. Instead, SAS includes Environmental Sensing Capability (ESC) component which uses spectrum sensing to provide the needed data for spectrum access decisions. As [248] states, spectrum sensing is not a trivial matter, especially with the strict requirements in SAS. ESC will not be used in the first phase of SAS deployment, which restricts the SAS operation in the zones with military incumbents near coastal areas until a suitable ESC technology is available. ESC technologies have already been developed and demonstrated in recent SAS trials [249]. Unlike LSA, SAS standardization is still in progress, but the industrial interest in CBRS Alliance [250] is strong and advances are expected in the near future. The first commercial SAS deployments are due in 2017 [251] in 3.55-3.7 GHz CBRS [252] band in the US.

LSA and SAS are currently defined for use only in the mentioned frequency bands with their specific incumbents, but the basic operational principles are straightforward to adopt to other bands. Having two different methods for licensed spectrum sharing is not optimal, and thus one of them could be chosen to provide a global solution, or they could converge. The ETSI LSA standardization was done partly in liaison with the 3rd Generation Partnership Project (3GPP) [253], which has studied how LSA could provide a global solution for a 3GPP MNO in [254]. LSA has also been recognized as one of the future technology trends for IMT in the ITU-R Working Party 5D on IMT systems [255]. Still, it remains to be seen how global the adoption of LSA will be.

Chapter 7

Conclusions

This thesis has considered the following research questions: Q1) How should field measurements be conducted and used to model incumbent spectrum utilization? Q2) How should field measurements be conducted and used to determine protection criteria for incumbents in a co-existence scenario with mobile broadband? and Q3) Which licensing methods and technological solutions are feasible to enable spectrum sharing in frequency bands with incumbents?

The following sections give conclusions with regard to each research question and the chapter is concluded with a section on future research directions.

7.1 Conducting and using field measurements to model incumbent spectrum utilization

Paper 1 describes a collaboratively developed spectrum observatory measurement system, which provides realistic data which can be used to accurately determine spectrum occupancy. Paper 4 describes how the measurement system sensitivity was improved through careful planning, use of band-pass filters, and a low-noise amplifier. Generic spectrum occupancy measurements covering a large frequency range are not optimal to reliably detect specific radio signals and services, and thus the measurement parameters such as bandwidth, scanning speed and antenna locations should be chosen taking into account the properties of the measured radio signals and services. The spectrum occupancy measurement results from the current spectrum observatories are limited to the vicinity of the measurement system installation location.

Previous single location spectrum occupancy studies are generally rather optimistic about the significance of their results. A cautious approach should be taken in making strong conclusions from spectrum occupancy evaluations from single fixed measurement locations. Paper 1 presents methodologies, which extend the previous state-of-the-art by using interference map concept to provide realistic spectrum occupancy data which is relevant over larger geographical areas. Such measurements covering larger geographical areas might be needed if the measurement results are to be used in making spectrum management decisions. However, installing and operating spectrum measurement systems in several locations would be expensive and such measurement systems have not been built yet. The improvements in the accuracy of the measurement system and in the increases in the covered geographical area both directly result in additional expenses.

Papers 2 and 3 demonstrated that radio environment mapping can be used to create realistic received signal strength indicator (RSSI) maps using Kriging interpolation method and field measurements of RSSI from optimally selected locations in a digital terrestrial TV test network. The computational complexity in Kriging is high, and almost as accurate results can be produced with less complex interpolation methods. Radio environment maps provide more accurate results than propagation prediction methods, and could be used for example to model incumbent spectrum utilization in geo-location databases of spectrum sharing frameworks. The weakness of the presented methodology is that the field measurements are expensive to conduct, and thus creating large radio environment maps might not be economically feasible. Measurement-capable mobile terminals could provide field measurement samples to be used in interpolation, but their accuracy would be inferior to those provided by professional level measurement devices.

7.2 Conducting and using field measurements to determine incumbent protection criteria in a co-existence scenario with mobile broadband

Field interference measurements to determine protection criteria for incumbents are not covered well in the current research literature. Field measurements are expensive to conduct as they require substantial human resources, test network infrastructure, professional level measurement devices, and radio licenses. However, field measurements are needed to study and verify hypotheses from computer simulations or theoretical analyses in realistic operating conditions, as field measurement conditions can not or are not practical to be adequately modeled in simulations.

The observed phenomena and the empirical data collected from field measurements guide the theoretical and laboratory measurement studies towards the most relevant subjects in practical implementations of wireless communications systems. If no unexpected phenomena are observed, the validity of the theoretical analyses and simulations is further confirmed. If no field measurements are conducted at all, it remains unknown whether the theoretical analyses are valid in realistic operating conditions.

A major weakness in using field measurements in co-existence studies is that they are very expensive and time-consuming to conduct. Only a limited number of measurements can be made, which stresses the importance of choosing the most relevant measurement scenarios, devices and parameters. Less expensive simulations and laboratory measurements should be used both to aid in the planning of field measurements and to complement the results obtained from field measurements.

The field environment introduces factors which cannot be controlled or reproduced, and makes the verification of the results more difficult. In fact, the results are valid only at the time when they were conducted and only in that one specific location and geometry between the interfering transmitter and the incumbent. Thus, field measurements require that additional information from the radio propagation environment needs to be recorded to allow further verification and analysis of the results.

To fill the gap in the research literature, this thesis proposes measurement methodologies to obtain realistic results from field interference measurements, taking into account the propagation environments and external sources of interference. The methodologies are based on the existing literature and experience gained from conducting field measurement campaigns. The main contributions from the conducted field measurement campaigns were the actual measurement results, while Paper 9 explicitly considers the methodologies and procedures needed to obtain realistic field measurement results. The presented methodologies evaluate the DTT receiver performance, but also the reception antenna system installation and especially the use of power amplifiers can significantly degrade the system performance and make it much more susceptible to interference.

7.3 The feasibility of licensing methods and technological solutions to enable spectrum sharing

Co-existence studies between different wireless communication systems are important as the current aim is to optimize their spectrum utilization and shift from static exclusive spectrum allocations to more dynamic co-existence of different systems within same frequency bands. As the same laws of physics apply to different wireless communications systems, observations from field measurements contribute to the generic knowledge regarding wireless co-existence. The introduction of this thesis contributes to these studies by giving an overview and a comprehensive list of references on research related to spectrum sharing.

The third research question is studied through several field interference measurement campaigns to determine incumbent protection criteria and by analyzing the spectrum observatory data to determine the occupancy and trends in incumbent spectrum utilization. The field interference measurement campaigns have been conducted in real TV White Space, LTE Supplemental Downlink and Licensed Shared Access test network environments, and the obtained measurement results have been contributed to the development of the European spectrum regulation.

The weaknesses of the field interference measurement methodologies have been described in previous section and also apply to the field measurement campaigns presented in this thesis. The main problem in measurement campaigns is the limited number of measurement results, as incomplete sets of field measurement results do not allow to make very strong conclusions. Sometimes the field measurement campaigns fail to measure the most relevant scenarios or parameters, as in for example Paper 5 where the time-variance of the interfering transmission was omitted. Subsequent laboratory and field measurements have confirmed that the time-variance is a major factor in defining the co-existence performance between digital terrestrial television (DTT) and mobile broadband (MBB).

Paper 6 has presented application pilot field trials and field measurements to verify the operation of TV White Space framework and to demonstrate the capabilities of the system to the industry and the regulators. The TV White Space application pilot trials have been conducted with early equipment from one manufacturer, and thus they contribute mostly to the technical development of the equipment and validation of the incumbent protection algorithms in geo-location databases. Field measurements were also conducted to validate the incumbent protection algorithms developed for LSA concept.

Thus far, the European Union (EU) has been able to repurpose enough spectrum for the current needs of MBB, and large-scale implementations of the spectrum sharing concepts described in the case studies are still absent. When the increases in the amount of MBB traffic continue, spectrum sharing will gain significance and commercial implementations of spectrum sharing frameworks will emerge.

In conclusion, no single spectrum sharing method can provide universally optimal efficiency in spectrum utilization. Thus, an appropriate spectrum sharing framework should be chosen taking into account both the spectrum utilization of the current incumbents and the future needs in wireless communications. For example, interference management in LTE Supplemental Downlink is straightforward and it can provide additional downlink capacity to meet the rapidly rising demand for downlink services such as video streaming.

7.4 Future research directions

The presented methodologies for field measurements to study incumbent spectrum utilization and incumbent protection criteria can be applied to relevant future measurement scenarios in co-existence of different wireless communications systems, such as 5th generation mobile networks (5G). For example, the co-existence compatibility of DTT and the new waveforms introduced in the future 5G networks, such as filter bank multicarrier (FBMC), need to be verified through field measurements.

Co-existence with emerging massive Internet of Things (IoT) is also an important subject to study in the future. The developments in the consumption of audiovisual media and in the regulation of the ultra high frequency (UHF) broadcasting spectrum determine the relevant measurement scenarios for DTT co-existence field measurements in the future. The near-future field interference measurements concentrate on studying the Long Term Evolution (LTE) Supplemental Downlink (SDL) concept to further validate its feasibility.

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