



**Coordinated Control and Spectrum Management
for 5G Heterogeneous Radio Access Networks**

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Executive summary

A new and flexible approach to spectrum usage and management is required in order to fulfil the requirements identified by the 5G PPP in their KPIs for 5G networks, i.e., 1000 times higher mobile data volume per geographical area, 10 to 100 times more connected devices, 10 to 100 times higher typical user data rate, 10 times lower energy consumption, end-to-end latency of less than 1ms and ubiquitous 5G access including in low density areas. Many spectrum sharing schemes have been proposed so far, and some of them have been tested in the field trials providing useful insights into the spectrum sharing issues. Based on the existing analysis, we observe that:

1. The popularity of traditional, well-tested and highly popular solutions, i.e., exclusive spectrum use and its counterpart - license exempt use – will not decrease in the near future.
2. While exclusive and open spectrum access will remain an important part of 5G networks, flexible spectrum management and sharing will give new degrees of freedom to network operators and could lead to beneficial technical and business cases.
3. In Europe, the Licensed Shared Access (LSA) approach has attracted the most attention mainly due to its favored status among network operators and service providers. On the other hand, the Spectrum Access System (SAS) solution is already under practical tests in US and should not be neglected.
4. The Licensed Assisted Access (LAA) approach is gaining popularity, thus the coexistence of licensed and unlicensed services is envisaged.
5. Another interesting option is the co-primary sharing scheme, as this approach gives new degrees of freedom to the network operators.
6. In the microscale level the flexible and/or full duplex technologies provide significant improvement in spectrum usage efficiency

From a real implementation perspective, the above solutions can be applied in various contexts (e.g., for TVWS, or with the use of dedicated databases supported by sensing function), however we believe that more flexible approaches to spectrum sharing (such as innovative Pluralistic Licensing or various cognitive radio oriented schemes) should be pursued and investigated further.

In conjunction with new approaches to spectrum management and sharing, the network architectures are evolving and incorporating concepts of virtualization and software control. A significant push towards Software Defined Networking (SDN) and Network Function Virtualization (NFV) is being made by all major players involved in realizing the 5G vision including researchers, network operators and regulators.

This document proposes a three-plane architecture which consists of spectrum management plane (spectrum management application), coordination and control plane, and infrastructure plane (or equivalently data plane). The key role in this architecture is played by the COHERENT central controller and coordinator which utilizes the available network graphs for spectrum usage. Although the network graph is still a topic of investigation and improvement, the initial definition of spectrum-related network graph has been defined. In that context it has been identified that the COHERENT controller and coordinator is a logically centralized entity, but can be practically distributed. Due to ownership issues that have been discussed, it is suggested that the COHERENT controller and coordinator will be managed per operator. Finally, practical implementation of the COHERENT software control in wireless communication networks requires definition of the set of required APIs/SDK which have been discussed in a separate chapter in this deliverable.

It has been identified that in a case of microscale spectrum sharing, the flexible duplexing scheme is a reliable proposition for practical implementation. Following the in-depth technical analysis, compatible with appropriate 3GPP documents and guidelines, the series of comprehensive experiments have been carried out. Achieved computer simulation results, included in this deliverable, proved the efficiency of this approach.

Identification of any flexible spectrum management scheme requires practical confirmation by means of true trials. In the last section of this deliverable the initial steps toward field trials carried out within the framework of the COHRENT project are presented.

List of abbreviations

3GPP	3rd Generation Partnership Project
5G PPP	5G Infrastructure Public Private Partnership
ACMA	Australian Communications and Media Authority
ACLR	Adjacent Channel Leakage power Ratio
API	Application Programming Interface
ASA	Authorized Shared Access
ASO	Analogue Switch Off
AWS	Advanced Wireless Services
BRS	Broadband Radio Service
BS	Base Station
C3	Central Coordinator and Controller
CBRS	Citizen Broadband Radio Service
CCA	Clear Channel Assessment <i>and</i> Combinatorial Clock Auction
CCDF	Complementary Cumulative Distribution Function
CDF	Cumulative Distribution Function
CEPT	Conférence européenne des administrations des postes et des télécommunications (European Conference of Postal and Telecommunications Administrations)
CN	Cognitive Network
CPE	Customer Premises Equipment
CSA	Co-primary Shared Access
CSI	Channel State Information
CUS	Collective Use of Spectrum
D2D	Device to Device
DL	Downlink
DTT	Digital Terrestrial TV
DVB-T	Digital Video Broadcast Terrestrial
EBS	Educational Broadband Service
EC	European Commission
ECC	Electronic Communications Committee
EIRP	Equivalent/Effective Isotropic Radiated Power
eLTE	enhanced LTE
eNodeB	evolved Node B
eNB	evolved Node B
EOC	Emergency Operation Centre
ERP	Effective Radiated Power
ESC	Environmental Sensing Capability

ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved UMTS Terrestrial Radio Access
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FM	Frequency Management
GAA	General Authorized Access
GE06	Geneva 2006 frequency plan
GFR	General Functional Requirement
GSMA	GSM Association
HAAT	Height above average terrain
HDTV	High Definition Television
HMN	Heterogeneous Mobile Network
HPC	High Priority Channel
ICT	Information and Communications Technologies
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
ISM	Industrial, Scientific and Medical
ITU	International Telecommunications Union
ITU-R	ITU Radiocommunication Sector
KPI	Key Performance Indicator
LAA	Licensed Assisted Access
LBT	Listen Before Talk
LSA	Licensed Shared Access
LSP	Limited Spectrum Pool
LTE	Long Term Evolution
LTE-A	LTE Advanced
LTE-U	LTE in Unlicensed Spectrum
LWA	LTE-WiFi [link] Aggregation
MAC	Medium Access Control
MBB	Mobile Broadband
MCD	Manually Configured Devices
MFCN	Mobile/Fixed Communications Networks
MFN	Multiple Frequency Network
mMTC	massive Machine-Type Communication
MNO	Mobile Network Operator
MOCN	Multi-Operator Core Network
MPEG2/4	Motion Picture Expert Group 2/4

MR	Mutual Renting
MSA	Multi-Stream Aggregation
MTC	Machine-Type Communications
MVNO	Mobile Virtual Network Operator
NBI	North Bound Interface
NFV	Network Functions Virtualisation
NRA	National Regulatory Authority
NTIA	National Telecommunications and Information Administration
O&M	Operations & Maintenance
OoB	Out of Band
OSA	Opportunistic Spectrum Access
PA	Priority Access
PAL	Priority Access License <i>or</i> Phase Alternate Line
PAPR	Peak-to-Average Power Ratio
PCAST	President's Council of Advisors on Science and Technology
PCS	Personal Communications Service
PHY	Physical
PL	Pluralistic Licensing
PMI	Precoding Matrix Indicator
PMR	Private Mobile Radio
PMSE	Programme Making and Special Events
PPDR	Public Protection and Disaster Relief
P2P	Peer-to-peer
PR	Physical Resource
PRB	Physical Resource Block
PT1	Project Team 1 (in the context of ECC)
PU	Primary User
PUCCH	Physical Uplink Control Channel
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
REM	Radio Environment Map
RI	Rank Indicator
RRM	Radio Resource Management
RRS	Reconfigurable Radio Systems
RSPG	Radio Spectrum Policy Group
RSRP	Reference Signal Receive Power

RSRQ	Reference Signal Receive Quality
RSSI	Received Signal Strength Indicator
RTC	Real Time controller
SAB	Services Ancillary to Broadcasting
SAP	Services Ancillary to Programme making
SAS	Spectrum Access System
SBI	Southbound Interface
SDK	Software Development Kit
SDL	Supplemental Downlink
SDMA	Space-division multiple access
SDN	Software Defined Network
SDR	Software Defined Radio
SE43	Spectrum Engineering 43 (in the context of groups in CEPT)
SEM	Spectrum Emission Mask
SFN	Single Frequency Network
SLA	Service Level Agreement
SMA	Spectrum Manager Application
SMR	Specialized Mobile Radio
SMRA	Simultaneous Multi-Round Auction
SINR	Signal to Interference plus Noise Ratio
SM	Spectrum Management/Manager
SON	Self-Organizing Network
SPR	Stakeholder Protection Requirements
SR	Security Requirements
SU	Secondary User
TBD	To Be Defined
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TETRA	TErrestrial Trunked Radio
TPC	Transmit Power Control
TR	Technical Report
TVWS	TeleVision White Space
UE	User Equipment
UHF	Ultra-High Frequency
UL	UpLink
uMTC	Ultra-reliable Machine-Type Communication
UMTS	Universal Mobile Telecommunications System

URC	Ultra-Reliable Communication
UTRA	UMTS Terrestrial Radio Access
V2X	Vehicle-to-X (or Vehicle-to-anything)
VHF	Very High Frequency
VMNO	Virtual Mobile Network Operator
VoIP	Voice over IP
VRP	Virtual Radio Processors
WCS	Wireless Communications Service
WG	Working Group
WRC	World Radiocommunication conference
WSD	White Space Devices
WGFM	Working Group Frequency Management
WiMAX	Worldwide Interoperability for Microwave Access
xMBB	extreme Mobile BroadBand

Table of Contents

Executive summary	4
List of abbreviations.....	6
Table of contents.....	11
List of figures	15
List of tables	16
1. Introduction.....	18
1.1. Requirements to 5G spectrum Management.....	18
1.2. COHERENT Goals.....	19
1.3. Document Structure and Relation with Other WPs in COHERENT	19
1.4. Summary of Results Towards Other Activities	20
1.4.1. Towards WP2	20
1.4.2. Towards WP3	20
1.4.3. Towards WP5 and WP6.....	20
1.4.4. Towards Standardization (WP7).....	20
2. Identification of the Most Promising Spectrum Sharing Strategies	21
2.1. Introduction of Spectrum Sharing.....	21
2.2. Technological Aspects of Spectrum Sharing	21
2.2.1. RAN/ Infrastructure Sharing and Mobile Virtual Network Operators (MVNO).....	21
2.2.2. Databases and Sensing.....	22
2.3. List of Existing Spectrum Sharing Schemes (in the Context of HMNs)	23
2.3.1. Exclusive Use of Spectrum (Individual Licenses).....	23
2.3.2. License Exempt Rules (Unlicensed or ‘Commons’)	25
2.3.3. Licensed Shared Access (LSA) Including Authorized Shared Access (ASA)	27
2.3.4. Citizen Broadband Radio Service with Spectrum Access System	29
2.3.5. Pluralistic Licensing	31
2.3.6. Licensed Assisted Access (LAA)	33
2.3.7. TeleVision White Space (TVWS)	35
2.3.8. Co-primary Shared Access	36
2.3.9. Summary of the Pros and Cons of the Spectrum Sharing Schemes	38
2.4. Existing Regulations	41
2.5. Trials	41

2.5.1.	Past EU Program Pilots	42
2.5.2.	TVWS Pilots and Commercial Deployments	42
2.5.3.	LSA Pilots.....	44
2.5.4.	CBRS Pilots.....	45
2.5.5.	LAA Pilots.....	45
2.5.6.	Infrastructure Sharing.....	45
3.	Spectrum Sharing in the Context of 5G Networks – a COHERENT Vision	46
3.1.	Requirements for 5G.....	46
3.2.	Identification of the Most Promising Spectrum Bands/Pioneering Bands a COHERENT Perspective.....	46
3.3.	A COHERENT Perspective on Spectrum Management.....	49
3.3.1.	Inter-operator Spectrum Sharing	49
3.3.2.	Intra-operator Spectrum Sharing	50
3.3.3.	Micro Level Spectrum Sharing.....	50
3.4.	Identification of most promising spectrum sharing schemes – a COHERENT perspective..	51
4.	COHERENT Spectrum Management, Coordination and Control System	53
4.1.	Reference work.....	53
4.1.1.	METIS/METIS II Achievements.....	53
4.1.2.	Radio Environment Maps and Cognitive Radio.....	55
4.2.	Considered Spectrum Management Architecture for Virtualized Wireless Networks	56
4.2.1.	COHERENT Control and Coordination Plane	57
4.2.2.	Spectrum Management Plane (Spectrum Management Application).....	58
4.2.3.	Infrastructure Plane.....	58
4.2.4.	Network graphs.....	58
4.2.5.	Virtualization Aspects	59
4.3.	Ownership Issues	59
4.3.1.	Spectrum Management Plane	59
4.3.2.	Coordination and Control Plane	61
4.4.	Prospective Interfaces	62
4.5.	Network Graph Definition for Spectrum Sharing.....	63
4.5.1.	Definition of Edge Metrics, Time Relation and Association with Frequency Bands.....	65
4.5.2.	Network Graph Definition for Spectrum Sharing – Specific Use Case.....	66
4.6.	Required functionalities	67
4.7.	Information Exchange – Specific Use Cases	71
4.7.1.	Use Case 1	71
4.7.2.	Use Case 2	73
4.7.3.	Use Case 3	73

5. Use Cases and Scenarios for Spectrum Sharing.....	75
5.1. Prospective Scenarios for Spectrum Management, Coordination and Control System.....	75
5.1.1. Micro-area Spectrum Sharing.....	75
5.1.2. Protection of Licensed Users and Agreed Transmissions.....	76
5.1.3. Management of Urgent Situations	76
5.1.4. Management of User Specific Aspects.....	76
5.1.5. Management of Vertical Handover.....	77
5.1.6. Data Caching in Local Databases	77
5.1.7. Management of the “Exclusive, Shared & License-Exempt” Radio Spectrum.....	77
5.1.8. WiFi Management	78
5.1.9. Mutual Renting of Exclusive Spectrum.....	78
5.1.10. Traffic Steering and Offloading	79
5.1.11. Channel Assignment in Enterprise WLANs	79
5.2. Use Case on Shared Infrastructure.....	81
5.2.1. Sharing Basics	82
5.2.2. Classification of Infrastructure Sharing.....	82
5.2.3. European Regulation for Infrastructure Sharing.....	82
5.2.4. Current Examples of Sharing Legislation and Regulation	82
5.2.5. Handling Military and Public Safety	84
5.2.6. Licence pricing	84
5.2.7. Recommendation	85
5.3. Use Case on Flexible Duplexing.....	85
5.3.1. Motivation.....	86
5.3.2. Problem Statement.....	87
5.3.3. Adjacent Carrier Leakage Power Ratio	87
5.3.4. Spectrum Emission Masks.....	87
5.3.5. Distinctive Cases	88
5.3.6. Coexistence Simulation Results.....	88
6. SDK and APIs for Spectrum Management.....	93
6.1. APIs for Northbound flows.....	94
6.2. APIs for Southbound flows.....	95
6.3. APIs for Eastbound flows	96
6.4. Programming Aspects	96
7. COHERENT Pilot.....	97
7.1. Spectrum sharing for Emergency Operational Centres (EOC).....	97
7.2. INEA Poznan, Poland	99

7.3. OTE Athens, Greece	99
8. Summary	100
References	101
A. Annex – Concise Collection of Legal Documents or Guidelines Defining the rules for Dynamic Spectrum Usage.....	111
A.1. Use cases classification in 3GPP TR	111
A.2. FCC decisions	112
A.3. FCC regulations enabling the use of UL FDD bands for downlink transmissions	113
A.4. Radio Spectrum Policy Group	114
A.5. ECC decisions /ETSI standards	116
A.6. 3GPP/5GPPP decisions, guidelines, expectations	119
A.7. Others regulations	120
A.8. Activities in Asia.....	121
A.9. Annex references:	121

List of figures

Figure 2-1. FCC’s 3-Tier Proposal for 3.5 GHz band, based on [PCAST_2012].....	30
Figure 2-2 Illustration of the LAA concept, based on: QUALCOM, https://www.qualcomm.com/invention/technologies/1000x/spectrum/unlicensed	33
Figure 2-3. Illustration of the LAA/LWA concept, based on: QUALCOM, https://www.qualcomm.com/invention/technologies/1000x/spectrum/unlicensed	34
Figure 4-1. Regulatory and usage scenario domains identified by METIS (based on Figure 2-2 in [METIS_2015_2]).....	53
Figure 4-2. Functional architecture - regulatory aspects (based on Figure 2-5 from [METIS_2015_2])	54
Figure 4-3. Functional architecture - operational aspects (based on Figure 2-6 from [METIS_2015_2])	55
Figure 4-4. A Generic METIS View on the spectrum management system (based on Figure 3-1 from [METIS_2015_2]).....	55
Figure 4-5. Generic REM concept.....	56
Figure 4-6. COHERENT spectrum management, coordination and control system.....	57
Figure 4-7. The generic ownership structure of the spectrum management system.....	60
Figure 4-8. COHERENT spectrum, coordination and control system – area-centric position of the C3 module	62
Figure 4-9 COHERENT spectrum, coordination and control system – operator and area-centric position of the C3	62
Figure 4-10. Identification of new interfaces for COHERENT Spectrum Management, Coordination and Control System	63
Figure 4-11. Illustration of the network graphs for spectrum management, coordination and control system.....	64
Figure 4-12. Illustration of the network graphs for spectrum management, coordination and control system for a specific use case	67
Figure 4-13. Message exchange for use case 1	72
Figure 4-14 Message exchange for use case 2	73
Figure 4-15 Message exchange for use case 3	74
Figure 5-1 Example of flexible duplex usage.....	75
Figure 5-2 System Architecture.....	80
Figure 5-3 An example of RSSI Map.....	80
Figure 5-4 An example of Link Statistics Map.	81
Figure 5-5 An example of Traffic Matrix Map.	81
Figure 5-6 HMN layout of victim operator. All the UEs are in UL.	89
Figure 5-7 Case scenario 1: OOB interferer is UE in FDD UL band.....	90
Figure 5-8 Case scenario 2: OOB interferer is BS in FDD UL band	90
Figure 5-9. SINR for UE in analysis sector of the main macro cell in victim’s HMN.	92
Figure 5-10. SINR for UE in small cell in victim’s HMN.	92

Figure 6-1 Information/Control flows associated with Spectrum Manager Application (SMA) 94

Figure 7-1. INEA – coverage of WiMax 802.16e network around Poznań area..... 99

Figure A-1: Radio frequency spectrum and corresponding radio services..... 111

Figure A-2: Overview of spectrum sharing initiatives undertaken in the USA by FCC and NTIA [A_Agre_2015] 113

Figure A-3: Overview of ETSI activities in relation to the process of promoting an harmonized approach and standardization of LSA within Europe..... 118

List of tables

Table 1. Pros and cons of the RAN infrastructure sharing idea in the HMNs from the MNO and regulatory point of view 22

Table 2. Pros and cons of the databases concept in the HMNs from the MNO and regulatory point of view 23

Table 3. Pros and cons of exclusive licensing in the HMNs from the MNO and regulatory point of view 24

Table 4. Pros and cons of the license exempt in the HMNs from the MNO and regulatory point of view 26

Table 5. Pros and cons of the LSA in the HMNs from the MNO and regulatory point of view 28

Table 6. Pros and cons of the SAS in the HMNs from the MNO and regulatory point of view 31

Table 7. Pros and cons of PL in the HMNs from the MNO and regulatory point of view..... 32

Table 8. Pros and cons of the LAA in the HMNs from the MNO and regulatory point of view 34

Table 9. Pros and cons of the TVWS concept in the HMNs from the MNO and regulatory point of view 36

Table 10. Pros and cons of the CSA in the HMNs from the MNO and regulatory point of view..... 37

Table 11. Summary of pros and cons for all identified spectrum sharing strategies from the perspective of mobile network operator 38

Table 12 Summary of pros and cons for all identified spectrum sharing strategies from the perspective of national regulatory authority 40

Table 13 METIS assessment criteria (source [METIS_2013]) 47

Table 14 Summary of the assessment in the frequency range 5.925 - 37 GHz. (source [METIS_2013]) 48

Table 15 Summary of the assessment in the frequency range 40.5 - 95 GHz. (source [METIS_2013]) 48

Table 16. Importance of identified functionalities with the reference to selected spectrum sharing strategies (Legend: importance level: H – high, L – low) 70

Table 17 UL/DL traffic ratios of different service types 86

Table 18. Simulation Setup 91

Table 19 PHY and MAC layer measurements in LTE and WiFi networks 95

Table 20: FCC technical documents on specific spectrum sharing activities..... 112

Table 21. List of FDD bands allowing DL transmission in the FDD uplink bands 114

Table 22: Regulatory situation of millimetre wave spectrum in different geographical areas worldwide [A_Yong_2007], [A_Geng_2009]	116
Table 23: Plans for using whitespaces in the band 470-790 MHz [A_RSPG_2011]	117
Table 24: Summary of ECC decisions and ETSI standards.	119
Table 25: New spectrum opportunities leveraged by TDD LTE.....	120
Table 26: Current activities undertaken by different 5G projects [A_5GPPP_2015]	120

1. Introduction

Flexible yet effective spectrum management is one of the promising key enablers for the success of 5G networks. The benefits that can be achieved by dense deployment of Heterogeneous Mobile Networks (HMNs) in 5G networks can be further enhanced by advanced spectrum sharing.

Given that the spectrum is allocated to different operators, and also due to the very high deployment density, the classical coexistence solutions within the licensed as well as unlicensed spectrum may not provide required isolation anymore. Also, classical approaches based on orthogonal spectrum sharing among operators in licensed bands may be inefficient in small-cell scenarios with changing numbers of users, variable area coverage of operators, and variable load. A new vision for spectrum utilization is required. It is then worth noticing that - similarly to previous cellular system generations - also the 5G network deals not only with new innovations in PHY/MAC layers, but also new spectrum sharing paradigms, together with efficient spectrum access techniques. Various approaches are possible as alternatives for licensed-only solutions, such as LSA, license exempt, co-primary sharing, pluralistic licensing, among others.

1.1. Requirements to 5G spectrum Management

It is envisaged that the future (5G) wireless networks will need to fulfil a set of significant requirements, known widely as 5G key performance indicators (KPIs). These KPIs include (following [5GPPP_2015_1], [5GPPP_2015_2]):

- “1000 times higher mobile data volume per geographical area.
- 10 to 100 times more connected devices.
- 10 times to 100 times higher typical user data rate.
- 10 times lower energy consumption.
- End-to-end latency of < 1 ms.
- Ubiquitous 5G access including in low density areas”.

The fulfilment of these KPIs will allow the true delivery of various classes of services to the end-users. It is often understood that 5G networks will need to manage [Monserrat_2015], [Marsch_2015]:

- High data rates and low latency communications for users, denoted usually as evolved (extreme) mobile broadband, eMBB (xMBB), as it should outperform the traditional MBB services
- Support scalable communications between billions of network-enabled devices; this type of service is often referred to as massive machine-type communications (mMTC),
- Extremely demanding requirements on availability and reliability; this issue is often referred to as Ultra-Reliable Communications, URC; in this class it is also envisaged to consider ultra-reliable machine-type communication, uMTC;
- Advanced communications between vehicles and other entities (other vehicles, devices, infrastructure elements), denoted as V2X.

It is widely agreed that the practical realization of the above requirements entails the application of new technologies and solutions where an advanced approach to spectrum utilization is envisaged as one of the key technical enablers. Recent simulation results show that depending on the considered scenario, up to 500 MHz or 1 GHz of spectrum would be needed for future networks. In that context, one of the possible solutions is to utilize new frequency bands higher than 6 GHz (such as centimetre and millimetre waves) as these frequency bands allow allocation of wide spectrum for short-range communications. On the other hand, a 5G network will be highly heterogeneous meaning that various

technologies (e.g., cellular networks with WiFi-based solutions) as well as various types of radio-access networks (e.g., macro-cells, dense small cells) will coexist in the same area. In that particular context a new, comprehensive (holistic) view on the spectrum management will be required. These two solutions (i.e., usage of higher frequencies and advanced spectrum management) have been foreseen by 5GPPP as possible key solutions for the 5G networks [5GPPP_2015_2].

Based on the discussion above, it can be imagined that a practical realization of the above solutions can result in the situation that no dedicated frequency band will be assigned solely for 5G transmissions. On the contrary, numerous sets of frequency subbands will be utilized by 5G systems due to the vast variety of services to be delivered to end-users and due to the high heterogeneity of the future networks.

1.2. COHERENT Goals

The COHERENT project aims to design, develop and showcase a novel control framework for 5G heterogeneous mobile networks (HMN), which leverages the proper abstraction of physical and MAC layer in the network and a novel programmable control framework, to offer operators a powerful means to dynamically and efficiently control spectrum and radio network resources in their increasing complex HMN.

COHERENT proposes the proper abstraction of physical and MAC layer states, behaviours and functions to enable a centralized network view of the underlying radio networks with significantly reduced signalling overhead. The centralized network view with sufficient but abstracted information on spectrum, radio links, interference, network topology, load information, and physical layer reality is essential to enable optimal resource allocation in the network.

One of the key goals of the COHERENT project is to investigate the true benefits that can be gained by the network operator and end-users through the application of the wireless network virtualization concepts and based on the recent achievements in the area of radio-environment-map design, practical conclusions from cognitive radio, legal regulations and field experiments (e.g., [Montserrat_2015], [Kliks_2016], [Liang_2015_1], [Liang_2015_2]). In the COHERENT project, we envisage the application of advanced spectrum management and coordination system which provides the tools for wireless network virtualization.

1.3. Document Structure and Relation with Other WPs in COHERENT

This document is Deliverable D4.1 “Report on enhanced LSA, intra-operator spectrum-sharing and micro-area spectrum sharing” for Work Package 4 “Flexible Spectrum Management”. It is organized as follows:

- **Chapter 2** presents an overview of the selected spectrum sharing strategies, it provides a brief description of each of them together with the summary of its pros and cons; moreover, for each spectrum sharing strategy the initial observation on its abstraction is induced. Based on the analysis we firstly identify the most promising spectrum sharing strategies, and second, we present our vision on the prospective use of spectrum in the future.
- **Chapter 3** presents COHERENT’s vision for spectrum sharing in the context of 5G networks. The feasibility of various spectrum bands is analysed with respect to the 5G requirements, and the approach to spectrum management is described in three separate contexts: intra and inter operator spectrum sharing, and micro level spectrum sharing.
- **Chapter 4** proposes the generalized and high-level system architecture for spectrum management, coordination and control; the key entity in that system is the COHERENT Central Controller and Coordinator (C3), which utilizes network graphs for better resource utilization. The analysis of this architecture is made from the perspective of wireless network virtualization. The system consists of three layers: spectrum management plane, control and coordination plane, and the infrastructure plane (i.e., the plane of physical

resources). Next, the interfaces between and within the planes are identified, and the set of functionalities and requirements for the whole system are discussed. Finally, it contains the definition of the network graph tailored to the flexible spectrum management.

This chapter covers the contribution towards WP2 and WP3, which is constituted by the proposal of the role of spectrum management system in the overall network architecture, as well as by the definition of the network graph.

- **Chapter 5** discusses the exemplary use cases and scenarios of application of the proposed spectrum management system.
- **Chapter 6** analyses the identified APIs and SDKs for efficient, flexible spectrum management and access. Thus, it provides a contribution towards WP2 and WP5.
- **Chapter 7** is the description of the considered trials on spectrum sharing which are planned to be demonstrated in the project lifetime.
- The report is concluded at the end, followed by the Annex with the in-depth discussion on legal regulations towards flexible spectrum sharing.

1.4. Summary of Results towards Other Activities

1.4.1. Towards WP2

One of the key outcomes of the first year is the definition of the whole spectrum management system architecture for the wireless networks which apply wireless network virtualization. Such architecture and identification of functionalities and requirements for each plane of the system will be used in WP2 for overall system planning and management.

1.4.2. Towards WP3

In WP4 the network graph definition focused on spectrum sharing issues has been proposed, and as such it constitutes the input towards WP3 on low-layer abstraction.

1.4.3. Towards WP5 and WP6

Identification of the pioneering bands and most promising spectrum sharing strategies defines the prospective experimentation scenario that will be realized in WP5 and WP6. Moreover, the set of SDKs and APIs has been identified for efficient spectrum sharing implementation.

1.4.4. Towards Standardization (WP7)

The main WP7 activity based on the work done in WP4 is planned to take place in ECC PT1. ECC PT1 will be informed about the COHERENT approach regarding the system architecture, considered co-existence scenarios, used parameters and scenarios for simulation as well as the initial simulations results.

Additional activities may take place in 3GPP RAN1, RAN2 and RAN3, depending on the scope of the approved work items. In RAN1 the studied items may include the coexistence between operators using adjacent channels in regular FDD mode or based on the concept of flexible spectrum usage and the eventual new required measurements. In RAN2 the signalling between base station and the User Equipment, including eventual NAS (Non Access Stratum) signalling may be standardized, while in RAN3 aspects related to coordination of spectrum usage may be standardized.

2. Identification of the Most Promising Spectrum Sharing Strategies

In this chapter we briefly discuss the advantages and drawbacks of selected spectrum sharing strategies from the perspective of their application in 5G networks with particular attention put in HMNs.

2.1. Introduction of Spectrum Sharing

It is highly expected that in the context of future wireless communication systems two traditional models of spectrum management and licensing schemes, i.e. exclusive use and license-exempt, will be replaced by more flexible versions. Although the static solutions are easily implemented in practice, it is envisaged that introduction of spectrum flexibility is somehow necessary to accommodate the expected traffic growth for 5G networks. Various approaches to advanced resource sharing (including not only spectrum but also infrastructure) have been foreseen as the emerging and important solutions to the problem of high spectrum scarcity and underutilization. As such, in the context of COHERENT framework and envisaged network abstraction model, these techniques need thorough analysis and detailed comparison. In this section we try to review the most promising resource sharing strategies, focusing mainly on the proposals for efficient spectrum sharing.

2.2. Technological Aspects of Spectrum Sharing

2.2.1. RAN/ Infrastructure Sharing and Mobile Virtual Network Operators (MVNO)

Brief description

Mobile operators have traditionally avoided sharing either the spectrum or their infrastructure mostly due to competition. Of course, the incumbents have not liked to share their network since they would lose some of their customers in favour to the shared operator. It was observed that there is a steady increase during the past years in the sharing among mobile operators but mainly this regards their infrastructure. However, the scheme of sharing some sort of either infrastructure or spectrum comes into the mind of operators for basically the following reasons. The average revenue per user (ARPU) has decreased while capacity demands have greatly increased, due to the use of smartphones and tablets that have dramatically increased the traffic. Therefore, only in the last few years the mobile sites have evolved from a few tens of Mbps of peak traffic to hundreds of Mbps or in some cases to Gbps traffic. Also the high cost of building and maintaining the masts puts the investments from operators in doubts and start thinking of infrastructure sharing at least in remote areas. A specific example in that context is constituted by the mobile virtual network operators (MVNO) which typically lease the infrastructure from traditional mobile network operators and which offer specific services to mobile users.

Advantages and disadvantages:

The main advantage of infrastructure sharing is the capital expenditure (CAPEX) decrease at least in remote areas where the traffic is low.

The disadvantage is that infrastructure sharing requires effective planning to establish a trustworthy relation between two or more mobile network operators (MNO).

Therefore, the key aspect in sharing is fairness, data transparency and service quality agreements among the sharing companies.

Table 1. Pros and cons of the RAN infrastructure sharing idea in the HMNs from the MNO and regulatory point of view

MNO		Regulator	
Pros	Cons	Pros	Cons
<p>The expenses for the RAN/infrastructure sharing decrease since multiple MNOs are sharing same infrastructure.</p> <p>Infrastructure sharing can increase the coverage in remote areas.</p>	<p>It requires careful design of the network infrastructure so that the cooperation will not break</p>	<p>Less complex for the regulator as it does not have to deal with different petitions from operators.</p> <p>Less environmental destruction</p>	<p>The regulator may lose the luxury of charging for different installations</p>

2.2.2. Databases and Sensing

Brief description

In applications of cognitive radio technology, the information of the available spectrum at certain location is stored in dedicated databases and can be accessed by any interested and allowed player (operator, regulator, policy maker) or user/device (such as mobile terminals, base stations). These databases can contain various types of data, starting from the definition of the operational policies and legal regulations (delivered by the regulators), through the limitations identified based on the considered transmission technology (defined by, e.g., operators), ending at the allowed interference level or transmit powers. Various solutions for such databases have been proposed in the literature [Holland_2015], [Wang_2015], [Kassem_2105], [Chowdhery_2012], [Li_2015], [Denkovski_2012].

One of the key aspects associated with the use of databases is the need of their periodic, continuous and accurate update. Such modification of the current status can be made based on e.g. permanent channel measurements carried out by, for example, mobile devices or dedicated sensors. Various (cooperative) spectrum sensing techniques can be considered as the tool for permanent updating of the databases.

The application of databases and spectrum sensing can be treated either as the separate spectrum sharing approach or just as a tool for realization of any of the sharing schemes discussed in the following. In the former case the interested party queries the database asking for permission for starting data transmission with the specified parameters (e.g., preferred frequency band, transmit power, expected connection duration, expected data rate etc.). In such an approach the detailed spectrum sharing rules will be defined by the regulator, operators and other key players, and stored in the database. A dedicated entity (or engine) will use its artificial intelligence to allocate the spectrum to the interested users, to monitor and enforce execution of its decisions and, if required, to apply necessary changes in spectrum assignment. Such a structure is not related to any of the spectrum sharing schemes, as any or none of them can be applied here. Such a view is highly related to the cognitive radio, where all of the spectrum utilization constraints can be relaxed and defined adaptively.

One can state that currently the databases will be rather treated as a specific tool required for application of advanced spectrum sharing scheme. Such database will need to be queried in order to get necessary information about e.g. LSA sharing rules applied to the specific location or time.

Advantages and disadvantages:

Databases seem to be the natural and necessary solution for practical realization of any flexible spectrum sharing schemes. In fact, realization of almost any of the solutions would rely on some sort of databases. The key difference will be in their level of complexity, size, frequency of updating information and flexibility. From that perspective, the only drawback (or rather immediate consequence) is the need for advanced algorithms for management and processing of big data stored in these structures. Moreover, each database needs to be periodically updated, thus selection of the spectrum sensing or monitoring tools will be necessary.

Table 2. Pros and cons of the databases concept in the HMNs from the MNO and regulatory point of view

MNO		Regulator	
Pros	Cons	Pros	Cons
Operators use typically various databases	Cost for deployment new hardware and its management	Definition of the coexistence rules can be delivered to the database	Spectrum could be fully flexible, so there is highly reduced interference control mechanism at regulator hands
There are already solutions in the market that could be used for database management	The need of advanced management algorithms for big data processing	The definitions can be changed (updated, modified) even frequently; application of new regulations is almost immediate	
Flexibility and automation in spectrum management			

Initial comments regarding abstraction

Databases and associated spectrum sensing algorithms are transparent to the coordinating entity, as these will be seen only as the tools for efficient spectrum sharing. The coordinator (orchestrator) will send queries to the database (or appropriate entity, such as management engine) asking for dedicated guidelines how the spectrum can be used. Thus, there is no need for any database abstraction.

2.3. List of Existing Spectrum Sharing Schemes (in the Context of HMNs)

In this section the most popular spectrum sharing strategies are briefly summarized and discussed in the context of their application in the COHERENT project. In each selected solution, the core idea of the spectrum sharing strategy is presented, followed by its pros and cons analysis.

2.3.1. Exclusive Use of Spectrum (Individual Licenses)

Brief description

In the classical, traditional case, the whole radio spectrum is statically allocated to various players (such as network operators) for exempt use. Thus, a certain operator is authorized to utilize a given frequency band based on the individual licenses. Such a spectrum division is

made usually at the national (country) basis, however international agreements (such as those made at WRC level) need to be fulfilled. Following these decisions each country creates their own frequency allocation plan and defines the rules, how the particular frequency bands can be utilized (e.g., the maximum transmit power is defined, types of services that can be delivered to the end-user etc.), trying to guarantee high level of electromagnetic compatibility between the services and systems.

From one hand side such an approach can be treated as a way for efficient interference management between various systems, as each frequency spectrum band has its own strict transmission rules the fulfilment of which must be ensured by the service provider. On the other hand, however, such static spectrum assignment can cause high spectrum underutilization, as the frequency bands which are not used at a certain time and geographical location, cannot be used by other operators/service providers due to the lack of license. This problem has been recently investigated in the context of increasing spectrum needs for high data rates delivery in new wireless communication systems, and was the main driver for the research performed in the cognitive radio field. Numerous papers dealing with new, advanced spectrum sharing schemes have been proposed, and the most popular solutions are described in the later sections.

Advantages and disadvantages:

Together with careful system design (i.e., proper definitions of spectrum masks and right measurements of signal power leaking to neighbouring systems), this approach to spectrum use guarantees minimization of the mutual interference. The operating parameters for a certain system are known (as these are defined by the standards and legal regulations), thus the management system and spectrum monitoring strategies are rather simple. From the mobile network operator (MNO) point of view, the exclusive use of dedicated spectrum allows for more stable investment plans and definition of developing strategies.

On the other hand, one can easily observe that such static assignment of certain frequency bands to services and licensed operators will be efficient only in the case when the number of different services is relatively low. As the traffic observed in the wireless systems is growing rapidly, as well as new technologies are released, we need to face with the problem of spectrum scarcity and its underutilization.

Table 3. Pros and cons of exclusive licensing in the HMNs from the MNO and regulatory point of view

MNO		Regulator	
Pros	Cons	Pros	Cons
Spectrum assigned for sole use	There are no easy ways for accessing new spectrum	Simple monitoring and interference management	Problem of spectrum scarcity and underutilization
Based on achieved license, stable investment and development plans can be defined	The need for resource sharing due to the lack of spectrum	Simple auction strategies	
Relatively simple and predictable interference monitoring and management	Big initial cost		

Initial comments regarding abstraction

In the context of abstraction of radio access network and its virtualization, exclusive use seems to be one of the simplest strategies, as static spectrum allocation to operators and services simply eliminates the spectrum aspects from the virtualization process. All of the layers of the stack model, as well as all virtualization functions, instrumentations entities or controllers will simply need to have access to the information on the available spectrum, and this information will not change in time in the short time scale. On the other hand, such static assignment reduces the degrees of freedom for more efficient system virtualization.

Furthermore, network operators will be able to provide reliable statistics on various systems available on certain geographical area, such as the amount of spectrum, allowed data rates, manageable traffic densities, maximum transmit power levels etc. These statistics will be stable (i.e. already averaged over the long observation time) and thus could be efficiently used in the network abstraction process. Of course, usage of frequency resources will require permanent monitoring in order to assess the amount of remaining resources. Such an approach could provide benefits for both intra- and inter-operator resource sharing schemes.

The following pieces of information would be needed by the network controller (manager, orchestrator, etc.):

- a. Long term information (rarely updated)
 - centre frequency
 - band ranges
 - allowed resource granularity
 - allowed transmit power and requirements for spectrum masks (related to allowed spectrum block)
 - maximal theoretic rates or capacity
 - assumed system setup, such as probability of blockade
 - allowed transmit schemes at certain geographical area (such as system type, e.g. General packet radio service (GPRS), LTE, TETRA, modulation formats, authorization types) due to the hardware limitations (i.e., it could be a case that for some reasons only a given hardware modules are available)
- b. Short term information (permanent monitoring)
 - Current occupancy of each resource block
 - Remaining resources
 - Planned handovers

2.3.2. License Exempt Rules (Unlicensed or ‘Commons’)

Brief description

On the opposite side to the exclusive spectrum use, the approach known as “spectrum commons” can be located. In this case each user is allowed to access a dedicated spectrum band with no additional licenses or permissions. The industrial, scientific and medical (ISM) bands are the excellent examples illustrating such spectrum use opportunities, where various systems can cooperate in the same geographical area (such as WiFi and Bluetooth operating in 2.4 GHz band). The benefits of such approach are evident – each interested player can start utilizing spectrum at its own needs. However, as the main advantage of the licensed spectrum assignment lays in strict interference management, the license exempt spectrum bands are said to be “interference limited”. Indeed, when no interference control mechanisms are applied and anyone can start offering its own services without any agreements with the other users, this situation will for sure results in system blockades. Various solutions to this problem have been proposed. However, with the continuously increasing traffic the fully unlicensed spectrum band would need to face with the problem of “tragedy of commons”. In such a case the vacant and unlicensed band will not be used at a particular moment due to the

permanent collisions in accessing the spectrum or due to extreme levels of in-band interferences.

Advantages and disadvantages:

Unlicensed spectrum use solves at some respect the problem of spectrum scarcity as it relaxes the needs of obtaining transmit licenses, and in consequence reduces the costs and creates the opportunities for new users to start using the spectrum without any delay. On the other hand, such an approach suffers from the lack of interference coordination and as such cannot guarantee the assumed service level agreements (measured by e.g. various quality-of-service metrics).

Table 4. Pros and cons of the license exempt in the HMNs from the MNO and regulatory point of view

MNO		Regulator	
Pros	Cons	Pros	Cons
No need for spectrum license (meaning also no cost for obtaining it)	No interference control mechanisms (problem in WiFi networks deployed by MNO leading to loss of quality control)	Better spectrum utilization	No incomes due to lack of auctions
Fast and simple system deployment	No SLA guarantee leading to user dissatisfaction		Almost no interference control
Large ecosystem of devices	Interference problems		
No interference control mechanisms (no additional actions needed from the MNO)	Distances are typically limited because of power limitations		

Initial comments regarding abstraction

Open access to frequency spectrum entails some specific requirements for network virtualization and abstraction. Similarly to the exclusive use approach described in the previous section, the information about the current spectrum occupancy will need to be provided continuously to the system controller (manager, orchestrator), but it will be hard or even impossible to estimate exactly the amount of remaining, vacant resources or assess the remaining system capacity. It is due to the fact that such spectrum access schemes are interference limited, and it is impossible to foresee what the number of users trying to access the spectrum will be. Of course, some daily trends could be helpful, but the real-time situation needs to be monitored permanently. In the case of exempt use each operator will know the exact amount of resources that remain unused, also such parameters as probabilities of blockade can be considered. Here, the knowledge on the amount of users and observed interference will rely mainly on some statistical derivations.

The following pieces of information would be needed by the network controller (manager, orchestrator, etc.):

- a. Long term information (rarely updated)
 - centre frequency

- band ranges
- allowed resource granularity
- allowed transmit power and requirements for spectrum masks (related to allowed spectrum block)
- maximal theoretic rates or capacity
- daily traffic characteristics
- b. Short term information (permanent monitoring)
 - current occupancy of each resource block
 - remaining resources
 - observed interference.

2.3.3. Licensed Shared Access (LSA) Including Authorized Shared Access (ASA)

Brief description

Licensed Shared Access (LSA) concept, originally introduced by the European Commission (EC) in [RSPG_2011_1] to respond to the industry interests, is a sharing model that aims at introducing additional licensed users on spectrum bands currently used by other incumbent systems. The LSA concept has gained growing interest in regulation, standardization and research in particular for the introduction of mobile communication systems in the bands that are allocated to mobile but currently encompass other type of incumbent usage. It enables the introduction of a limited number of new radio systems based on an individual licensing scheme with quality of service (QoS) guarantees for both the new entrant and the incumbent. The LSA concept is based on voluntariness and thus requires acceptance from the involved stakeholders and agreement on the terms and conditions for sharing. The rights to access the band are given to the entrant LSA licensee by the national regulatory authority (NRA) according to this agreement.

The first application area for LSA in Europe under study is the 2.3-2.4 GHz band which has been allocated to the mobile service and identified for international mobile telecommunications (IMT), but currently used for other types of incumbents such as the programme making and special events (PMSE) service depending on the national situation. Regulatory efforts in CEPT have developed the initial sharing framework for LSA and consecutive studies have developed harmonized technical conditions, cross-border coordination, guidelines for the LSA sharing framework, incumbent usage, implementation examples, and technical sharing solutions specifically between the mobile broadband and incumbent PMSE service in the 2.3-2.4 GHz band. As a result, the regulatory framework for LSA in the 2.3-2.4 GHz is ready for national adoption but so far no deployments exist.

From the architecture and implementation perspective, the LSA concept is envisaged to be realized with two new additional components on top of existing cellular architecture: LSA Repository and LSA Controller. These have key roles in the management of interference along with the varying LSA band availability so that incumbents remain free from harmful interference. The LSA Repository has the role of storing and updating the information about the LSA spectrum band availability and its usage conditions. It acts as the middle point between the incumbent and LSA licensee domains and collects the spectrum usage information from the incumbent. The LSA Controller is located in the mobile network side and its role is to ensure the protection of the incumbent user and mobile network by calculating the protection areas based on the information received from the LSA Repository and the information on the mobile network layout. These two additional building blocks can be integrated into the existing cellular architecture in a straight forward manner as currently studied in standardization.

The Authorized Shared Access (ASA) falls under the LSA model as a special case where the LSA concept is applied to spectrum bands that have been allocated to the mobile service and identified for IMT by the International Telecommunication Union Radiocommunication

Sector (ITU-R) at WRCs but currently encompass other type of primary use [Matinmikko_2014].

Advantages and disadvantages:

The LSA concept is a sharing model that aims at providing attractive operational conditions for both the incumbent and the entrant systems in terms of protection from harmful interference. The approach for mobile broadband to access new bands with LSA is based on building a limited number of new functionalities on top of the existing cellular architecture which makes its adoption easier. The challenge is the voluntariness of the adoption of LSA. In particular, the incumbents need to be convinced to open up their deployed bands for sharing which is not easy without true incentives. The main advantages and disadvantages from MNO and regulator point of views are summed up in Table 5. The summary is drawn up based on [Mustonen_2014] and [Mustonen_2015].

Table 5. Pros and cons of the LSA in the HMNs from the MNO and regulatory point of view

MNO		Regulator	
Pros	Cons	Pros	Cons
LSA can be implemented with relatively small changes to the infrastructure of the existing mobile network. LSA does not require any changes to the air interfaces or internal procedures of the MNO	Required LSA database and management units. Various interference control mechanisms needed and also need to guarantee LSA licensees predictable interference conditions. LSA requires investments on the base stations supporting the new bands	More efficient spectrum utilization	Challenges: To provide certainty for MNOs investments, there should be long-term availability of LSA spectrum. The LSA band availability for MNOs in a harmonized manner, globally or at least in Europe, would ensure economies of scale.
When investing in new RATs, better support for LSA is obtained due to new features like cell re-selection, traffic steering, carrier aggregation, load balancing, SON and dual connectivity	New secure coordination protocols for exchange of information between incumbents and LSA licensees (network confidentiality)	No changes to incumbent systems	New systems (LSA licensees) should be compatible with the incumbent systems and their evolutions in such way that ideally no changes are forced on them.
Foster innovation, new business models, more services to be created (new localized services)	LSA licensee (for instance MNO) needs to have mechanisms to respond to the changes in the incumbent user's spectrum usage and to be able to modify its spectrum usage accordingly (certain QoS must be guaranteed also in case	Shortening the required time to gain access to spectrum (compared to traditional methods such as re-farming)	NRA has to monitor that all users are behaving in accordance to implemented rules

MNO		Regulator	
Pros	Cons	Pros	Cons
	when LSA resources become unavailable)		
	Possible lack of incumbent voluntariness. LSA is foreseen to be based on the voluntariness and the incumbent can define on which bands, geographical areas and times to allow additional usage via licensing		Ensuring fairness, equality and transparency in case of several LSA Licensees interested in the same frequency resource can be challenging task for NRA

Initial comments regarding abstraction

In general, the case of LSA is very similar to the exclusive use one, as the information about the available resources can be estimated or even calculated in advance with very high accuracy. The key questions related to the LSA approach are twofold. The first one is associated with the type of licenses granted to the licensee by the licensor (primary spectrum holder), as various models can be used here. If, for example, the selected spectrum band will be granted for common use or so-called non-orthogonal spectrum sharing, then analogous problems appear for such a band as have been identified for license exempt case. On the other hand, the primary license owner could further borrow the spectrum resource for exempt use, thus the observations made for that mode are valid.

The second issue, which is important in the LSA case, is the time-scale for which the current LSA policy is applied. In other words, from the virtualization point of view the information on the duration of the applied LSA policy is necessary – the controller needs to know when the rules of spectrum usage will change. If the primary spectrum holder will agree to offer its part of spectrum in the LSA mode for long time periods that it will reduce the information overhead delivered to the network. Otherwise, short periods for resource sharing based on LSA policy will entail frequent modification of the rules.

Besides the information types mentioned in the previous sections (i.e., on license exempt or licence only approaches), in the LSA mode the following pieces of information would need to be accessed:

- a. Long term information (rarely updated)
 - LSA policy (type of renting)
 - Time scale of each LSA decision
- b. Short term information (permanent monitoring)
 - Depending on the selected LSA policy, the status of current utilization of shared resources

2.3.4. Citizen Broadband Radio Service with Spectrum Access System

Brief description

The Citizen Broadband Radio Service (CBRS) sharing model is a three-tier sharing model introduced by the FCC in the US for the 3550 – 3700 MHz band [PCAST_2012], [Sohul_2015]. It enables additional usage in a band with existing incumbent usage on both licensed and license-exempt bases while protecting the incumbents’ rights. It introduces

additional licensed users (Priority Access Licenses (PALs)), which have operational certainty similar to the LSA licensees, as well as additional license-exempt General Authorized Access (GAA) users. These GAA users need to be registered as CBRS users, so there will be a finite number of GAA users but their operations are not protected from other CBRS users as PALs.

The key component for the management of interference in this concept is the Spectrum Access System (SAS) that coordinates the spectrum usage of the CBRSs to protect the incumbents and PALs from other CBRS users. SAS is a combination of controlling functions and database for the coordination of interference. Additionally, the CBRS concept has adopted Environmental Sensing Capability (ESC) for monitoring the incumbent activity which would detect the appearance of specific incumbents.

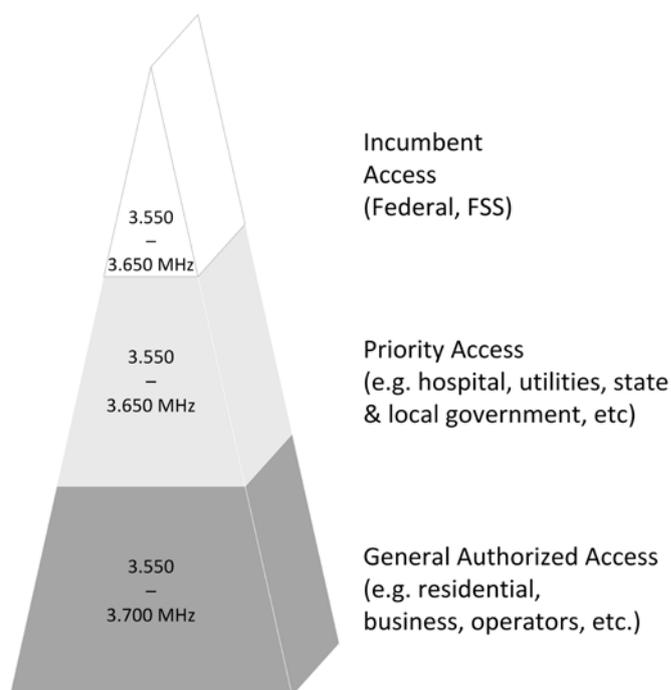


Figure 2-1. FCC’s 3-Tier Proposal for 3.5 GHz band, based on [PCAST_2012]

Advantages and disadvantages:

The US three-tier CBRS model is a more complex sharing model than the LSA concept as it introduces a third tier of opportunistic access which is not present in the LSA concept. The CBRS model provides a rich ecosystem by opening the door for new players to access the market. It enables more dynamic operations to improve the spectrum usage efficiency. However, the complexity of the concept is high. PAL licenses are issued on a census track level which can result in very small areas for the licenses resulting in very complicated interference scenarios.

Table 6. Pros and cons of the SAS in the HMNs from the MNO and regulatory point of view

MNO		Regulator	
Pros	Cons	Pros	Cons
For GAAs: more spectrum in use timely via dynamic frequency assignment	Big investments to the infrastructure: - Rather complex SAS architecture (databases, sensing, coordination of different tiers etc.). - Establish network of dedicated sensor nodes for incumbent detection	More efficient spectrum utilization	FCC needs to work with all stakeholders to provide the necessary certainty for commercial operations
	Interference control	Reduce the need for re-planning	Difficult to define spectrum allocation rules due to mutual arguing of the representatives of the three access tiers. Additional administrative burden.

Initial comments regarding abstraction

SAS architecture is more complex than LSA and thus the abstraction of it is a challenging task.

Besides the information types mentioned in the previous section, in the SAS architecture the following pieces of information would need to be accessed:

- a. Short term information (permanent monitoring)
 - SAS dynamically assigns and maintains CBRS spectrum use in real time, and there will be no fixed spectral location for PA or GAA allocation
 - Citizen broadband radio service devices (CBSD) must be able to determine their geographic coordinates every 60 seconds and report any changes in its position within 60 seconds to the SAS

2.3.5. Pluralistic Licensing

Brief description

The main idea of Pluralistic Licensing was proposed in [Holland_2012] as an innovative approach to spectrum sharing between primary and secondary players (operators). Let us quote the main definition: pluralistic licensing concept can be understood as “the award of licenses under the assumption that opportunistic secondary spectrum access will be allowed, and that interference may be caused to the primary with parameters and rules that are known to the primary at the point of obtaining the license” [Holland_2012]. Here we assume that the primary operator will choose from a range of offered PLs, each with a different fee structure, and each specifying alternative opportunistic access rules that can be mapped to associated interference characteristics [Holland_2012], [Kliks_2015]. As the core license is still granted to the primary operator, the main control mechanism is kept by the primary, as in that light

the primary might trade off the form and degree of opportunistic access for a various licensing fees or another incentive.

The decisions under the PL can be made on short- or long term, they can be also applied on the geographical basis. There might be some control mechanisms applied between co-primary operators apparent at the same locations. Once the decisions are made, and the offers are available to interested secondary operators, they will use a “cognitive” mechanism to access the band, whereby the detail of the access mechanism (i.e. if the use of sensing or databases will be required, etc.), as well as its radio characteristics, depends on the context within which the band is chosen to operate. This context, agreed by the primary operator, defines the extent to which the secondary must avoid interference with the primary, and hence the associated rules on the secondary.

Advantages and disadvantages:

As a very dynamic solution, the concept of PL creates new degrees of freedom in system design and management. The spectrum holders (operators) can create their own rules for spectrum sharing depending on their priorities associated with, e.g., company development strategy, financial status or geographical conditions (such as expected traffic). On the other hand, the natural consequence of increasing system flexibility is in increased complexity of its management. Furthermore, the problem of interference (even potential interference) could become crucial here.

Table 7. Pros and cons of PL in the HMNs from the MNO and regulatory point of view

MNO		Regulator	
Pros	Cons	Pros	Cons
Flexible spectrum sharing scheme	More advanced spectrum management tools are required	Reduction of the spectrum scarcity problem	Less influence on the spectrum management
Allow for adaptive management of owned spectrum	Higher risk of potential interference existence due to agreed (and dynamically changed) license granting system	Better spectrum utilization	Role of regulator can be minimized as the new operators can be granted with spectrum access with no permissions
Creates opportunities for benefits maximization (new revenue sources)	Potential interference induced to other systems (operators)	Dynamic licensing should lead to achievement of better SLAs of various players	Potentially high interference risks
Possibilities for various, parallel sharing schemes depending on assumed priorities	Complexity in devising sharing rules and agreements		

Initial comments regarding abstraction

The dynamic spectrum sharing scheme entails the need of continuous exchange of information of currently applied spectrum sharing policies. As these policies can vary in time and location, the information provided to the system controller (manager, orchestrator, etc.) has to be up-to-date and highly accurate. Besides the typical pieces of information that would

be needed for network virtualization (mentioned while describing exclusive use and license-exempt cases), application of PL can result in the exchange of following messages:

- a. Long term information (rarely updated)
 - Details of the applied PL policy (type of renting, allowed transmit powers, allowed level of interference rise etc.)
 - Time scale of each PL decision
- b. Short term information (permanent monitoring)
 - Depending on the selected PL policy, the status of current utilization of shared resources

2.3.6. Licensed Assisted Access (LAA)

Brief description

Particular attention has been put on the new ways of exploitation of unlicensed frequency band located around 5 GHz. Key industrial players consider the application of the LTE technology in the unlicensed bands, leading to the development of the so-called LTE-Unlicensed solution (LTE-U) and establishment of the dedicated LTE-U forum [LTE-U_Forum]. Operation in an unlicensed band entails the need for fair coexistence of WiFi users with LTE-U. One of the approaches is to dynamically select clear channels in order to avoid the presence (and interference) of WiFi transmission. However, as the presence of vacant WiFi channels cannot be guaranteed, one of the requirements related to the way of spectrum access is the well-known Clear Channel Assessment (CCA) or Listen-Before-Talk (LBT) approach, somehow typical for unlicensed spectrum use. From the WiFi perspective, LTE-U transmission will look like another WiFi client.

The idea of License Assisted Access (LAA), introduced in Rel. 13 of the LTE standard, assumes that the unlicensed band can be used alongside with the licensed one. As various scenarios can be considered here, one important example would be to transmit all control data using licensed band and support user data transmission with the aggregation of licensed and unlicensed spectrum. By assumption, if the traffic observed will be low enough to be managed by the means of licensed bands connections, the unlicensed bands will be released. Typically, LAA is considered mainly in the context of support of downlink traffic by means of utilization of unlicensed spectrum bands. Rich literature has been published in the recent years [Qimei_2015], [Lien_2016], [Ratasuk_2014], [Li_2015_2], [Liu_2105] and [Ibars_2015].

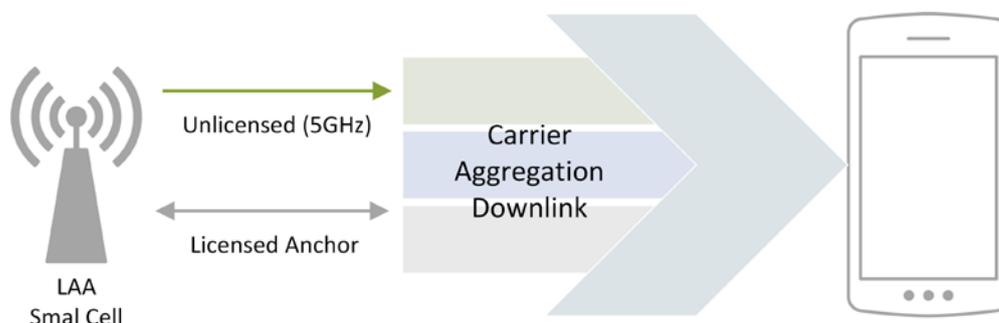


Figure 2-2 Illustration of the LAA concept, based on: QUALCOM, <https://www.qualcomm.com/invention/technologies/1000x/spectrum/unlicensed>

Various modifications and improvements of this concept have been proposed, just to mention the idea of LTE-WiFi aggregation (known as LWA), where the operator decides to use already deployed WiFi network for data transmission, or eLAA (enhanced LAA), where spectrum aggregation will be considered also for uplink connectivity. It is envisaged that the updated version of LAA will be included in the next LTE standard releases.

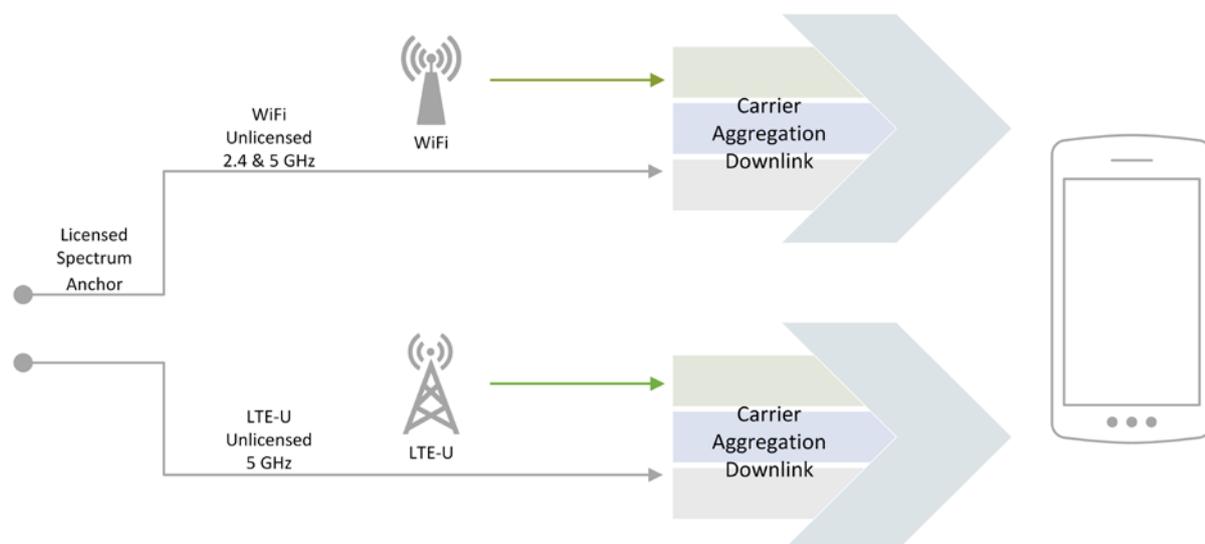


Figure 2-3. Illustration of the LAA/LWA concept, based on: QUALCOM, <https://www.qualcomm.com/invention/technologies/1000x/spectrum/unlicensed>

Advantages and disadvantages:

The key advantage of the LAA scheme lays in the achievement of better performance (in terms of better downlink throughput) by the end user, as these schemes are mainly designed for downlink transmission. However, this concept can be easily generalized and considered as the advanced way for utilization of unlicensed bands for supporting licensed transmission. In such a case, one needs to deal with all limitations of the “license exempt” mode applied typically in the unlicensed band, and described previously. The option of vacant channel identification, considered for LAA, will be no longer valid as the traffic in these bands will increase.

Table 8. Pros and cons of the LAA in the HMNs from the MNO and regulatory point of view

MNO		Regulator	
Pros	Cons	Pros	Cons
Possibility of offloading some traffic to unlicensed band	Lack or very limited maintenance of interference in unlicensed bands	Better utilization of resources	Higher utilization of unlicensed bands can lead to the tragedy of commons
Achievement of higher sum rate in the cell/network	When interference is too high it may result in connection drops	No need for specific rules for licensed users operating in unlicensed band (typical rules will be applied)	

Initial comments regarding abstraction

From the perspective of the network abstraction the case of joint utilization of licensed and unlicensed bands can be seen as the specific mixture of the exclusive use and license exempt approaches described above. The controller would need to know all the details related to the usage of licensed part of spectrum, and in addition to that it will require information about the possibilities of unlicensed spectrum usage.

2.3.7. TeleVision White Space (TVWS)

Brief description

TeleVision White Space (TVWS) refers to unused radio spectrum capacity on terrestrial television broadcast bands. In most cases only Ultra-High Frequency (UHF) part of the terrestrial TV band is considered. The TV UHF band begins globally from 470 MHz and ends at 698, 790, or 862 MHz depending if both 700 MHz and 800 MHz, only 800 MHz, or neither of them has been allocated for mobile broadband, respectively. If TVWS covers also Very High Frequency (VHF) terrestrial TV, the frequency range is typically around 174 – 230 MHz.

The European television network frequency allocations have been agreed in Geneva in 2006. An area with allocated frequencies is called allotment in [ITU_2006]. The television frequency use in each country is under slow, e.g. from 2006 to 2030, but constant change. The TV broadcast network has changed from analogue Phase Alternate Line (PAL) to Digital Video Broadcast Terrestrial (DVB-T) and further from DVB-T to DVB-T2. During the transition period both earlier technology and the new technology are simultaneously in use. Termination of Analogue TV transmission is called Analogue Switch Off (ASO). It has been the major trigger for TVWS as one analogue TV channel requires full 8 MHz (UHF) or 7 MHz (VHF) channel bandwidth, and several digital TV channels can fit in one DVB-T multiplex requiring the same 7 or 8 MHz channel. DVB-T2 replaces Motion Picture Expert Group 2 (MPEG2) video compression with MPEG4 being able to carry even more TV channels in one 7 or 8 MHz channel. Simultaneously, demand for High Definition Television (HDTV) has partially decreased the spectral benefit of the transition. Geneva 2006 (GE06) allotments, analogue TV network and DVB-T network have been designed Multiple Frequency Network (MFN), meaning that the coverage areas neighbouring TV transmitters use different TV frequency channels and typically the design leaves empty TV frequency channels between them. DVB-T2 support Single Frequency Network (SFN) design, where neighbouring TV transmitters can transmit on the same frequency channel. Although it is possible to make country-wide SFN TV broadcast networks, so far European broadcast networks continue to follow GE06 allotments and to design MFN-based DVB-T2 broadcast networks. Increased efficiency of terrestrial TV spectrum, which has become available due to DVB-T, DVB-T2 and SFN, has made it possible to clear the 800 MHz band (in 790 – 862 MHz) and 700 MHz band (in 698 – 790 MHz) for exclusive Long Term Evolution (LTE) licenses.

The White Spaces of terrestrial TV broadcasting have been utilised for Program Making and Special Events (PMSE) like wireless microphones and in-ear monitors. A significant part of PMSE use was on 800 MHz band, but as the band was cleared, they had to be moved to lower frequencies of terrestrial TV band. PMSE use is secondary to terrestrial TV, thus PMSE use is not allowed to interfere with terrestrial TV service. The licensing regulation of PMSE radio transmitters varies largely in Europe. Some of the countries require a license and exact location, time, and frequency to be reported to the regulator (UK), some of the countries require a license but details of use are not mandatory (Finland), some of the countries have PMSE equipment on terrestrial TV band license free (Netherlands), some countries have dedicated TV channels for PMSE use, where a license may or may not be required. Also various combinations of these licensing regulations exist. A further complication in PMSE use is that in most countries where licensing is required a significant amount (up to 90 – 95 %) of PMSE equipment are operated without getting the license.

There may also be other country-specific use like defence communication on terrestrial TV frequencies.

In addition to clearing and auctioning of 800 and 700 MHz bands, there are initiatives to clear all terrestrial TV UHF spectrum for mobile broadband [GSMA_2014]. Already during the possible transition period from the current terrestrial TV use to mobile broadband use,

partially the spectrum could be used for mobile broadband by introducing Supplemental DownLink (SDL) LTE channels [Lamy_2014] or co-primary allocation for terrestrial TV and mobile broadband [ITU_2015_1].

In Europe, Ofcom has decided to create TVWS regulation. The regulation is published as statement [Ofcom_2015_1]. The regulation refers to ETSI harmonized standard for White Space Devices (WSD) [ETSI_2014_1], and most of the interference protection is based on the work in ECC CEPT SE43 [ECC_2011], [ECC_2013_1], [ECC_2013_2]. Digital Terrestrial TV (DTT) protection is computed by Ofcom to several pixel maps stating the maximum transmission power in each pixel at each frequency channel. The geolocation database provider computes which pixel maps should be applied and which pixels should be taken into account for the operational parameters of the WSD. For the protection of PMSE, Ofcom provides the list of PMSE licenses and PMSE venues. The geolocation database provider computes the protection against the PMSE licenses and PMSE venues. Ofcom has a direct control all default parameters used in computation and a capability to issue restriction applied by all databases or individual database to all devices or to specified devices. The WSDs are license-exempt in the UK. There is also a Manually Configured Devices (MCD) regulation [Ofcom_2015_2]. The main purpose for MCD licenses is to allow the use of equipment, which cannot geo-locate or which is in a location where geo-location is not possible.

Finland has legislation for TVWS under name Cognitive Radio Networks [Finlex_2014]. The content is that Cognitive Radio Networks are used on frequencies 470 – 862 MHz without protection and so that they must not cause interference to other radio use. There is no regulation for TVWS in Finland.

Table 9. Pros and cons of the TVWS concept in the HMNs from the MNO and regulatory point of view

No	MNO		Regulator	
	Pros	Cons	Pros	Cons
Geolocation database	Access to spectrum, which is not possible otherwise	Secondary or tertiary priority means that continuity is not guaranteed	Dynamic automated protection	Requires PMSE reporting
Improves spectral efficiency	The total spectral capacity is increased compared to not using TVWS frequencies.	As the target is to get exclusive licenses on TV UHF band, TVWS use might weaken the position in regulator negotiations.	Better use of national resources	TVWS may become additional burden when clearing for mobile broadband

2.3.8. Co-primary Shared Access

Brief description

The concept of co-primary shared access (CSA) bases on the assumption that multiple operators (with the same privileges) decide to jointly use a fragment of their licensed spectrum [Singh_2015], [Irnich_2013], [METIS_2013]. Two CSA cases can be defined: mutual renting (MR), where operators keep their individual licenses to use spectrum, but they can mutual rent part of the spectrum based on prior requests; and limited spectrum pool

(LSP), in which case the dedicated fragment will be commonly used by all operators based on the group licenses. The former case can be considered as a specific form of LSA between limited set of players, whereas in the latter various forms of cooperation can be envisaged. In the so-called orthogonal sharing common frequency resources can be shared in the time-, frequency-, or spatial division multiple access modes (TDMA, FDMA or SDMA), while the application of non-orthogonal approach entails simultaneous usage of resources causing some inter-operator interference.

Advantages and disadvantages:

Application of CSA allows for more efficient spectrum utilization (operators can rent a portion of spectrum if there is a need), but at the same time the risks related to the inter-operator spectrum sharing can be minimized as the set of peer operators and the cooperation rules are known beforehand. The price for such opportunity is in reduction of exclusively used resources, as a portion of the spectrum has to be reallocated to the common pool.

Table 10. Pros and cons of the CSA in the HMNs from the MNO and regulatory point of view

MNO		Regulator	
Pros	Cons	Pros	Cons
Potential advantages due to the larger available spectrum for data transmission	Reduction of the exclusively used frequency fragment	Better utilization of frequency resources	Reduced control on the ways how the spectrum is actually used (decisions are left to operators)
Operators can predefine the cooperation rules		Interference management through mutual agreements between operators	
A variety of co-primary sharing options exist, one may adapt it to its needs			

Initial comments regarding abstraction

Application of CSA scheme in the virtualized network requires access to the updated information on the accurate rules that specify how the spectrum can be utilized. In particular, it has to be known in advance, which operators are allowed to cooperate, what the key agreements made by them are (this information can be hard to access due to its private nature), which portion of licensed spectrum is allocated for common pool etc. Based on that observation the following long- and short-term data can be identified:

- a. Long term information (rarely updated)
 - Details of the applied CSA mode (MR or LSP; amount of spectrum devoted for this purpose by each involved operator; in case of LSP – the information about the agreed spectrum access mode; in both cases, MR and LSP, agreed time of renting/using the spectrum)
 - Time scale of each CSA decision
 - Some details from the agreement between the operators
- b. Short term information (permanent monitoring)

- In both orthogonal and non-orthogonal sharing, information on the actual, temporary parameters such as interference level, number of served user (thus amount of remaining resources)

2.3.9. Summary of the Pros and Cons of the Spectrum Sharing Schemes

For easier comparison we present the pros and cons of each identified spectrum sharing strategy in form of two summary tables, where the first one (Table 11) represents the MNO perspective, whereas the second (Table 12) – regulatory perspective.

Table 11. Summary of pros and cons for all identified spectrum sharing strategies from the perspective of mobile network operator

Strategy	MNO perspective	
	Pros	Cons
Exclusive licensing	Spectrum assigned for sole use	There are no easy ways for accessing new spectrum
	Based on achieved license, stable investment and development plans can be defined	The need for resource sharing due to the lack of spectrum
	Relatively simple and predictable interference monitoring and management	Big initial cost
License Exempt Rules	No need for spectrum license (meaning also no cost for obtaining it)	No interference control mechanisms (problem in WiFi networks deployed by MNO leading to loss of quality control)
	Fast and simple system deployment	No SLA guarantee leading to user dissatisfaction
	Large ecosystem of devices	Interference problems
	No interference control mechanisms (no additional actions needed from the MNO)	Distances are typically limited because of power limitations
LSA/ASA	LSA can be implemented with relatively small changes to the infrastructure of the existing mobile network. LSA does not require any changes to the air interfaces or internal procedures of the MNO	Required LSA database and management units. Various interference control mechanisms needed and also need to guarantee LSA licensees predictable interference conditions. LSA requires investments on the base stations supporting the new bands
	When investing in new RATs, better support for LSA is obtained due to new features like cell re-selection, traffic steering, carrier aggregation, load balancing, SON and dual connectivity	New secure coordination protocols for exchange of information between incumbents and LSA licensees (network confidentiality)
	Foster innovation, new business models, more services to be created	LSA licensee (for instance MNO) needs to have mechanisms to respond to the changes in the incumbent user's

Strategy	MNO perspective	
	Pros	Cons
	(new localized services)	spectrum usage and to be able to modify its spectrum usage accordingly (certain QoS must be guaranteed also in case when LSA resources become unavailable)
		Possible lack of incumbent voluntariness. LSA is foreseen to be based on the voluntariness and the incumbent can define on which bands, geographical areas and times to allow additional usage via licensing
CBRS with SAS	For GAAs: more spectrum in use timely via dynamic frequency assignment	Big investments to the infrastructure: - Rather complex SAS architecture (databases, sensing, coordination of different tiers etc.). - Establish network of dedicated sensor nodes for incumbent detection
		Interference control
PL	Flexible spectrum sharing scheme	More advanced spectrum management tools are required
	Allow for adaptive management of owned spectrum	Higher risk of potential interference existence due to agreed (and dynamically changed) license granting system
	Creates opportunities for benefits maximization (new revenue sources)	Potential interference induced to other systems (operators)
	Possibilities for various, parallel sharing schemes depending on assumed priorities	Complexity in devising sharing rules and agreements
LAA	Possibility of offloading some traffic to unlicensed band	Lack or very limited maintenance of interference in unlicensed bands
	Achievement of higher sum rate in the cell/network	When interference is too high it may result in connection drops
TVWS	Access to spectrum, which is not possible otherwise	Secondary or tertiary priority means that continuity is not guaranteed
	The total spectral capacity is increased compared to not using TVWS frequencies.	As the target is to get exclusive licenses on TV UHF band, TVWS use might weaken the position in regulator negotiations.
Co-primary Shared Access	1) Potential advantages due to the larger available spectrum for data transmission 2) Operators can predefine the cooperation rules	1) Reduction of the exclusively used frequency fragment

Strategy	MNO perspective	
	Pros	Cons
	3) A variety of co-primary sharing options exist, one may adapt it to its needs	

Table 12 Summary of pros and cons for all identified spectrum sharing strategies from the perspective of national regulatory authority

Strategy	Regulator perspective	
	Pros	Cons
Exclusive licensing	Simple monitoring and interference management	Problem of spectrum scarcity and underutilization
	Simple auction strategies	
License Exempt Rules	Better spectrum utilization	No incomes due to lack of auctions
		Almost no interference control
LSA/ASA	More efficient spectrum utilization	Challenges: To provide certainty for MNOs investments, there should be long-term availability of LSA spectrum. The LSA band availability for MNOs in a harmonized manner, globally or at least in Europe, would ensure economies of scale.
	No changes to incumbent systems	New systems (LSA licensees) should be compatible with the incumbent systems and their evolutions in such way that ideally no changes are forced on them.
	Shortening the required time to gain access to spectrum (compared to traditional methods such as re-farming)	NRA has to monitor that all users are behaving in accordance to implemented rules
		Ensuring fairness, equality and transparency in case of several LSA Licensees interested in the same frequency resource can be challenging task for NRA
CBRS with SAS	More efficient spectrum utilization	FCC needs to work with all stakeholders to provide the necessary certainty for commercial operations
	Reduce the need for re-planning	Difficult to define spectrum allocation rules due to mutual arguing of the representatives of the three access tiers. Additional administrative burden.

Strategy	Regulator perspective	
	Pros	Cons
PL	Reduction of the spectrum scarcity problem	Less influence on the spectrum management
	Better spectrum utilization	Role of regulator can be minimized as the new operators can be granted with spectrum access with no permissions
	Dynamic licensing should lead to achievement of better SLAs of various players	Potentially high interference risks
LAA	Better utilization of resources	Higher utilization of unlicensed bands can lead to the tragedy of commons
	No need for specific rules for licensed users operating in unlicensed band (typical rules will be applied)	
TVWS	Dynamic automated protection	Requires PMSE reporting
	Better use of national resources	TVWS may become additional burden when clearing for mobile broadband
Co-primary Shared Access	1) Better utilization of frequency resources 2) Interference management through mutual agreements between operators	1) Reduced control on the ways how the spectrum is actually used (decisions are left to operators)

2.4. Existing Regulations

This section aims to shed light onto the regulatory aspects around spectrum sharing worldwide. Nowadays, and for a few years, it is understood that the frequency spectrum is a scarce public resource which has to be used judiciously in order to keep up with the growing demand of spectrum resource and the proliferation of new radio services. This well-known concept indicates the large number of existing radio systems, especially concentrated in portions of the spectrum below 10 GHz, looking at this from the perspective of European frequency allocation. For the sake of completeness, an interesting work describing the taxonomy of spectrum access models can be found in [Buddhikot_2007], which clearly highlights how existing ways of consuming spectrum are obsolete.

During the past ten years, new ways of improving spectrum usage efficiency has led to devise the concept of sharing the radio frequency spectrum between different stakeholders. Few but extremely important facts motivate this direction, starting from the obvious reason that an improved spectral efficiency would be beneficial to sustain the demand of new mobile broadband services (MBB). In addition, new market opportunities create revenue with reduced costs although at the price of new challenges. For all these reasons, spectrum sharing has received tremendous effort worldwide, pursuing different directions, from research institutions, industries and regulatory bodies.

2.5. Trials

This section provides a brief collection of various trials on flexible spectrum usage which have been carried out all over the world in the recent years. As the detailed analysis of each of this section is fairly beyond the scope of this document, the goal of this chapter is to highlight the importance of the role that flexible spectrum sharing is playing now in the community and will be playing in the future.

Once we have identified the EU program pilots, we list the vast number of trials in TV White Spaces. This is followed by the concise presentation of selected spectrum sharing trials.

2.5.1. Past EU Program Pilots

- ACROPOLIS: Advanced coexistence technologies for radio optimisation in licensed and unlicensed spectrum
- SACRA: Spectrum and energy efficiency through multi-band cognitive radio
- CREW: Cognitive Radio Experimentation World
- QoS MOS: Quality of service and Mobility driven cognitive radio systems
- QUASAR: Quantitative Assessment of Secondary Spectrum Access
- FARAMIR: Enabling Spectrum-Aware Radio Access for Cognitive Radios Quality of service and Mobility driven cognitive radio systems
- SAMURAI: Spectrum Aggregation and Multi-User MIMO: Real-World Impact
- oneFIT: Opportunistic networks and Cognitive Management Systems for Efficient Application Provision in the Future Internet
- SENDORA: Sensor Network for Dynamic and Cognitive Radio Access
- SAPHYRE: Sharing Physical Resources - Mechanisms and Implementations for Wireless Networks
- COGEU project: Cognitive radio for an efficient sharing of TV white space in European context
- Mission Defined Radio
- SENDORA: design of a wireless sensor network aided cognitive radio system
- CROWN: Cognitive Radio Oriented Wireless Networks
- SECRICOM: The Impact of CR/SDR on Multi-Agency/National Crisis Management
- ETARE: Enabling technologies for SDR compliant tactical networks Mobile Ad Hoc Wideband Waveform(s)
- COST IC0902: Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks
- COST IC0905 - TERRA: Techno economic regulatory framework for radio spectrum access for CR/SDR

2.5.2. TVWS Pilots and Commercial Deployments

- Gaborone, Botswana March 2015 – Present Project Kgolagano
- Boane Municipality, Maputo, Mozambique August 8, 2015 – Present TV white spaces Mozambique
- Accra, Ghana | March 2014 – Present Accra TVWS pilot network is the first of its kind in West Africa
- Koforidua, Ghana | 2013 – Present Koforidua Polytechnic TVWS trial

- Oshana, Ohangwena, and Omusati, Namibia | August 2014 – Present World’s “largest” TV white space pilot
- TV White Spaces Trial in the Philippines Asia, July 2013
- South Africa Commercial Pilot Africa, July 2013
- Cape Town, South Africa, March 2013, September 2013
- Polokwane, South Africa, July 2013 – Present University of Limpopo TVWS Trial
- Dar es Salaam, Tanzania May 2013 – Present Dar es Salaam TVWS trial
- Kenya "Mawingu" Commercial Pilot Africa, February 2013
- Singapore Island Country Club, National University of Singapore, Gardens by the Bay, and Other Sites, September 2012 – Present
- Cambridge, United Kingdom, June 2011 – April 2012 Cambridge White Spaces Trial
Claudville, Virginia North America, September 2009
- Tang Valley, Bumthang, Bhutan, February 2014 – Present Bhutan TVWS trial connects remote health unit
- The Island of Bohol, Philippines | July 2013 – Present Philippines TVWS Pilot Improves Fisher Folk Registrations
- Tono City, Iwate Prefecture, Japan | November – December 2013 Long-distance broadband networking using TV white space for disaster scenarios
- Tacloban, Philippines | November 2013 TVWS in Disaster Response
- Fu-Hsing Township, Taiwan | September 2013 – Present TVWS Field Trial for rural aboriginal Fu-Hsing Township
- Boane Municipality, Maputo, Mozambique | August 8, 2015 – Present TV White Spaces Mozambique
- Gaborone, Botswana | March 2015 – Present Project Kgolagano
- Oshana, Ohangwena, and Omusati, Namibia | August 2014 – Present World’s “largest” TV white space pilot
- Zomba, Malawi | July 2013 – Present Malawi White Spaces Pilot
- Dar es Salaam, Tanzania | May 2013 – Present Dar es Salaam TVWS Trial
- Nanyuki, Kenya | February 2013 – Present Kenya Mawingu TVWS pilot
- Turku, Finland 2011 - 2015 WISE – White space test environment for broadcast frequencies
- London, United Kingdom | October 2014 – Present London Zoo TVWS trial to save the animals
- London, United Kingdom | July 2014 NICT tests combined LTE and 802.11af device communicating with TVWS database at Ofcom white space pilot
- Glasgow, Scotland, United Kingdom | April 2014 – April 2015 Next generation Wi-Fi and city sensing
- Oxford, UK, Flood defence.

- Orkney Islands, Scotland, United Kingdom | October 2013 Internet on ships and boats
- Isle of Bute, Scotland, United Kingdom | June 2012 – December 2013 White Space Rural Broadband Trial on the Isle of Bute
- Seattle, Washington | March 2015 – Present Seattle Center
- Washington County, Maine, USA | June 2014 – Present Washington County Maine TVWS Deployment
- Louisa County, Virginia, USA | April 2014 – Present Louisa Water Tower TVWS deployment demonstrates resilience of TVWS-based WiFi
- Dover, Delaware, USA | Spring 2014 Delaware State Library Pilot
- Humboldt County, California, USA | October 2013 – Present Humboldt County Pilot
- Skokie, Illinois, USA | October 2013 – Present Skokie, IL Pilot
- Topeka, Kansas, USA | October 2013 – Present Kansas State Pilot
- Pascagoula, Mississippi | October 2013 – Present Pascagoula, MS Pilot
- Concord, New Hampshire, USA | October 2013 New Hampshire State Pilot
- Pittsburgh, Pennsylvania, USA | October 2013 – Present Using TVWS to connect vessels in Pittsburgh waterway
- Morgantown, West Virginia, USA | July 2013 – Present West Virginia University Deployment
- Various Locations, USA | July 2013 Libraries WhiteSpace: National Pilot
- La Pointe à David, Gatineau Valley, Quebec, Canada | October 2012 – Present The Great Outdoors Trial
- Wilmington, New Hanover County, North Carolina, USA | January 2012 – Present Wilmington “Smart City” Deployment
- Kingston, Jamaica | January 2015 – Present Jamaica Connected Nation Project
- Montevideo, Uruguay | May 2014 – Present Plan Ceibal to connect remote schools pilot in Uruguay
- London UK, Broadband coverage enhancement: King's College London.

2.5.3. LSA Pilots

Finnish LSA trials have been pioneering in the development of the LSA concept presenting the world’s first live LSA trial in the 2.3 GHz band for sharing between LTE and incumbent wireless cameras (PMSE) in 2013. The trials have continued in 2014-2015 with a series of consecutive trials with enhanced features in academic, industry, standardization and regulatory fora. The trials have been built on top of commercial TD-LTE equipment in the 2.3-2.4 GHz band including real base stations, network management system, core network and UE. The LSA trials have shown how the LTE base stations were taken into use in the LSA band and how the band was evacuated when the incumbent appeared. In addition to the Finnish trials, LSA pilots are also on-going in Italy by an industry consortium coordinated by the Joint Research Centre (JRC) of the European Commission. There is also a LSA pilot in France.

2.5.4. CBRS Pilots

The first CBRS pilots will begin 2016 on 3.5 GHz band in the US.

2.5.5. LAA Pilots

First over-the-air trial of LAA technology has been carried out in November 2015 in Nuremberg in Germany. Two big companies have been involved, i.e., Qualcomm, a worldwide manufacturer who delivered LAA test equipment, and Deutsche Telekom, who provided access to licensed spectrum for LTE anchor carrier improved with access to 5GHz band. As provided in [PRNewsWire], "the team measured and demonstrated LAA's extended coverage and increased network capacity in utilizing unlicensed spectrum compared to Wi-Fi, as well as smooth and opportunistic aggregation of unlicensed spectrum during drive tests which also included seamless inter-eNB handovers." The fair coexistence between LAA and Wi-Fi in unlicensed 5 GHz bands was also demonstrated under different radio interference conditions and for a varied number of interfering nodes.

2.5.6. Infrastructure Sharing

Greek infrastructure sharing has taken place between two mobile operators Vodafone and Wind who signed a 15 years contract for active network sharing agreement for services allocated to 2G and 3G networks which mainly took place for rural areas. According to GSM association (GSMA), Vodafone and Areeba in Cyprus have signed an agreement for site sharing. The same applies between O2 and T-Mobile.

3. Spectrum Sharing in the Context of 5G Networks – a COHERENT Vision

3.1. Requirements for 5G

As mentioned at the beginning of this deliverable, the evolution of mobile communication systems has culminated in the dawn of a 5G vision, which envisages providing diverse services (both human and machine centric) in terms of Quality of Service (QoS) requirements and applications [Osseiran_2014]. In order to address these challenges, a multitude of performance targets have been identified for 5G, to be achieved in 2020 time-frame. The foremost is massive broadband, i.e. enhancing existing data rates by several orders of magnitude. For example, a 1000 times increase over existing 4G aggregate data rate [Osseiran_2014], [Andrews_2014]. Similar requirements are being envisioned for other related metrics such as edge data rate and peak data rate [Andrews_2014], [Wang_2014]. It is well understood that this can be achieved by addition of new spectrum, improvement in the spectral efficiency of existing systems, higher number of antennas, and network densification [Andrews_2014].

In contrast, a myriad of novel and significantly more challenging targets have emerged from the application of various wireless technologies to machine-centric domains such as machine type communications (MTC) or machine to machine (M2M) communications [Osseiran_2014]. It comprises of two main paradigms namely massive MTC and mission-critical MTC. In massive MTC, the main idea is to connect a large number of machines such as sensors, actuators, and other devices to a common platform, thereby paving the way for Internet of things. Most of these machines will likely be low-cost, requiring low-data volumes and energy consumption, but long deployment periods. On the other hand, mission critical MTC scenarios are usually characterized by very low latency, high reliability, and high availability. This has led to an emergence of new use cases, which often consist of very stringent requirements in terms of latency, reliability, and availability, collectively referred to as Ultra-Reliable Communications (URC) in 5G systems. URC is primarily envisioned to be applied at short time-scales, where it has a multitude of applications such as vehicle to vehicle communication, or smart grid control. Other notable applications of low latency communications include tactile internet and two-way gaming. A generic target envisioned for ultra-reliable communications in 5G is 99.999% reliability with 2 ms latency [Popovski_2014]. However, this presents novel challenges at multiple levels, and requires complete rethinking of the existing system design approaches. URC networks differ from conventional mobile broadband systems in that the focus is not on the peak and median performance, but on the situation of lower 0.0001 percentile of users. URC network design is essentially based on the analysis of worst case scenarios, and the preventive measures which one can take to avert them. There may be a multitude of factors contributing to reliability impairments at a network level. In particular, mobility related variations in the channels of users and existence of multiple nodes in the network, competing for the same resources, may lead to a significant increase of complexity.

Furthermore, requirements in terms of energy and cost efficiency are also important, and are in fact closely related to the aforementioned use-cases and scenarios. According to [Andrews_2014], Joules per bit and cost per bit need to fall by at least 100 times. In particular, due to the extreme network densification and increased bandwidth, highly efficient self-organizing mechanisms will be required for enabling energy and cost reductions [Hossain_2015], [Peng_2015].

3.2. Identification of the Most Promising Spectrum Bands/Pioneering Bands a COHERENT Perspective

5G services will require a combination of frequency spectrum in lower bands, for coverage purposes, and in higher bands, with large contiguous bandwidth, for capacity purposes [Uusitalo_2016]. Current cellular systems operate in frequencies lower than 6 GHz, it is expected as next step to extend cellular systems to frequencies higher than 6GHz. The current categorization of spectrum bands for 5G is mainly divided into two main groups, namely, bands below and above 6GHz.

Regarding bandwidth requirements, according to [METIS_2015_1], the main parameters to be considered for 5G bandwidth calculation are:

- The individual user traffic models (driven by applications and services),
- The density of individual users,
- The targets on QoS for each user,
- Frequency band reusability,
- Spectrum efficiency.

Frequency Bands Below 6 GHz

Frequency bands below 6 GHz were defined at WRC '15, and are intended mainly for macro cellular use. The main characteristics of these bands are [Butler_2015]:

- capacity and coverage
- consistent QoS across time and space
- support of outdoor-to-indoor coverage
- support of wide-area M2M communication

Considering the current demand of spectrum for 4G and projecting it as future bands for 5G, ITU-R is studying the release of several bands for different nations as part of the current ITU-R research cycle. These include, but are not limited, to 3300–3400 MHz, 4400–4500 MHz, and 4800–4990 MHz, which are currently supported by China. For Europe, the bands considered are 1427–1452 MHz, 1452–1492 MHz, 3400–3600 MHz, and 3600–3800 MHz; and for the United States 470–694 MHz and 1695–1700 MHz [ITU_2014], [Tan_2015]. It is forecasted that 5G will require enough spectrum available in bands below 6 GHz to cope with the demand of traffic in urban and suburban areas, and in medium dense hotspots, as well to satisfy the requirement for seamless coverage of 5G services: extreme Mobile BroadBand (xMBB), massive Machine-Type Communication (mMTC), etc. [Uusitalo_2016].

Frequency Bands Above 6 GHz

Frequency bands above 6GHz are scheduled to be defined at WRC '19, and are intended to offer greater bandwidths, and to fulfil the high contiguous bandwidth demand for xMBB [Uusitalo_2016]. These bands are ideally suited for use in small cells, to complement macro cells in a HMN environment, and in wireless backhaul links [Kim_2016].

The main challenge of using these bands for cellular communications is the high propagation loss when compared with propagation in lower frequencies. However, the short wavelengths allow to build antenna arrays of small physical size, and to form highly directional beam patterns with a very large antenna gain [Kim_2016].

The feasibility to use bands above 6GHz, and the suitable selection of the frequencies, is still being studied. For example, in [METIS_2013] the assessment of the spectrum in the range 5.925 – 95 GHz was performed with the goal to find additional bands for 5G systems, and with emphasis on the European situation. The outcome of the assessment was a prioritization of the bands that fulfilled the criteria listed in Table 13.

Table 13 METIS assessment criteria (source [METIS_2013])

METIS search criteria:

- Primary / co-Primary allocation to MOBILE / FIXED in Article 5 of the ITU-R Radio Regulations Service (including bands used for backhaul)

- **Bandwidth:** Continuous spectrum of several hundred MHz below 40.5 GHz and at least 1 GHz above 40.5 GHz is seen as a minimum requirement to fulfil user needs
 - In the first round no carrier aggregation capability is assumed, i.e., the bandwidth has to be contiguous. However, if this does not lead to satisfactory results, simple carrier aggregation scenarios to combine a small number of non-contiguous spectrum chunks could be assumed to be supported by METIS in a second step.
 - Bands that can accommodate only one network deployment should not be excluded initially, i.e., no ultimate need to accommodate multiple parallel networks is assumed.
- Paired and unpaired spectrum is considered (both, TDD and FDD networks are options).
- The availability of a suitable existing regulatory framework is seen as benefit.

The conclusions on the assessment of frequency bands in the range 5.925 - 37 GHz found in [METIS_2013] are summarized in Table 14, and for frequency bands in the range 40.5 - 95 GHz summarized in Table 15.

Table 14 Summary of the assessment in the frequency range 5.925 - 37 GHz. (source [METIS_2013])

Band (GHz)	Size [GHz]	Priority
9.9 - 10.6	0.7	Medium / High
17.1 - 17.3	0.2	Low
17.7 - 19.7	2.0	Low
21.2 - 21.4	0.2	Low
27.5 - 29.5	2.0	Medium
31.0 - 31.3	0.3	Medium
31.8 - 33.4	1.6	High
36.0 - 37.0	1.0	Low

Table 15 Summary of the assessment in the frequency range 40.5 - 95 GHz. (source [METIS_2013])

Band (GHz)	Size [GHz]	Priority
40.5 – 42.5	2	Medium
42.5 – 43.5	1	High
43.5 – 45.5	2	Low
45.5 – 47.0	1.5	High
47.2 – 50.2	3	High
50.4 – 52.6	2.2	Medium-Low
55.78 – 57.0	1.22	High
57 – 66	7	High
66 – 71	5	High
71 – 76	5	High
81 – 86	5	High

An alternative summary of candidate frequency bands above 6GHz for 5G proposed by some countries can be found in [Haifeng2015]. In addition to these kinds of assessments, the feasibility to operate in these high frequency bands is being studied from technical and practical perspectives. For example, in [Kim_2016] the authors reported a positive result using the band of 28 GHz, with a bandwidth of 800 MHz and TDD frame structure.

3.3. A COHERENT Perspective on Spectrum Management

In this section we provide the description of the COHERENT perspective to the spectrum management in three separate contexts: intra and inter operator spectrum sharing, and micro level spectrum sharing

3.3.1. Inter-operator Spectrum Sharing

The conventional approach for spectrum sharing between network operators is based on exclusive and dedicated access. It prevents inter-operator interference trivially, but often leads to serious underutilization of spectrum, especially in the bands over 6GHz. Moreover, exclusive access lacks flexibility, scalability, and consequently may result in higher costs to the operator. In order to cope with these issues, a multitude of inter-operator spectrum sharing schemes are envisaged for future, which aim at enhancing overall spectrum utilization via shared access to spectral resources. Among these, co-primary spectrum sharing is of paramount importance from a 5G standpoint. Its constituent scenarios such as mutual renting and limited spectrum pool are particularly relevant, and can be used in conjunction with vertical sharing and unlicensed horizontal sharing schemes, to enable an efficient use of spectrum [METIS_2013], [Irnich_2013]. Mutual renting entails granting individual licenses to operators, which enable them to rent parts of their licensed spectrum to other operators upon request. In limited spectrum pool, a group license is granted to an operator for using a common pool of spectral resources, which is shared with a group of operators; all having equal access rights. The orthogonal sharing of licensed spectral resources is often trivial, and can be enabled in time [Middleton_2006], frequency [Bennis_2009], and spatial domains [Jorswieck_2014]. In contrast, non-orthogonal sharing is not straight-forward, as inter-operator interference is a serious issue. A combination of orthogonal and non-orthogonal sharing is discussed in [Etkin_2007]. Game theoretical approaches for spectrum sharing have been considered in cooperative [Suris_2007], as well as non-cooperative settings [Etkin_2007]. In this context, cooperation between operators constitutes an exchange of parameters e.g. interference prices and channel state information (CSI). On the other hand, in non-cooperative settings, operators act as self-interested players and independent decision makers. It is obvious that non-cooperative formulation is more realistic as the operators are competitors by nature, and may not be willing to exchange network parameters and proprietary information. Moreover, the games among operators can be played in a one-shot [Hailu_2014], or a repeated manner [Singh_2015_2].

Other relevant approaches include auction mechanisms [Huang_2006]. However, auctions are not straight-forward to implement, especially on a short time-scale, and involve issues such as monetization and third party participation. This motivates the need for non-cooperative approaches, which can act at short time-scale without an exchange of network parameters or propriety information among operators. To this end, a coordination protocol acting on the level of RAN is proposed in [Singh_2015], under the assumption that operators agree to a set of negotiation rules. The signalling overhead between the operators is low, and the knowledge of the other-operator CSI is not assumed. There is no monetization involved, but a RAN internal virtual currency is agreed upon by the operators. The core idea is that operators exchange favours, which entails utility gain for one operator and the loss for the other operator. A favour is exchanged only when one operator asks for it, and the other operator is willing to grant it. Thus, operators are not forced to act, but they wilfully engage in an

opponent-blind operation, with the benefits of non-monetized spectrum use. The overhead cost is a few bits of inter-operator signalling per protocol time unit. For example, in order to apply this approach in a COHERENT framework, an interface will be required to enable the exchange of signalling between the controllers of different operators. The role of the controller of a given operator is to engage in exchanging favours based on the underlying network graph. This leads to several interesting research questions; when to ask for a favour? and if granted, how to disseminate it among the network nodes? This problem can be understood as a spectrum sharing game between multiple network graphs, controlled by their respective controllers.

3.3.2. Intra-operator Spectrum Sharing

As the sharing of spectrum can be done only between various players, the problem of intra-operator sharing can be treated as a specific case of the inter-operator strategy described in the previous section. As the key goal of the COHERENT is to focus on virtualization of the network, including its radio access part, the target of the intra-operator sharing analysis is to concentrate on the perspective of PHY/MAC abstraction. In particular, the main efforts have to be put on the derivation of the spectrum usage information from the abstracted low layers, in order to aggregate the spectrum sub-bands and further process with the purpose of high-level spectrum provisioning, reconfiguration and spectrum access parameters tuning in operator's radio access networks, and especially small cell networks. The dependency of various spectrum sharing strategies on the deployed infrastructure is an important investigation subject, especially when the impact of the mobile front-haul and back-haul will be considered.

Furthermore, having in mind the network abstraction principle, the application of selected ideas known from the cognitive radio field for HMNs has to be analysed, including the solutions based on policy-oriented spectrum management radio networks. Various spectrum sharing strategies, for example those analysed in this document should be mapped/projected on the programmable spectrum management concept. Integration of the policy-based approach with PHY/MAC abstraction has to be done.

3.3.3. Micro Level Spectrum Sharing

In order to meet the demand of expected 1000-fold traffic volume increase from now to year 2020, it is commonly believed by both academia and industry that cellular network will go to hyper-dense deployment [Bhushan_2014]. In addition to the cellular network densification, device-centric architectures are becoming one of the disruptive technologies for 5G [Boccardi_2014]. There are plenty of challenges in denser small cell deployment and device-centric architectures: for example, small cell to small cell interference issues between femto cells which are deployed by subscribers without prior network planning. From spectrum sharing perspective, denser networks provide new challenges for flexible and efficient spectrum usage, especially when small cells belonging to multiple networks or multiple operators are massively deployed in the same geographic area.

The microlevel spectrum sharing in this section refers to the spectrum sharing for micro/pico/femto cell area, or for device-to-device (D2D). For instance, spectrum asking favours and spectrum sharing through contracts are also proposed for coordinating spectrum sharing between femto and micro cells of different network operators [Singh_2015_3], [Duan_2014]. According to Qualcomm, ASA/LSA is optimal for small cells since those (small-cell base stations) can be closer to incumbent than macro base stations. In [Teng_2014], a co-primary spectrum sharing method is proposed for multiple operator networks in local area with densely deployed cells. For unlicensed spectrum bands, [Zhang_2015] introduced a mechanism called Almost Blank Subframes (ABS) and an interference avoidance scheme to mitigate the interference between WiFi and LTE/LTE-A systems when both transmit in the same unlicensed spectrum.

In addition to the radio access links, also wireless backhaul links are consumers of spectrum. A wireless backhaul link operating in mm-wave bands is a considerable option for small cell deployments. Wireless backhauling also fits better to the plug and play nature of small cell deployments. Further, wireless backhaul solutions are the only possibility in vehicular environments, e.g. trains, buses and cars. In-band backhauling (aka self-backhauling) uses the same frequency band for backhaul and radio access links while in out-band backhauling the radio access links and backhaul links operate on different frequency bands [Boyu_2015]. In-band wireless backhaul can be used between base stations for co-operative communications, reducing the cost and complexity of backhaul network deployment. In-band backhauling has obvious cost benefits also from frequency reuse perspective, making more efficient use of spectrum resources as they can be shared dynamically.

In recent years, D2D communications have been studied and standardised by 3GPP and the proximity services have been added into LTE in 3GPP Release 12. In parallel with the standardisation efforts, basic research is being undertaken to address the many fundamental problems in supporting D2D in cellular networks. One fundamental issue is how to share the spectrum resources between cellular and D2D communications. Based on the type of spectrum sharing, D2D can be classified into two types: in-band and out-of-band, similarly as the wireless backhaul. In-band D2D can be further classified into two categories: overlay and underlay. Overlay means that cellular and D2D transmitters use orthogonal time/frequency resources, while underlay means that D2D transmitters opportunistically access the time/frequency resources occupied by cellular users. The second issue is how D2D users should choose between communicating directly or via the base station. Analysis work on these two major issues is published in [Lin_2014].

Yet another aspect of micro level sharing is flexible duplexing. Shortly, flexible duplexing means that the conventional FDD and TDD duplexing schemes are mixed or enhanced somehow to support better mobile broadband services characterised by asymmetric downlink and uplink bitrates. Those new types of services are more popular in hotspots, where small cells are deployed. Flexible duplexing schemes are classified in [Wan_2014] based on the level of flexibility, eventually leading to the full duplex scheme where a transceiver can transmit and receive signals simultaneously with the same frequency resource. The efforts in COHERENT project focus on dynamic spectrum sharing schemes. Then the spare UL resources, mainly from macro cell UL frequency bands, are used for DL transmission in small cells, or for D2D communications.

3.4. Identification of most promising spectrum sharing schemes – a COHERENT perspective

One of the key aspects covered by the COHERENT project lays in defining new ways for advanced and flexible spectrum management for future wireless networks, and in particular in the context of wireless network virtualization. Proposed generic model for spectrum management, its position in the whole COHERENT ecosystem, respective interfaces and communication ways, would be applicable for any considered spectrum sharing scheme. It would be highly beneficial to provide various mappings between the generic model and practical implementations of selected spectrum sharing strategies, and such an exercise is envisaged in the project lifetime.

For further detailed discussions we have however identified the following strategies:

1. The popularity of exclusive spectrum use and its counterpart - license exempt approach – will not decrease in the nearest future. Thus the traditional solutions will be considered as the reference.
2. From the European point of view, the selection of LSA is somehow natural mainly due to the popularity of such a solution in operators and service providers; on the other hand, the SAS solution is under practical tests now in US, thus it should not be neglected.

3. The LAA approach is gaining popularity, thus the coexistence of licensed and unlicensed services is envisaged.
4. An interesting option is the co-primary sharing scheme, as this approach gives new degrees of freedom for operators.

Clearly, from the perspective of real implementation, the above solutions can be applied in various contexts (e.g., for TVWS, or with the use of dedicated databases supported by sensing function), however we think that more flexible approaches to spectrum sharing (such as innovative Pluralistic Licensing or various cognitive radio oriented schemes) may require further investigation.

Finally, from the microscale the idea of flexible duplexing is very promising and will be considered for further analysis.

4. COHERENT Spectrum Management, Coordination and Control System

In this section we discuss in details the spectrum management, coordination and control system proposed in COHERENT.

4.1. Reference work

The need for advanced spectrum management has been considered in various research activities for a few years. As the exclusive access spectrum facilitates precise interference management, it guarantees the fulfilment of agreed service level agreements (SLAs) between operators and their clients. However, numerous spectrum measurements have shown that such an approach leads to high spectrum underutilization. This resulted in development of various spectrum sharing strategies, as described in Section 2. However, application of advanced spectrum sharing schemes entails the implementation of the appropriate management system. In the following we briefly discuss selected solutions proposed in the referenced work.

4.1.1. METIS/METIS II Achievements

The topic of spectrum management was thoroughly investigated in METIS project, which was a predecessor to the current METIS-II initiative. The project’s main results of spectrum management were presented in Deliverables D5.3 [METIS_2015_1] and D5.4 [METIS_2015_2], and are summarised below in a concise form. First, as shown in Figure 4-1, two domains for spectrum sharing have been identified, a regulatory framework and spectrum usage scenario domains. In the first domain three key classes have been proposed – primary user modes (dedicated licensed spectrum usage scenario and horizontal sharing), Licensed Shared Access (LSA) mode (mandatorily connected with vertical sharing, and optionally with horizontal sharing), and unlicensed mode (obviously connected with the unlicensed horizontal sharing and optionally with vertical sharing). The terms vertical and horizontal sharing refer to the level of hierarchy applied between the licensees, i.e., in horizontal sharing both stakeholders (e.g. mobile network operators) share the spectrum with equal usage rights and in vertical sharing some hierarchy is applied.

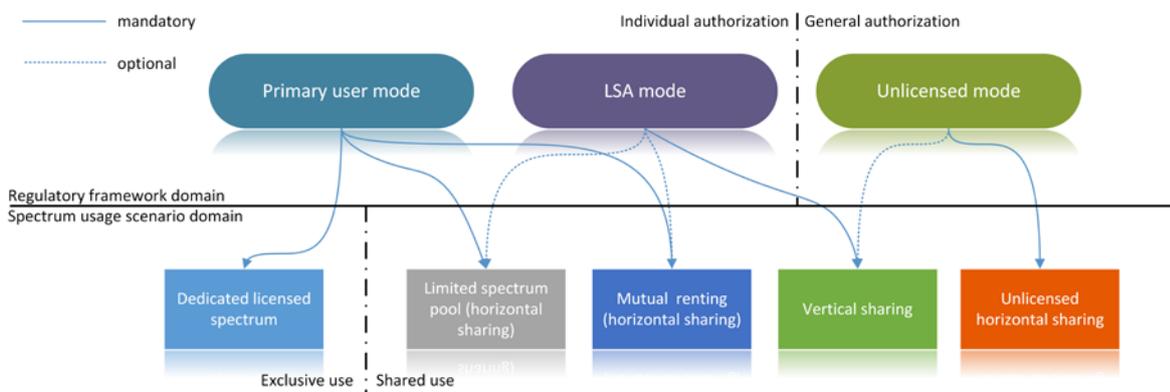


Figure 4-1. Regulatory and usage scenario domains identified by METIS (based on Figure 2-2 in [METIS_2015_2])

In general, the spectrum has been split in two parts – below and above 6 GHz. In the former case, the particular attention is put on new spectrum management frameworks and in the latter, new spectrum bands can be assigned to specific use-case scenarios. Again, this approach is in line with the envisaged solutions defined by 5G PPP in [5GPPP_2015_2].

After the key enablers were identified, the next step is to define the functional architectures for regulatory (Figure 4-3) and operational (Figure 4-3) aspects of spectrum usage. In the former case, it is assumed that the national regulatory authority (NRA), or other legal

regulatory/control body will play a significant role in defining the long-term rules for spectrum allocation, assignment, licensing and enforcement. Thus, one can observe a set of databases (with policies, spectrum resources, sharing agreements etc.) and a dedicated engine for evaluation of these rules. The engine contacts with the spectrum controller which is a part of the operator infrastructure. On the other hand, mobile operators (or other stakeholders) will have the appropriate tools for final radio resource management, spectrum monitoring etc. The spectrum controller will have access to the information on the spectrum usage rules (e.g., information on LSA spectrum, on license-exempt spectrum, on the co-primary spectrum etc.), and will have the opportunity to discover other systems through the monitoring functions. More details of these functionalities can be found in the METIS deliverables.

Both of these two aspects, i.e. regulatory and operational, have been jointly presented in the concise form as shown in Figure 4-4. Please note that this approach is an exemplification of the more generic concept of advanced spectrum management systems developed widely in the context of cognitive radio, and particularly of the policy-based spectrum management and radio environment maps (REMs), which will be discussed later in this section.

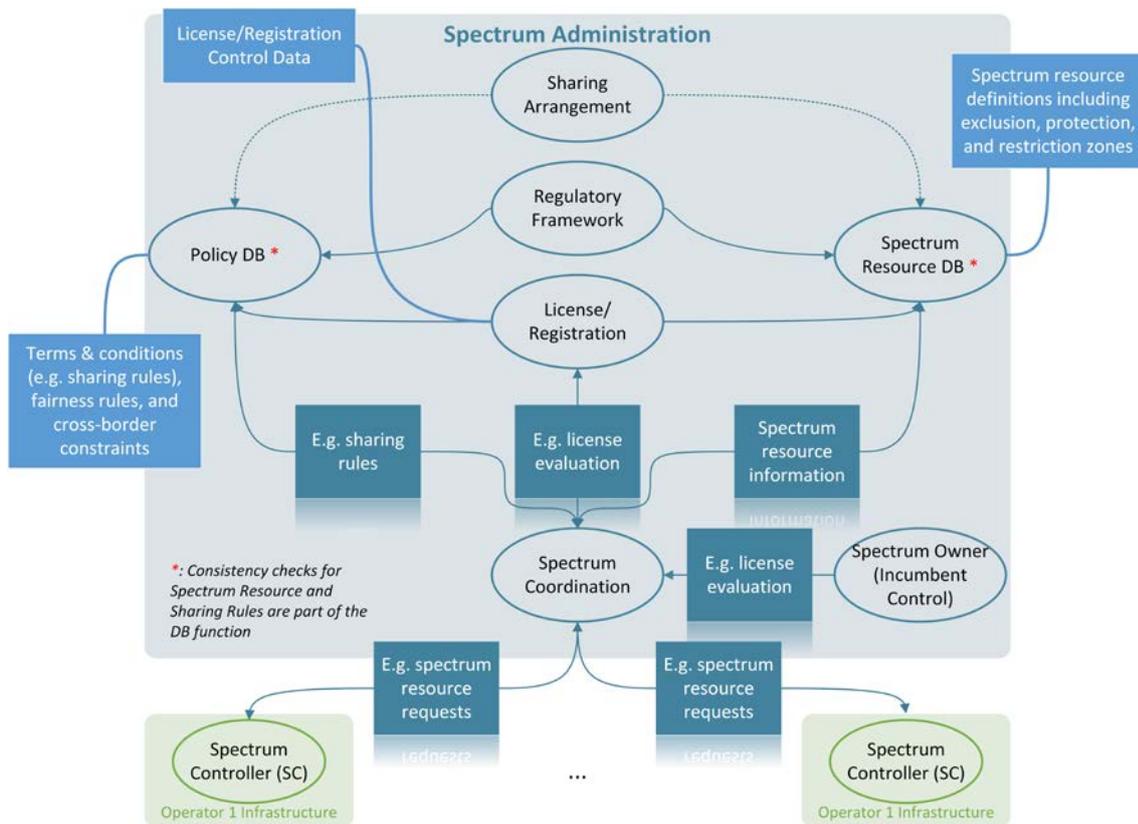


Figure 4-2. Functional architecture - regulatory aspects (based on Figure 2-5 from [METIS_2015_2])

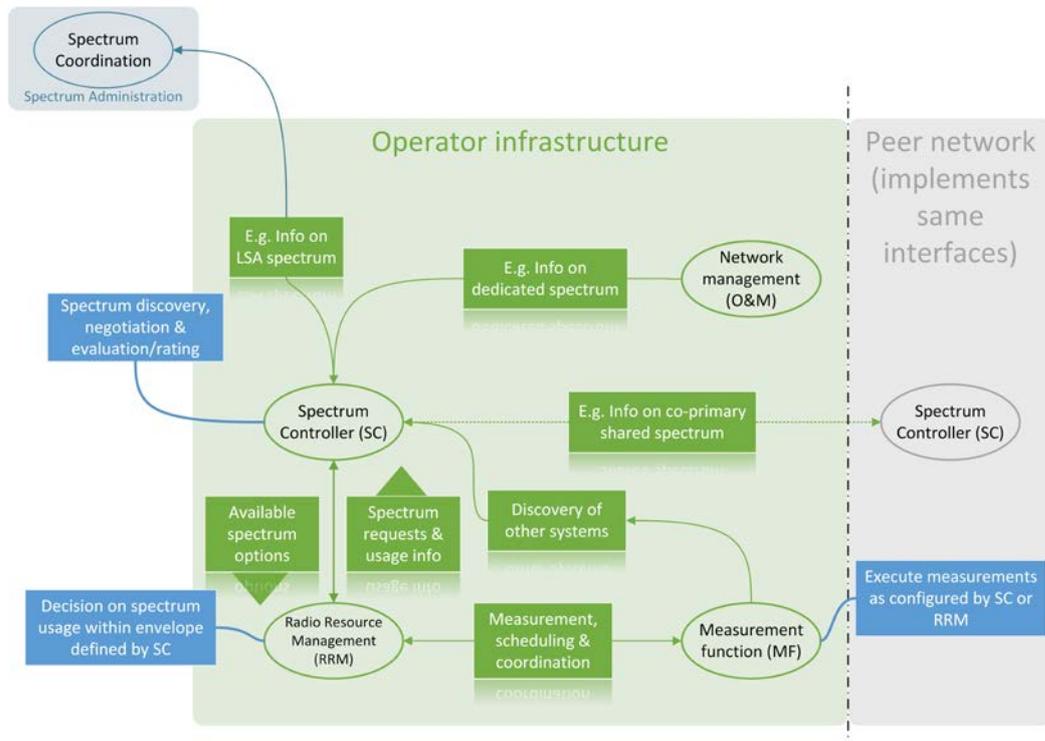


Figure 4-3. Functional architecture - operational aspects (based on Figure 2-6 from [METIS_2015_2])

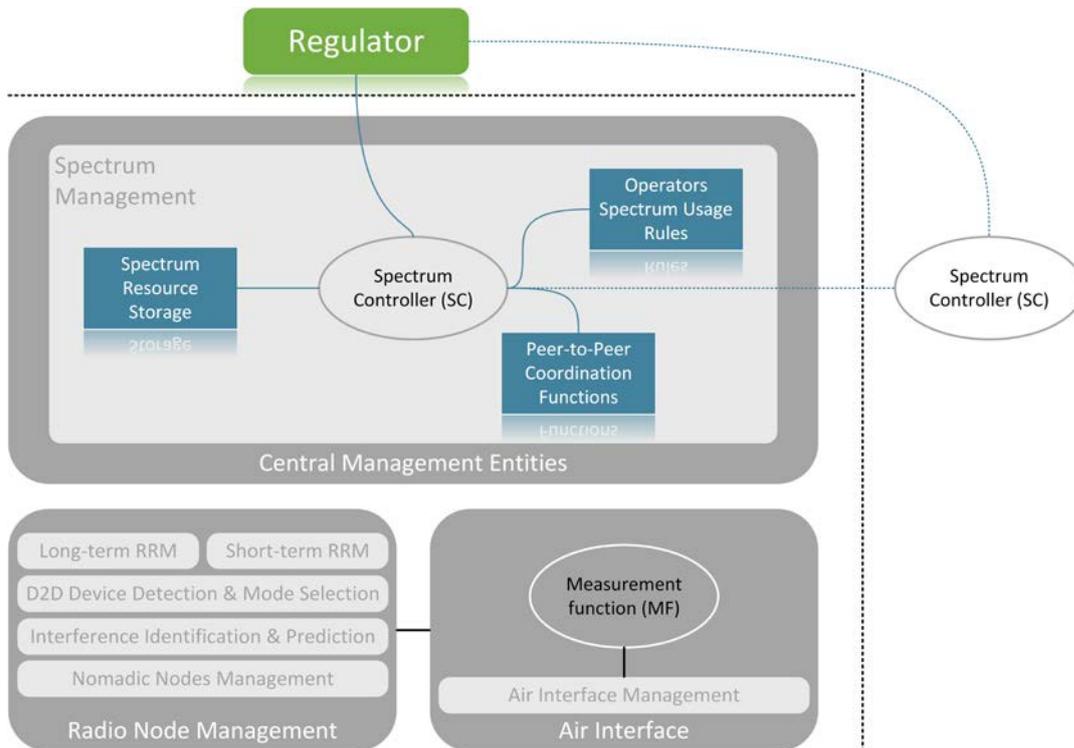


Figure 4-4. A Generic METIS View on the spectrum management system (based on Figure 3-1 from [METIS_2015_2])

4.1.2. Radio Environment Maps and Cognitive Radio

A Radio Environment Map (REM) is in principle the ensemble of advanced database and storage devices administered by a dedicated management system [Yilmaz_2013],

[Beek_2012], [Romero_2015]. The functional architecture of the REM concept is shown in Figure 4-5. It has four basic building blocks. The distributed measurement module periodically collects radio signal statistics from the region covered by REM. The REM database is a knowledge base storing history of spectrum occupancy information by region, where the granularity of REM depends on the implementation of the measurement module. The REM manager generates and maintains the REM. The control application utilizes the REM information for spectrum management.

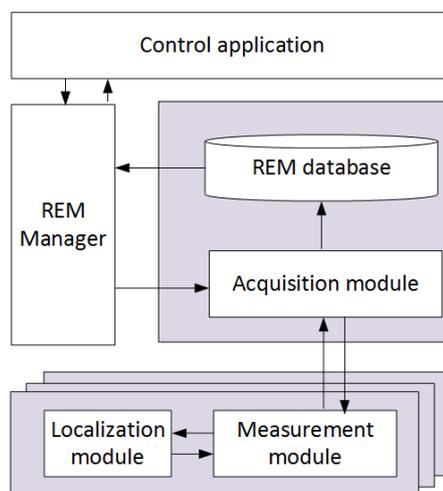


Figure 4-5. Generic REM concept

The REM approach is aligned with the recent concept of Radio Access Network (RAN) virtualization [Liang_2015_1], [Liang_2015_2] in which network functions are separated from the underlying proprietary hardware. Successful implementation of wireless networks virtualization relies on orchestrating storage, database and hardware resources. The role of REM in virtualized 5G networks is to enable efficient spectrum management.

4.2. Considered Spectrum Management Architecture for Virtualized Wireless Networks

One of the key objectives of the COHERENT project is to propose the architecture for efficient virtualization of the 5G systems. Below we provide the description of the considered spectrum management and control framework, where we concentrate on both high level architectural aspects and on the lower level spectrum coordination and monitoring functions.

In our analysis of the spectrum management, coordination and control system we consider three groups of users:

- *spectrum regulators* – such as NRAs, which are responsible for the high level regulation of spectrum management rules, and monitoring of its execution,
- *spectrum usage right holders or licensees* – such as mobile network operator (MNO), or a virtual mobile network operator (VMNO), incumbents, etc. which benefits from usage of the spectrum
- *mobile users (mobile terminals)* – the end users or more generally clients of, e.g., the network operators.

In the context of spectrum management, coordination and control, the last group can be omitted as they only utilize the spectrum assigned to them by the spectrum usage right holder. On the other hand, the main role of spectrum regulators is to provide guidelines for spectrum usage, thus they are key players in spectrum management. Finally, MNOs possess the rights for spectrum control and coordination within bands licensed to them. Clearly, these two roles can overlap, i.e., it is possible

that MNOs will possess their own, local/private spectrum management systems for the whole set of frequencies assigned to them.

Having these observations in mind, as well as the key investigation subject of COHERENT project being the wireless network virtualization, the whole proposed structure can, in general, be divided into three planes: spectrum management system plane (or equivalently spectrum manager application), spectrum control and coordination plane (realized by means of COHERENT central controller and coordinator; in terms of network virtualization this plane corresponds to the spectrum control function) and infrastructure plane (which consists of network graph; please note that the infrastructure plane includes also such physical resources as spectrum). The key idea is illustrated in Figure 4-6.

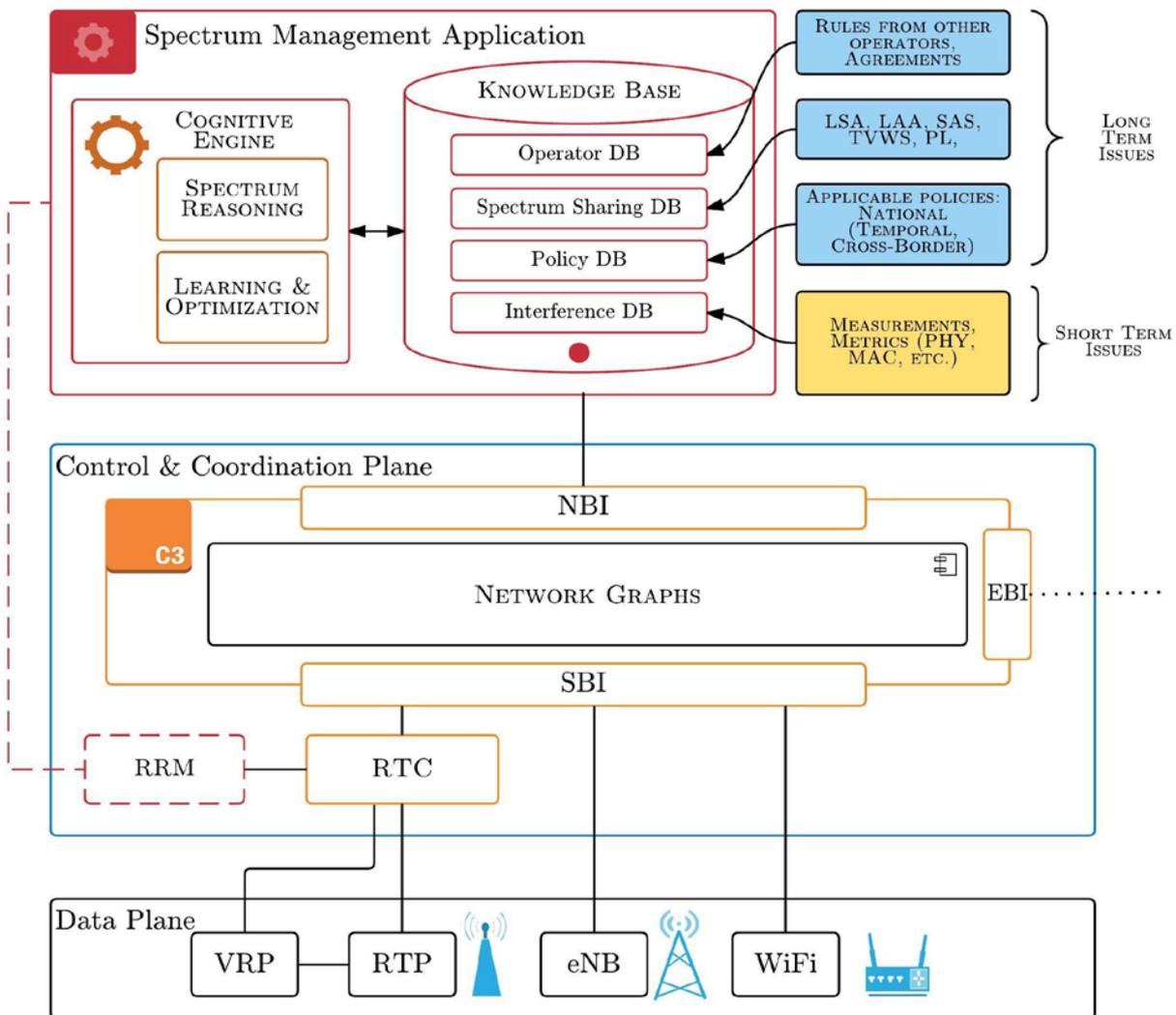


Figure 4-6. COHERENT spectrum management, coordination and control system

4.2.1. COHERENT Control and Coordination Plane

The central control entity in the whole system is the Central Controller and Coordinator (C3). As its name suggests, it is responsible for continuous coordination and control of the spectrum assignment and practical realization of high-level directives obtained from the spectrum manager. In other words, C3 will be responsible for implementation of the whole set of rules provided by the spectrum manager (for example guidelines on the spectrum sharing rules at certain frequency band) in the real network. The interface between the spectrum management application and the coordination functions will be called Northbound Interface (NBI), as only

the high level messages will be exchanged between these two planes. Next, the interface between the real network (abstracted in the form of a network graph) and the C3 entity will be called Southbound Interface, as highly detailed information will be exchanged. Please note that we envisage that real time control, including for example radio resource management is a part of the C3.

4.2.2. Spectrum Management Plane (Spectrum Management Application)

Beside the C3 component, one can observe the presence of the spectrum reasoning, enforcing and optimization entity, which can be treated as the spectrum management engine, a dedicated entity responsible for management of long-term decisions (e.g., evaluation of the LSA rules between the operators, queries the databases managed by the NRA for the spectrum usage rules). It is also responsible for processing of various queries originated from C3. For example, an MNO C3 entity can identify that more spectrum would be necessary in a given location, and such a request will be processed in the spectrum management plane.

It is further envisaged that the spectrum management engine will have access to the set of various databases such as LSA database, radio-environment map databases, policy repositories, or open databases. These databases can be updated at any time either manually by the dedicated administrators (such as NRA representatives, MNO license managers etc.), or in an automated manner by dedicated monitoring modules (for example entries in the interference maps can be monitored permanently and updated periodically by dedicated sensors). In order to allow such functionality a set of standardised interfaces for database/repository access has to be defined.

Besides databases, the spectrum management engine should have access to dedicated storage modules in order to cache some sensitive and frequently accessed data, or to store long-term trends or statistics, e.g., in spectrum use to enhance spectrum assignments in the future. Finally, the definition of the dedicated protocols for communications with external databases (such as WiFi Passpoint databases accessed through the Access Network Query Protocol (ANQP)) and with other spectrum managers is required.

4.2.3. Infrastructure Plane

Data transmission always takes place over the physically available communications medium (i.e., frequency spectrum) and utilizing the really deployed infrastructure (such as base stations, remote radio heads, access points). Implementation of virtualisation concept bases on the abstraction of the physical network and assumes the unequivocal mapping between the logical (abstracted) unites/entities and the physical hardware. In the COHERENT project we consider the network abstraction by means of the network graphs. Therefore, there is also a need to define all elements of the so-called *hardware abstraction layer*, if we apply the analogy to computer science terminology.

4.2.4. Network graphs

Although managed in a softwarised and virtualised way, spectrum has to be understood finally as the physical resources which are used to carry user or control data in the physically deployed wireless network. In order to allow the C3 for an efficient implementation of the spectrum sharing rules defined by the spectrum manager, we propose to apply the network graph theory. A COHERENT network graph is an abstract representation of the physical network and the wireless links, and it is an integral part of C3 entity. The abstraction processes and the resultant network graphs can be quite diverse depending upon the level of details that are captured from the physical network. Once created, such a network graph can be further used by the C3 entity for optimisation of spectrum resource utilization. As the network graphs concept is applied within the COHERENT project for various purposes, we will call the graphs used for spectrum management *spectrum-network-graphs*. These graphs will constitute the connection between the spectrum coordination and control plane and the

physical network of a certain operator. It will then reflect in an abstracted way how the spectrum resources are assigned to particular nodes and how these resources can be flexibly used for better utilisation.

4.2.5. Virtualization Aspects

The concepts and associated benefits put forward by Software Defined Networking (SDN) and Network Function Virtualisation (NFV) will be an important feature of 5G networks.

Virtualisation is a fundamental concept in SDN/NFV and it is evident that many legacy network functions together with their management and control have to be addressed in this new SDN/NFV scope. As SDN/NFV requires the introduction of new management and orchestration functions, the concepts behind spectrum management and the utilisation of different types of information databases have to be revisited as well. Spectrum management functions together with associated concepts of REM and policy databases have to be made compatible to the new management and orchestration concepts that are applied in the SDN and NFV technology domain. Although practical differences may remain, the COHERENT network architecture does have many similarities to the SDN/NFV concepts. One main similarity is the provision of RAN control in the software-domain which requires the abstraction of the underlying heterogeneous networks through a virtualization layer. Figure 4-6 shows a simplified SDN-enabled architecture for spectrum management and control as considered in COHERENT. The underlying physical networks are virtualized by bringing many network functions into the software domain. The underlying physical network shall most likely be a hybrid of legacy enhanced Node B (eNodeB) and Wi-Fi APs together with new physical radio entities that apply a particular functional split to bring many RAN functions to the software domain. A particular functional split chosen results in some functionality associated with Radio Transmission Points (R-TPs) and the rest with Virtual Radio Processors (VRPs). In COHERENT, these two entities are controlled via Real Time Controller (RTC) which is primarily responsible for radio resource allocation. The C3 is an abstraction and control umbrella that span across an operator's heterogeneous networks and facilitates the optimisation of network functions through software control. It exposes the state of the network to higher level network applications such as the spectrum manager and can then enforce the optimisation decisions on to the physical network through software control. Although spectrum manager sits on top of the hierarchy in the COHERENT architecture, its presence at a lower level is ensured though an interface with local (e.g. cell-specific) Radio Resource Management (RRM) function. This is to acknowledge that certain spectrum management and sharing decisions make more sense when considered in a small geographical scope (e.g. D2D communication). In such cases, the spectrum manager application can make decision to which the RRM and RTC comply in a particular segment of the wireless network.

4.3. Ownership Issues

4.3.1. Spectrum Management Plane

In our previous discussion, we focused on the functional split of the whole spectrum management and coordination system and identified three separate planes. However, it is not so straight-forward who will be responsible for the maintenance and creation of the whole management system. First, the generic rules for spectrum management defined by NRA are obligatory for any stakeholder interested to use of frequency resources. On the other hand, the same stakeholder can sign mutual agreements to define specific rules for joint (also flexible) spectrum usage.

In the simplest situation where there will be a dedicated legal entity (company etc.) who will deliver spectrum related information and services to interested stakeholders. For example, mobile network operators can acquire an external spectrum management system (under possession of this legal entity) for the current guidelines for spectrum sharing or spectrum

occupancy metrics. The spectrum management system will be a dedicated space for storing generic rules (which should be dynamic in the context of 5G networks). This spectrum management system can be treated as an external unit with open access policies (in such a case it will be managed by the administration representatives).

However, as already indicated, various stakeholders can sign agreements to define the details of the spectrum sharing. For example, rules for the LSA or for infrastructure sharing can be defined. In that context, each stakeholder should create. A dedicated interface and protocol is needed to enable information exchange between the external and internal spectrum management modules.

Both external and internal spectrum management systems, will contain the functional blocks described in the previous section: spectrum management engine, databases and repositories, and monitoring modules for permanent control of the spectrum usage. Information delivery to and from the system will be done through dedicated standardised interfaces.

Finally, one can imagine that there exists a potential business niche for the companies that deliver a specific functionality for the stakeholders, e.g., mobile network operators. Operators could use cloud services for database management or benefit from a network of spectrum sensors deployed and managed by a separate entity.

The whole structure of the ownership of the spectrum management system is illustrated in **Figure 4-7**, which corresponds to the spectrum management plane from Figure 4-6).

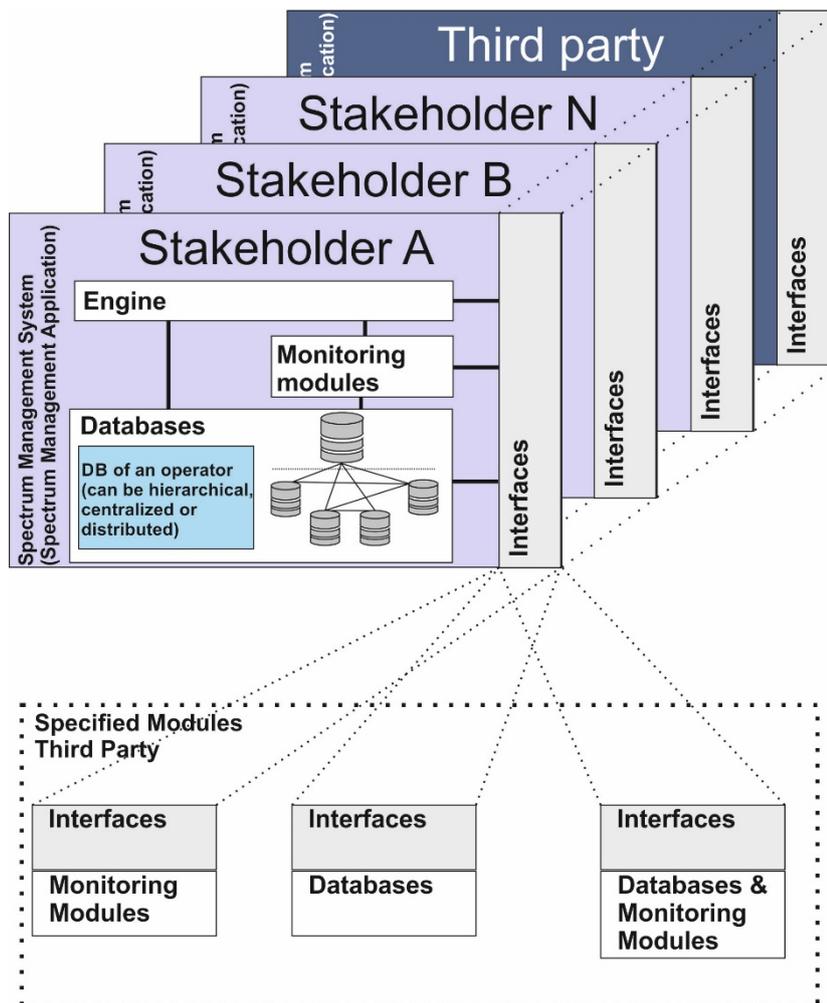


Figure 4-7. The generic ownership structure of the spectrum management system

4.3.2. Coordination and Control Plane

Let us now focus our analysis on the central controller and coordinator. First, one may observe that the C3 module is centralised and independent in the sense that it possesses full knowledge on a certain geographical area. It will have access to the detailed network graphs that reflect various states and features of the physical wireless communication network. Such knowledge will result in efficient network optimisation performed by the controller. However, it is not practically possible or even necessary to have a full knowledge on everything gathered in the network. The optimisation process of the wireless network in the ultra-dense urban area will not benefit from information about the network parts located far away from the considered area. As a consequence, there will be more C3 controllers, each of them responsible for control of the specific geographical area. This entails the need for dedicated interface for information exchange between the controllers.

In other words, one may think on C3 as logically centralised entity, which is composed of multiple physically distributed C3 control instances in the networks. Each C3 instance collects regional network information and share it with other C3 instances. Therefore, other C3 instance has the network states of the other C3 instances and thus it is called logically centralised. The interface for C3 instances to communicate is called east-west interface.

Theoretically, one can also imagine that the coordinator and controller could possess the information about every network deployed in the considered area. In such an *area-centric* approach the coordination and control mechanisms will be treated as shared functionality among operators (see Figure 4-8). In other words, all operators will share their information on network graphs in order to provide better optimization of the network. However, although theoretically possible, applicability in practice depends on the willingness of an operator to share sensitive information about its clients. Thus, in our further discussion we concentrate on the *operator-and-area-centric* approach, as shown in Figure 4-9. In this solution, every operator is in possession of its own C3 module which optimizes their network based on the available network graphs. As the application of spectrum sharing algorithms assumes the cooperation between multiple (at least two) operators, the cooperating operators will interchange some information about their own network graph in order to optimize the spectrum usage. For example, once the controller of one operator makes a decision on the spectrum usage in certain area, it will inform the controller of neighbouring operators about its decision. This will cause an update of network graphs managed by all operators. It means that there is a need for a definition of inter-controller interface for exchange of spectrum-usage information.

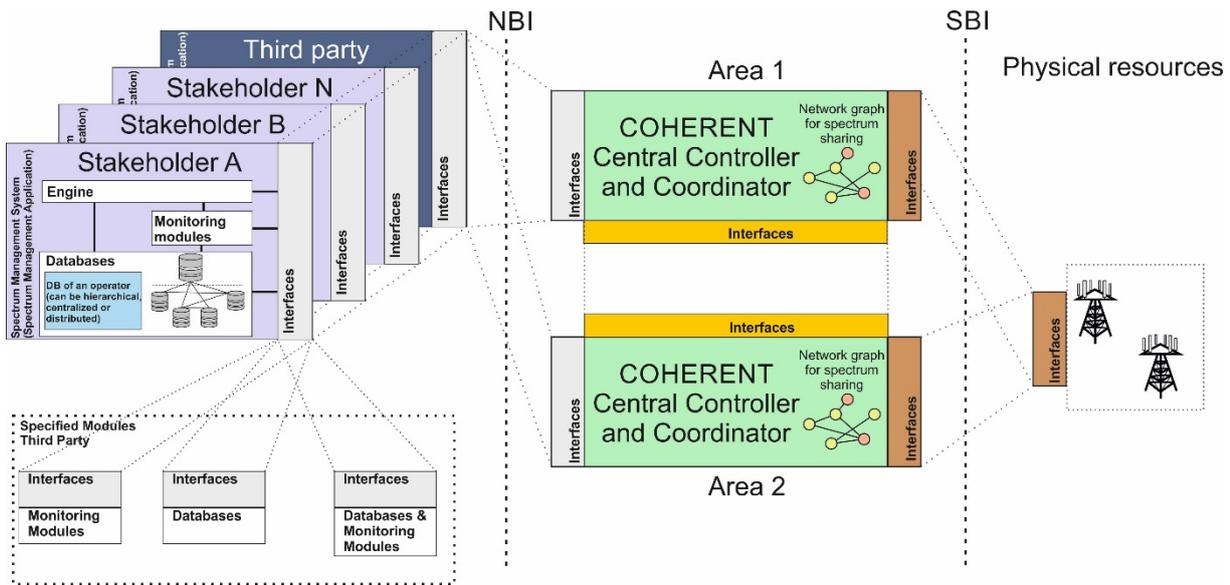


Figure 4-8. COHERENT spectrum, coordination and control system – area-centric position of the C3 module

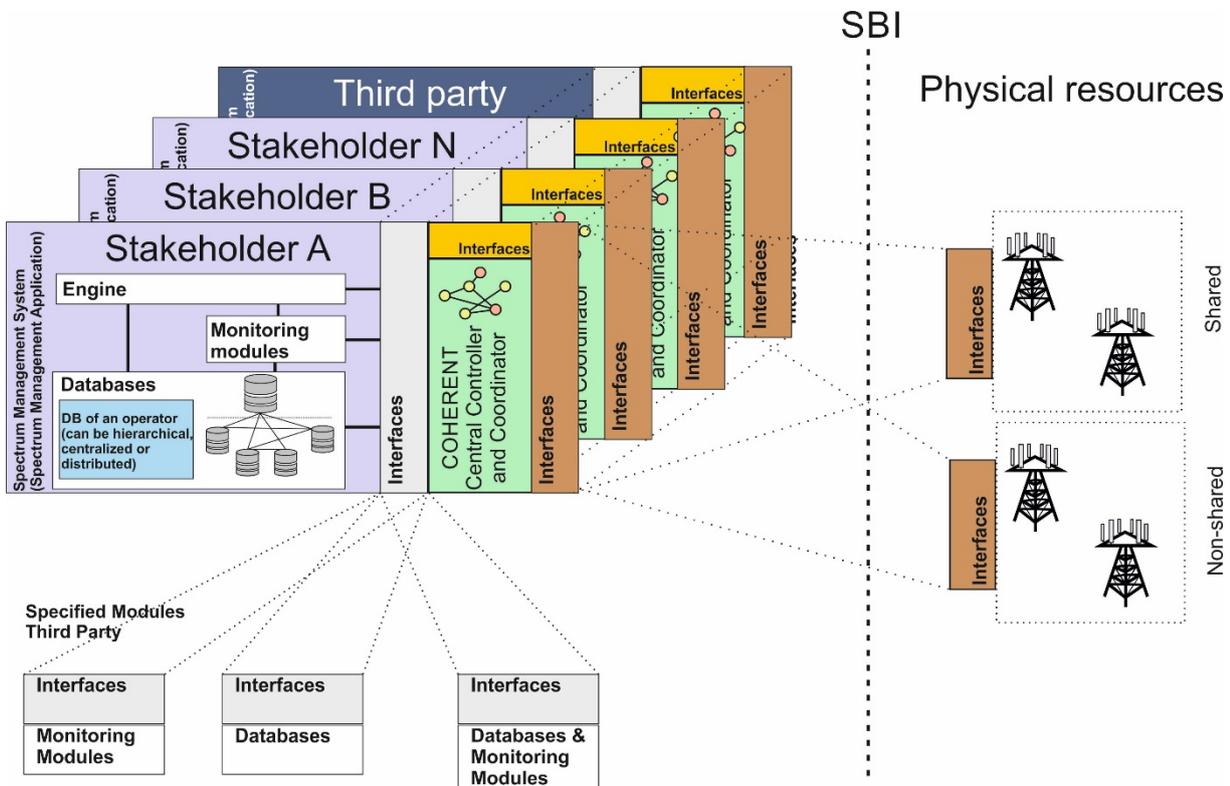


Figure 4-9 COHERENT spectrum, coordination and control system – operator and area-centric position of the C3

4.4. Prospective Interfaces

In terms of spectrum management, coordination and control mechanism, the COHERENT Central Controller and Coordinator should exchange messages between other parts of the system using the following interfaces (graphically presented in Figure 4-10):

- a. Northbound interface (NBI) or C3-SM – which connects the C3 module of a stakeholder with the spectrum management system of the same stakeholder; this interface is denoted with grey colour in Figure 4-10
 - b. Southbound Interface (SBI) or C3-PR – which connects the C3 module with the physical resources of the same stakeholder or dedicated infrastructure provider; this interface is represented as light brown rectangle in Figure 4-9
- Eastbound Interface (EBI) or C3-C3 interface – which connects the C3 modules belonging to different stakeholders; this interface is denoted as yellow rectangle in Figure 4-9. Moreover, the Spectrum Management Systems belonging to various owners (operators, third parties etc.) should be able to exchange information between themselves. This communication can be realized via the dedicated SM-SM interface. Depending on the realization, C3-C3 interface can be merged logically with the SM-SM interface creating broader EBI.
 - One may observe the presence of SM-NRA interface (denoted this using dotted lines), which reflects the way how the stakeholders communicate with the NRA or other legal bodies.

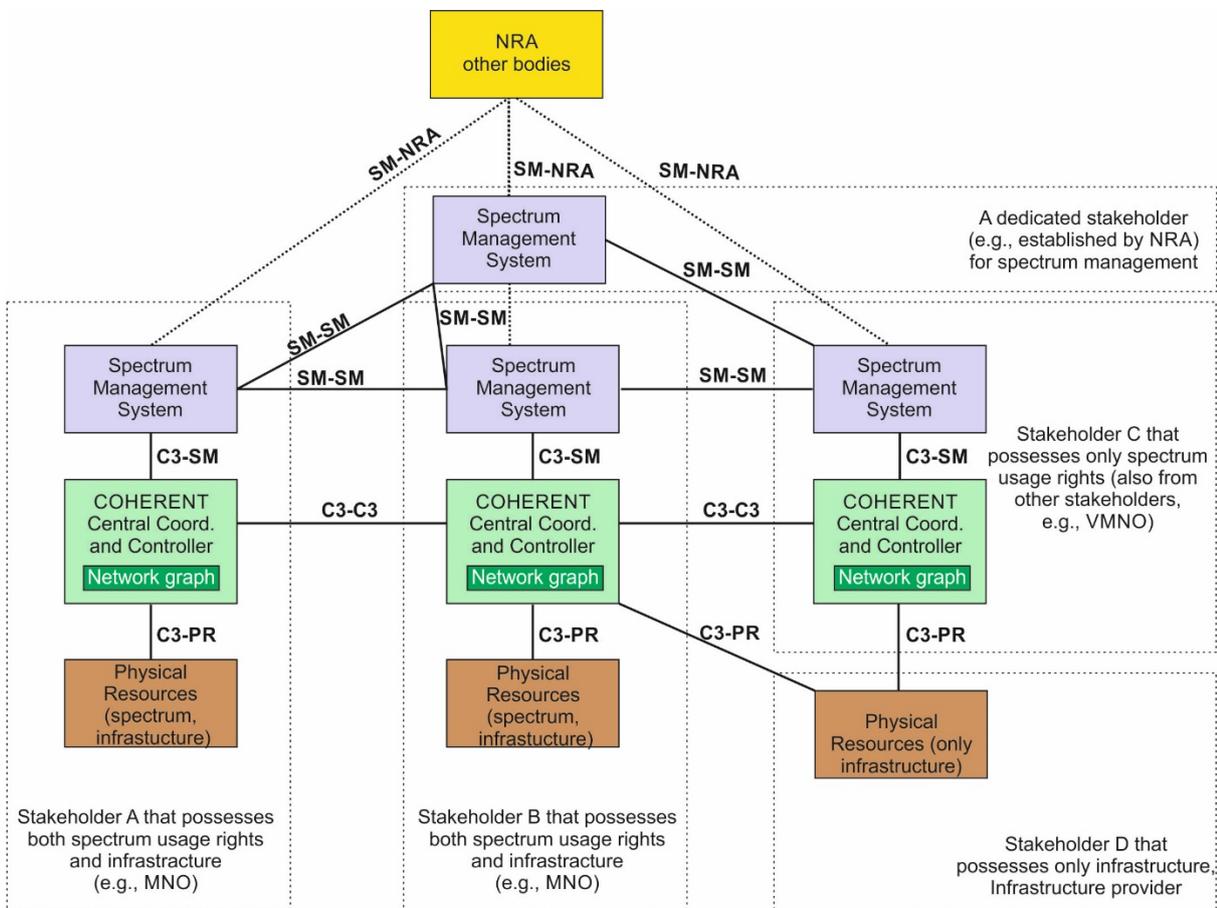


Figure 4-10. Identification of new interfaces for COHERENT Spectrum Management, Coordination and Control System

4.5. Network Graph Definition for Spectrum Sharing

Having in mind the generic structure of the spectrum management, coordination and control system, as well as the identified roles of each plane, we can now focus our discussion on the network graph definition and high- and low-level network abstraction. The generic initial idea is presented in Figure

4-11, where the base stations of two mobile network operators are deployed over certain geographical area jointly with some WiFi Access Points. The network by first operator is depicted by means of solid hexagons, and its base stations are denoted as BS 1.x, where x stands for the number of base station. Analogously, the network by second operator is represented by means of dashed hexagons with the vertices described as BS 2.x.

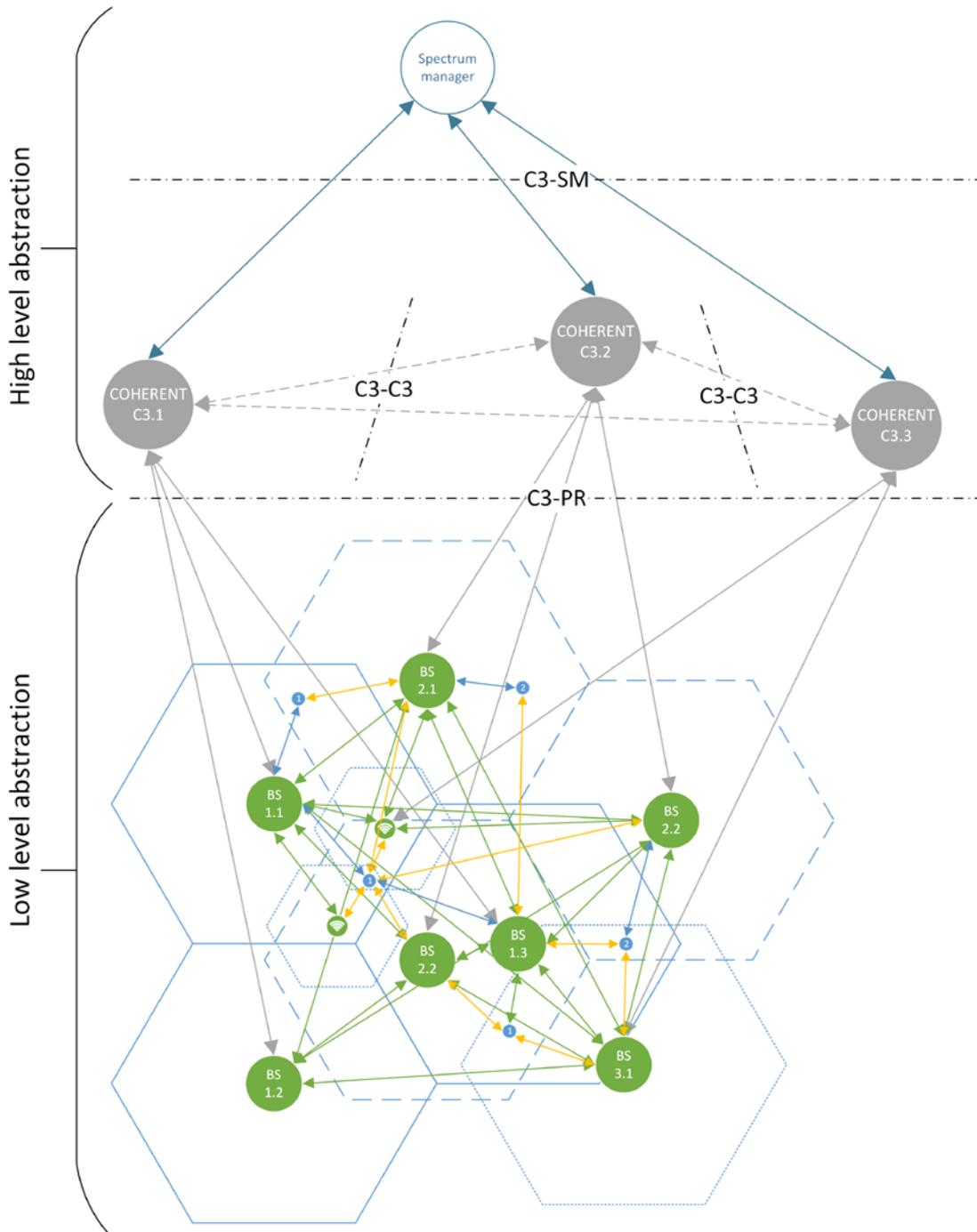


Figure 4-11. Illustration of the network graphs for spectrum management, coordination and control system

One may observe the presence of already discussed elements, such as Spectrum Management plane, coordination and control plane (where the controllers are managed by the certain operator are denoted as local controllers, C3.x) and the set of network graphs. For simplicity we show only one Spectrum Management System which is connected to the network of controllers (let us remind that the Spectrum Manager can be either centralized, distributed or realized even using cloud-mechanism),

and each controller manages a certain fragment of the whole network abstracted in the low-level by means of the spectrum network graph. In that network graph, shown in Figure 4-11, the base stations (or access points, Remote Radio Heads etc.) are denoted by means of green circles, whereas mobile terminals are depicted as blue circles. In the example shown in the figure there are several base stations managed by various operators (denoted as BSs) and some WiFi Access Points deployed over the certain area. Moreover, there are several mobile terminals assigned proprietarily to their operators (the numbers inside the blue nodes represent the corresponding operator).

These vertexes (green and blue nodes) are mutually connected by means of three-color edges: blue, green, and yellow. The metrics assigned to each edge characterizes the connection between the two connected nodes and will be used by the C3 entity for network optimization (in our context for spectrum usage). Referring to spectrum sharing, coordination and control we have identified three logically separated network subgraphs, which may be further merged:

- First subgraph created by blue edges represents an operator (e.g., BS 1) and its clients. For example, the edge between the blue node with number 1 and the green node BS. 1; the metric assigned to this edge can represent the cost of utilizing certain frequency resource when the client 1 is assigned to base station BS 1.
- Second subgraph created by yellow edges defines any relation between the clients of one operator and the base stations (access points etc.) of other operators. Clearly, subgraphs blue and yellow can be easily merged.
- Third subgraph, made of green vertexes and green edges, defines the rules how the operators can share the spectrum among them.

4.5.1. Definition of Edge Metrics, Time Relation and Association with Frequency Bands

The key aspect here is to precisely define the metrics which will be associated with the network edges. First let us observe that the metrics can reflect either existing state of the network, or can provide information on the potential usage of that edge in the prospective applications. In the former case the blue or yellow edges can contain information about the number of requested or already assigned resource blocks, allowed transmit power, traffic type, impact of that link to the overall interference etc. In the second case, the edge will provide information on the prospective cost of usage that link. In order to capture this case, we propose to assign to each edge two tuples of metrics which will reflect the current and prospective states of the network.

Additionally, in the context of spectrum sharing and possible utilization of several frequency bands for data transmission, each edge has to contain information about each allowed frequency band for that link. For example, if the mobile terminal 1 is allowed to use frequency band A, B and C if it is connected to Op.1, or bands E and F if it is connected to Op. 2, then all these cases have to be reflected in the edges. Again, we propose to assign the set of tuples that will illustrate the current and prospective situation on each possible frequency band.

Finally, the proposed format of the set of tuples would be:

- (Band 1, Metrics 1-N, current state) – (Band 1, Metrics 1-N, prospective state)
- (Band 2, Metrics 1-N, current state) – (Band 2, Metrics 1-N, prospective state)
- (Band N, Metrics 1-N, current state) – (Band N, Metrics 1-N, prospective state)

For example, if the network graph will contain information about the load and interference observed currently in band 2.3 GHz and possibly in the future, the tuples will look as follow:

$$(2.3-2.4 \text{ GHz, Load, 2 Mbps}) - (2.3-2.4 \text{ GHz, Load, 3 Mbps})$$

(2.3-2.4 GHz, Interference power, -70 dBm/8MHz) – (2.3-2.4 GHz, Load, -60 dBm/8MHz)

In this example the current load on the particular network edge is 2 Mbps but it can be increased to 3Mbps without violating any constraints; at the same time the interference will increase from -70 to -60 dBm per each 8 MHz band.

The exemplary metrics assigned to the particular subgraphs could be the following:

- Blue and yellow subgraphs: the edges could be associated with the information about the intra- and inter-operator spectrum utilization (such as number of resource blocks, interference induced to other users etc.)
- Green subgraph – will contain information about the rules how the operators can share frequency resources among themselves.

Note that the network graph discussed above is almost direct representation of the existing or future state of the network; the key research goal now would be in the abstraction of this network graph that will be optimized for virtualization and consecutive network optimization. This could be done in various ways and is subject of further investigation.

4.5.2. Network Graph Definition for Spectrum Sharing – Specific Use Case

In this section we graphically represent the whole spectrum management, coordination and control system for the specific use case when one mobile user (blue node) would like to transmit some data and is allowed to use either a regular link, a link with LSA or a link with LAA approach. The exemplary sets of information assigned to each edge (and reflecting existing state) are shown in the Figure 4-12. In this particular case we consider one mobile user which can apply one of the spectrum sharing methods for efficient data delivery. In our example we have selected a very specific case, where the control data will be transmitted using the LAA strategy and user data can be transmitted using the LSA method. Moreover, the regular LTE link will be used for delivery of some information about a state of the network, about a relation between operators etc. Thus, we can assume that Operator 1 and Operator 2 share the spectrum using LSA strategy; in consequence, both operators know the rules of spectrum sharing, e.g., the maximum transmit power (in mW or dBm) which can be applied, the required spectrum mask, the maximum level of interferences (using normalized metrics) which can be induced to neighbouring system, possible bands for spectrum sharing etc. The similar information can be identified for other spectrum sharing strategies (e.g., for LAA). In general, such kind of information is associated with the green edges, which usually contain the boundary (minimum or maximum) values and the parameters which are used for transmission cannot violate them. The sub-network created by green edges and base stations (as vertexes) defines the rules for spectrum sharing between the operators.

On the other hand, the current parameters used for transmission and related to the applied spectrum sharing strategy are associated with the yellow edges. Please note that this subgraph the nodes represent both base stations and mobile terminal. For example, the yellow edges contain the level of interference observed by other operators (or amount of interference induced by the mobile terminal associated to one operator to other operator) due to spectrum sharing.

The last set of information covers data about the regular transmission (i.e., with no spectrum sharing) between the mobile terminal and its home mobile network associated with it. For example, it can be the interference raise in the neighbouring cells due to the start of new data transmission by this mobile terminal. The subgraph that is used to represent this kind of data is created by blue edged and vertexes representing mobile terminals and base stations.

Please note that for the sake of clarity of Figure 4-12 we have intentionally shown only some fragments of the three types of network graphs.

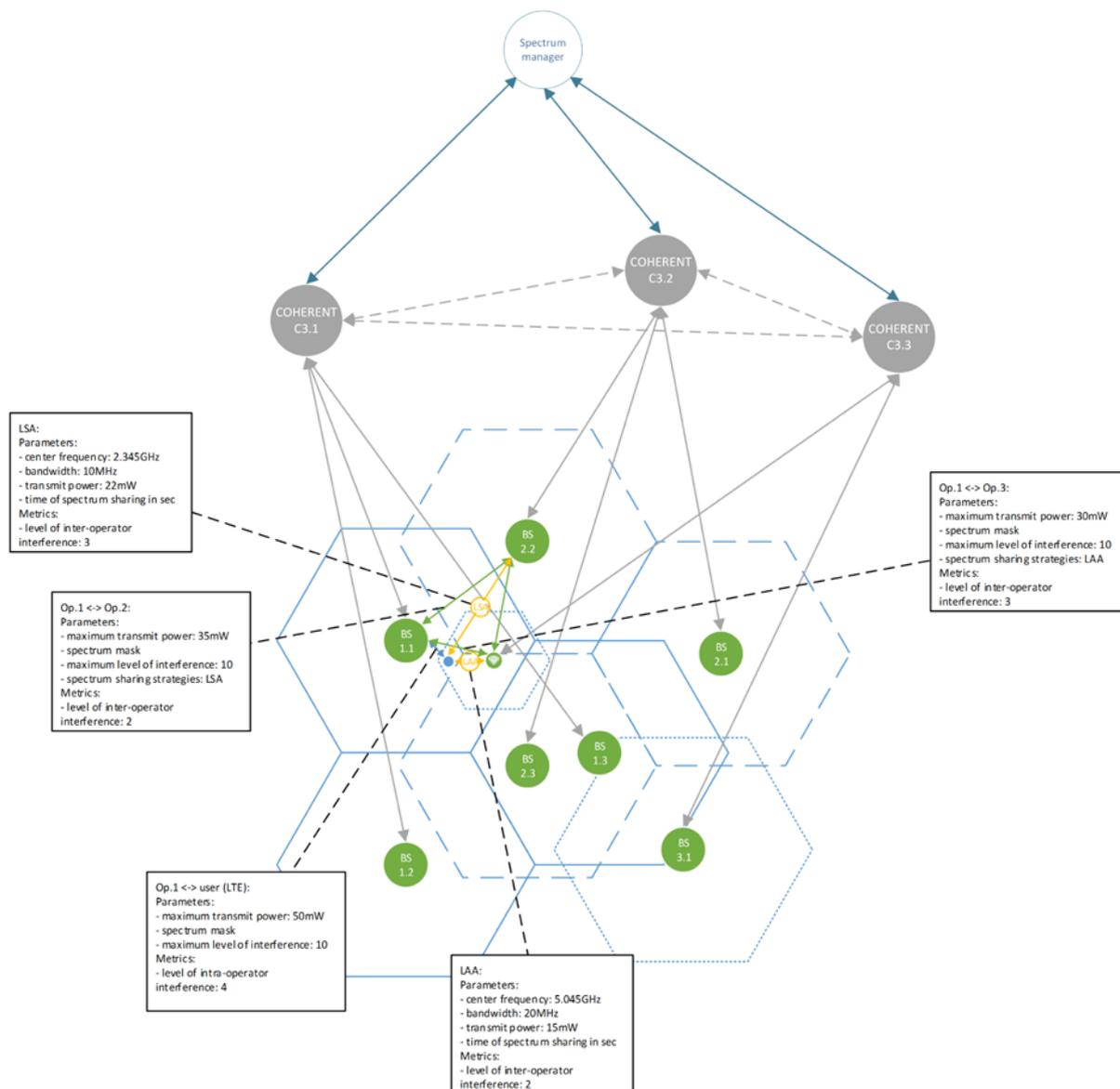


Figure 4-12. Illustration of the network graphs for spectrum management, coordination and control system for a specific use case

4.6. Required functionalities

The ETSI standard TS 103 154 [ETSI_2014_2] defines the functionalities for the LSA system operating in 2.3 GHz band. The list of functionalities and requirements presented in that standard is comprehensive and it covers most of the important aspects from the LSA perspective. Below, we first generalize these LSA functionalities and requirements to any potential spectrum sharing scheme. Finally, we present a dedicated *importance* matrix that indicates the levels of importance of each functionality when referred to the identified spectrum sharing strategies presented in Chapter 2. These identified functionalities and requirements characterize the COHERENT spectrum management, coordination and control system.

General Functional Requirements (GFR):

- Spectrum Resource Sharing (GFR1)

The Spectrum Management System shall support flexible spectrum management and spectrum/infrastructure sharing in various cases (both horizontal, vertical, mix etc.).

Various stakeholders can be involved in the spectrum sharing, for example, in LSA case one there are incumbents and LSA licensees, whereas co-primary sharing involves two mobile network operators, for example.

- Quality of Service (GFR2)

The system shall support provision of agreed Quality of Service (or even Service Level Agreement) to each involved stakeholder.

- Information Exchange between Stakeholders (GFR3)

Involved stakeholders shall be facilitated to exchange information between each other in order to effectively manage the spectrum (e.g., via monitoring of the current status of the spectrum usage etc.)

- Multiple Stakeholders Support (GFR4)

The system shall support the co-existence of many stakeholders (e.g., incumbents, licensees, equal-right MNOs etc.)

- Sharing Framework Support (GFR5)

The overall system shall support the national solutions and regulations related to spectrum.

- Confidentiality of Spectrum Resource Information (GFR6)

Various mechanisms shall be implemented to ensure required level of confidentiality between the stakeholders. These will be different for various spectrum sharing strategies.

- Provision of Failure Indication (GFR7)

Practical implementation of a flexible spectrum management system relies on immediate and accurate detection of any potential failures in spectrum usage, as this will lead to interference issues. The spectrum sharing system has to support this functionality.

- System Data Storage Function (GFR8)

The whole spectrum management system should support access to the information required for efficient implementation of the agreed spectrum sharing strategy between the interested stakeholders. Such access will be granted by supporting entry, storage and modification of the above-mentioned information.

- System Reporting Function (GFR9)

Monitoring of spectrum resource utilization among various stakeholders should lead to periodic (or in broader aspect – scheduled) or on-demand report generation. Various forms of these reports shall be possible, i.e., prepared in a human-understandable form, or tailored to the needs of specific entities of the system.

- Support of Scheduled Operation (GFR10)

The spectrum sharing system shall support realization of any scheduled actions among interested stakeholders.

- Support of On-Demand Operation (GFR11)

The spectrum sharing system shall support realization of any allowed on-demand actions.

- Support for Pre-Configuration (GFR12)

The Spectrum Management System shall support the pre-configuration of the spectrum resource usage among stakeholders based on the limited set of predefined protection requirements for each interested stakeholder. Such pre-configuration can be applied to the whole or part of specified spectrum band or can be defined to the specific geographical area.

- Verification of Inputs to the Spectrum Management System (GFR13)

The system for flexible spectrum management shall be equipped with a tool for verification of any possible input delivered to the system, e.g., the requirements delivered by one stakeholder can be rejected if they violate other agreements and guidelines.

- System Availability to Stakeholders (GFR14)

Information about the available system shall be accurate and reliable. The system has to guarantee the preventing mechanisms against any malicious attacks or various failures or accidents.

- System Operation in case of Change of Sharing Arrangement or Sharing Framework (GFR15)

The system will be fully flexible if it will allow the (scheduled or immediate) changes of sharing arrangements.

Stakeholder Protection Requirements (SPR)

- Protection of Information of the Stakeholder (SPR1)

The spectrum management system shall protect the sensitive information of the interested stakeholder. Following [ETSI_2014_2] the system shall allow the stakeholder to store a description of the spectrum resources and its availability.

- General Protection of the Stakeholder (SPR2)

The system shall support various mechanisms to ensure the fulfilment of the spectrum usage and protection requirements of any stakeholder by other stakeholders; this is particularly important in the hierarchical spectrum sharing schemes

- Variation of Stakeholder's Usage and Protection Requirements (SPR3)

Stakeholders shall be allowed to change their requirements on spectrum resource usage and protection. The system shall provide this information to any other affected stakeholder. An example could be the change of the requirements by incumbents which influence the licensees, or the change of the spectrum usage plans in co-primary sharing.

- End-to-end Acknowledgment of Operational Changes (SPR4)

In general, the system shall support the opportunity to prove that one of the stakeholders (e.g., the licensee) has implemented required changes in response to the changes initiated by other stakeholder (e.g., incumbent).

- Support of Constraints on Stakeholder's Transmissions (SPR5)

Interested stakeholder shall be allowed to provide the spectrum usage in the form of a set of constraints that have to be fulfilled by other stakeholders interested in the usage of the spectrum resources. These constraints can be, for example, the constraints on the transmit power or radio characteristics, or interference limits observed by interested stakeholder.

Security Requirements (SR)

- Data Integrity (SR1)

The spectrum management system shall provide mechanisms to ensure the integrity of the data stored in the system and the data exchanged between any of the interested stakeholders.

- Data Authenticity (SR2)

The spectrum management system shall provide mechanisms to ensure the authenticity of the data and information stored in the system and the data exchanged between any of the interested stakeholders.

- Data Confidentiality (SR3)

The spectrum management system shall provide mechanisms to protect the data and information stored in the system from unauthorized access.

- Identity management and authentication (SR4)

The spectrum management system shall provide mechanisms to provide identity management and authentication of any interested stakeholder.

- Support of Authorization Profiles (SR5)

The system shall support the creation of dedicated authorization profiles assigned to defined groups or types of stakeholders.

Table 16. Importance of identified functionalities with the reference to selected spectrum sharing strategies (Legend: importance level: H – high, L – low)

Functionality	Sharing Policy							
	LE	SC	LSA	SAS	LAA	PL	TVWS	CoP
GFR1	L	L	H	H	H	H	H	H
GFR2	H	L	H	H	H	H	H	H
GFR3	L	L	H	H	L	H	H	H
GFR4	L	H	H	H	H	H	H	H
GFR5	H	H	H	H	H	H	H	H
GFR6	H	H	H	H	H	H	H	H
GFR7	L	L	H	H	H	H	H	H
GFR8	L	L	H	H	H	H	H	H
GFR9	L	L	H	H	H	H	H	H
GFR10	L	L	H	H	L	H	H	H
GFR11	L	L	H	H	L	H	H	H
GFR12	L	L	H	H	L	H	H	H
GFR13	L	L	H	H	L	H	H	L
GFR14	H	H	H	H	H	H	H	H
GFR15	L	L	H	H	L	H	H	H
SPR1	H	L	H	H	L	H	H	H
SPR2	L	L	H	H	L	H	H	H
SPR3	H	L	H	H	L	H	H	H

Functionality	Sharing Policy							
	LE	SC	LSA	SAS	LAA	PL	TVWS	CoP
SPR4	L	L	H	H	L	H	H	H
SPR5	L	L	H	H	L	H	H	H
SR1	H	H	H	H	H	H	H	H
SR2	H	H	H	H	H	H	H	H
SR3	H	H	H	H	H	H	H	H
SR4	L	L	H	H	L	H	H	H
SR5	L	L	H	H	L	H	H	H

4.7. Information Exchange – Specific Use Cases

In the context of spectrum sharing, we consider a set of operators with a set of base stations and one COHERENT central controller and coordinator (C3). Each C3 manages a group of base stations and spectrum sharing on the particular geographic area. Let us denote the C3 for Operator 1 as C3.1 and the group of base stations for Operator 1 as BS1.x, where x describes the base station number.

4.7.1. Use Case 1

In the first case Operator 1 reports the demand for a new spectrum, which has to be gained from other operators (stakeholders). The information exchange may look as in Figure 4-13

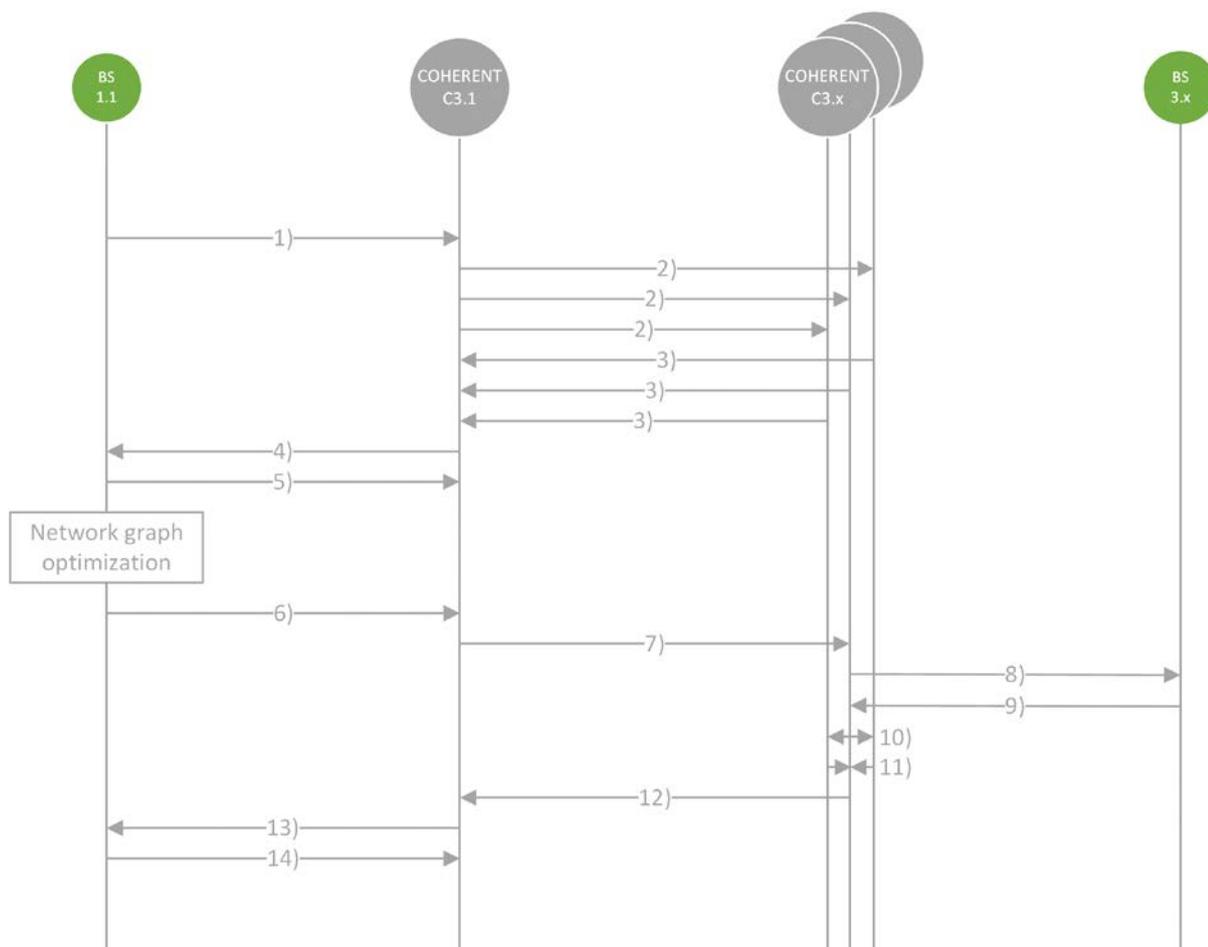


Figure 4-13. Message exchange for use case 1

1. The base station (BS 1.1) reports demand for spectrum, e.g., 20MHz.
2. C3.1 checks its own resources (uses a network graph) and if there is a real need for new resources asks other central controllers (C3.x) about spectrum availability.
3. The C3s (C3.x) responds by sending the parameters of available spectrum.
4. The C3 (C3.1) analyses the received information about available spectrum, utilize and update (if needed) its network graph, and chooses the spectrum and the parameters of transmission for BS 1.1. It informs the BS 1.1 about its decision.
5. The base station (BS1.1) confirms to the C3 (C3.1) the reception of the information about selected spectrum.
6. C3 (C3.1) sends that information to the owner of selected spectrum (e.g. C3.3).
7. C3 (C3.3) informs the base stations (BS 3.x) that the selected spectrum will be occupied.
8. The base stations (BS 3.x) acknowledge.
9. Next the C3 (C3.3) informs other C3s (Cx) that the selected spectrum will be occupied.
10. Other C3s (Cx) acknowledge.
11. (Optional) C3 (C3.3) confirms that the selected spectrum can be used.
12. (Optional) C3 (C3.1) confirms that the selected spectrum can be used.
13. (Optional) The base station (BS 1.1) acknowledges.

4.7.2. Use Case 2

In the second case, Operator 1 requests to release its spectrum which is currently shared with other operators. Message exchange is shown in Figure 4-14.

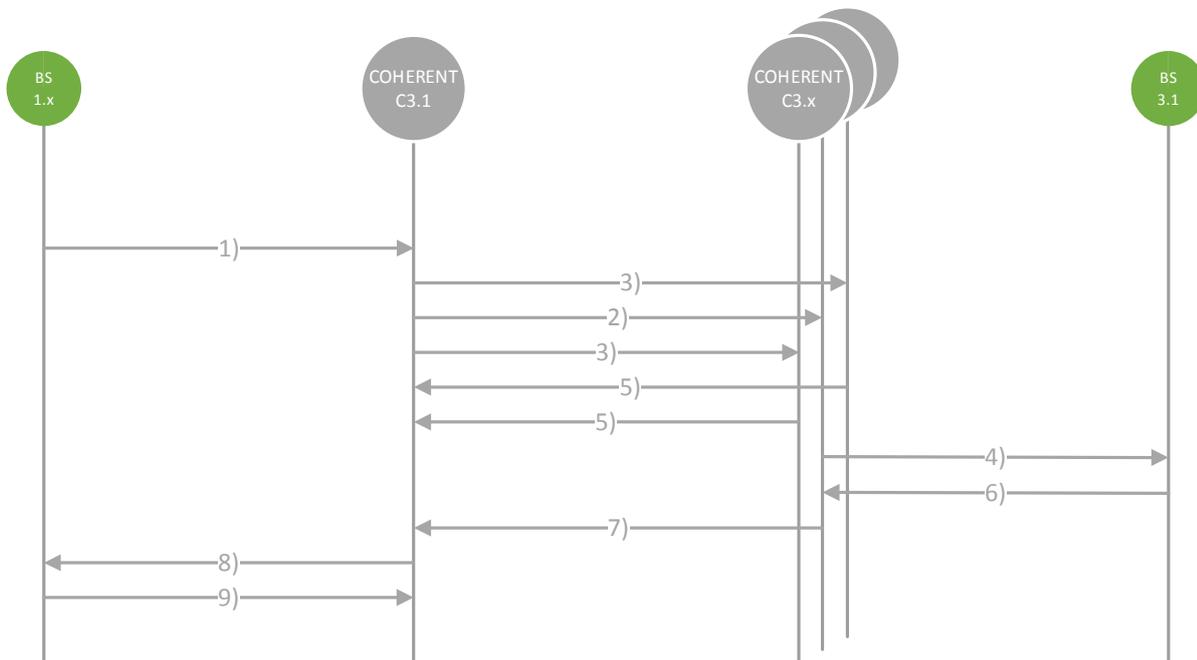


Figure 4-14 Message exchange for use case 2

1. The base stations (BS 1.x) informs its C3 (C3.1) that it needs more spectrum and probably other operators have to release occupied spectrum.
2. C3 utilizes its network graph and validate the request; if no additional spectrum resources can be assigned to BS1.x, this C3 (C3.1) informs other C3s (C3.3) which occupy the spectrum that a specific frequency band has to be released.
3. C3 (C3.1) informs other C3s (C3.x) that the spectrum will be occupied by its users.
4. C3 (C3.3) which occupy the spectrum sends information about releasing spectrum to the base station (BS 3.1).
5. The rest of C3s (C3.x) confirm that the spectrum will be occupied by the users associated logically with to C3.1.
6. The base station (BS 3.1) releases the spectrum and sends information that the spectrum has been released.
7. The C3.3 informs C3.1 that the spectrum has been released and that the spectrum will be occupied by Operator 1.
8. The C3.1 informs the base stations (BS 1.x) that the spectrum has been released.
9. The base station (BS 1.x) acknowledges.

4.7.3. Use Case 3

In the next case Operator 1 releases occupied spectrum (for example, as this is no longer needed or the scheduled leasing period is to be finished soon). Message exchange is shown in Figure 4-15.

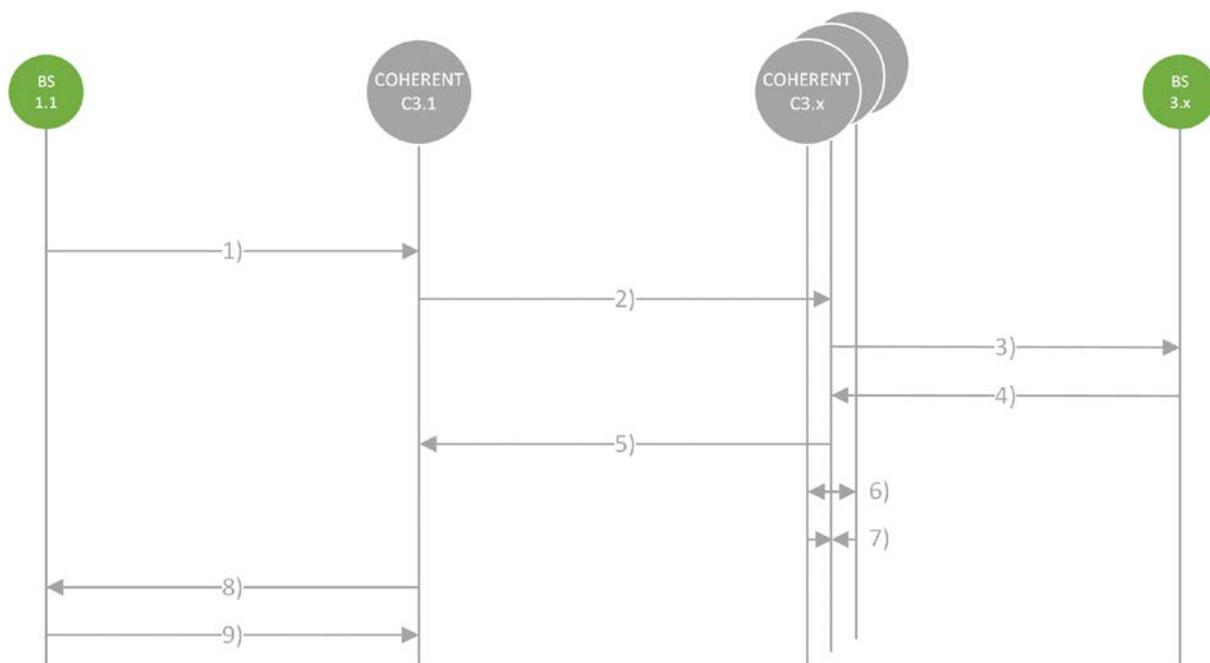


Figure 4-15 Message exchange for use case 3

1. The base station (BS 1.1) informs that the occupied spectrum has been released.
2. C3 (C3.1) sends the information about releasing spectrum to interested C3 (C3.3) whose spectrum was occupied.
3. C3 (C3.3) informs the base stations (BS 3.x) that the spectrum has been released.
4. The base stations (BS 3.x) acknowledge.
5. C3 (C3.3) confirms that the spectrum has been released.
6. C3 (C3.3) sends the information that the spectrum is available to other central controller (C3.x).
7. C3s (C3.x) acknowledge.
8. C3 (C3.1) confirms that the spectrum has been released.
9. The base station (BS 1.1) acknowledges.

5. Use Cases and Scenarios for Spectrum Sharing

In this section we present the identified scenarios and use cases for spectrum sharing in virtualized networks.

5.1. Prospective Scenarios for Spectrum Management, Coordination and Control System

Apart from the common functionality associated with a spectrum manager such as efficient radio spectrum utilization and ensuring compliance with applicable policies and regulations, the COHERENT spectrum manager will also perform several additional functions that mainly stem from heterogeneous networks control, spectrum sharing concepts and the software-defined network abstraction and control architecture. In COHERENT, most of these new functions relate to spectrum management and inter-operator spectrum sharing, however, it is adequate to address them in the context of a particular objectives/use-cases considered for further research. Therefore, this section presents the functionalities of the COHERENT spectrum manager in view of specific objectives considered in WP4.

5.1.1. Micro-area Spectrum Sharing

In this section the high level functionality of COHERENT spectrum manager is provided for micro-area spectrum sharing. In the COHERENT context, micro-area spectrum sharing converges in practice to the flexible duplexing method. Flexible duplexing can be briefly opened as a more flexible way of utilizing the static spectrum allocations for DL and UL with the possibility of exploiting the spare frequency bands or time slots in LTE UL (or DL) for the low power DL (or UL) transmission, depending on the current DL and UL traffic demand which may vary a lot in a very short period of time. A high level illustration of spare macro cell FDD UL band usage for small cell DL transmission is presented in Figure 5-1.

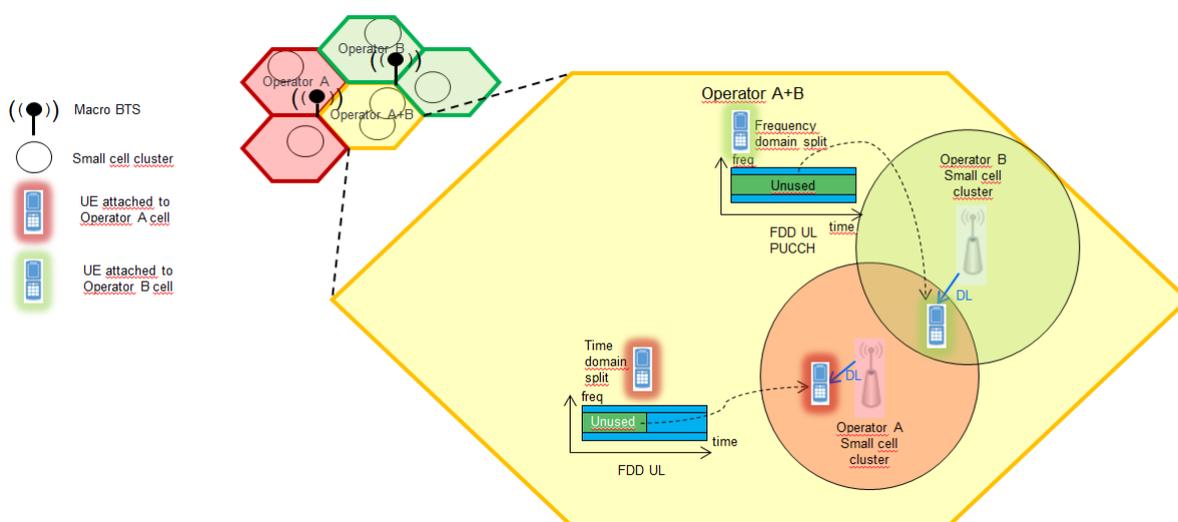


Figure 5-1 Example of flexible duplex usage

The COHERENT spectrum manager should fulfil at least the following mandatory requirements for flexible duplex operation:

1. Monitoring of the network (HMN) status including interference measurement reports, monitoring of spectrum usage (frequency resource utilizations), time resource (subframes) utilizations, data rate and QoS requirements and mobility status

2. Bookkeeping. The following real-time information produced by Monitoring is stored in the databases: flexible duplexing usage and overall spectrum usage. Also long-term data like LSA/SAS usage and its potential conflicts to the flexible duplexing use, policies and regulations (for instance where and on which bands flexible duplexing is possible) as well as rules from other operators should be stored there.
3. Engine, which is responsible of making decisions of flexible duplex usage (turn on/off, reconfigure dynamically), signalling the usage of flexible duplexing towards the lower layers (including the physical HMN) and processing of the information stored in various databases (that can be distributed physically, logically etc.)

5.1.2. Protection of Licensed Users and Agreed Transmissions

In the context of spectrum sharing the protection of licensed users is one of the most important issues. The users who use the shared spectrum have to guarantee a suitable level of Quality of Services (QoS) for both sides. It can be done using exactly specified rules, databases, spectrum masks or interference monitoring systems. One can imagine a situation when some user reports the demand for spectrum. The first thing to do is to let the users check if spectrum is available in the particular geographical area. If there is spectrum available, the users have to still meet all requirements and rules for sharing e.g. maximum transmit power, maximum level of interference, maximum time of spectrum sharing etc. Provided that the users meet the requirements the spectrum can be used, but taking into account that channel conditions or the location of the user can change. Here a monitoring system may be required for ensuring the fulfilment of the requirements. This entity can be realized on the side of the operator which shares the spectrum or on the side of the operator which uses the spectrum, or it can be realized by an external entity. If the requirements are not met the monitor can order the spectrum user to reconfigure the parameters or to cease the spectrum usage.

5.1.3. Management of Urgent Situations

The urgent situations can occur when the incumbent system needs immediately the access to own spectrum. In this case the incumbent system can report the demand for spectrum to each user who use its spectrum or, preferably, it can report to the C3 and wait for the acknowledgement that the spectrum has been released. On the other hand, the high demand for the spectrum can be needed in case of a natural disaster or a terrorist attack. In this case a large number of police officers, medical staff, and fire fighters may cover one location. Thus in order to assure the high quality of communication and the convergence in the required area, the additional resources can be needed. It means that one needs some procedures, systems or entity, e.g., COHERENT Central Controller and Coordinator which allows for the fast allocation of resources and facilitates the coexistence between systems.

5.1.4. Management of User Specific Aspects

Users have different demands for spectrum. One of them needs spectrum for the high quality real-time transmission, another needs spectrum for VoIP services etc. In this case Spectrum Manager or COHERENT C3 should provide the mechanisms for the best spectrum utilization, e.g. optimization methods. On the other hand, some users may also care about energy efficient transmission because the charging level of the battery in the terminal is low. Moreover, terminals have different parameters and capabilities. It means that one of them can use only a specific frequency using e.g. 2G or 3G transmission and another terminal has implemented LTE standards and e.g. it can use more advanced modulation and coding techniques. Thus, it is clear that COHERENT C3 or Spectrum Manager have to provide the mechanisms which allow for the best network performance.

5.1.5. Management of Vertical Handover

In the support for vertical handover COHERENT C3 or Spectrum Manager have to cope with different types of streams and also switching between frequency, e.g., from ISM band to LTE band. It is additionally complicated if the shared spectrum scenario. In this case COHERENT C3 or Spectrum Manager has to know which spectrum on the particular geographical area is available and has to know the rules of spectrum sharing. Moreover, the handover metrics, the handover decision algorithm and handover procedure should be also provided by COHERENT C3 or Spectrum Manager.

5.1.6. Data Caching in Local Databases

The COHERENT network graph has a hierarchical structure, that allows PHY and MAC measurements and estimates to be stored locally in network nodes (as identified in the project milestone: COHERENT, Milestone 3.1: “Network Graphs Defined for Small Cell Networks as Inputs for WP2, WP4, WP5 and WP7”, March 2016). Here, a network node can mean either a network element or a collection of such, with a common memory. This memory can be used to cache computations and data from C3 that were used when making scheduling decisions.

Moreover, the COHERENT controller framework has a likewise hierarchical structure, where the C3 layer provides a logically centralized network view, based on information provided by COHERENT controllers administrating network equipment within certain regions and RATs. For scalability and time-critical applications, real-time control actions are carried out by local control functions (e.g. scheduling) at relevant nodes. This locality can simultaneously be used to hide information from central control layers, allowing decisions to be made via local negotiations between nearby network elements.

For this to be feasible, long-term management decisions must be cached in local databases. This caching is done on a write-through basis, where management decisions made by a C3 are relayed to the network elements, together with the most relevant channel state measures, via local databases. These local databases communicate only on a semi-static time scale to the central coordinator, making them trustworthy as a third party. Hence, we allow resource distribution negotiations to be done north of the (technology dependent) south interface, between network nodes potentially associated to different operators and different technologies.

5.1.7. Management of the “Exclusive, Shared & License-Exempt” Radio Spectrum

In the context of logically centralized control over heterogeneous networks, as considered in COHERENT architecture, the spectrum manager has to manage different chunks of radio spectrum belonging to exclusive, shared and license-exempt access classes. While the management of exclusive access spectrum is an integral part of existing mobile networks, the use of shared spectrum for inter-operator spectrum sharing and license-exempt spectrum bands for achieving higher user throughput opens up new avenues for network performance improvement.

In inter-operator spectrum sharing, depending upon the spectrum sharing model, the spectrum manager has to exercise a specific level of control over the shared radio spectrum. An operator can share radio spectrum, based on a sharing agreement, with other operators that use the same RAT, with a limited set of “allowed” networks using different RATs, and with an open access approach where a RAT agnostic spectrum sharing mechanism can be realized. In the former two cases, network-specific spectrum sharing functions can be implemented and integrated in the network’s control plane or provided by an arbitrator entity for a joint control over shared spectrum. In the latter case, the spectrum sharing can be based on cognitive and dynamic spectrum access concepts. Each of these possibilities present its own associated set

of requirements and functions to the COHERENT spectrum manager. In network-specific spectrum management, a network may access the shared spectrum based on its collected information without exposing any information to other participant networks. In the arbitrator provided or joint control case, the networks may be required to share certain network-specific information to the arbitrator. While many aspects of this management and control will be determined by the rules of spectrum sharing agreement and applicable regulatory policies, the spectrum manager has to implement the control functions over the shared spectrum to realize the sharing benefits from an operator's perspective. The specific set of information that will be required for the management of shared spectrum includes real-time measurements (e.g. state of the shared spectrum, availability, network traffic conditions, etc.) and long-term information (e.g. applicable policies, allowed operating parameters etc.).

In accessing the license-free spectrum bands, the spectrum manager has to determine the criteria for spectrum access that is beneficial for the network performance while maintaining fairness with other license free networks. The fairness criteria in co-existence with other networks, while also considered in inter-operator spectrum sharing, is a more important and challenging consideration in the context of accessing license-free spectrum bands. The difficulties arise due to the diversity of network technologies, lack of coordination and the absence or scarcity of regulatory rules to which all network may be forced to comply. As it is more difficult to realize common management and control over license-free spectrum bands, the spectrum manager has to aggregate information about its own network (e.g. topology, network status, resource allocation etc.) and about the state of license-free spectrum to make independent spectrum management decisions. However, selfish spectrum access decisions can reduce the joint utility of the shared spectrum and therefore, the spectrum manager has to actively seek the objective of achieving fair co-existence with other networks without compromising on its own network performance.

5.1.8. WiFi Management

The WiFi bands or so-called ISM bands can be accessed without licenses or permissions. These bands are also considered in case of the LAA spectrum sharing technique, where the dynamically selected clear channels can be used for e.g. LTE transmission. In this case COHERENT Controller and Coordinator should know which channels are clear and what are the parameters of the transmission to avoid the harmful interference. It can be done using a monitoring function in COHERENT C3, which should provide the information about e.g. the number of users, the level of interferences, the maximum transmit power etc. Additionally, in case of e.g. LTE-U when no channels are free, the system controller should know the rules of spectrum sharing for unlicensed band.

5.1.9. Mutual Renting of Exclusive Spectrum

Mutual renting (MR) is one of two primary cases of CSA, the other being limited spectrum pool (LSP). In MR, operators keep their individual licenses to use spectrum, but they can mutual rent part of the spectrum based on prior requests. The operators are not assumed to be willing to share their users' demands, wherefore the renting has to be done through trading network resources (in particular spectrum) against others.

MR protocols take into account that each operator is serving several network elements, each experiencing different interference patterns from other operators' elements, when they are sharing the same physical resources. Operators will therefore act as players, offering favours by allowing coplayers to share limited fractions of their spectrum, in return for the same favour on the coplayers' resources. As the operator is assumed to hide the preferences of its users from its competitors, instantaneous reciprocity is assumed. In the case of two competing players, the abstracted game was solved in [Hailu_2014], where it was shown that honest bidding gives socially optimal distribution of spectrum. The same conclusion is drawn

experimentally in [Hailu_2016], when resources are allowed to be shared between restricted subsets of a given set of players.

5.1.10. Traffic Steering and Offloading

Traffic steering refers to the intelligent manipulation of user/service-specific data over a network's resources for improving particular quality metrics such as reducing network load, achieving higher user throughput, or service differentiation. Traffic steering in mobile networks is a self-organized way to distribute the network traffic load and the end-users across heterogeneous networks (e.g. LTE and Wi-Fi) in the RAN segment. These concepts are not entirely new and existing mobile networks already provide some implicit ways to condition the traffic in core network and wireless access parts for example through handovers. These solutions however, are mostly static in nature or manually controlled based on observed parameters.

The RAN part of a mobile network is usually the main bottleneck for cost-saving and performance gains due to several reasons such as limited available radio spectrum and dynamic interference environment. In view of the anticipated availability of dedicated, inter-operator shared and license-free spectrum for future mobile networks together with software-based control functions, the COHERENT spectrum manager can utilize more efficient traffic steering techniques to improve the network performance. Moreover, if inter-network spectrum sharing is extended to infrastructure sharing, the traffic steering can significantly improve the observed QoS for the end-users. There are three main requirement categories that will need to be addressed for intelligent traffic steering under the COHERENT spectrum manager (i) real-time analytics about the radio spectrum (dedicated, shared, license-free) (ii) state of heterogeneous networks including traffic conditions in the core network and (iii) algorithms for management and configuration of traffic flows over a network's own resources and on shared infrastructure.

5.1.11. Channel Assignment in Enterprise WLANs

Interference management in Enterprise WLANs is a major research topic. This is due to both the widespread usage of the WiFi technology and to the contention-based channel access mechanism. These two aspects can lead to severe performance degradation if interference is not kept under control. One of the most common way of performing interference management is through dynamic channel assignment.

In [Achanta_2006], the authors proposed an approach where APs select a suitable channel based on the local knowledge of neighbouring APs. In [Zhou_2012], the authors proposed a heuristic that assigns channel to APs by considering the effect those partially overlapping channels have on the WiFi network throughput. In [Mishra_2005], the authors formulate the channel assignment a graph colouring problem [Bondy_2008].

In this context we plan to work on a channel assignment algorithm that runs in the COHERENT Centralized Controller & Coordinator (C3) and that relies on the network monitoring information that C3 controller obtains in order to analyse and calculate the optimised channel assignment configuration across the entire network.

The channel assignment algorithm will be triggered every time the controller detects that the interference level has reached a specific threshold. This can, for example, be based on detecting localized congestion in the wireless spectrum or a drop in the overall throughput of the network. Once the channel assignment algorithm is executed, the controller determines the optimal new configuration and applies the channel assignment configuration. A high level view of the system architecture is sketched in Figure 5-2.

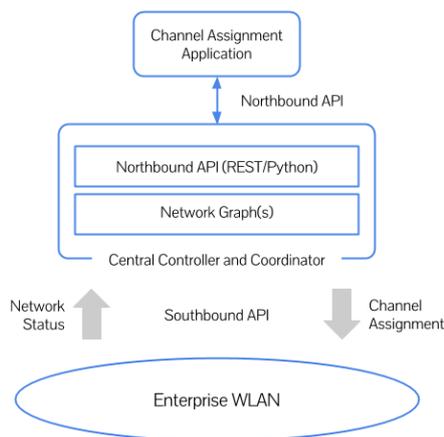


Figure 5-2 System Architecture

The Channel assignment “App” runs on top of the Central Controller and Coordinator (C3) and accesses the network graphs using the C3 Northbound API. In time the network graphs are built by the C3 which polls the network elements (i.e. WiFi Access Points) collecting the relevant statistics. Once a new channel assignment is computed the application layer conveys the assignment to the C3 using the northbound interface. The controller is then in charge of configuring all the network elements in order to reflect the new channel assignment plan.

Channel assignment decisions are taken using the network graph. The network graph provides full view of the network status in terms of link quality allowing network applications to reason about the channel quality. Three different network graphs are envisioned for this work and are being implemented on the COHERENT SDK: the RSSI Map, the Link Stats Map, and the Traffic Matrix.

Figure 5-3 sketches a sample RSSI Map. The (directed) edges represents the RSSI level between pairs of nodes. Triangles represent WiFi APs, while circles represent WiFi Stations.

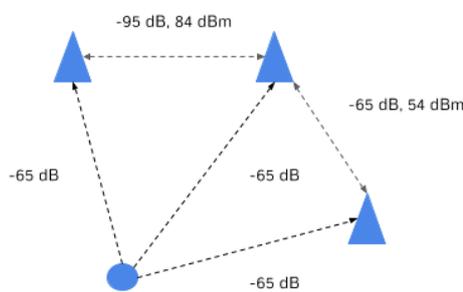


Figure 5-3 An example of RSSI Map.

Figure 5-4 sketches a sample Link Statistics Maps. The (directed) edges are annotated with the link delivery probability (P) and the link throughput (T) for each of the supported Modulation and Coding Schemes.

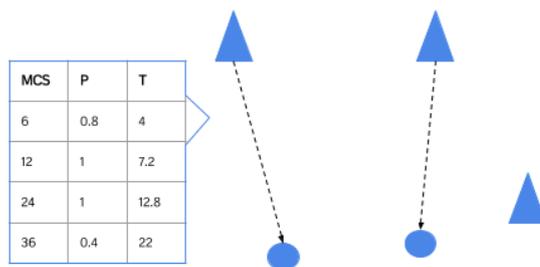


Figure 5-4 An example of Link Statistics Map.

Finally, Figure 5-5 sketches a sample traffic matrix map. The (directed) edges are annotated with the uplink and downlink traffic (in bytes). Binning can also be used in order to classify traffic according the frame length.

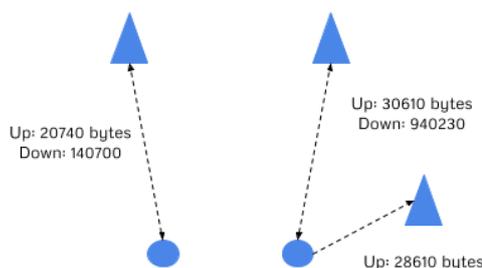


Figure 5-5 An example of Traffic Matrix Map.

5.2. Use Case on Shared Infrastructure

Network sharing agreements of mobile operators are motivated by cost saving and efficiency improvement. For governments the spectrum policy changes should in the best case improve the services of citizens, increase competition, increase the efficiency of spectrum resource utilization, and decrease cost of administration. Cerre report [Cerre_2016] recommends that the use of spectrum assignment to achieve objectives other than an efficient allocation of a scarce resource, should be clearly justified and in several instances limited. The mobile network services are often simplified to coverage and capacity. Although network sharing can bring cost saving both in coverage (below 1 GHz) and capacity networks (above 2 GHz), the service improvement of network sharing is highlighted in most rural areas of coverage networks. The rural areas are challenging for profitable network service business and government has interest to get also the people in rural areas connected. The government has a legal status to administer the frequency use. The spectrum licenses are the primary method for administration. The assignments should be open and aligned on the type of radio spectrum use. Duration of rights of use should ensure regulatory predictability and be aligned with the investment cycles which may be long for digital infrastructures. As changing licensing rules and adding new requirements during the licensing period causes resistance, the best time for license rule changes is when new licenses are issued. Most countries in the world are licensing at least one of the primary mobile broadband coverage bands, 600, 700, or 800 MHz between 2016 and 2020. The license rules should be considered carefully from network sharing point of view because in many cases network sharing is the only way to extend the mobile broadband coverage to most rural areas. In the following sections, we describe with various issues, which are linked to network sharing, and at the end we give general recommendation for national regulatory authorities (NRA) when issuing the coverage band spectrum licenses for rural areas [Cerre_2016].

5.2.1. Sharing Basics

The network sharing possibilities are implemented in laws, regulation, spectrum, and service provider licenses. The most basic requirement for sharing is that sharing is allowed. Allowing sharing leaves the decision power to the license holders if they share or not, and NRA does not have a pre-agreed method to influence the decision. Stating the conditions, under which NRA may force sharing, in the licenses is a better policy. In sharing agreements where one license holder has a priority over the other, the priority user must report its network use in reasonable accuracy to management system in order for the lower priority user to benefit from the capacity, which is unused. The lower priority user has to adapt its own use, e.g. decrease transmission power, narrow the bandwidth, or change the frequency, according to management system command. The simplest management system is the licensing process of NRA.

In the sharing agreements, where there is no priority difference or where the sharing is based on full geographic, spectral, or time differentiation, all sharing parties should follow the agreement and report only deviations from the agreement rules [Kokkinen_2015].

5.2.2. Classification of Infrastructure Sharing

GSMA classifies infrastructure sharing in site, mast, Radio Access Network (RAN), core networks sharing and in roaming [GSMA_2012]. In site sharing the operators share the site location but each operator has own masts, antennas, cabinets, and backhaul. In mast sharing, the operators install their own antennas in a shared mast or other physical structure. Each operator also has own cabinets and backhaul. In RAN sharing, the operators share the masts, antennas, backhaul, access network equipment like base stations or NodeBs and related controllers. Each operator has an own core network, logical network, spectrum, and network management. In core network sharing, the operators share either core transmission ring or one or more core network functionalities, which include home location register (HLR), switching centre, billing platform, value added systems. In network roaming, traffic of one operator's subscriber is carried and routed on another operator's network. Roaming is based on agreement and it does not require any shared investment in infrastructure.

5.2.3. European Regulation for Infrastructure Sharing

Rights of way and access to passive infrastructure implementation varies in Europe [EC_2015]. Symmetric access to passive infrastructures is planned in 15 EU member states. Binding (in Greece) and non-binding (in Belgium) regulation has been issued with regard to active and passive infrastructure sharing. Currently 19 MNOs in 12 Member States are involved in various types of active sharing agreements, i.e. Cyprus, the Czech Republic, Denmark, Finland, France, Greece, Hungary, Poland, Romania, Spain, Sweden and the United Kingdom. Regulatory and competition authorities have begun to scrutinize some of these agreements in order to minimize the risk that some types of sharing agreements may lead to a decrease in competition.

5.2.4. Current Examples of Sharing Legislation and Regulation

Infrastructure sharing legislation and regulation between mobile operators can be implemented in various ways. This section discusses spectrum license transfer in Finland, infrastructure company owned by mobile operators in Finland, independent infrastructure company in the UK, spectrum trading in the UK, secondary use on mobile band in Norway, secondary use on TV band in Finland, wholesale operator in Mexico, community spectrum in Mexico, separation of urban and rural areas in Italy.

Spectrum licence transfer: In Finland, government may transfer a spectrum license at the request of a licence holder unless the transfer prevents competition, causes interference or risks national security. A transfer within a corporate group between the parent company and its fully owned subsidiary is not be regarded as a licence transfer [Finlex_2012].

Infrastructure company owned by mobile operators: The Finnish Shared Network is a joint operation by operators DNA and TeliaSonera Finland. It builds a new, shared mobile network for Northern and Eastern Finland. The 2G, 3G and 4G networks cover half of Finland's total geographical area and serve approximately 15 per cent of the population. Finnish Shared Network Ltd is not a telecommunications operator and it does not offer network packages or a customer service function. The only direct customers are its shareholders Sonera and DNA [Yhteisverkko_2015].

Independent infrastructure company: Arqiva is the UK's largest independent provider of wireless sites. They offer space on towers, masts and rooftops for our customers' wireless equipment. They currently have 8,700 active sites and a total of more than 16,700 sites available for sharing [Arqiva_2015].

Spectrum trading: In the UK, Ofcom may authorise the transfer by the holder of a wireless telegraphy licence, or the holder of a grant of recognised spectrum access, of rights and obligations arising as a result of such a licence or grant. The transfers may contain all or any of the rights and obligations under a licence or grant such that the rights and obligations [WT_2006].

Secondary use allowed on mobile band: In Norway, the latest mobile network radio licenses contain permission for secondary use. Holder of the mobile radio licenses the primary user of the allocated frequencies. To ensure effective utilization of frequency resources, it may be necessary to allow secondary use of the same frequencies. This means that other operators can access the allocated spectrum on a secondary basis, using technologies such as cognitive radio. It is essential that the secondary use does not cause harmful interference to the holder the mobile radio license. The secondary frequency usage is not entitled to protection from the primary user of the band [Samferdselsdepartementet_2015].

Secondary use allowed on TV UHF band: In Finland, the frequency ranges used for the operation of cognitive radio systems are 470-790 MHz until 31 December 2016 and 470-694 MHz, from 1 January 2017. Cognitive radio systems are not protected from harmful interference of other radio communications and they may not cause interference to other radio communications [Finlex_2014].

Wholesale operator (Mexico): In Mexico, 700 MHz band is auctioned to a wholesale operator under a procedure called Red Compartida. The Red Compartida will sell all of its capacities and services, in a disaggregated and non-discriminatory manner, only to operators with infrastructure and to virtual operators (concession holders and traders). It will not compete with their clients since it will not sell services directly to end users [RC_2015].

Community spectrum. In December 2014, Mexico's regulator issued a plan to reserve some of the radio spectrum for indigenous and community use under 15-year non-profit licences. This could encourage more communities to set up their own mobile services. The community networks are installed, owned, and operated by small, mostly indigenous communities [Economist_2015].

Separation of urban and rural areas (Italy): In the band from 3695 to 3800 MHz, AgCom and the Ministry for Economic Development separate urban and extra-urban areas based on the resident population. National mobile operator frequencies will cover all urban areas and will be auctioned. Extra-urban areas will be licensed through a beauty contest (the famous beauty contest). They are awarded if the operators are willing to pay more (will weigh the offer for 30 percent) and to ensure the most efficient coverage (and this will weigh 70 percent in the contest). Macro-regional frequencies will be the instrument to counter the digital divide in remote areas of Italy, thanks to "fixed wireless". All this is in Lot A [Fontanarosa_2015].

5.2.5. Handling Military and Public Safety

Public Protection and Disaster Relief (PPDR) may partially operate on the mobile IMT bands. Possible arrangements are that there is a fixed frequency allocation for PPDR, PPDR uses commercial mobile network with a priority status, there is a dedicated operator for PPDR, and a possible spectrum sharing arrangement can be implemented using Licensed Shared Access (LSA) or Citizen's Broadband Radio Service (CBRS).

Fixed frequency allocation: France has allocated 2 by 5 megahertz and 2 by 3 megahertz in the 700 MHz band for a broadband PPDR dedicated network. The decision for the 698 – 703/753 – 758 MHz and 733 – 736/788 – 791 MHz allocations was incorporated into the legal corpus but will be enacted in July 2019. Grous [Grous_2013] studied the economic impact of 2x10 MHz allocation for PPDR in 10 European countries [MCC_2016].

Prioritized frequency allocation with CBRS: In the US on 3.5 GHz band, Incumbent Access users represent the highest tier in this framework and receive interference protection from all Citizens Broadband Radio Service users. Protected incumbents include federal shipborne and ground-based radar operations and frequency selective surface (FSS) earth stations in the 3600-3700 MHz band and, for a finite period, grandfathered terrestrial wireless operations in the 3650-3700 MHz portion of the band. Non-federal incumbents must register the parameters of their operations with the Commission and/or an SAS to receive protection from Citizens Broadband Radio Service users [FCC_2016].

Prioritized frequency allocation with LSA: In Europe on 2.3 GHz band, ECC Decision aims at harmonising implementation measures for mobile/fixed communications networks (MFCN), including broadband wireless systems (BWS). It includes the least restrictive technical conditions (LRTC), taking into account the existing standardisation framework and activities at the worldwide level, and an appropriate frequency arrangement. For the purpose of this ECC Decision, Licensed Shared Access (LSA) is the recognised approach by CEPT for administrations wishing to introduce MFCN while maintaining the current incumbent use. Regulatory provisions based on LSA can ensure this long term incumbent use of the band [ECC_2014].

Priority in commercial network: A study by European Commission concludes that using commercial mobile networks with a priority status is most cost efficient for PPDR. The Study team concluded that commercial mobile broadband networks could be used for mission-critical services with the right legal, regulatory and contractual framework and only if several requirements are fully met. The Study team is further proposing specific measures to build the confidence of mission-critical users in the commercial mobile networks [SCF_2014].

5.2.6. Licence pricing

Pricing the secondary or shared radio licenses is most straightforward by carrying out a spectrum auction. Other examples could be a generic radio license pricing model, free or administrative license fee, or using a per capita price from the main spectrum auction. The current spectrum auctions can generally be categorized in package offers allowing Combinatorial Clock Auction (CCA) and package offers not allowing Clock Auction and Simultaneous Multi-Round Auction (SMRA) models.

The Finnish Communications Regulatory Agency (Ficora) has a general method to compute spectrum fee, by the formula:

$$\text{Fee} = K1 * Kasuk * K6b * B0 * S * P,$$

where K1 is spectrum band coefficient, Kasuk is population density coefficient, K6b is system coefficient, B0 is proportional bandwidth, S basic fee coefficient, and P is basic fee [Ficora_2016].

The use of license-exempt band is typically free and if a license is required, the regulator in many countries must collect a fee from the license applicant. In Finland, the minimum fee is 18 € in 2016.

A reference for the price when the rights are transferred from a nationwide operator to a local rural operator could be based on per capita pricing. The per capita price is calculated by dividing the operator's auction price with population of the country. The reference price for the rural operator could be the inhabitants on the rural operator's coverage area multiplied with the per capita auction price.

5.2.7. Recommendation

The licenses for mobile coverage bands are issued rarely and there are only few available. The mobile licenses are typically for 10 - 20 years. It is a quite strong self-delusion if someone claims to be able to forecast the ICT development for 20 years. The license rules may determine the possibility to build the rural coverage in many countries. In most countries, mobile networks are the only realistic way to extend broadband connectivity on rural areas. The coverage band license rules can set development path or take such development away for decades. The most future-proof licenses are such that they encourage to long-term network infrastructure investments but at the same time allow flexibility and hooks the regulator to ensure that the politically set rural development targets can be met.

1. Issue long-term licenses for coverage bands. The licenses contain permission to operate a radio network, protection from interference and barrier of entry against competitors. These all are essential for attracting investors.
2. Set as strict coverage requirements as possible by discussing with operators. Rural areas are not money-making machines, in practise the rural networks are subsidised by winnings from urban areas.
3. Allow and encourage infrastructure sharing between operators on rural areas, see Infrastructure company owned by mobile operators.
4. Allow secondary use on mobile frequencies, see Secondary use allowed on TV UHF band and Community spectrum.
5. Utilise the industry interest to invest in dynamic spectrum sharing tools like TVWS, CBRS, and LSA to implement the secondary frequency use.
6. Add a statement that when requested by the regulator, the license holder must report, frequency, time and location of the spectrum use. The license holders will become incumbents for a yet-to-be-developed more efficient communication system during its license period.
7. Add a statement that re-allocation of the auctioned spectrum block may take place within the band during the license period. This helps re-farming and provides flexibility at the end of license period.
8. State that if agreed coverage requirements are not met, the regulator has right to take actions. If the conditions of fulfilling the requirements should be clearly stated. The possible actions would be good to specify at least on a general level.

5.3. Use Case on Flexible Duplexing

In this section, the flexible duplexing background work and motivation are depicted. In addition to the motivation for flexible duplex usage, problem formulation for flexible duplex in LTE systems is presented. Appropriate transmitter and receiver characteristics are introduced, including both BS and UE sides. Distinctive cases chosen for the study and simulations are presented, finally followed by the coexistence simulation results and interpretation of them.

5.3.1. Motivation

The traditional cellular communication systems were designed for some typical voice services with the assumption of symmetric DL and UL traffic ratio in one cell, e.g. the symmetric paired spectrum for FDD systems where there are separate frequency bands for DL and UL. Therefore, it could accommodate a fixed ratio of the maximum DL and UL traffic correspondingly. Such spectrum allocation in each region is quite static, generally will not change within tens of years before refarming or re-allocation. In practice, the ratio between UL and DL traffic changes over the time, then the static allocation of the frequency resources between DL and UL transmission in LTE is not efficient to support dynamic asymmetric cell traffic. According to some statistics of mobile network traffic, including [CISCO_2015], measured traffic ratio between DL and UL would be around 4:1 and with the increased portion of video data for mobile traffic (2/3 by 2018), the ratio between DL and UL would be increased further. Table 17 shows the characteristics of some popular internet services used on MBB networks.

Table 17 UL/DL traffic ratios of different service types

Service type	UL/DL ratio (average)
Online video	1:37
Software download	1:22
Web browsing	1:9
Social networking media	4:1
Email	1:4
P2P video sharing	3:1

Such popular types of services as above are more popular in hotspots where small cells are deployed with limited number of active users per cell. In the small cell hotspot deployment scenario, the DL and UL traffic demand in one cell may fluctuate with times or places. Considering UL/DL traffic asymmetry and the limited available spectrum, mechanisms to utilize the underutilized UL resources should be considered. When more asymmetric DL/UL carrier aggregation scenarios (e.g., 3 DL/1 UL, 2 DL/1 UL) are deployed, it is expected that the uplink resources are more and more underutilized. However in some cases, UL traffic can be heavier than DL traffic depending on traffic situations (e.g., cloud computing). It can be also noted that asymmetry in DL/UL traffic intensity may not be directly translated to asymmetric resource utilization due to different data rate/spectral efficiency between DL and UL. Considering the imbalance between the static resource allocation and the varied and asymmetric traffic load between DL and UL, flexible duplexing is seen as an essential method for LTE and forthcoming 5G systems. The flexible duplex usage is seen reasonable to be limited only for the low power small cell scenario, considering that DL transmission power of a small cell is comparable with a UE's transmission power, which will not cause coexistence problem to the legacy UL transmission [3GPP_2015_1]. The flexible duplexing method becomes more essential for 5G scenarios where the required peak rates and user experienced data rates increase significantly, and resource requirements on UL and DL would change dynamically with traffic patterns and QoS requirements.

The other conventional duplexing technique is TDD where DL and UL are sharing the same frequency band on a time domain basis. TDD has increased its popularity in particular in small cell deployments. TDD has also the advantage that it supports asymmetric radio resource division between UL and DL either in fixed or dynamic manner. And there already exist LTE terminals capable of FDD/TDD joint operation and Multi-Stream Aggregation

(MSA). Thus, using spare FDD UL band for small cell DL transmission using either FDD or TDD can be recognized as one of very potential use cases for flexible duplexing.

5.3.2. Problem Statement

Based on current impressions, the technology base of 5G is the LTE evolution. Therefore, LTE background information and current 3GPP (and ECC PT1) work are taken as starting points to define the problem, boundary conditions (constraints), challenges and simulation scenarios. And as for regulation issues, potential solutions should be identified. For example, in some bands the DL transmission is allowed in FDD UL bands, see Table 21 in Annex A. Responses of European, US and Japan regulators regarding the usage of FDD UL band for DL transmissions can be found in [3GPP_2015_1], [3GPP_2015_3].

The most determinant BS and UE TX and RX characteristics that must be taken into account when estimating the flexible duplex method's influence to interference are the unwanted emissions of BS and UE transmitters. Unwanted emissions consist of Out of Band (OoB) emissions and spurious emissions. OoB emissions are unwanted emissions immediately outside the channel bandwidth resulting from the modulation process and non-linearity in the transmitter but excluding spurious emissions. The OoB emissions requirements for BS and UE transmitters are specified in terms of Adjacent Channel Leakage power Ratio (ACLR) and Spectrum Emission Mask (SEM). Unwanted emissions outside of this frequency range are limited by a spurious emissions requirement.

Spurious emissions are emissions which are caused by unwanted transmitter effects such as harmonics emission, parasitic emission, intermodulation products and frequency conversion products, but exclude out of band emissions. Spurious emissions are not considered in the flexible duplex coexistence studies since they have no impact there, only OoB emissions are relevant in the studies.

The ACLR and SEM characteristics, among others, are explained in detail in [3GPP_2014_2] and [3GPP_2014_1] for BS and UE, respectively. These two are also briefly defined in the following two subsections.

5.3.3. Adjacent Carrier Leakage Power Ratio

The ACLR is defined as the ratio of the filtered mean power centered on the assigned channel frequency to the filtered mean power centered on an adjacent channel frequency. For a BS, ACLR is defined for 1st and 2nd adjacent E-UTRA carriers of the same bandwidth and for 1st and 2nd adjacent UTRA carriers. Separate limits are defined for each channel bandwidth and both RANs.

For an UE, ACLR ratio is defined between the assigned band and only the 1st adjacent E-UTRA carriers of the same bandwidth and the 1st adjacent UTRA carriers.

5.3.4. Spectrum Emission Masks

For a BS, the Operating band unwanted emissions aka SEMs define all unwanted emissions in each supported downlink operating band plus the frequency ranges 10 MHz above and 10 MHz below each band. Multiple sets of minimum requirements for SEMs are defined in [3GPP_2014_2], depending on the E-UTRA carrier number, BS class, BS category and in-band power settings.

For an UE, the SEMs are defined significantly differently compared to the BS ones. The SEM domain starts from the \pm edge of the assigned E-UTRA channel bandwidth, not from the operating band edges. The SEM domain range depends on the assigned E-UTRA channel bandwidth. For instance, for 10 MHz channel bandwidth the SEM range is 15 MHz. See [3GPP_2014_1] for complete definitions.

5.3.5. Distinctive Cases

A small cell scenario with non-ideal backhaul defined in Annex A.2 in [3GPP_2014_3] was selected as a starting point for the first flexible duplexing simulations done in COHERENT. Seven macro cells were selected there, each having 3 sectors. The simulation statistics were collected in one sector of the macro cell and in the small cell located in that macro cell sector. The “area”, where the statistics were collected, was treated as a “victim operator”. Remaining two macro cell sectors, other small cells in the same macro cell coverage area as well as other macro cells and small cells were treated as “aggressor operators”.

Two distinctive scenarios were chosen to study and simulate the impact of flexible duplexing usage:

1. The reference case without flexible duplexing. An aggressor UE attached to a small cell transmits UL traffic in FDD UL band which is adjacent to the victim macro and small cell UL bands. The aggressor UE's OoB emissions cause interference the victim's macro and small cell BSs.
2. The case of interest where flexible duplexing method is used. The scenario is similar to the first one except aggressor's small cell BS transmits in DL using the UL band adjacent to the “victim system”. The OoB emissions of the aggressor are studied and simulated.

The results are introduced and explained in the next section.

5.3.6. Coexistence Simulation Results

The effect of enabling flexible duplexing is studied by means of a system simulator. We measure the level of OOB interference caused by an aggressor operator into a victim operator located in the adjacent FDD UL band. The impact of the OOB emissions caused by the aggressor into the victim operator is measured in terms of signal-to-interference-noise (SINR) for the victim's UEs. We will first observe the case in which the aggressor uses its FDD UL band for normal UL communication. Then the aggressor operator will switch its transmission to DL, using the same FDD UL band. To study the coexistence, we will observe in the victim's UEs the impact of OOB emissions of the aggressor due to flexible duplexing, and compare to the case in which the aggressor uses the UL band for normal UL communication.

For the victim operator we consider a HMN, based on [3GPP_2013_1], [3GPP_2013_2], in which all the UEs communicate in UL. The victim's network consists of seven macro cells. One macro cell located at the centre of the network is regarded as the main macro cell. The six macro cells around the main one will provide a source of co-channel interference in victim's network. Each of these cells are separated at angular steps of 60 degrees and at a constant inter-site-distance (ISD) of 500 meters with respect to the main macro cell. Figure 5-6 depicts the layout of the victim's HMN. Each one of the macro cells is divided into three sectors. One of the sectors in the main macro cell is regarded as the main sector for our analysis (see shaded sector in the figure). In this sector we place a small cell, which is part of the victim's HMN, also communicating in UL. Each macro cell has a macro BS in the centre which is in a fixed position. The small cell, instead, is placed in the sector following a uniform distribution, and subject to be no closer than 105 meters of the main macro BS [3GPP_2013_2].

In each sector of the macro cells a UE is placed following a uniform distribution. Actually, two UEs are placed in the sector for analysis in the main macro cell, one associated to the main macro BS, and other to the small cell, considering that each one has the strongest received power from its respective BS. The UE associated to the main macro cell in the analysis sector, and the UE associated to the small cell, are the UEs selected for our analysis. For these UEs we will measure the SINR considering the OOB emissions of the aggressor operator. The remaining UEs are co-channel interferers. In addition, the intra cell co-channel

interference between the two UEs for the analysis is considered. Figure 5-6 shows an example of a network instance; interference links are not shown for simplicity. The described layout of the victim operator is common to the two scenarios to be evaluated next, namely, the case in which the aggressor operator transmits in UL and the case in which it transmits in DL.

In the analysis that follow, it is assumed that the level of OOB emissions from the aggressor’s operator is determined by ACLR, and that these emissions are flat, propagating entirely over the adjacent band. This assumption follows from a preliminary study on emissions, in which we verified that for these scenarios the ACLR is more restrictive than the SEM requirement [3GPP_2014_1], [3GPP_2014_2].

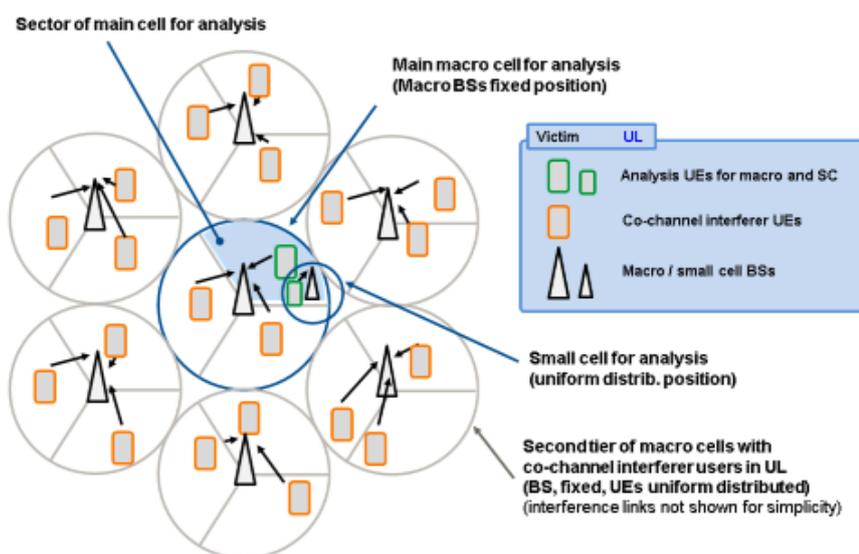


Figure 5-6 HMN layout of victim operator. All the UEs are in UL.

In the first scenario we address the case in which the aggressor uses its FDD UL band for normal UL transmission. For this purpose, a small cell belonging to the aggressor’s HMN is overlapped into the victim’s HMN. An example of a network instance is shown in Figure 5-7. In this case we assume that the UE associated to the aggressor’s small cell causes an OOB emission with an ACLR of 30 dB from the UE transmission power, considering UL power control. This level emission is multiplied by 50 to simulate an approximate level of additive OOB emissions caused by other UEs transmitting in other resource blocks and other small cells. These emissions are regarded as interference for the UEs under analysis in the victim’s network, and its effect will be measured by the SINR.

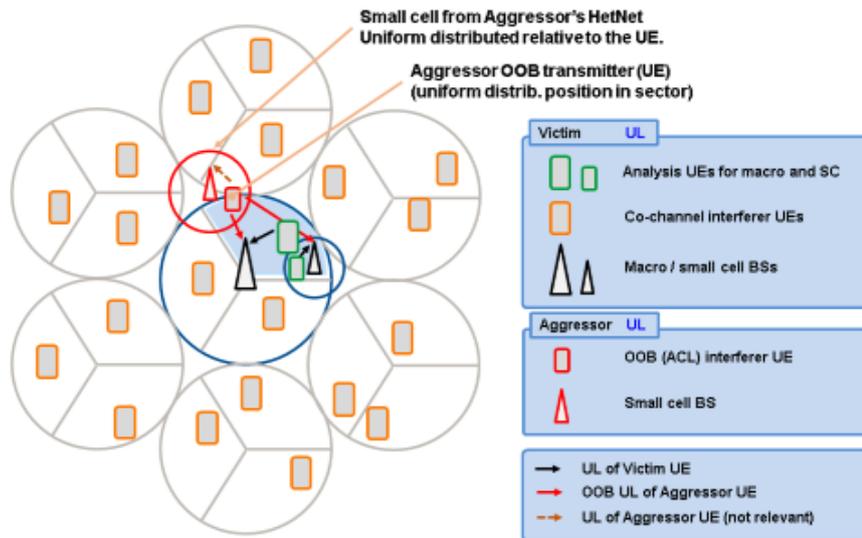


Figure 5-7 Case scenario 1: OOB interferer is UE in FDD UL band

In the second scenario we address the case in which the aggressor uses its FDD UL band for DL transmission. In this case the small cell belonging to the aggressor's HMN switches its transmission to DL. An example of a network instance is shown in Figure 5-8. In this case we assume that the aggressor's small cell BS causes an OOB emission with an ACLR of 45 dB from the transmission power, considering perfect DL power allocation. This emission is regarded as interference for UEs under analysis in the victim's network, and its effect will be measured by the SINR. DL power allocation was calculated based on the UE's receiver sensitivity.

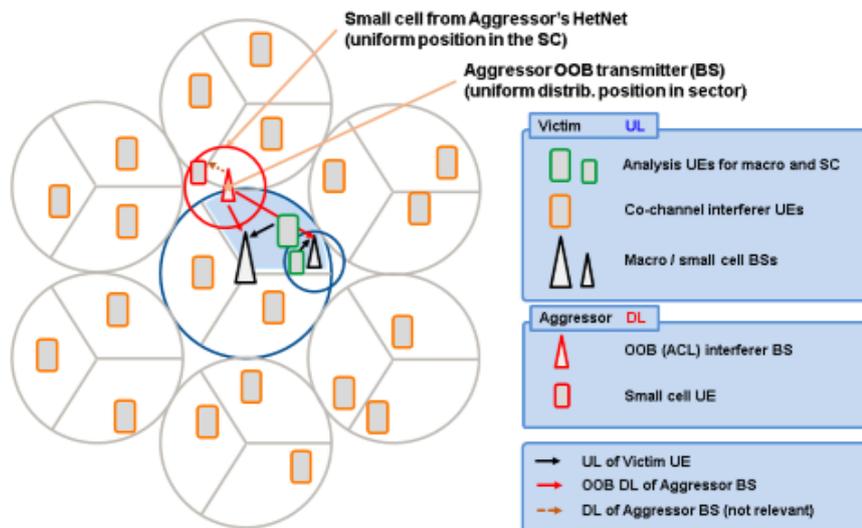


Figure 5-8 Case scenario 2: OOB interferer is BS in FDD UL band

In the simulations we consider the case in which the aggressor's source of OOB interference is located in the sector under analysis in the victim's main macro cell. Therefore, in the first scenario the aggressor's UE is placed in the sector, and the respective small cell BS at a location uniformly distributed such that the UE is associated to the BS respecting the minimum distances stated in Table 18. For the second scenario the aggressor's small cell BS is placed in the sector, and the respective UE at a location uniformly distributed respecting the minimum distances stated in Table 18.

The analysis of the aggressor’s OOB interference is measured in one of the victim’s resource block used for UL data transmission. Table 18 lists resource block 49 as example. It is assumed that the OOB emission caused by the transmission of an aggressors UE expands over the entire bandwidth of the victims with constant power. The simulation is done for the case of outdoor UEs, using the path model urban macro with line of sight specified in [3GPP_2015_2]. CLR values were obtained from [3GPP_2014_1] and [3GPP_2014_2]. Additional settings are listed in Table 18.

Table 18. Simulation Setup

	Macro {small} cells (Victim and co-channel interf - UL)	Scenario case 1 UE (OOB Aggressor – UE in UL)	Scenario case 2 Small cell (OOB Aggressor – BS in DL)
Layout	Circular grid, 3 sectors per site, 7 sites, the central one is the main victim macro cell, with one main sector for analysis	UE in main sector of main victim macro cell	Cell in main sector of main victim macro cell. Uniform in macro cell and according to minimum distances below
UE TX power	Determined by UL pwr. ctrl., and allocated to one PRB.	Determined by UL pwr. ctrl., and allocated to one PRB.	
BS TX power			30dBm / 10MHz
OOB emission criterion		ACLR = 30 dB (TR 36.101)	ACLR = 45 dB (TR 36.104)
Analysis PRB number	49	Additive OOBof 50 PRBs	
Carrier frequency	2.0GHz		
Distance-dependent path loss	ITU UMa LOS according to Table B.1.2.1-1in TR 36.814		
Outdoor/Indoor UEs	All UEs are outdoor	UE is outdoor	Not relevant
Shadowing	Std. dev. = 4 dB (UMa, LOS)	Std. dev. = 4 dB (UMa, LOS)	Std. dev. = 4 dB
Fast fading:	None		
Antenna Height:	25m	1.5m	5 m
Antenna gain + connector loss	17 dBi		
Antenna configuration	SISO 1x1		
Antenna pattern	For sector, horizontal 2D, Phi3dB = 70 deg. Am = 25 dB. TR 36.814 {omni-directional}	Omni-directional	Omni-directional
Number of UEs	1 in each cell/sector for coexistence evaluation.	1	One always present in the PRB under consideration
Transmitters dropping	UEs are uniformly distributed in each sector of each cell	UE is uniform. distributed in main sector of main macro cell. Corresponding BS is uniform distrib. in the disc around this UE.	BS is uniformly distributed in the main sector of the main macro cell
Cell radius:	500 m. {det. By cell selection}	100 m.	100 m.
Minimum distances	Macro BS – associated UE: 35 m. Macro BS - cluster center: 105 m.	Main macro BS – Agr. UE: 10 m. Small cell - UE: 5m	Main macro BS – Agr. BS: 10 m.
Traffic model:	Full buffer		
Noise figure BS	5 dBi {5 dBi}		
UE speed	None (static)	None (static)	Not relevant
Cell selection criteria	RSRP	RSRP	Not relevant
Target RX power	-105 dBm / 180 kHz {-95 dBm / 180 kHz}	-105 dBm / 180 kHz	Not relevant
Rx sensitivity			-97 dBm / 10 MHz

We proceed to perform a Monte Carlo simulation generating 1000 network instances. In each network instance we place UEs and small cells as stated, and then calculate the proper transmission power using UL power control or DL power allocation, for UL and DL cases respectively. Next, path losses are calculated for each link according to the distance and antenna heights. Finally, three SINRs are calculated in each instance for the two UEs under analysis in the victim’s network. First we obtain the SINR considering only co-channel interference in the victim’s network. This is a baseline reference to study next the impact of OOB emissions. Second, we obtain the SINR considering co-channel interference as well as the OOB emissions of the aggressor’s UE transmitting in UL. This case is the reference against which we will compare the relative effect of flexible duplexing. Third, we obtain the SINR for the flexible duplexing case, considering co-channel interference as well as the OOB emissions of the aggressor’s BSs transmitting in DL.

Simulation results are presented in terms of the cumulative distribution function (CDF) of the SINRs obtained in all the network instances. Figure 5-9 shows the CDF of the SINR for the UE in the analysis sector of the main macro cell. Figure 5-10 shows the CDF of the SINR for the UE in the small cell.

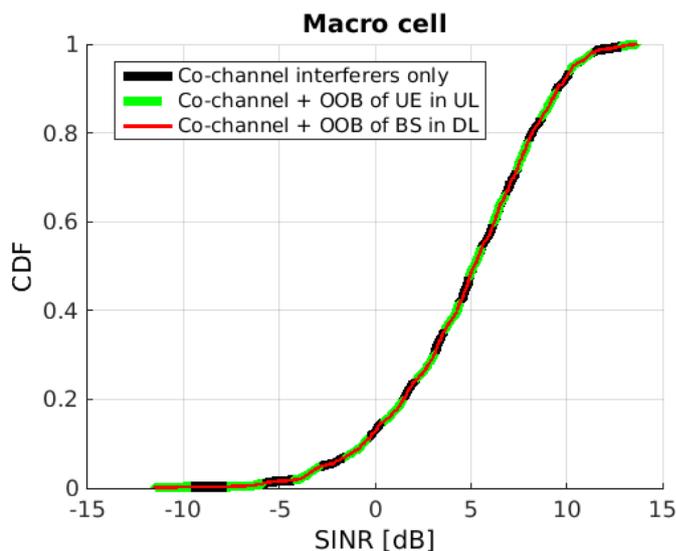


Figure 5-9. SINR for UE in analysis sector of the main macro cell in victim’s HMN.

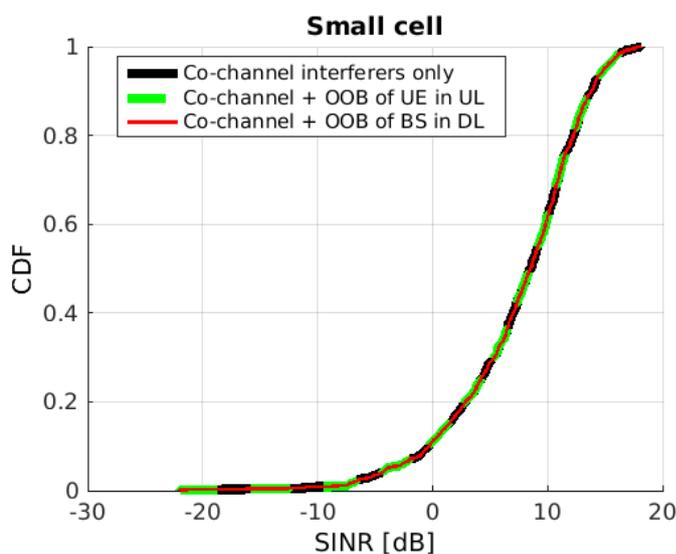


Figure 5-10. SINR for UE in small cell in victim’s HMN.

From the results obtained we observe that for both victim UEs, the influence of OOB emissions in the SINR of the UEs is negligible. The result is the same for the case of normal UL communication, as well as for the case of flexible duplexing. It is observed that this is an interference limited scenario in which the co-channel interference in the victim’s network dominates against the OOB emissions leaked from the adjacent FDD band. We conclude that, for the system under evaluation, the level OOB emissions due to flexible duplexing are similar, and negligible, as the ones created by the UEs in normal UL communication.

6. SDK and APIs for Spectrum Management

Software applications are seldom self-contained entities and rely on other processes to provide additional functionality to operate properly. This reliance generally spans across all the functional units of a software program which includes collecting the required information, processing them and providing an output. The Application Programming Interface (API) specifies the proper way through which one application can request supporting functionality or services from another application. Typically, APIs are implemented through function calls and the relevant API modules are bundled together with a Software Development Kit (SDK) that can be used to create new applications. The COHERENT architecture aims to provide a software-based control framework over heterogeneous networks to higher level application programs. Therefore, it will also provide the necessary tools for the development and operational support of these network applications. This section presents an overview of the SDK and associated APIs that will be required for the spectrum management and sharing tasks considered in COHERENT.

In COHERENT, the spectrum management and sharing tasks are associated with Spectrum Management Application (SMA). The SMA, in essence, is a software application that runs on top of a virtualized network infrastructure and aims to optimize the physical radio resource utilization and sharing procedures in heterogeneous networks. The development and operation of this application will require handling several types of information (short-term and long-term inputs) aggregated through well-defined interfaces, processing these inputs, deriving spectrum sharing and management decisions, and implementing them through interaction with local and possibly remote Central Controller and Coordinator (C3) module/s. Just like any other software application, the development of COHERENT SMA will rely on the provision of the above mentioned operational and control functionalities through a supporting SDK with well-defined APIs for network programmability and control. Such an SDK and associated APIs for abstracting the physical network resources and controlling them through C3 module/s will be developed during the COHERENT project timeframe. In order to facilitate the development of the required SDK modules and associated APIs, the requirements of the SMA have to be explicitly identified. This will not only help in a swift demonstration of the capabilities of the COHERENT SMA, but also serve to advocate interest in utilization of the developed SDK for other network applications that can exercise a software control over radio access networks and optimize any particular network performance aspect.

There is a need for careful consideration when designing the APIs for a particular purpose. Once the APIs are used by certain applications, it is generally difficult to change them without compromising on the function and/or performance of applications that use them. Additionally, not identifying the requirements properly can lead to missing functionality and APIs that may be difficult address at a later stage. Therefore, this section aims to summarize the broad sets of functionalities that the COHERENT SMA may require in order to carry out optimization of the radio resource utilization. These requirements relate to network abstraction (condensation of diverse inputs collected at different network entities) and enforcement of spectrum management and sharing decisions (software control implemented through C3). On a higher abstraction level, the COHERENT SMA relies on some broad classes of information for its operation. These classes can be made such that they not only reflect the source of the information but also the relevant interfaces through which support for its collection needs to be provided. To this end, three types of information and control flows can be associated with the SMA, (i) Northbound: the network abstraction process for spectrum management that condenses the state of the network into a form that is needed by the SMA for its operation, (ii) Southbound: the outputs in the form of control decisions that will be implemented by the COHERENT software control architecture involving the C3/s and possibly the Real-Time Controller/s (RTC), (iii) East/Westbound: information flow between SMA instances operating in different network domains for coordination and/or spectrum sharing. Figure 6-1 presents these three main information and control flows.

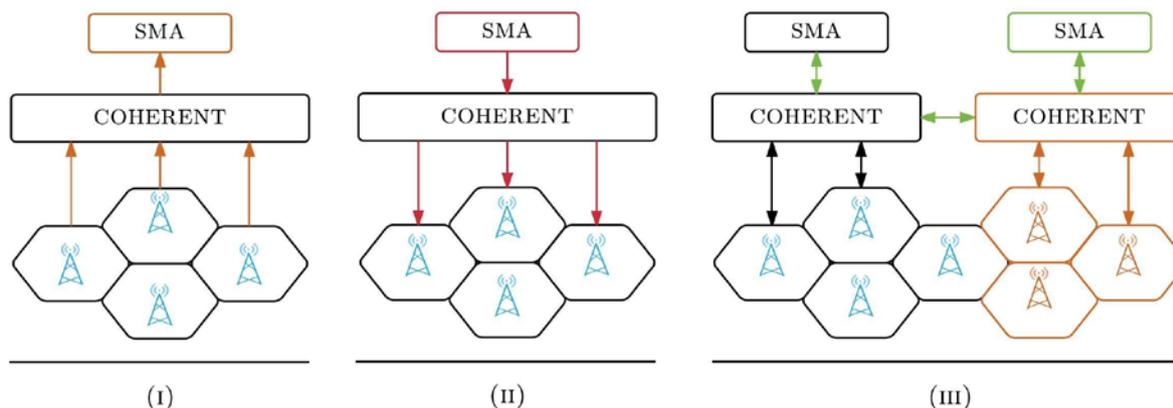


Figure 6-1 Information/Control flows associated with Spectrum Manager Application (SMA)

6.1. APIs for Northbound flows

Spectrum management concerns optimization of the RF spectrum utilization and the direct source of the required information for that is the radio access network. A large number of radio spectrum parameters are sensed by different devices that operate in the radio access network. Additionally, a network generally maintains state information based on these observed parameters, e.g. network load, spectrum utilization. These parameters and measurements can be used to create a diverse set of abstract network views depending upon the actual abstraction process implemented in the network. In COHERENT, the abstraction process is carried out by the controller (C3) in response to the requests that come from network management applications. The controller not only keeps the current network graph up-to-date, but can also create further application-specific abstractions resulting in diverse views of the network state. This diversity may be found in the types of information abstracted from the low level sensing results and network’s operational parameters. It should be noted that, at the level of the controller, the network abstractions are essentially data structures (suited to the requirements of an application) that are stored in the working database/storage structure of the controller.

Considering that heterogeneous networks will be abstracted through the network abstraction process, the devices that operate exclusively in the RAN segment and generate different RF measurements can be quite diverse. These measurements could be used to generate a real-time low-level abstract view of the heterogeneous networks that can then be used to generate other subsets or higher level abstract views, useful for spectrum management and other network applications. For the sake of brevity and to confine the focus to SDK and APIs definition, we take two of the most common wireless access technologies as a representation of heterogeneous networks i.e. LTE and WiFi networks. The end-user terminals in these networks are connected to the network infrastructure through direct wireless links (ad hoc and relay mode connectivity may also be possible). The selection and configuration of these wireless links is based on many RF measurements taken at the end-user terminals as well as at the devices that serve as network attachment points (e.g., eNodeB, WiFi Access Points, etc.). As spectrum access issues relate to the physical and MAC layers, the measurements of interest from the spectrum management perspective also come from these layers. However, additional measurements taken at higher layers in the end-user terminals as well as in the rest of the network entities could also be utilized for spectrum sharing decisions. Table 19 provides the list of well-known measurements/parameters associated with physical and medium access layers in LTE and WiFi networks. Please note, that similar or additional measurements can be associated with other types of networks such as spectrum sensing results in cognitive radio networks which serve to indicate secondary access opportunities. The description of parameters presented in Table 19 is provided in other project documents, specifically in Milestone 3.1 and Deliverable 3.1.

Table 19 PHY and MAC layer measurements in LTE and WiFi networks

LTE Measurements	RSRP, RSSI, RSRQ, CQI, Received Interference Power, Thermal Noise Power, Sounding Reference Signal, Uplink Receive SINR, Time Difference of Arrival, Angle of Arrival, Timing Advance, Channel State Indicator, PMI, RI, Frame Structure Parameters, Resource Utilization/Availability Statistics, UE capability.
WiFi Measurements	RSSI, Received Channel Power Indicator, Beacon Report, Frame Report, Channel Load, Scheduling Granularity Information, Noise Histogram, Station Statistics, Neighbour Reports.

Apart from the measurements and parameters listed in Table 19, several other pieces of network-level information can be aggregated for facilitating spectrum management and sharing decisions. These parameters may have to be derived from some of the primitive measurements taken at different network entities (e.g. information such as network load, user distribution, traffic characteristics etc.) or introduced as new measurements required for supporting a particular type of network function.

For the northbound flows specific to spectrum management, the SDK will consider the following sets of functionality and associated APIs.

- **Measurement collection:** APIs for collecting the primitive and composite inputs (described above) that can serve as triggers for spectrum management and sharing decisions undertaken at the spectrum management application. Much of the network graph for spectrum management and its derivatives will be based on this functionality and the APIs developed for this purpose.
- **Network abstraction:** Network abstraction shall constitute a broad set of APIs that can be used for generating several abstract views of the network (e.g. network graph, topology information, radio resource view, etc.). At the most basic level, APIs for generating heterogeneous network graph or a subset of the pre-existing graphs on the request of SMA will be provided. This may also include the generation and storage of the resultant data-structures in specific storage locations accessible to the SMA and other applications.

6.2. APIs for Southbound flows

The southbound flows are primarily meant to implement any specific spectrum management and sharing decision through the COHERENT software control. These decisions could be very granular, e.g., setting transmit/receive parameters in a particular small-cell or very broad, e.g., enforcing a network-wide spectrum sharing rules. The core module in COHERENT architecture to implement these decisions is the C3 module which shall exercise its software control functions on top of the virtualized network infrastructure.

The specific set of APIs and functionality provided for software control through C3 can be derived from the different spectrum management and sharing use-cases. For example, implementing LSA rules shall require the provision of information about the concerned networks, scope of sharing, and relevant parameters. These could be provided as input to particular functions (e.g. through direct function calls) provided by the C3 to the spectrum manager application. Considering that a large number of decisions related to spectrum can be taken at the application level in heterogeneous networks, the SDK shall provide the following sets of functionality and associated APIs.

- **APIs for spectrum management:** Based on the network graph abstraction, the SMA can take different decisions about the utilization of radio spectrum in the network that can apply to the whole or a particular segment of the network such as a macro cell or a cluster of

small cells. The COHERENT SDK will provide control over the parameters that govern spectrum access at these different levels. APIs for configuring the radio resource management functions of the network and spectrum utilization will be considered.

- **APIs for spectrum sharing:** The second major consideration for SMA is sharing the spectrum with other networks based on the sharing agreement. Although the overall scope of spectrum sharing between/among networks may be determined by the applicable policies and regulations, the SDK should provide the necessary controls to acquire and release the shared spectrum on demand of the SMA. Additionally, SMA can utilize the shared spectrum differently than the dedicated spectrum and will therefore need the necessary APIs to do the required configurations.

6.3. APIs for Eastbound flows

In COHERENT, the eastbound flows are considered between/among multiple network operators utilizing the COHERENT software based network control. From the spectrum manager application perspective, these flows are primarily used for inter-network information exchange (e.g. through exposing subsets of operator-specific network graphs, spectrum utilization and availability information, etc.) and for communicating and coordination spectrum sharing decisions. Many inter-operator spectrum sharing decisions and rules are based on sharing agreements and on the applicable policies and regulations enforced by the regional or national regulatory authorities. Additionally, information about the state of radio spectrum can be associated to the presence of a Radio Environment Maps that may either exist in a local database or be provided by a third-party. This information may also be exchanged among network operators through eastbound interfaces among C3.

6.4. Programming Aspects

A primary consideration from a network application developer perspective is the independence in choice for the high level programming language used for developing the application logic and the ease of integration within the COHERENT architecture for network control. In other words, the developer should be free to program his application logic in any high-level programming language of choice and should be able to integrate it with the COHERENT C3 module through the provided northbound APIs. This implies that regardless of the language choices made for the COHERENT software control, the interfaces should be generic enough to allow different types of applications developed on different platforms. This aspect will be considered and the northbound interface will be generic enough to support most application development platforms.

7. COHERENT Pilot

In dense urban areas, mobile traffic volume in a region may undergo dynamically changes during the day because of rush hours or some special events happened in that region. When the traffic demand in a region is extremely high so that more spectrum is required to provide extra capacity, the mobile broadband shall have the flexibility to temporally provision more spectrum in the region, in order to guarantee users' quality of experience. The extra spectrum can be obtained from utilization of higher frequency bands (such as mm-waves), from intra-operator spectrum reallocation including flexible duplexing, inter-operator spectrum sharing, application of such solutions as Licensed Shared Access (LSA) from incumbent spectrum owners or Spectrum Access Systems (SAS), or other methods.

Even though spectrum sharing may seem the most feasible for dense urban areas, but also in rural areas from economical point of view it may be more beneficent to share a radio channel than to have a dedicated one at higher cost.

Efficient application of any spectrum sharing scheme will be possible only when a mobile network operator will be able to consume enough spectrum opportunities to guarantee reliable backhaul and fronthaul connection, depending on the operator's network infrastructure. The ability to flexible, yet precise spectrum control and management also in the context of x-haul is important to ensure realization of the Service Level Agreements (SLA) for the operator's clients.

Licensed Shared Access (LSA) can provide a competitive advantage for an operator in today's business environment. This is because an operator may allocate additional resources using LSA in a speedy way allowing him to follow customers' demand for bandwidth. The control of the spectrum will be managed by the operator or regulator so that the main user will always experience the expected quality of service.

Although much effort is and will be put on harmonization of spectrum usage around the world in the upcoming WRC15/19 conferences, it is the national regulator who defines the detailed rules of spectrum usage in a given region. Moreover, special spectrum usage templates can be defined for specific events triggering unusual bandwidth demand. For example, specific mass event (such as visit of a VIP or organization of mass sport contests), where many mobile users may request for high-quality uplink broadband services. These services may be provided for example by using the downlink direction of FDD channel.

In other cases, like industrial control or telemetering, a low amount of high quality licensed bi-directional spectrum may be needed. This in turn can be provided for example in the un-used time-frequency resources of the FDD uplink channel.

Finally, an operator may consider application of advanced schemes for offloading traffic to other 3GPP and non-3GPP networks in order to realize the committed SLAs. Clearly, such offloading can be done for either capacity or coverage, allowing user-centric service delivery.

Some examples of flexible duplexing, such as TDD or DL only in the uplink FDD frequency channel were already addressed in the previous 3GPP RAN studies. Their applicability is conditioned by the national regulations and by the ability to manage the interference within an operator deployment and in some cases also between operators.

The presence of customizable spectrum management and control framework can be a good candidate for 5G networks supporting flexible and effective mobile broadband access schemes. The new spectrum access schemes may be relevant to a number of vertical use cases, as identified in this document, as this use case proposes the ability to setup user-centric, service delivery supporting flexible spectrum access.

7.1. Spectrum sharing for Emergency Operational Centres (EOC)

Description

Fast, reliable and effective coordinated emergency and disaster management, as well as emergency preparedness belong to the key duties of the legal authorities of a given region. However, the need for

guaranteeing safety for great number of citizens in highly crowded or populated areas (e.g. big cities, agglomerations, concert halls, malls, mass events) entails the necessity for secure, reliable and immediate information exchange among various players. Such a situation can result in potentially quite challenging requirements for high peak-data rates and overall average throughput. In an extreme case the bandwidth demand may be so high that it will consume the total amount of spectrum assigned to the operator. However, such a high bandwidth demand is usually only observed infrequently for a given, finite time period and moreover at certain location. Emergency Operation Centre (EOC) responsible for management of a given region is a key player in such a case as it is the central control, command and coordination facility with legal authority for the strategic view and management. However, in order to fulfil such requirements, EOCs will need to find enough amount of resources (including spectrum and infrastructure) for data transmission. In this use case we concentrate on advanced spectrum leasing schemes for efficient EOC functioning, where classical solutions like LSA or SAS may not work effectively enough. Moreover, because none of the already operating solutions in 3.6-3.8GHz band (selected by polish EOC) has implemented *listen-before-talk* functionality thus LSA or SAS would simply not work in this case. More advanced spectrum solutions have been indicated by ECC in its strategic plan for years 2015-2020 documents [CEPT_2014] and are under consideration by dedicated project teams (such as FM49, which is working on Radio Spectrum for PPDR services).

Challenges and innovation

The main challenge is to define highly flexible spectrum management strategy that will guarantee secure and reliable delivery of broadband PPDR services to the key actors, e.g. EOC, while maintaining the operation of other networks possibly unchanged. Here, in case of mass disaster, the goal is not only to share the RAN or infrastructure in order to serve higher data rates, but also to temporarily change the priorities of users served by the network, or even switch off part of the services in order to guarantee fast and reliable EOC functioning. It means that when the disaster happens the EOC could become one of the key incumbent users at the price of additional cost to the network operator and its users. New spectrum usage paradigms should be defined in such a case, that will lead to improved performance and spectrum utilization. However, at the same time the normal users (served by the network before the crisis) should be granted minimum throughput in order to guarantee their SLAs.

Benefits / key capabilities

- Insurance of reliable broad band PPDR service delivery in critical situations
- Flexible use of frequencies below 6GHz for PPDR services (e.g., one can concentrate on 3.5GHz band)
- Better traffic management – high peak rate traffic can be managed effectively due to better frequency utilization

Plans for the EOC pilot in Poland

The pilot is going to be performed in the city of Poznań (one of the major cities in Poland). The regional EOC is based in Poznań but does not have any license for radio channels. Therefore, EOC has approached INEA asking if there is any chance for leasing or sharing of radio channels in 3.6-3.8GHz band assigned to INEA. This is not a trivial question since INEA operates Wimax 802.16e network in this band and does not have any single channel which would be unused. Therefore, INEA has asked researchers in COHERENT project about what would be the best scheme for such a cooperation having in mind that existing INEA 802.16e equipment does not support *listen-before-talk* functionality. After a few discussions at COHERENT advanced leasing with dynamic user priorities was proposed. Currently researchers from COHERENT are preparing technical details taking into account technical specifications of the selected equipment and their configuration. To be more specific EOC decided to test eLTE system from Huawei (<http://e.huawei.com/en/products/wireless/elte-trunking>) operating on 3.4-3.8GHz band. EOC would also like to install two eNodeB at two location belonging to city hall. EOC would like to use at least one 10MHz channel. However, INEA current configuration utilizes only 7MHz channels. Moreover,

further analysis such as frame duration, split between DL and UL, needs to be performed to allow for best coexistence between the two systems. In general lots of preparations need to be performed in advance before the pilot. To complicate things even further the radio planning needs to be prepared for the various cases which will take into account changing priority levels between customers.

In general, this pilot will be a good proof of concept of advanced leasing scheme where legacy equipment may not support advanced sharing schemes similar to SAS. Moreover, we expect that such a scheme may be better suited for emergency operation where the change of priorities need to be performed at a great speed and should not depend on status of synchronization among parties.

7.2. INEA Poznan, Poland

INEA wireless network consists of WiMax 802.16e and WiFi 5GHz equipment and is deployed over Wielkopolska region (west part of Poland). The network is most dense around Poznań area and Figure 7-1 presents the complexity of the current radio channel allocation and radio planning for 3.6-3.8GHz band occupied by WiMax 802.16e network. Since WiMax technology is at decline [Mathias_2011] and does not allow to offer new services, thus INEA is looking for different opportunities to utilise the 3.6-3.8GHz band. Spectrum sharing schemes provide a promise for additional revenue, and spectrum sharing for Emergency Operational Centres (described in the previous section) is one of the use cases.

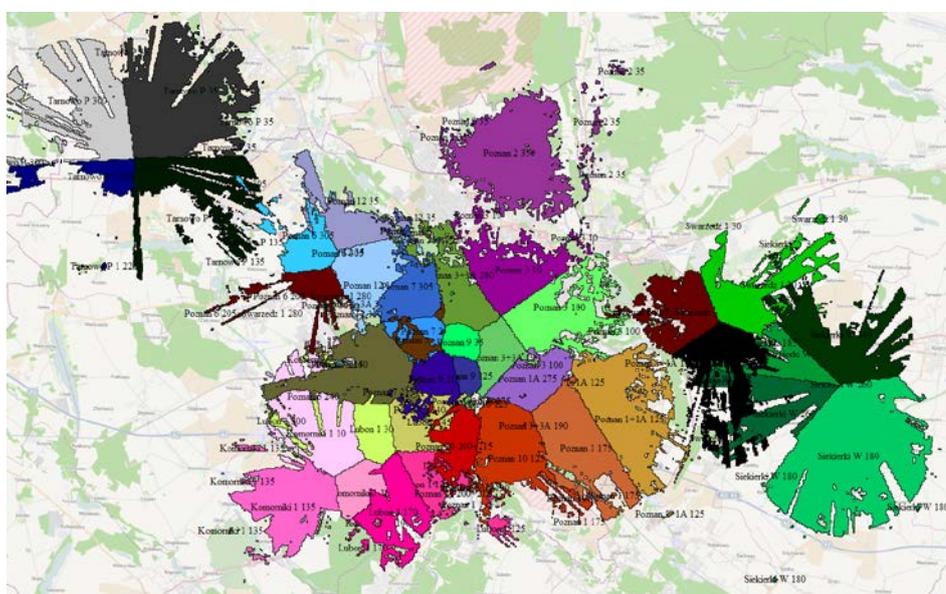


Figure 7-1. INEA – coverage of WiMax 802.16e network around Poznań area

7.3. OTE Athens, Greece

The OTE labs are hosting a 3G/4G FDD network along with a WiMAX network that has been recently transformed to LTE at 3.4-3.6 GHz spectrum but is not yet operational. There is a possibility to present trials from different users who want to access this spectrum. In addition, the lab consists of cognitive cellular networks (CCNs) with two kinds of cases. The first one is where secondary users (SU) are trying to access the spectrum of cognitive networks which are occupied mostly by primary users (PU). These PUs are the ones who primarily pay for accessing the spectrum of cognitive networks (CNs), while the SUs are dynamically searched for spectrum availability. The CN adapts dynamically its network in order to provide with the best network capabilities for both users. The second case is where secondary small cell (femtocell, picocell) networks dynamically share the licensed spectrum of primary networks. Usually the secondary users/networks have lower priority in accessing the available spectrum than the PUs/primary networks.

8. Summary

This document examines the idea of advanced and flexible spectrum sharing from various perspectives. It starts with an overview of existing spectrum sharing schemes, and corresponding technical and legal guidelines. The COHERENT view on the spectrum usage in the context of 5G networks and beyond is presented based on the state of the art of the spectrum management in wireless communication systems. The spectrum management system that communicates with the COHERENT central controller and coordinator framework is proposed and the functionality is analysed. The prospective use cases regarding the new spectrum management have been identified. Some initial simulation results regarding the micro-area spectrum sharing, i.e. flexible duplex, are presented. The thoughts on the design of APIs and SDK required for efficient spectrum management in virtualized wireless networks have been discussed. Finally, initial decisions regarding the planned trials in the project have been presented.

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A. Annex – Concise Collection of Legal Documents or Guidelines Defining the rules for Dynamic Spectrum Usage.

A.1. Use cases classification in 3GPP TR

In 2012, the European Commission (EC) published a communication¹ on the subject of spectrum sharing:

Spectrum sharing contracts can provide users with legal certainty while creating market-based incentives, including financial compensation, to identify more beneficial sharing opportunities in the internal market, if National Regulatory Authorities (NRAs) grant shared spectrum access rights to additional users of a frequency band.

As further discussed in [A_RSPG_2013], access and use of spectrum is authorized under licensed and license-exempt ways. Besides these two ways to grant spectrum access, the concept of Licensed Shared Access (LSA) made its way, starting from the initial industry effort Authorized Shared Access (ASA).

Licensed Shared Access (LSA) could provide new sharing opportunities on a European scale under a licensing regime, while safeguarding national current spectrum usages which cannot be reformed. It is not intended that LSA will be an initial or temporary phase prior to the reforming of any band. Consequently, general sharing conditions should be agreed at European level, taking into account national particularities in bands designated for LSA at EU level, thus offering new opportunities for providing services with a good Quality of Service in spectrum within Europe. This new concept needs to be further developed, in particular regarding the possibility to dynamically modify licensing conditions within the framework of the recently adopted EU regulation

In the remainder of this chapter, regulatory aspects which facilitate the adoption of spectrum sharing worldwide are discussed, to create the ground for selecting the most promising approaches and develop new spectrum sharing techniques within the COHERENT project.

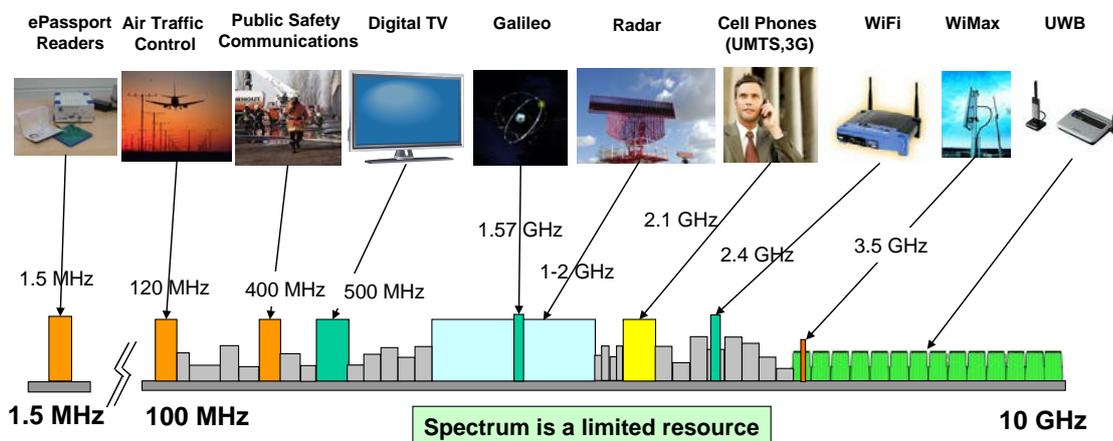


Figure A-1: Radio frequency spectrum and corresponding radio services.

¹ COM (2012)478 Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Promoting the shared use of radio spectrum resources in the internal market.

A.2.FCC decisions

In the USA, the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA) are responsible for managing the radio spectrum: *that portion of the electromagnetic spectrum at frequencies between 3 kHz and 300 GHz*. The FCC and NTIA manage non-Federal (industry, state and local governments, and others) and Federal use of spectrum, respectively [A_Agre_2015]. NTIA works closely with federal agencies to manage the radio spectrum through the Inter-department Radio Advisory Committee (IRAC). In 2013, the president memorandum assigns the spectrum policy team the task to produce a report on how NTIA and FCC incorporate spectrum sharing in their activities.

Table 20: FCC technical documents on specific spectrum sharing activities.

Spectrum sharing scheme	Document	Description
Spectrum Access System (SAS)	Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth, PCAST Report, (July 2012)	The database centric model, which supports spectrum sharing with three levels of hierarchy in spectrum usage (see Figure below). “Two possible frequency bands, AWS-3 in the 1.7 GHz band (a total bandwidth 65 MHz) and 3.5 GHz with a total bandwidth 150 MHz. “FCC considers the lower 100 MHz in the 3.5 GHz band (3.550 – 3.650 GHz) being used by federal systems, such as costal / macro radar and by fixed satellite systems, for shared access in addition to the yet unused upper 50 MHz (3.650 – 3.700 GHz).” [A_Gundlach_2014]
TV WhiteSpace (TVWS)		“FCC regulation mandates that each network contacts a certified database and provide information about its location and transmission parameters to query the available TVWS channels at its geographic location. As such, the DM can perform the function of the spectrum broker in this setting. Furthermore, FCC categorizes TV band devices into fixed and portable/personal devices. Fixed devices are high power base stations that are used, for example, to provide internet access in under-served areas.” [A_Khalil_2014]

Summary of Selected Spectrum Sharing Initiatives

Spectrum Sharing Initiative	Primary Sharing Mechanism	Spectrum Band(s)	Shared Bandwidth	Incumbent Users	New Users	Status
Advanced Wireless Services (AWS-3)	Manual coordination of protection zones	1695–1710, 1755–1780, and 2155–2180 MHz	40 megahertz	Fed/Non-Fed (1695–1710); Fed (1755–1780)	Licensed	Mar 2014: Report and Order (R&O) Nov 2014–Jan 2015: Auction
3.5 GHz Citizens Broadband Radio Service (CBRS)	Spectrum Access System for 3-tiered access	3550–3700 MHz	150 megahertz	Fed	Licensed for priority access; Licensed by rule for general authorized access	Apr 2015: R&O and Second Further Notice of Proposed Rulemaking (FNPRM) Jun 2015: Public Notice
MedRadio	Listen before talk	401–406 MHz (402-405 already shared)	2 megahertz	Fed/Non-Fed	Licensed by rule	Mar 2009: R&O
Medical Micropower Networks	Dynamic frequency selection	413–419, 426–432, 438–444, and 451–457 MHz	24 megahertz	Fed/Non-Fed	Licensed by rule	Nov 2011: R&O
Medical Body Area Networks	Manual coordination	2360–2400 MHz	40 megahertz	Fed/Non-Fed	Licensed by rule	May 2012: First R&O and Further NPRM
Commercial Space Launch	Manual coordination	420–430, 2200–2290, 5650–5925 MHz	375 megahertz	Fed	Licensed	May 2013: NRPM and Notice of Inquiry (NOI)
Federal Earth Stations	Manual coordination	10 bands in the C, Ku, Ka, and V satellite bands	13.275 gigahertz	Non-Fed	Federal allocation	May 2013: NRPM and NOI
Level Probing Radar (LPR)	Directional, contained emissions	5.925–7.250, 24.05–29.00, 75–85 GHz	16.275 gigahertz	Fed/Non-Fed	Unlicensed	Jan 2014: R&O and Order
600 MHz Incentive Auction	TV white spaces database	512–698 MHz (42-144 megahertz to be repurposed)	20–34 megahertz	Non-Fed (Broadcast)	Unlicensed – guard bands	Jun 2014: R&O Aug 2015: Public Notice Aug 2015: R&O
TV White Spaces	TV white spaces database	54–60, 76–88, 174–216, 470–698 MHz	Varies (est. to average 107 megahertz)	Non-Fed (Broadcast)	Unlicensed – unused TV channels	Apr 2012: Third Memorandum Opinion and Order
U-NII Expansion	Dynamic frequency selection	5.350–5.470 GHz (U-NII-2B); 5.850–5.925 GHz (U-NII-4)	Additional 195 megahertz	Fed/Non-Fed	Unlicensed	Apr 2014: First R&O (under study)
60 GHz Unlicensed	Manual coordination of narrow beams, low power	57–64 GHz	7 gigahertz	Fed/Non-Fed	Unlicensed	Aug 2013: R&O
70-80-90 GHz Millimeter Wave	Manual coordination of narrow beams	71–76, 81–86, and 92–95 GHz (except 94.0–94.1)	12.9 gigahertz	Fed/Non-Fed	Licensed (70/80 GHz); Unlicensed (90 GHz)	Mar 2005: Memorandum Opinion and Order

Figure A-2: Overview of spectrum sharing initiatives undertaken in the USA by FCC and NTIA [A_Agre_2015]

A.3.FCC regulations enabling the use of UL FDD bands for downlink transmissions

3GPP, while recognizing the typical 4:1 traffic asymmetry, has decided to “Identify and document potential regional/band-specific regulatory possibilities/constraints for the use cases of utilizing UL spectrum for transmission from the network to UEs”

As part of the work were sent Liaison Letters to a number of administrations. The FCC response is included in the 3GPP document RP-150575 [A_FCC_2015_1] and the table of FDD bands allowing DL transmission in the FDD uplink bands is reproduced below:

Table 21. List of FDD bands allowing DL transmission in the FDD uplink bands

Frequency Range (MHz)	3GPP band UL	Description	Technical rules (Part & Subpart)	Authorized Operations in 3GPP UL Portion	Power limits and frequencies
699-716	12, 17	Lower 700	Part 27 Subpart C	base, fixed, control, mobile, portable	27.5, 27.50(c)
777-787	13	Upper 700	Part 27 Subpart C	base, fixed, control, mobile, portable	27.5, 27.50(b)
814-824	26	SMR	Part 90 Subpart S	mobile, control	90.613, 90.635
824-849	5, 26	Cellular	Part 22 Subpart H	base, mobile	22.905, 22.913
1695-1710	TBD	AWS-3 unpaired	Part 27 Subpart C	mobile, portable	27.5, 27.50(d)
1710-1755	4	AWS-1	Part 27 Subpart C	fixed, mobile, portable	27.5, 27.50(d)
1755-1780	66	AWS-3 paired	Part 27 Subpart C	mobile, portable	27.5, 27.50(d)
1850-1915	2, 25	PCS	Part 24 Subpart E	base, mobile, portable	24.229, 24.232
1915-1920	TBD	H block	Part 27 Subpart C	fixed, mobile, portable	27.5, 27.50(d)
2000-2020	23	AWS-4	Part 27 Subpart C	fixed mobile and portable and waiver to allow base	27.5, 27.50(d)
2305-2315	30	WCS	Part 27 Subpart C	base, fixed, mobile and portable	27.5, 27.50(a)
2496-2690	41	BRS/EBS	Part 27 Subpart C	main, booster, base, mobile and other user stations	27.5, 27.50(h)

A.4. Radio Spectrum Policy Group

As mentioned in [A_RSPG_2013], the Radio Spectrum Policy Group (RSPG) was established by the Commission with the following purpose:

The RSPG shall assist and advise the Commission on radio spectrum policy issues, on coordination of policy approaches, on the preparation of multiannual radio spectrum policy programmes and, where appropriate, on harmonised conditions with regard to the availability and efficient use of radio spectrum necessary for the establishment and functioning of the internal market.

In past years, the RSPG has expressed opinions on the Collective Use of Spectrum (CUS) within several technical documents, in which different spectrum sharing arrangements are discussed, in light also of cognitive radio principles. In [A_RSPG_2011], the RSPG reviewed different spectrum sharing arrangements and identified in higher frequency bands than what used nowadays, such as millimetre waves, potential candidates to facilitate new radio services. In [A_RSPG_2011], the RSPG further explores policy implications on the use of White Spaces, and underpinning the concept of LSA, which

is built upon the initial idea of ASA. It is worth to embrace the definition of CUS provided by the RSPG:

Collective Use of Spectrum allows an unlimited number of independent users and/or devices to access spectrum in the same range of designated CUS frequencies at the same time and in a particular geographic area under a well-defined set of conditions.

In [A_RSPG_2011] the RSPG argues that CUS has been successfully implemented in the frequency range 863-870 MHz, in which millions of different devices are in use, including wireless microphones, sensors and people and goods tracking, to name a few. The clear harm in case of spectrum sharing consists of the interference which might impair the quality of the services provided. To counteract against this threat, a number of techniques were developed with time, including Detect and Avoid (DAA), Transmit Power Control (TPC), Low Duty Cycle (LDC) and Listen Before talk (LBT). All the mentioned techniques have the objective to enable systems which can guarantee certain level of quality of service (QoS). Furthermore, to relieve the problem that lower frequency bands (below 10 GHz) are relatively crowded, there is an increasing interest in exploiting frequency bands above 40 GHz, where ample ranges of frequency bands, in particular unlicensed, can be exploited still, provided that existing technical limitations can be overcome. Technical limitations mainly come from the more severe propagation environment as soon as radio communications exploit higher frequency bands (e.g. millimetre wave). On the other hand, the more severe propagation conditions provide the benefit of further reducing interference between systems sharing the same portion of spectrum.

The RSPG has in addition evaluated several spectrum sharing models and in particular: administrative mode, also referred to as command and control, which is regulated by national regulatory authorities; market based model such as auctions; LSA. In particular, for LSA, as mentioned above, starting from the idea of authorized shared access, developed in past years the concept of licensed shared access, to foster spectrum utilization in the frequency range in which a licensee already operates but which is encouraged to share the spectrum with new users, fulfilling specific technical constraints and regulations set forth by national authorities in order to enable services over the shared spectrum with QoS guarantees.

At last, given the growing interest worldwide in utilizing higher frequency bands such as millimetre waves, it is worth mentioning the regulations for using such portion of the spectrum, as shown below.

Table 22: Regulatory situation of millimetre wave spectrum in different geographical areas worldwide [A_Yong_2007], [A_Geng_2009]

Region	Frequency Band (GHz)	Tx Power	EIRP	Antenna Gain	Description
USA	7 (57-64)	500 mW	40 dBm (Av.) 43 dBm (Max.)	NS	For bandwidth > 100 MHz translate from average power density of 9 $\mu\text{W}/\text{cm}^2$ and 18 $\mu\text{W}/\text{cm}^2$ at 3 m
Canada	7 (57-64)	500 mW	40 dBm (Av.) 43 dBm (Max.)	NS	For bandwidth > 100 MHz translate from average power density of 9 $\mu\text{W}/\text{cm}^2$ and 18 $\mu\text{W}/\text{cm}^2$ at 3 m
Japan	7 (59-66)	10 mW (Max.)	NS	47 dBi	
Australia	3.5 (59.4-62.9)	10 mW (Max.)	150	NS	Limited to land and maritime deployment
Korea	7 (57-64)	10 mW			
Europe	9 (57-66) Min. 500 MHz	20 mW (Max.)	57 dBm (Max.)	37 dBi	ETSI Recommendations

A.5. ECC decisions /ETSI standards

To sustain the growing demand of new MBB services has led for a few years the EC to conclude that spectrum sharing could be one of the key components to relieve the problem of spectrum availability, together with spectrum refarming. The EC is further making the effort to create harmonized frequency bands to use for spectrum sharing across the European countries, closely cooperating with NRAs. If combined also with a unified set of spectrum sharing techniques, this approach could offer the possibility of fostering the European market for MBB. Different studies were done in the past few years exploring different frequency bands and taking into account different techniques, as discussed herein below.

Along the direction of identifying new spectrum opportunities and technical enablers for spectrum sharing, the Electronic Communications Committee (ECC) of CEPT defines as ‘White Space’:

A label indicating a part of the spectrum, which is available for a radio communication application (service, system) at a given time in a given geographical area on a non-interfering / non-protected basis with regard to other services with a higher priority on a national basis, ECC Report 159 [A_ECC_2013_1]

The preliminary assessment carried out in [A_ECC_2013_1] was extended in [A_ECC_2013_2] for whitespace devices (WSDs) in the UHF frequency band between 470-790 MHz (the result of the digital dividend below 800 MHz) in relation to the adoption of a GEO-location database and other technical requirements to enable WSDs in the band 470-790 MHz. Essentially, the approach consists in resorting to the GEO-location database to determine which frequencies are available in the geographical location of the users. Furthermore, [A_ECC_2013_2] describes the approaches and algorithms to use in the database to ensure development, maintenance and operation of the GEO-location database, and to enable protection of incumbent services. The same technical document is used to convey information related to the necessary location accuracy, which is needed to the enable spectrum access of the WSDs through the GEO-location database.

Table 23: Plans for using whitespaces in the band 470-790 MHz [A_RSPG_2011]

Country	Status
UK	Consulted on the feasibility of implementing geo-location in November 2010 and issued a statement in September 2011 which aims to establish a regulatory framework to enable White Space Devices and geo-location databases to emerge in the UK. Trials also underway in Cambridge focused on the use of TV White Space (see annex C for more information).
Ireland	PMSE licences can currently be granted in the 470 – 790 MHz band within Ireland. ComReg’s test and trial licence scheme provides an opportunity for spectrum users to apply for temporary test licences within the 470 – 790 MHz band for dynamic spectrum access technology. Test licences have been granted in the past for cognitive radio testing purposes.
Denmark	White spaces in the frequency band 470 - 790 MHz could until recently (October 2010) be used for PMSE with a frequency that is not used for DTT in a given geographical area, as described in section 7.7. above.
Germany	Licensed the current white space spectrum in traditional scheme to PMSE (SAB/SAP; ENG), PMR and wind-profilers
France	White spaces in the frequency ranges 174-223 MHz, 470-790 MHz and 823-832 MHz have been designated for professional wireless radio microphones under a general authorisation regime on a non-protection, non-interference basis.

The initial approach proposed by cognitive radio of opportunistic spectrum access (OSA), which allows radio terminals to access licensed spectrum whenever a whitespace occurs, or in other words the license owner does not use it, showed some clear limitation due to the unpredictable nature of spectrum availability, the duration of a spectrum vacancy and complex technical implications. OSA hence would not provide any QoS guarantee. Subsequently Qualcomm proposed ASA, combining the concept of cognitive radio with licensing in geographical regions where the incumbent operator underuse the frequency bands allocated. The ASA concept takes advantage of licenses assigned by the regulator to the ASA licensee. The commission as further step has promoted LSA as the technical and non-technical enabler of LSA as thoroughly presented in [A_Mustonen_2015]. LSA is technically similar to ASA, since it allows access to shared spectrum on a non-interfering basis but in addition, it emphasizes more the licensing part. LSA, despite constitutes one of the most promising approaches to enable spectrum sharing, is not the only one and came up beside “Licensed-Exempt” [A_RSPG_2013]:

The right to use the spectrum is afforded to devices that meet certain technical conditions to share the spectrum and which have a low probability of causing interference to other services. The regulator takes no responsibility for protecting individual users of licence-exempt devices against interference and does not provide a legal guarantee for ensuring a certain quality of service (QoS). An example of licence-exempt use is the 2.4 GHz spectrum for the provision of Wi-Fi access service.

Currently, LSA is considered within Europe as the enabler for MBB within the frequency range 2.3-2.4 GHz [A_ECC_2014_1]. Initially, under the ASA concept, the spectrum allocated was 2.3 GHz (sharing with military and wireless cameras) and 3.8 GHz (mobile with satellite). From an historical perspective, based on the investigations of the Correspondence Group on Cognitive Radio Systems (CG-CRS), the Working Group Frequency Management (WGFM) decided to extend the concept of ASA to LSA. In September 2012, the WGFM established Project Team FM 53 and Project Team FM 52, respectively to provide CEPT with guidelines with respect to LSA and to develop ECC decision on the harmonized band plan within 2.3-2.4 GHz for Mobile/Fixed Communications Networks (MFCN) and the adoption of LSA within the same frequency range. As discussed in

[A_Mustonen_2015], the ECC decision on the 2.3-2.4 GHz band was taken in June 2014 [A_ECC_2014_2].

or completeness, the time plan for LSA within ETSI is shown in figure below.

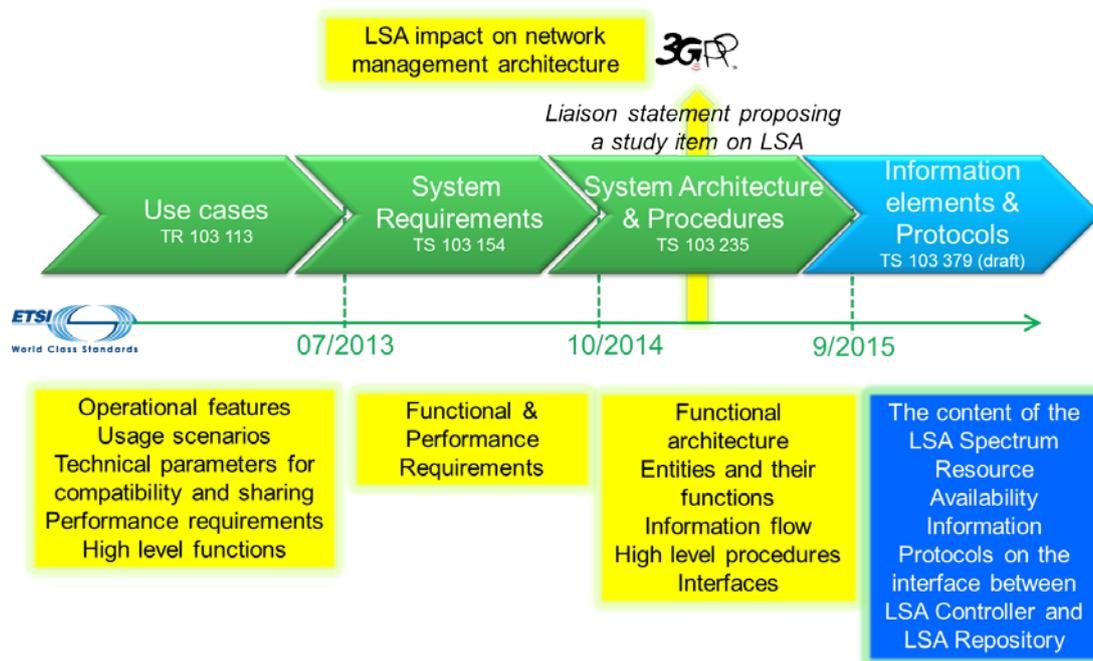


Figure A-3: Overview of ETSI activities in relation to the process of promoting an harmonized approach and standardization of LSA within Europe.

ETSI develops standards for telecommunications in Europe and has addressed several problems, including compatibility between different radio services [A_ECC_2014_3]. As such, spectrum sharing falls within the competences of this organization. In recent years, ETSI Reconfigurable Radio Systems (RRS) produced server technical reports on the topic, exploring different scenarios such as spectrum on demand [A_ETSI_2009], and the applicability of cognitive radio concepts [A_ETSI_2010]. The EC gave mandate to ETSI RRS to work on LSA in 2011, with the scope to allow more bandwidth for mobile network operators, allowing the access within the frequency region of 2.3-2.4 GHz. ETSI RRS produced the first report in response to this mandate in [A_ETSI_2013] and in [A_ETSI_2014_1] systems requirements for access to the 2.3-2.4 GHz band were provided. The RRS group made in addition the effort to map high level functions which are required to enable LSA to the elements of candidate architecture, as discussed in [A_ETSI_2014_2]. For completeness, the RRS includes also TV whitespaces, usage of new spectrum for public safety usages and the reconfiguration of radio apparatus through radio applications.

Table 24: Summary of ECC decisions and ETSI standards.

Spectrum sharing scheme	Document	Description
LSA	ECC report 205 (February 2014)	The report contains: a general analysis of LSA, current practises in terms of spectrum management and frequency authorizations and applications of LSA to the mobile application case [A_Matinmikko_2014], particularly in the 2.3-2.4 GHz.
	ECC Decision (14) BB “Harmonized technical and regulatory conditions for the use of the band 2.3-2.4 GHz for MFCN” (Mobile/Fixed Communications Networks)	The purpose of this ECC Decision is to provide harmonized technical and regulatory conditions for the use of the band 2.3-2.4 GHz for mobile/fixed communications networks (MFCN) (including broadband wireless systems).
TVWS	ECC Report 159 “Technical and operational requirements for the possible operation of cognitive radio systems in the ‘White Spaces’ of the frequency band 470-490 MHz” (November 2011)	“The report focuses on the protection of incumbent, or primary, use of the spectrum. Within the band, other systems to protect, in addition to TV signals, are program making and special event (PMSE) equipment, radio astronomy, and aeronautical radio navigation. The report also analyses potential interference from white spaces devices to adjacent bands. As sensing was concluded to be inadequate for the protection of incumbent services these studies were expanded with a report on the technical requirements for white space devices and geo-location databases.” [A_Matinmikko_2014]
	ECC Decision (11) 06 “Harmonised frequency arrangements for mobile/fixed communications networks (MFCN) operating in the bands 3400-3600 MHz and 3600-3800 MHz”	CEPT administrations shall designate the frequency bands 3400-3600 MHz and 3600-3800 MHz on a non-exclusive basis to mobile/fixed communications networks (MFCN), without prejudice to the protection and continued operation of other existing users in these bands.

A.6.3GPP/5GPPP decisions, guidelines, expectations

3GPP defined already in Release 6, the function of Multi-Operator Core Network (MOCN) as an option to enable both network and spectrum sharing [A_3GPP_2003]. In more recent releases, the topic has been further developed, as shown in [A_3GPP_2010] for the Release 8 and in [A_3GPP_2011] for the Release 10. Indeed, the MOCN function shall allow different operators to share the same carrier.

Motivated by the huge increase of spectrum demand, 3GPP has further explored the possibility to establish LTE communications over unlicensed portions of the spectrum. A specific study item under the name of Licensed-Assisted Access (LAA) to unlicensed spectrum was made for the Release 13 as shown in [A_3GPP_2015]. As discussed in [A_Mustonen_2015], in April 2015, ETSI RRS sent a liaison statement to 3GPP SA5 to begin a study item on LSA in order to identify the enablers which would lead to LSA as a global solution. On the other hand, in [A_Qualcomm_2014], the possibility of

leveraging on unpaired spectrum whereby the use of TDD was discussed. The use of unpaired spectrum could open up to new portions of bands over different frequencies. Relying on [A_Qualcomm_2014], the following new spectrum opportunities coming out of this approach are described below.

Table 25: New spectrum opportunities leveraged by TDD LTE.

Global unpaired spectrum	1.9 GHz (B39) 1890 to 1920 MHz	2.3 GHz (B40) 2300 to 2400 MHz	2.6 GHz (B38) 2570 to 2620 MHz	2.6 MHz (B41) 2496 to 2690 MHz	Around 3.6 GHz (B42/43) 3.4 to 3.6 and 3.6 to 3.8
Potential spectrum	40 MHz	100 MHz	50 MHz	194 MHz	400 MHz

The 5G Infrastructure Association has recently established a Working Group (WG) on Spectrum in order to focus on the following objectives [A_5GPPP_2015]:

1. Promote European results
2. Facilitate common interests across projects
3. Maximize the outcome towards relevant technical bodies
4. Establish a knowledge base from project results
5. Liaise with regulatory bodies and industry associations
6. Improve understanding of spectrum research important
7. Coordinate with other researchers worldwide to ensure convergence and compatibility.

Several 5G projects are currently involved in exploring new spectrum opportunities with the discussion setting a delimiter for frequency bands below and above 6 GHz. The frequency bands above 6 GHz open up to the possibility of using for instance millimetre wave communications.

The following projects conduct specific activities on spectrum under the general coordination of the 5G Spectrum WG:

Table 26: Current activities undertaken by different 5G projects [A_5GPPP_2015]

Project	Activities
5G-Xhaul	Focus on 60 GHz band for fronthaul/backhaul
COHERENT	Management schemes for shared spectrum
FANTASTIC-5G	Spectrum access below 6 GHz
METIS-II	Spectrum rationale and technical aspects related to spectrum
mmMAGIC	Spectrum above 6 GHz, including mm-waves
Speed-5G	Dynamic spectrum access
5G-Crosshaul	Integrated fronthaul/backhaul options in the frequency range up to 100 MHz with specific focus on the 50 – 90 GHz range

A.7. Others regulations

In Australia, the Australian Communications and Media Authority (ACMA) is the entity in charge of managing the radio frequency spectrum. In the five-year spectrum outlook (FYSO) technical report,

ACAM discusses several spectrum requirements and management issues within the horizon between years 2015 and 2019 [A_ACMA_2015]. In this report ACMA discusses several themes related to spectrum management from the perspective of Australian authorities and the focus on the 400 MHz, 800-900 MHz and 1800 MHz bands. The general trend is to incentive the use of spectrum in a more efficient manner, including using spectrum sharing approaches. The adoption of Dynamic Spectrum Access (DSA) and Cognitive Radio System (CRS) as overlay technologies in the VHF/UHF frequency was explored in [A_ACMA_2016]. Within the same document, it was explored also the possibility to use underlay technologies such as ultra wideband.

In New Zealand, as described in [A_Ofcom_2015], the government department in charge of spectrum management has established in 2014 a temporary arrangement for access to TV whitespaces. Such an arrangement was made with the objective to grant licenses to whitespace devices without the need of a database, with the only requirement that they comply with FCC rules or ETSI standard EN 301 598.

In Canada, the Industry Canada (IC), the government department released in 2012 its decision to enable access to TV whitespaces, permitted on a no-protection, no interference basis to licensed users within the same frequency band, without limitations on the number of database administrations. In 2015 the IC released further technical specifications and operational requirements for whitespace devices, which broadly follows US requirements for equipment types and technical characteristics. In addition, the Canadian authority planned two auctions, one for the 700 MHz band and a following one for the band between 2500 and 2690 MHz in the broadband radio services band. The overall goal is to double mobile spectrum from 270 to 528 MHz by 2015. In addition, IC has opened large block of spectrum in the 70/80/90 GHz range, as well as new bands in the 28 GHz range for backhaul equipment [A_Fernando_2013].

A.8. Activities in Asia

In Singapore the Infocomm Development Authority (IDA) approved in November 2014 the rules enabling access to TV whitespaces on a licence-exempt basis provided that devices comply with the technical requirements specified by the IDA, contact a licensed database to obtain channel availability, and are registered with the IDA following a validation process [A_Ofcom_2015]. The device types and requirements are broadly in line with the US model, although Singapore allows for variable EIRP levels (like the UK/ETSI model). The IDA has introduced two High Priority Channels (HPC). These channels can only be activated when there are no common TV whitespace channels available given location. The HPC access will be managed by the Geo-location Database and the allocation method (including any fees to be imposed) will be left to the commercial decisions of the Database providers.

Further insights about spectrum regulatory aspects can be found in [A_ECO_2014], with particular emphasis on the Japanese situation.

A.9. Annex references:

- [A_3GPP_2003] “Network Sharing; Architecture and Functional Description,” TR 23.851, v1.0.0 3GPP, Sept. 2003.
- [A_3GPP_2010] “Network Sharing; Architecture and Functional Description,” TS 23.251, v8.2.0, 3GPP March 2010.
- [A_3GPP_2011] “Network Sharing; Architecture and Functional Description” TS 123.251, v10.1.0, 3GPP March 2011.
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- [A_ECC_2013_1] ECC Report 159 “Technical and operational requirements for the operation of cognitive radio systems in the ‘white spaces’ of the frequency band 470-790 MHz”.
- [A_ECC_2013_2] ECC Report 186, “Technical and Operations Requirements for the Operation of White Space Devices Under GEO-Location Approach,” Jan. 2013.
- [A_ECC_2014_1] “Licensed Shared Access (LSA),” *ECC Report 2015*, Feb. 2014.
- [A_ECC_2014_2] “Harmonized Technical and Regulatory Conditions for the Use of the Band 2300-2400 MHz for Mobile/Fixed Communications Networks (MFCN),” *ECC Decision (14)02*, CEPT, June 2014.
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- [A_ETSI_2010] “Reconfigurable Radio Systems; Cognitive Radio Concept,” ETSI TR 102.802 v1.1.1, Feb. 2010.
- [A_ETSI_2013] “Mobile Broadband Services in the 2300-2400 MHz Frequency band Under Licensed Shared Access regime,” ETSI TR 102.113, July 2013.
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