Mobile and wireless communications Enablers for the Twenty-twenty Information Society-II

Deliverable D3.2
Enablers to secure sufficient access to adequate spectrum for 5G

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Abstract
This deliverable considers aspects to enable and secure access to adequate and sufficient spectrum for 5G. This includes quantity and quality assessment of the spectrum demand for 5G use cases and user groups, recognizing the bands considered for WRC-19, novel dynamic spectrum access concepts, necessary technical enablers and 5G spectrum management architecture.

Executive summary

Main challenges of spectrum management in future 5G networks are to integrate numerous frequency bands from within a wide range of spectrum under the appropriate spectrum access condition (like exclusively licensed / shared / license-exempt), and to cope with the diverse spectrum requirements from different user groups.

Success of 5G depends on the access to sufficient amount of contiguous, wide and globally harmonized new frequency bands. Frequency bands under consideration for the provision of 5G services range from 600/700 MHz up to the 86 GHz. For the first 5G roll-out phase, for bands below 6 GHz, the 700 MHz and the 3400-3800 MHz are in focus while, and for bands above 6 GHz, parts of the range 24.25-29.5 GHz offer a good potential depending on the national/regional circumstances.

The spectrum bandwidth demand for 5G services depends on a number of factors, including the use case, the applications used, the deployment scenario, the frequency band, etc. Three xMBB use cases and one uMTC use case, as defined in METIS-II, were analysed in this Deliverable. For example with varying assumptions, a total bandwidth demand of 2.4-7.1 GHz was estimated for the use case “dense urban information society”. For the use case “connected cars – traffic efficiency and safety”, analysis show a bandwidth demand estimate of about 400-800 MHz for communication ranges of 500-1000 m.

The concept for spectrum management and spectrum sharing for 5G mobile networks developed in the METIS project is enhanced in order to cover also radio spectrum already designated to potential new 5G user groups (e.g. for vertical industry applications like ITS or PPDR). Furthermore, the technology components for flexible spectrum usage developed in METIS are complemented by additional technical enablers, covering e.g. application context awareness and QoS driven scheduling.

In order to support flexible spectrum management, a holistic functional architecture is proposed. For the respective regulatory authority domain, the LSA architecture reference model defined by ETSI is enhanced in order to support additional sharing methods and to manage spectrum resource user authorization in a more flexible way. The mobile network operator domain comprises a central “Spectrum Assignment Coordination” (SAC) entity which takes the assignment decisions, supported by a number of further entities. Moreover, options for implementing the functional spectrum management architecture into network management concepts like e.g. virtualized networks are considered, focusing on the implementation of the SAC entity, as the other spectrum management entities may be either connected directly to the SAC or already part of the Operations Support System in the mobile network operator domain.

Contents

List of Abbreviations and Acronyms

3GPP	Third Generation Partnership Project
4K / 8K	resolution of 4000 / 8000 pixels
5G	5th Generation of mobile networks
5G-PPP	5G Private Public Partnership
AAS	Advanced Antenna System
AP	Access Point
ARCF	Automatic Radio Configuration data handling Function
BER	Bit-Error Rate
BH	Backhauling
BPL	Building Penetration Loss
bps	bit per second
BS	Base Station
BSS	Business Support System
BW	Bandwidth
CBRS	Citizens Broadband Radio Service
CBSD	Citizens Broadband radio Service Devices
CDF	Cumulative Distribution Function
CEPT	Conférence Européenne des administrations des Postes et des Télécommunications
CM	Configuration Management
CMOS	Complementary Metal-Oxide-Semiconductor
CN	Core Network
CSI	Channel State Information
D2D	Device-to-Device
dB	decibel
dBm	dB referenced to one milliwatt
DCS	Dynamic Channel Selection
DFS	Dynamic Frequency Selection
DL	Downlink
DM	Domain Management

DN	Destination Node
DTT	Digital Terrestrial Television
EC	European Commission
ECC	Electronic Communications Committee
EE	Energy Efficiency
EIRP	Equivalent Isotopically Radiated Power
EM	Element Management
eMBB	enhanced Mobile Broadband
EN	Egress Node
ETSI	European Telecommunications Standards Institute
fc	frequency carrier
FCC	Federal Communications Commission
FWA	Fixed Wireless Access
GAA	Generalized Authorized Access
Gbps	Gigabit per second
GHz	Giga Hertz
GLDB	Geo-Location Data Base
GSA	Global mobile Suppliers Association
Hz	Hertz
ICF	Inter-operator Coordination Functions
ID	Identifier
IMT	International Mobile Telecommunications
IMT-2020	IMT for year 2020 and beyond
IO-IF	Inter-Operator Interface
IRP	Integration Reference Point
ISC	Indoor Small Cell
ISD	Inter-Site Distance
Itf-N	Northbound Interface
ITS	Intelligent Transport Systems

ITU	International Telecommunication Union
ITU-R	ITU - Radiocommunication sector
km	kilometre
km^2	square kilometre
KPI	Key Performance Indicator
LAA	Licensed-Assisted Access
LBT	Listen-Before-Talk
LC	LSA Controller
LDM	Layer Division Multiplexing
LN	Local Network
LNApp	LN Application
LoS	Line-of-Sight
LR	LSA Repository
LSA	Licensed Shared Access
LSRAI	LSA Spectrum Resource Availability Information
m	metre
m^2	square metre
M2M	Machine-to-Machine
MANO	Management and Orchestration
Mbps	Megabit per second
MCS	Modulation and Coding Set
MFCN	Mobile/Fixed Communications Networks
MHz	Mega Hertz
MIMO	Multiple Input Multiple Output
mm	millimetre
mMTC	massive Machine-Type Communications
mmW	mm-Wave
MNO	Mobile Network Operator
MO	Multi-Operator
ms	millisecond
MTC	Machine-Type Communications
MU-MIMO	Multi-User MIMO
NDS	Network Deployment Scenario
NE	Network Element
NFV	Network Functions Virtualization

NFVI	Network Functions Virtualization Infrastructure
NFVO	NFV Orchestrator
NLoS	Non-LoS
NM	Network Management
NN	Nomadic Node
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
NRA	National Regulatory Authority
O2I	Outdoor-to-Indoor
OAM	Operation, Administration and Maintenance
OFDM	Orthogonal Frequency-Division Multiplexing
OP	Operator
OR-IF	Operator-Regulator Interface
OSC	Outdoor Small Cell
OSS	Operations Support System
PA	Power Amplifier
PAL	Priority Access License
PNF	Physical Network Function
PPDR	Public Protection and Disaster Relief
QAM	Quadrature Amplitude Modulation
QCI	Quality Class Indicator
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RAN	Radio Access Network
RF	Radio Frequency
RMC	Rural Macro Cell
RRM	Radio Resource Management
RSC	Regulatory Spectrum Coordination
RSPG	Radio Spectrum Policy Group
s	second
SAC	Spectrum Assignment Coordination
SACF	Spectrum Assignment Coordination Function
SAM	Spectrum Access Modes

SAS	Spectrum Access System
sBH	Self-backhauling
SC	Small Cell / Self-Configuration
SDN	Software Defined Networking
SE	Spectral Efficiency
SINR	Signal to Interference plus Noise Ratio
SLA	Service Level Agreement
SMS	Spectrum Management System
SN	Source Node
SON	Self-Organizing Network
SRAI	Spectrum Resource Availability Information
SRC	Spectrum Resource Coordination
SR-IF	Interface between the "Operator Spectrum Management" and the Radio Resource Management
SRS	Spectrum Resource Storage
SSE	Spectrum Sharing Enablers
SSR	Service-specific Spectrum Requirements
SUR	Spectrum Usage Rules
TDD	Time Division Duplex
TeC	Technology Component
TPC	Transmitter Power Control
TRP	Transmission Reception Point
TV	Television

TVWS	TV White Space
UC	Use Case
UE	User Equipment
UHD	Ultra-High Definition
UHF	Ultra-High Frequencies
UL	Uplink
UMC	Urban Macro Cell
uMTC	ultra-reliable Machine-Type Communications
US	United States (of America)
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VCO	Voltage Controlled Oscillator
VMNO	Virtual MNO
VNF	Virtualized Network Function
VNFM	VNF Manager
VRM	Virtualized Resource Management
WAN	Wide area Network
WiB	Wideband reuse one
WLAN	Wireless Local Area Network
WP5D	Working Party 5D
WRC	World Radiocommunication Conference
WRC-15	WRC in 2015
WRC-19	WRC in 2019
xMBB	extreme Mobile Broadband

1 Introduction

5G networks will have to cope with mobile data rates and availability requirements in extreme dimensions. In addition to mobile broadband applications for the public, also services currently operated via separate dedicated wireless networks (e.g. Public Protection and Disaster Relief (PPDR) and Intelligent Transport Systems (ITS)) as well as needs from new mobile user groups like the energy, factory or health sector are to be incorporated into the 5G system design for economic reasons.

There is a common understanding among relevant research and standardisations bodies that the diverging requirements can be roughly grouped into the following three service categories:

1. **Extreme Mobile Broadband (xMBB)** with high throughputs as well as and low-latency communications, and extreme coverage with reliable moderate rates over the coverage area. This will require a mixture of frequency spectrum comprising lower bands for coverage purposes, and higher bands with large contiguous bandwidth to cope with the capacity demand, including wireless backhaul solutions.
2. **Massive Machine-Type Communications (mMTC)** with wireless connectivity for tens of billions of network-enabled devices with prioritization on wide area coverage and deep indoor penetration. This might be fulfilled in particular within spectrum bands below 1 GHz.
3. **Ultra-reliable Machine-Type Communications (uMTC)** with ultra-reliable low-latency and/or resilient communication links. For such purpose, in general, dedicated spectrum bands are considered necessary, whereas the frequency range will depend on the application.

Detailed investigations revealed that the requirements of these service categories cannot be fulfilled by increasing the density of mobile networks and the spectral efficiency of radio access technologies alone. Therefore, also additional spectrum bands, in particular allowing for wide channel bandwidth operations are to be made available. Besides using spectrum exclusively available for mobile communications, also spectrum sharing (e.g. Licensed Shared Access (LSA) in bands occupied by other incumbents, operation in unlicensed bands as well as mutual usage of spectrum among operators) offer means to complement the overall spectrum availability.

1.1 Objective of the document

The objective of this Deliverable is to deliver concepts and scenarios for future spectrum usage for existing and new (e.g. vertical industries) user groups, facilitated by innovative technical enablers, and a holistic spectrum management approach.

1.2 Structure of the document

In section 2, frequency bands for the provision of 5G services are considered. This includes the bands in the range 24 - 86 GHz selected for sharing and compatibility studies for WRC-19, and bands below 6 GHz subject to regional and national roadmaps for the rollout of 5G.

The spectrum bandwidth demand for 5G is investigated in section 3. Several methodologies for spectrum demand are introduced, and the spectrum demand for different use cases is analysed, both below and above 6 GHz.

Section 4 deals with dynamic spectrum management, by looking at varying concepts and introducing respective technical enablers.

A holistic spectrum management architecture, embracing the regulatory authority domain as well as the mobile network operator domain, is presented in section 5.

Section 6 provides the conclusions of this deliverable. References used are listed in section 7.

Annex A contains a summary of Technology Components (TeCs) from the METIS-I project.

In Annex B and Annex C, details on spectrum demand calculation procedures and parameters are given.

2 Frequency bands for 5G

Future IMT-2020/5G services are expected to address a wide range of new advanced applications that will have a diverse range of characteristics. These characteristics may be suited to different frequency ranges from the lower frequency up to the higher bands.

2.1 Frequency bands subject of studies in ITU-R

WRC-15 agreed on a WRC-19 Agenda Item (1.13) to consider the identification of frequency bands for the future development of International Mobile Telecommunications (IMT), including possible additional allocations to the mobile service on a primary basis, in accordance with Resolution 238 (WRC-15). This involves conducting and completing the appropriate sharing and compatibility studies for a number of bands between 24-86 GHz in time for WRC-19, see Figure 2-1.

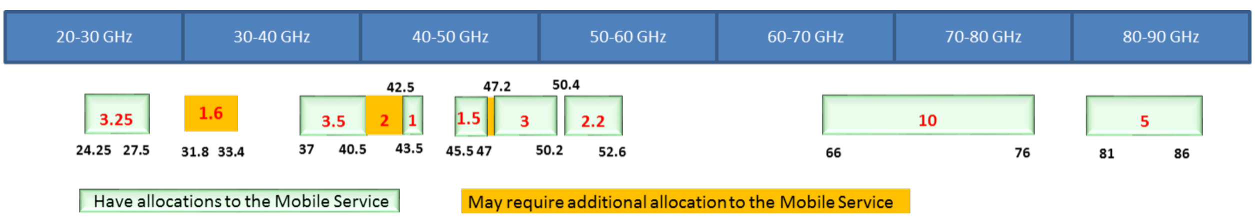


Figure 2-1: Frequency bands to be studied in ITU-R for IMT-2020 until WRC-19.

The compatibility and sharing studies for these bands are being carried out in ITU-R Task Group 5/1.

2.2 European spectrum roadmap towards 5G

With the release of the European Commission's "5G Action Plan" [EU16-COM588] and the respective EC Mandate [RSCOM16-40rev3] to CEPT "to develop harmonised technical conditions for spectrum use in support of the introduction of next-generation (5G) terrestrial wireless systems in the Union", the EC is aligning the Member States on a 5G vision placing Europe at the heart of 5G innovation and commercial possibilities.

In its "Strategic Roadmap towards 5G for Europe" [RSPG16-032] the RSPG sets out its priorities and recommendations for pioneer frequency bands for the introduction of 5G terrestrial wireless systems in Europe as follows:

- The RSPG considers the frequency band 3400-3800 MHz to be the primary band suitable for the introduction of 5G-based services in Europe even before 2020 given that it is already harmonised for mobile networks and offers wide channel bandwidth.
- The RSPG is of the opinion that 5G will need to be deployed also in bands already harmonised below 1 GHz, including particularly the 700 MHz band, in order to enable nationwide and indoor 5G coverage.
- The RSPG recognises the need to ensure that technical and regulatory conditions for all bands already harmonised for mobile networks are fit for 5G use.
- The RSPG recommends the 24.25-27.5 GHz (hereinafter '26 GHz') band as a pioneer band for Europe to be harmonised before 2020.

It is important that the EC has established a common timetable for the launch of 5G networks by end 2018 and for commercial 5G services by end 2020. This challenging time schedule will facilitate Member States to develop national 5G plans and especially driving to of at least one 5G enabled major city by end 2020 and all urban areas and major terrestrial transport paths to have uninterrupted 5G coverage by 2025.

Creating an environment for investment and commercial rollout of 5G applications and services is imperative and crucial to secure access to appropriate spectrum below and above 6 GHz to enable early commercial 5G deployments.

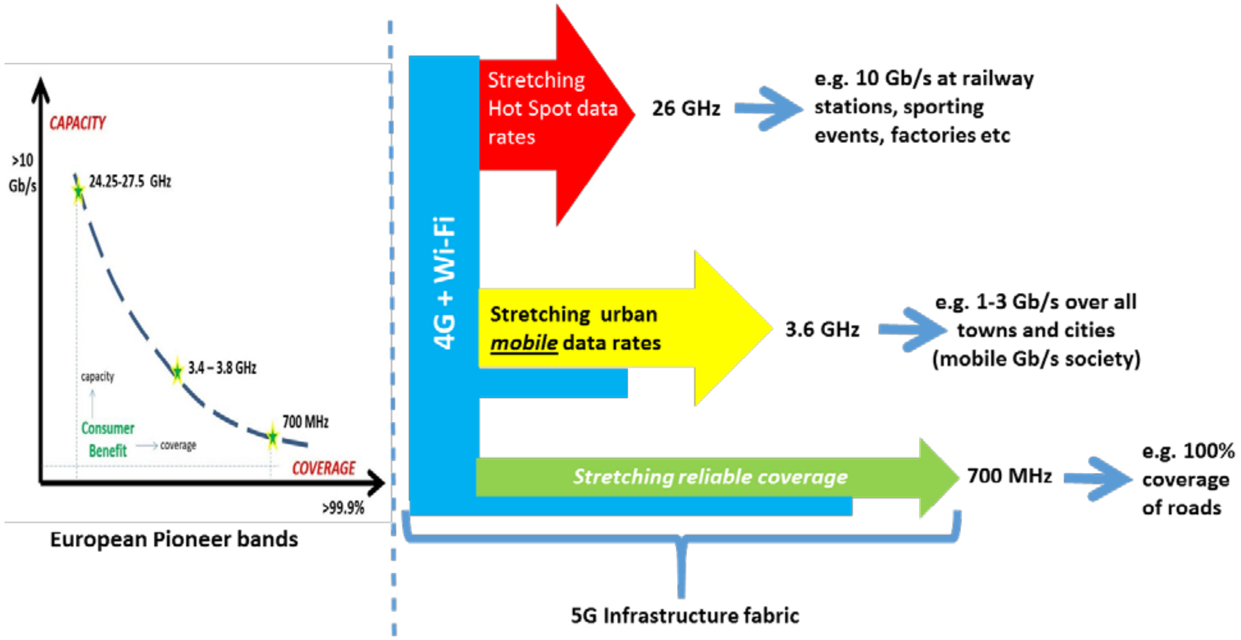


Figure 2-2: European 5G roadmap with the pioneer bands.

The CEPT ECC (Electronic Communications Committee) approved a comprehensive list of actions regarding the fifth generation of mobile technology (5G) named "CEPT roadmap for 5G" [ECC16-110A17] outlining the CEPT's actions and plans for 5G.

2.3 The frequency band 3400 – 3800 MHz

In different regions, parts of the bands 3400-3600/3800 MHz are identified for IMT. In Europe/CEPT the entire band 3400-3800 MHz is harmonized for mobile/fixed communications networks (MFCN) in an ECC Decision [ECC11-DEC06]. Based on the 5G Action Plan from EC and the respective EC Mandate to CEPT, activities are ongoing to assess the suitability to 5G of the harmonised technical conditions contained in this Decision.

As already mentioned in section 2.2, the 3400-3800 MHz is a strategic pioneer band to enable an early 5G take-up. This band can provide large contiguous bandwidths of spectrum (up to 100 MHz or higher).

The studies in CEPT concentrate on the following aspects:

- characteristics of 5G impacting unwanted emissions
- required bandwidth (maximum / minimum channel bandwidth)
- advanced antenna techniques used in 5G

In Japan, according to the national report “Radio Policies Towards 2020s” published by the Japanese Ministry of Internal Affairs and Communications, amongst other bands the 3.6-4.2 GHz frequency range is selected as national suitable candidate for 5G. Early system trials are planned for the range 3.6-4.1 GHz [GSA16].

The China Academy of Information and Communication Technology has announced a 5G trial in the 3.4–3.6 GHz band. In addition, the band 3.3–3.4 GHz is being studied China.

The US Federal Communications Committee (FCC) [FCC15-47] has established a CBRS (Citizens Broadband Radio Service) wireless broadband use (with technology neutral approach) on a shared basis in the 3550-3700 MHz band. The CBRS is governed by a three-tiered spectrum authorization framework to accommodate a variety of commercial uses on a shared basis with incumbent federal and non-federal users of the band. In CBRS, access and operations will be managed by a dynamic spectrum access system and three tiers: incumbent access, priority access, and general authorized access (see also section 4.1.2). As the CBRS spectrum is technology neutral, this spectrum can also be used by 5G. Furthermore, the “Mobile Now” Act [US17-MNA] proposes further studies for a number of bands, including 3100-3550 MHz and 3700-4200 MHz, which would offer at least an additional 500 MHz of spectrum in the 3.5 GHz range.

2.4 The 28 GHz range

In November 2016, the US FCC published a final rule detailing the use of spectrum bands above 24 GHz for mobile radio services [FCC16-89]. In this rule, a regulatory framework is established for the use of these bands for the development of the next generational evolution of wireless technology. These rules should promote the development of highly beneficial technologies, in particular the so-called 5G technology. With this rule, the band 27.5-28.35 GHz is put into focus for initial 5G commercialization in the US. According to [GSA16], also in other large markets such as Korea (26.5-29.5 GHz) and Japan (27.5-29.5 GHz), the 28 GHz spectrum is one of the main potential candidates for first deployments of 5G in higher bands.

Trials are being conducted at 28 GHz. One of the major US operators announced plans to demonstrate technology advances using spectrum at 28 GHz [Mey17]. The work is then set to include trials using a pre-commercial 28 GHz system. Also a ‘pre-standards 5G test network’ using 28 GHz spectrum has been established in the US [TMO17] [Pea16] where in preliminary tests throughput rates of several gigabits per second, and latency below 2 milliseconds when streaming four simultaneous 4K videos across the 5G interface, were achieved. Another major operator in the US recently worked on outdoor 5G trials also using 28 GHz spectrum [Goo16]. This trial showed multi-gigabit speeds by delivering fixed and mobile wireless, both indoors and outdoors, with varying line-of-sight conditions. Further aspects to prove the applicability of 28 GHz are being tested, for example, handover between 5G base stations is a key technology that supports Gbps-level wireless communications anywhere, anytime [Sam16]. This trial in Korea showed successful handover between 5G base stations in the outdoor environment.

Furthermore, key hardware elements working at 28 GHz have been developed, e.g. a 5G modem to support some specifications in the US and Korea [Moo16]. Moreover, 5G-ready antenna at 28 GHz have been shown in global events such as MWC 2016 [All16]. Recently a prototype of a massive-element (approximately 500 elements) Active Antenna System (AAS) for base stations that support 28 GHz spectrum has been developed, with a view toward the application of 5G [NEC16]. The power amplifiers – which it noted are the primary point of energy consumption in the radio module of a device – convert the low-power signal of a device into a high-power signal suitable for transmission over the air. It has been shown that new power amplifiers (PA) simultaneously double output power and improve the PA energy efficiency by more than 50 percent [All16].

3 Spectrum bandwidth demand

3.1 Methodologies for spectrum bandwidth demand analysis

Considerations on the spectrum bandwidth demand analysis have a major impact on cost and even feasibility to achieve the targeted QoS when planning a new radiocommunication system like 5G.

There are three basic sets of parameters shaping the required bandwidth:

1. The targeted Quality of Service (QoS): The parameters associated to these values are depending on the service provided.
2. The physical deployment of the network elements: Not only the positions of the Transmission Reception Points (TRP) and the User Equipment (UE) need to be taken into account, but also the radio propagation environment characteristics.
3. The achievable area spectral efficiency: For the abovementioned physical deployment, i.e. for a two-dimensional model with full bandwidth occupancy, this value can be expressed as [ITU06-1046]:

$$\frac{bit/s}{Hz\,m^2}$$

   This value of course will heavily depend on the technical components used by all involved equipment (i.e. TRPs and UEs), and therefore will evolve in future 5G systems, as it was the case also for the previous mobile generations.

Three major estimation approaches have been analysed for 5G/IMT-2020 in ITU-R: a “traffic forecast-based approach”, an “application-based approach”, and a “technical performance-based approach”. The difference of these approaches lies on the actual input parameters for the estimation. For the “traffic forecast-based approach”, the user demand forecasts predicting future usage of IMT is utilized, while for the “technical performance-based approach” certain KPIs and capabilities are used to estimate the bandwidth. The “application based approach” considers the delivery of a range of xMBB data rates to a range of user densities. In the following, a short overview of existing spectrum demand analysis methodologies is given, and their pros and cons are analysed. Furthermore, spectrum bandwidth demand analysis methodologies are proposed, including preliminary results for xMBB use cases derived from applying these approaches. In addition, a spectrum demand analysis method for MTC use cases is provided, and estimated results for an uMTC use case example.

3.1.1 Overview of current spectrum demand analysis methodologies

Traffic forecast-based

A traffic forecast-based methodology was used for the calculation of terrestrial spectrum requirement estimation for International Mobile Telecommunications (IMT) for previous WRCs to estimate the spectrum requirement of IMT [ITU13-2290]. This methodology provides a systematic approach that incorporates service categories, service environments, radio environments, market data analysis and traffic estimation, traffic distribution among radio access technique groups, required system capacity calculation and resultant spectrum requirement determination.

The spectrum demand estimation takes place on the basis of the knowledge of the different IMT Radio access technologies area spectral efficiency for each of the four different TRP layers considered: macro-cells, micro-cells, pico-cells and hot spots, in the three deployment scenarios (Dense Urban, Sub-Urban and Rural) included for the evaluation.

ITU-R spectrum needs estimates for 5G

In February 2017, the respective ITU-R Working Party (WP5D) finalized the work on spectrum needs for 5G/IMT-2020 for frequency ranges between 24.25 and 86 GHz. The work in WP5D was based on [ITU15-2083], which identifies three main usage scenarios currently envisaged for 5G/IMT-2020, while acknowledging the possible emergence of additional use cases.

Considering the above, WP5D considered various approaches and examples with different levels of detail in the modelling to determine the spectrum needs of 5G/IMT-2020 for xMBB use cases in frequency ranges between 24.25 and 86 GHz [ITU17-WP5D]. The results are summarized in Table 3-1.

Table 3-1: Spectrum needs for different frequency ranges between 24.25 GHz and 86 GHz [ITU17-WP5D].

	Examples	Associated conditions (details in Annex A of [ITU17-WP5D])	Spectrum needs in total (GHz)	Spectrum needs (GHz) per range
Application-based approach	1	Overcrowded, Dense urban and Urban areas	18.7	3.3 (24.25-33.4 GHz range) 6.1 (37-52.6 GHz range) 9.3 (66-86 GHz range)
		Dense urban and Urban areas	11.4	2.0 (24.25-33.4 GHz range) 3.7 (37-52.6 GHz range) 5.7 (66-86 GHz range)
	2	Highly crowded area	3.7	0.67 (24.25-33.4 GHz range) 1.2 (37-52.6 GHz range) 1.9 (66-86 GHz range)
		Crowded area	1.8	0.33 (24.25-33.4 GHz range) 0.61 (37-52.6 GHz range) 0.93 (66-86 GHz range)
Technical performance-based approach (Type 1)	1	User experienced data rate of 1 Gbit/s with *N* simultaneously served users/devices at the cell-edge, e.g., Indoor	3.33 (*N*=1), 6.67 (*N*=2), 13.33 (*N*=4)	Not available
		User experienced data rate of 100 Mbits/s with *N* simultaneously served users/devices at the cell-edge, for wide area coverage	0.67 (*N*=1), 1.32 (*N*=2), 2.64 (*N*=4)	Not available
	2	eMBB Dense Urban	0.83-4.17	Not available
		eMBB Indoor Hotspot	3-15	Not available
	3	With a file transfer of 10 Mbits by a single user at cell-edge in 1 msec	33.33 GHz (one direction)	Not available
		With a file transfer of 1 Mbit by a single user at cell-edge in 1 msec	3.33 GHz (one direction)	
		With a file transfer of 0.1 Mbits by a single user at cell-edge in 1 msec	333 MHz (one direction)	
Technical performance-based approach (Type 2)	–	Dense urban micro	14.8-19.7	5.8-7.7 (24.25-43.5 GHz range)
		Indoor hotspot		9-12 (24.25-43.5GHz and 45.5-86 GHz range)
Information from some countries based on their national considerations	–	–	7-16	2-6 (24.25-43.5 GHz range) 5-10 (43.5-86 GHz range)

METIS-I

In [MET14-D53], a methodology for bandwidth requirement evaluation is extensively studied. The described method is based on system level evaluations with the consideration of a homogeneous network and user equipment deployment. Spectrum requirement evaluations with this methodology have been carried out for different use cases, for which the traffic requirement is determined by the UEs throughput demand and the number of UEs according to the description in [MET15-D61], while the spectral efficiency is estimated based on the UEs SINR Gaussian distributions with different achievable values. Based on the total traffic demand and the average spectral efficiency, the overall bandwidth demand for each use case can be derived. Note that the SINR values are directly related with several key factors, including the network deployment density, the technology components being available, the actual level of frequency band usage, etc. Therefore, this methodology is a kind of technical performance-based approach.

3.1.2 Performance-based spectrum bandwidth demand analysis framework for 5G

In 5G systems, diverse applications could be deployed and multiple performance requirements may need to be met at the same time, e.g., traffic volume density and user experienced data rate. Furthermore, very different QoS levels will be required by different network slices and services, i.e. the network needs to be able to manage spectrum resources depending on priorities and requirements. Thus, the spectrum demand analysis should take into account the multiple requirements for multiple deployment scenarios. In addition, multi-band deployment may be a promising solution to enhance capacity and coverage at the same time, thus the spectrum demand analysis should also take into account the offloading schemes to estimate the potential bandwidth requirements when using several carrier frequencies, with different performance in terms of propagation characteristics and applicability of technical components (like massive MIMO). The following spectrum bandwidth demand analysis framework is proposed to solve the above issues.

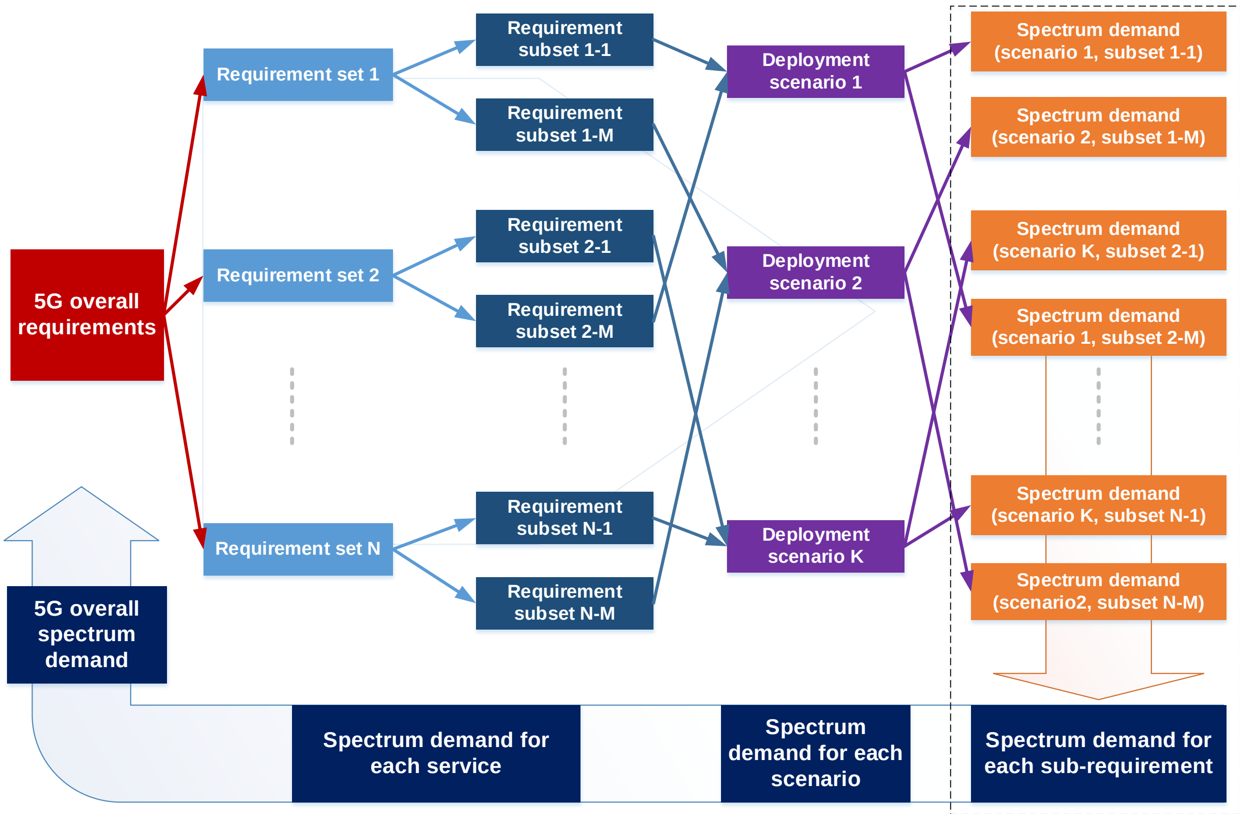


Figure 3-1: Framework of spectrum bandwidth demand analysis for 5G.

This technical performance-based framework of spectrum bandwidth demand analysis for 5G is shown in above Figure 3-1. To be specific, the rationale of this spectrum bandwidth demand analysis is to break down the overall performance requirements of 5G systems into different requirement sets according to the specific use cases. Then the requirements in each set can be further divided into different subsets, each of which is then mapped to different deployment scenarios. As in each deployment scenario the key deployment solutions and parameters are defined, it is feasible to estimate the transmission capability of the network via numerical analyses or system level simulations. Combining the performance requirements in each subset and its mapping relation to the specific deployment scenario, with the estimated transmission capability of the network in each deployment scenario, we can get the spectrum bandwidth demand. In this way, we can explicitly show the contribution of each deployment scenario in terms of spectrum bandwidth demand. After that, we can accumulate the spectrum demand of different subsets for each scenario and derive the scenario-related spectrum demand. We can also combine the spectrum bandwidth demand of each subset together to get the corresponding spectrum bandwidth demand of each performance requirement set. Since the performance requirement set is directly connected with a specific 5G use case, it is straightforward to obtain the spectrum bandwidth demand for this specific 5G use case. If the spectrum bandwidth demand of all the identified use cases is available, the overall spectrum demand of 5G systems can be derived accordingly.

3.1.3 Spectrum bandwidth demand analysis in a Voronoi cell area

The Bandwidth (BW) requirement analysis previously developed in the METIS project [MET14-D53] was based on the assumption of different achievable values of SINR Gaussian distributions (which feasibility finally depends on the performance of deployed Technology Components (TeCs), and on the assumption of homogenous distribution of UEs and TRPs in the scenario. In fact, the performance of any TeC is evaluated in terms of SINR Gaussian distribution enhancement (highest mean value) compared with the previous state of the art. As an example, in [ZTE17] the evaluation of a NR MIMO system is reflecting this Gaussian behaviour for different frequencies and deployment scenarios, with different achievable mean values. Also the evaluation of different achievable SINR values included in [MII16-D21] shows the performance in terms of mean value increase from a Gaussian distribution.

In order to obtain more accurate BW requirement estimations, and to link this value to the actual two dimensions of TRPs and UE deployment, an enhanced approach with randomization of both elements over the scenario area is proposed in METIS-II.

This proposed methodology is based on the analysis of the BW requirements for fulfilling the targeted QoS on a local scenario (it is not a nationwide requirement as the ones provided by ITU), and therefore the selection of the most demanding local scenarios will lead to the appropriate values.

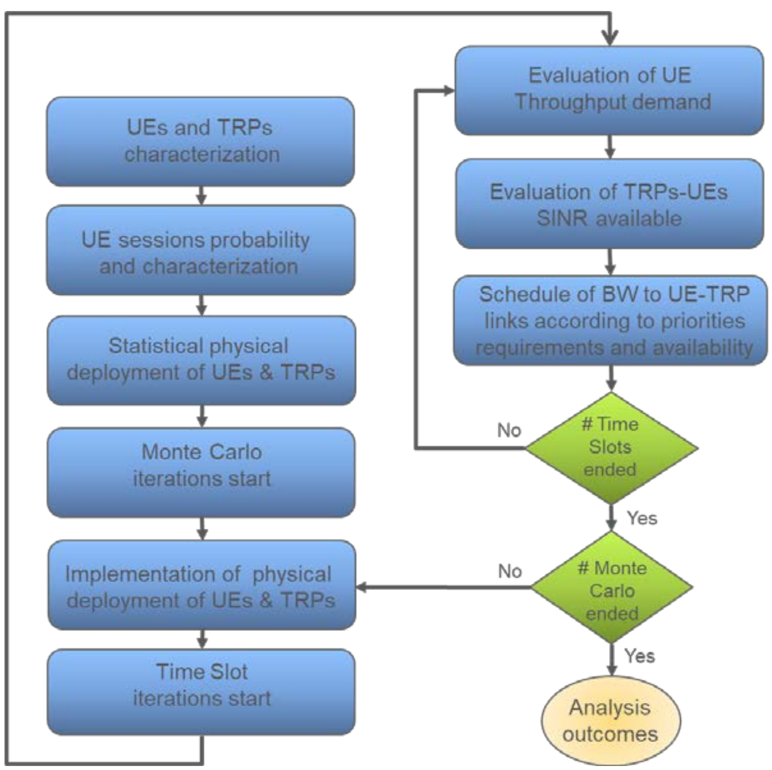


Figure 3-2: Spectrum demand analysis tool.

In Figure 3-2, the flow diagram of the respective spectrum demand analysis tool is presented. It is based on a statistical analysis of the achievable values of QoS for different configurations, by using a Monte Carlo Approach for the most relevant parameters.

The procedure follows the following approach and steps:

1. Inclusion of UEs and TRPs characterization parameters, for each of the carrier frequencies considered to be used in the scenario. Up to three different layers of TRPs are taken into consideration: Base Stations, Small Cells for high-density areas and hot-spots (small cells for ultra-high density areas). Also different classes of UE categories can be included, each one with its own values of characterization parameters. These values will determine, depending on the physical deployment of the network, the achievable area spectral efficiency.
2. For each UE in the scenario, the probability (depending on its UE class mentioned above) assigned for different sessions Quality Class Indicator (QCI) is established. The QCI of a session determines not only the traffic pattern of the device, but also the priority for assignment from network point of view and the values with which the service is considered to be fulfilled or maintained with some degradation, as could be the video quality degradation assuming lower throughput available. These values will determine the QoS targets for different sessions.
3. In order to include more realistic deployments, beyond the canonical regular grid for Base Stations (BSs) and random deployment for small cells (SC), the number and statistical distribution of TRPs and UEs will configure different physical deployments in each Monte Carlo implementation.
4. The number of Monte Carlo iterations to be implemented can be selected, each one with different distributions of TRPs and UEs.
5. The UEs and TRPs are then physically located in the scenario, according to the following procedure:
    a. An inter-site distance (ISD) is established, but the BSs are deployed with a controlled random error in both distance and angle between BSs. Several values have been used, but 20% on phase and distance error from actual regular grid scenarios, lead to the more realistic approach. The outside polygon obtained from the Voronoi cells from this distribution will be considered as the scenario area.
    b. There is a value for UE density in the full scenario that will lead to a first random distribution of UEs over the full scenario area.
    c. Zones of high density of users (with an associated radius and UE density) can be randomly distributed along the scenario area. This will account for more dense populated areas inside the scenario.

   d. SCs for high density areas can be set at different random distance from the high density area centre.
   e. Zones of ultra-high density of users (with an associated radius and UE density) can be randomly distributed along the scenario area. This will account for hot-spot areas.
   f. SCs for ultra-high density areas can be set at different random distance from the high density area centre.
6. Once the physical distribution of all TRPs and UEs is fixed (for the current Monte Carlo iteration), several time slots are taken into account to evaluate the QoS achieved by the different sessions established by the UEs.
7. In each time slot the following evaluations are carried out:
   a. The throughput requirement of each UE, depending on its type of session and the associated traffic pattern.
   b. The values of each UE-TRP SINR, according to the Gaussian distributions values introduced, and taking into account the physical distance between UEs and TRPs in the scenario.
   c. The bandwidth scheduled by each TRP in the scenario (and therefore the remaining BW not scheduled) according to the needs and priority established.
8. Once the selected number of time slots and Monte Carlo iterations are completed, the achieved service level (three levels have been considered: full service, service continuity, and pure connectivity) for any UE in the scenario is evaluated, and the BW used by each TRP in the scenario to fulfil this level.

The detailed parameters that could be selected in each simulation and the actual values for different UCs are included in the Annex C.

For the results exposed in this deliverable, most of the parameters have been set up mainly accordingly with the simulation scenarios defined in [MII16-D21]. The outcome is therefore a look up table of the achievable service level depending on the used BW as shown the figures in section 3.2.1.

3.1.4 Spectrum demand analysis for xMBB with radio spectral efficiency models

In METIS-II, we have broken down the performance requirements of 5G system into different sets for different user case families [MII16-D11]. For xMBB services, the performance requirements are further divided into multiple subsets for specific use cases. In each use case, there are many KPIs and related target values to be met, e.g., for xMBB services, the most important two performance KPIs are traffic volume density and user experienced data rate. It is expected that user experienced data rate is highly dependent on the interference environment and also coverage performance, which might lead to more ambitious spectrum demand compared with other KPIs. Therefore, we focus on the performance requirement in terms of user experienced data rate and use the methodology introduced in section 3.1.2 to analyse the spectrum bandwidth demand of each use case in a quantitative manner.

To be specific, in METIS-II there are three xMBB related use cases, i.e., use cases UC1, UC2 and UC3, whose key deployment assumptions and performance requirements are summarized as in Table 3-2.

Table 3-2: Summary of key deployment assumptions and performance requirements for use cases UC1, UC2 and UC3 (taken from [MII16-D11] and [MII16-D21]).

	UC1 Dense urban information society	UC2 Virtual reality office	UC3 Broadband access everywhere
BS deployment	HetNet (macro layer with ISD of 200m and micro layer with multiple small cells per macro sector)	12 sites per floor with ISD of 20m	Macro layer with ISD of 1732m
Carrier frequency	Below 6 GHz for macro layer and above 6 GHz for micro layer	Both below and above 6 GHz	Below 6 GHz
Experienced user throughput (requirement)	DL: 300Mbps, UL: 50Mbps	DL: 1Gbps, UL: 1Gbps	DL: 50Mbps, UL: 20Mbps

As indicated by the table above, for 5G deployments, quite a wide range of spectrum including both below and above 6 GHz can be taken into account, hence one fundamental question to answer is how many spectrum bandwidth in each band is needed for an operator to enable a specific use case. Regarding the above discussion, it seems reasonable to estimate the spectrum demand under three cases, e.g., with below 6 GHz only, with above 6 GHz only, and with both below and above 6 GHz at the same time. The first two cases can be taken as the upper bound spectrum needs within a certain single band, while the latter one can show the trade-off achieved if multi-carrier deployment is available. The key issue here, however, is to estimate the spectrum efficiency of each layer (band) for different use cases especially for multi-carrier deployment. In order to align the analysis with ITU-R vision report [ITU-R M.2083], we assume that the spectrum efficiency for below 6 GHz is 3 times of IMT-Advanced system requirement for each deployment environment (including macro layer in dense urban, indoor hotspot and rural macro layer). Note that there is no requirement on the spectrum efficiency of micro layer in dense urban in ITU-R, and in METIS-II, it is assumed that similar performance requirement, i.e., 3 times of urban micro in IMT-Advanced should be met for below 6 GHz. For above 6 GHz, no specific requirements were defined in the report, especially for the 5%-tile spectrum efficiency. It is known that due to the propagation characteristics in high frequency, e.g., more severe path loss and penetration loss, higher Doppler spread and phase noise level, some coverage issue may exist together with high frequency deployment. On the other hand, the introduction of large scale antenna system is regarded as a promising technology to compensate the severe fading in high frequency to improve the coverage performance. Therefore, at least for now, it is difficult to say 3 times spectrum efficiency of IMT-Advanced can be achieved with high frequency only. In order to cover more possibilities, we assume the spectrum efficiency of IMT-2020 with high frequency is 1-3 times of IMT-Advanced.

In order to illustrate the method to calculate the spectrum bandwidth demand, detailed parameters and calculation procedure are provided in Table 3-3. Note that in this table, spectrum demand analysis is only for below 6 GHz as one example, and the method itself can be directly reused for other cases.

Table 3-3: An example analysis of spectrum bandwidth demand with detailed calculation procedure.

Example use case where K cells per sector are deployed	Below 6 GHz	
	Downlink	Uplink
Experienced user throughput (Mbps) required in METIS-II*[1]	R_{DL}	R_{UL}
SE per user for 10 user per sector (bps/Hz) *[2]	SE_{DL_REF}	SE_{UL_REF}
Estimated user number per sector for all operators*[3]	N	
Number of operators	M	
Estimated user number per sector per operator	N/M	
SE per user for above user number per sector (bps/Hz) *[4]	SE_{DL_REF} *K/N/M/10	SE_{UL_REF} *K/N/M/10
Bandwidth (DL/UL, MHz) per operator	R_{DL} /(SE_{DL_REF} *K/N/M/10)	R_{UL} /(SE_{UL_REF} *K/N/M/10)
Bandwidth (DL+UL, MHz) per operator*[5]	R_{DL} /(SE_{DL_REF} *K/N/M/10) + R_{UL} /(SE_{UL_REF} *K/N/M/10)	
Total bandwidth (MHz)	R_{DL} /(SE_{DL_REF} *K/N/10) + R_{UL} /(SE_{UL_REF} *K/N/10)	

*[1]: According to [MII16-D11].

*[2]: According to ITU-R vision report, the 5th percentile user spectral efficiency is the 5% point of the CDF of the normalized user throughput. The normalized user throughput is defined as the number of correctly received bits, i.e., the number of bits contained in the SDUs delivered to Layer 3, over a certain period of time, divided by the channel bandwidth and is measured in bit/s/Hz. Note that the edge user spectrum efficiency is defined assuming 10 active

users per sector are served. Note that for multiple layer scenarios (e.g., UC1) with co-channel deployment, the spectrum efficiency should be the sum of spectrum efficiency of all sites in each layer in order to minimize the total spectrum bandwidth demand. In addition, for multiple layer scenario (e.g., UC1), the detailed calculation of equivalent spectral efficiency can be found in Annex B.1

*[3]: According to [MII16-D11].

*[4]: If the active user number changes, the spectrum efficiency of edge user should be scaled accordingly due to different resource amount available.

*[5]: The required spectrum bandwidth amount in each direction is assumed to well match the traffic amount in corresponding direction, which can be achieved with advanced 5G technologies, e.g., flexible duplexing for both paired and unpaired spectrum.

3.1.5 Spectrum bandwidth demand analysis methodology for MTC

Aforementioned spectrum bandwidth demand analysis methods mainly consider xMBB services where traffic volume and user throughput are important metrics. MTC services, mMTC and uMTC, have quite different requirements than xMBB, and thus the spectrum demand of MTC services may not be properly estimated by the xMBB-oriented methods. For delay-critical uMTC such as remote tactile applications every packet should be delivered immediately within the delay limit, regardless of traffic volume. This means that the instantaneous data rate is more important than the traffic volume and the average data rate. Therefore, bandwidth demand analysis should be based on the instantaneous data rate requirement. For some mMTC services with small packet sizes, random access may account for the majority of the spectrum use. Then, MAC design could make a substantial impact on the bandwidth demand.

Extensive link- and system-level simulations will be needed to accurately estimate the spectrum demand of the MTC services. However, the wide variety of MTC services makes it difficult to efficiently perform the simulations for each case. It is desired to have a methodology to calculate the spectrum demand without complicated simulations, still providing a basic understanding of the required amount of the spectrum. In this section, we propose a methodology for the spectrum bandwidth demand analysis of MTC services. Our objective is to have a simple arithmetic formula to estimate the bandwidth demand.

There are three major factors affecting the spectrum bandwidth demand of MTC services:

- Delay: the instantaneous data rate of a link must be high enough to deliver a packet with the allowed air interface delay
- Link reliability: spectral efficiency (modulation and coding scheme) of a link must be chosen properly to ensure the link reliability requirement is met
- Medium access: there must be large enough radio resources to accommodate potentially many users.

It is unlikely that a service is constrained by all three factors. Rather, we expect that the spectrum bandwidth demand of each MTC service will be dominated by one of these factors.

Out of the three factors, we have identified six basic parameters for the bandwidth demand formula. Note that the spectrum bandwidth demand is closely coupled with the network dimensioning and the medium access design. Therefore, we need to distinguish the network dimensioning and design related parameters from the service specific parameters (see Table 3-4).

Table 3-4: Parameters for MTC spectrum bandwidth demand analysis.

Service specific input parameters	
L_{pkt} [bit]	Size of a packet
R_{gen} [sec^{-1}]	Packet generation frequency (number of packets generated per second)
D_{req} [sec]	Radio interface delay requirement
Network architecture and dimensioning related parameters	
S_{mcs} [bps/Hz]	Modulation and coding order of the transmitted packets • It should be determined to achieve the link reliability requirement of the service
N_{dev}	Number of devices accessing the spectrum bandwidth
Medium access related parameters	
η_{MA}	Medium access efficiency (between 0 and 1)

Link reliability requirement determines S_{mcs}. Then, the bandwidth demand based on the delay requirement can be expressed as

$$W_{delay} = \frac{L_{pkt}}{S_{mcs} D_{req}}.$$

Similarly, the bandwidth demand based on the medium access requirement can be calculated by

$$W_{MA} = \frac{L_{pkt} R_{gen} N_{dev}}{S_{mcs} \eta_{MA}}.$$

Here, η_{MA} refers to the medium access efficiency which ranges between 0 and 1. When $\eta_{MA} = 1$, it means that the medium access is perfectly coordinated, resulting in no loss of radio resources due to the contention process or packet collision. Conversely, $\eta_{MA} = 0$ represents an uncoordinated medium access without a possibility of retransmission and packet loss. In that case, the spectrum demand will go to infinity. In general, η_{MA} depends on the level of medium access coordination and the allowed retransmissions and/or packet losses. It is known that the maximum value of η_{MA} for delay-tolerant slotted ALOHA is 0.368 [MZS+16]. More example of the calculation of η_{MA} is available in Section 3.2.4.

Finally, the overall spectrum demand is determined by the maximum of W_{delay} and W_{MA}.

$$W_{req} = \max(W_{delay}, W_{MA}) = \max\left(\frac{L_{pkt}}{S_{mcs} D_{req}}, \frac{L_{pkt} R_{gen} N_{dev}}{S_{mcs} \eta_{MA}}\right).$$

3.2 Spectrum bandwidth demand of 5G use cases

3.2.1 Results for xMBB with the analysis tool described in section 3.1.3

Several simulations were carried out on the performance of UC1 and UC3 with the analysis tool described in section 3.1.3.

UC1 Dense Urban Scenario

This scenario is composed by 37 BS with 200 m ISD (and 20% in angular and distance error) in which also 100 high density small cells (SCs) are present, accordingly a random distribution (detailed values for the UC1 scenario parameters are included in Annex C). In Figure 3-3, one of the scenarios (several scenarios have been created accordingly with the Monte Carlo analysis approach) is show, in which the 37 BS are represented by a triangle, and the 100 SCs are represented as circles.

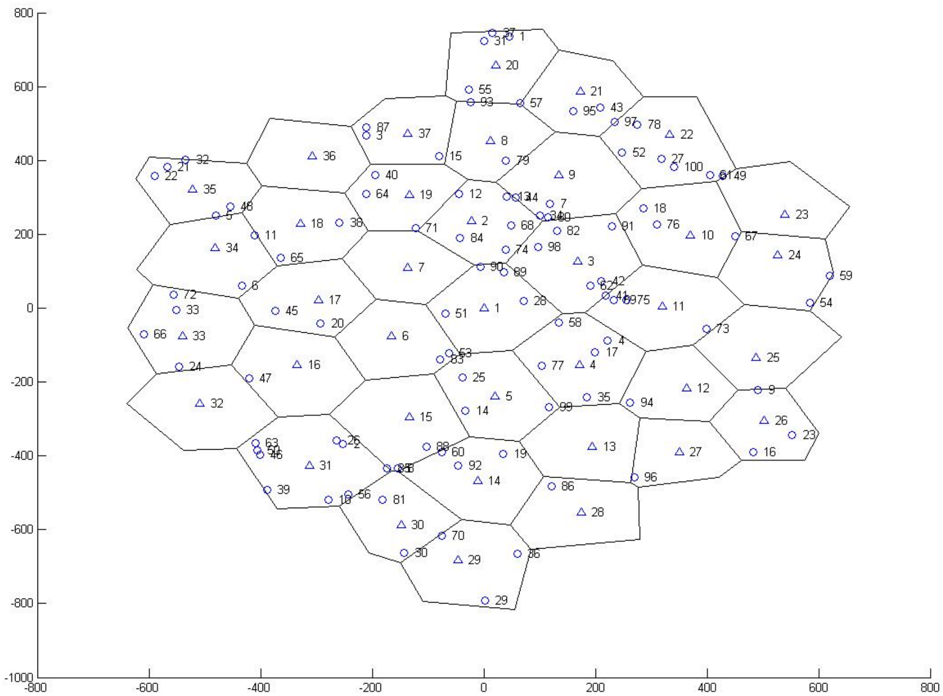


Figure 3-3: UC1 scenario with BS Voronoi cells.

For this type of scenario, the analysis has been carried out taking into account two frequency carriers, fc1 and fc2 with the following values for the achievable Gaussian distributions:

- BS mean SINR value:
  - 2 dB for fc1
  - -2 dB for fc2
- SC mean SINR value
  - 2 dB for fc2 (no fc1 connectivity)

These mean SINR values are according with the outcomes achieved in [MII16-D21]. Different BW availability for the two carriers presented in the scenario fc1 and fc2 have been included in order to check the evolution of achieved service levels. All details on the used parameters values are included in Annex section C.1

<u>If fc1 = 200 MHz and fc2 = 1000 MHz</u>

With this values, the used BW in the different BS is exhausted at both fc1 (Figure 3-4) and fc2 (Figure 3-5).

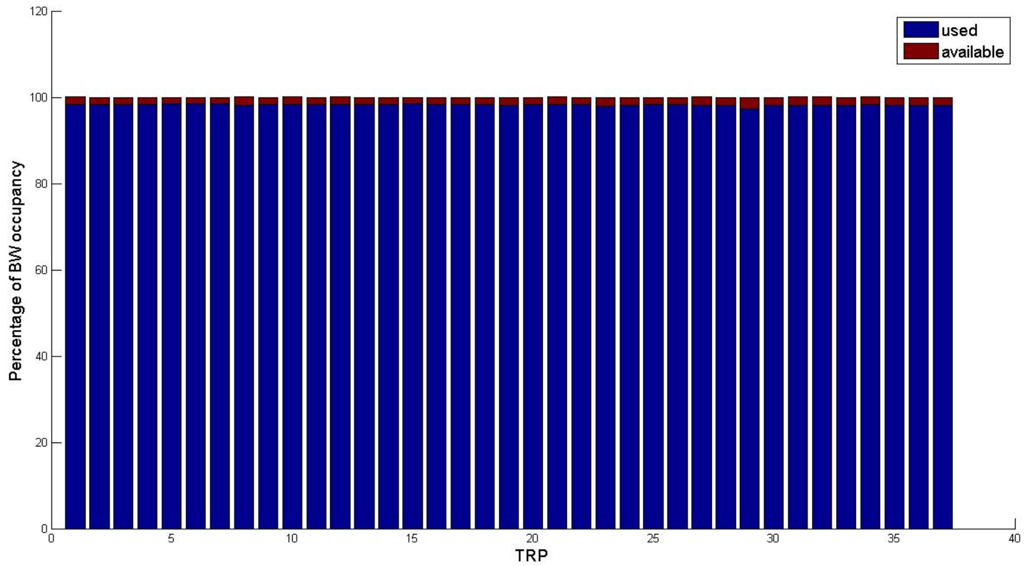


Figure 3-4: Percentage of BW usage at fc1 by all BSs (analysis 1).

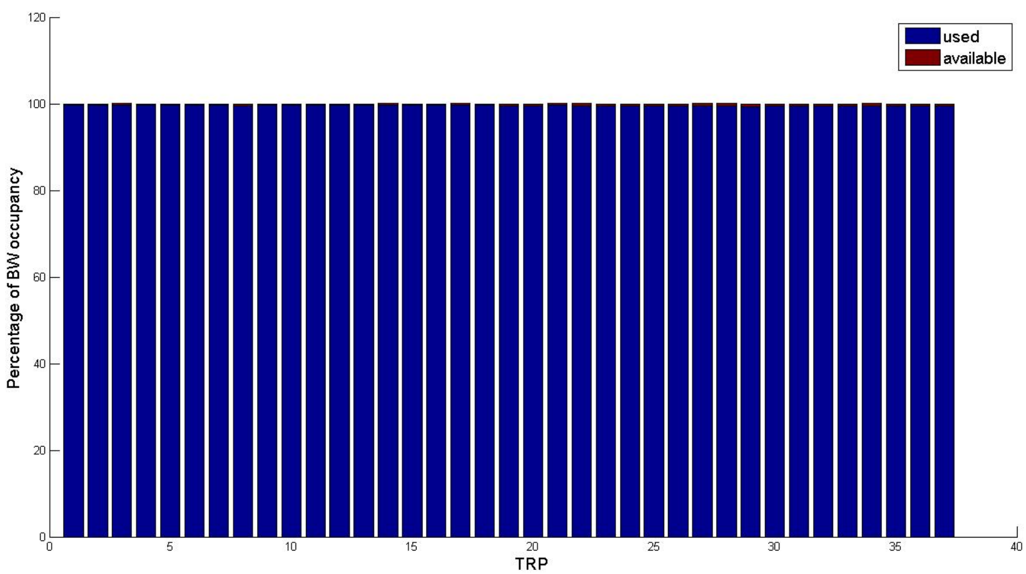


Figure 3-5: Percentage of BW usage at fc2 by all BSs (analysis 1).

Also the 100 SCs present in the scenario have exhausted the allocable BW, as shown below in Figure 3-6.

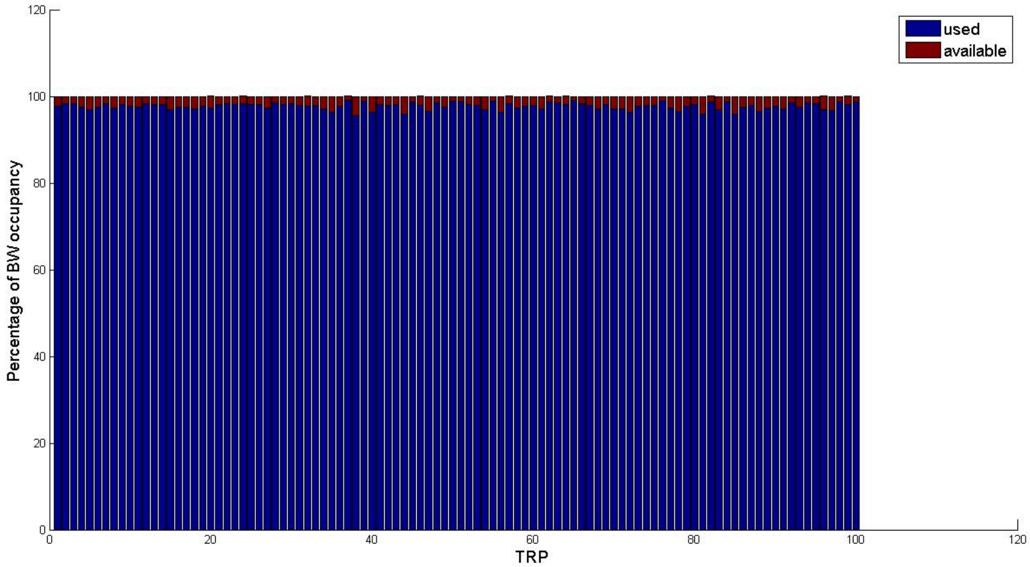


Figure 3-6: Percentage of BW usage at fc2 by all SCs (analysis 1).

In this case it is foreseen that there will be a high level of UEs that will not achieve the required service level, i.e. a degraded service should be provided in order to share the BW resources between different UEs demanding more quality of service. In Figure 3-7, it is shown the outcomes from the simulator, indicating that for all UE classes (class 1, class 2 and class 3) there is a lack of service, and even so for class 2 (more likely to demand high throughput services), where the achieved percentage of satisfied users is below 60%.

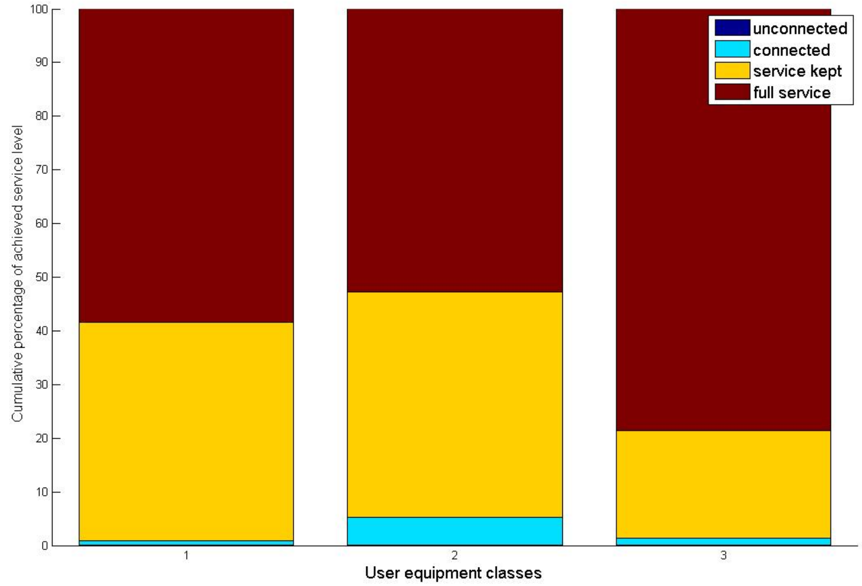


Figure 3-7: UC1 achieved service levels for different UE classes (analysis 1).

Therefore, based on the analysis of this case, the BW is insufficient for the deployment of dense urban networks (UC1).

<u>If fc1 = 200 MHz and fc2 = 3000 MHz</u>

In order to fulfil all the requirements, the fc2 carrier was increased from 1 to 3 GHz. It should be noted that fc2 carrier has worse propagation characteristics than fc1. The achievable mean SINR from the BS is only -2dB, but fc2 is used by both BSs and SCs, located near the high density areas.

With these values, the used BW in the different BS at fc1 is around 60% usage, and around 90% at fc2, as can be seen from Figure 3-8 and Figure 3-9.

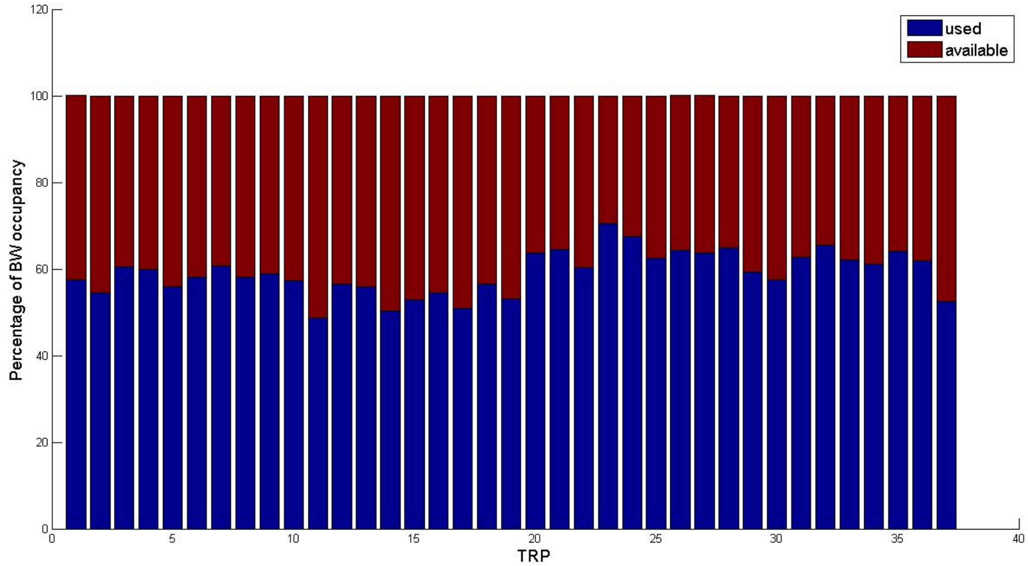


Figure 3-8: Percentage of BW usage at fc1 by all BSs (analysis 2).

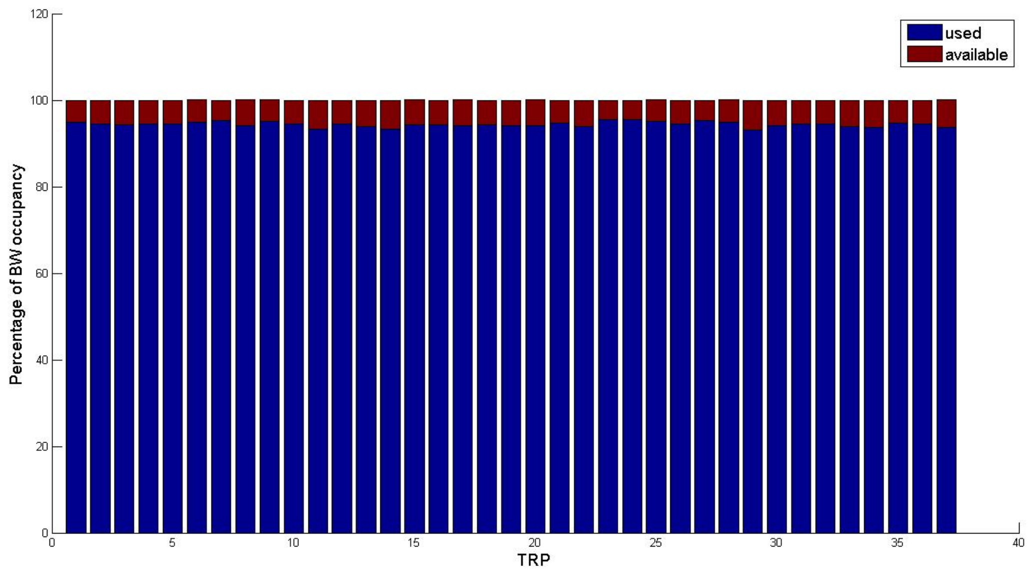


Figure 3-9: Percentage of BW usage at fc2 by all BSs (analysis 2).

The 100 SCs present in the scenario have used around 70% of the available fc2 BW, as shown in Figure 3-10.

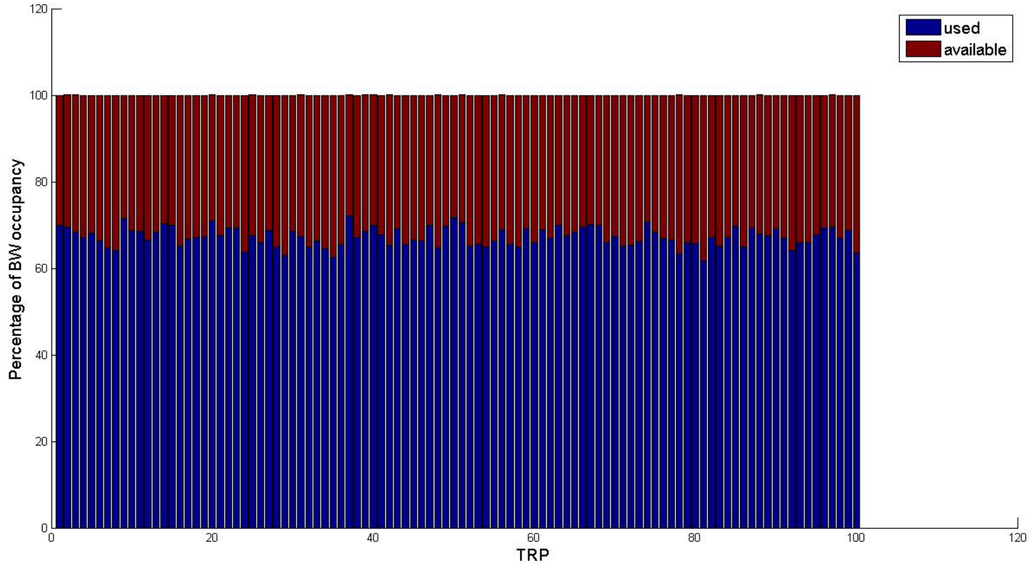


Figure 3-10: Percentage of BW usage at fc2 by all SCs (analysis 2).

In this case some BW is still available in SCs (without coverage on all UEs in this scenario) but also some percentage of BW is still not used by the BSs. Therefore, it is foreseeable that for most of the users the BW requirements are fulfilled with regard to service provision, as it is shown in Figure 3-11. Only for UE class 2 (usually high demanding services, but with lower performance RF characteristics than UE class 1) still 10% of users that will have a degraded service, and 1.7% not achieving any kind of service.

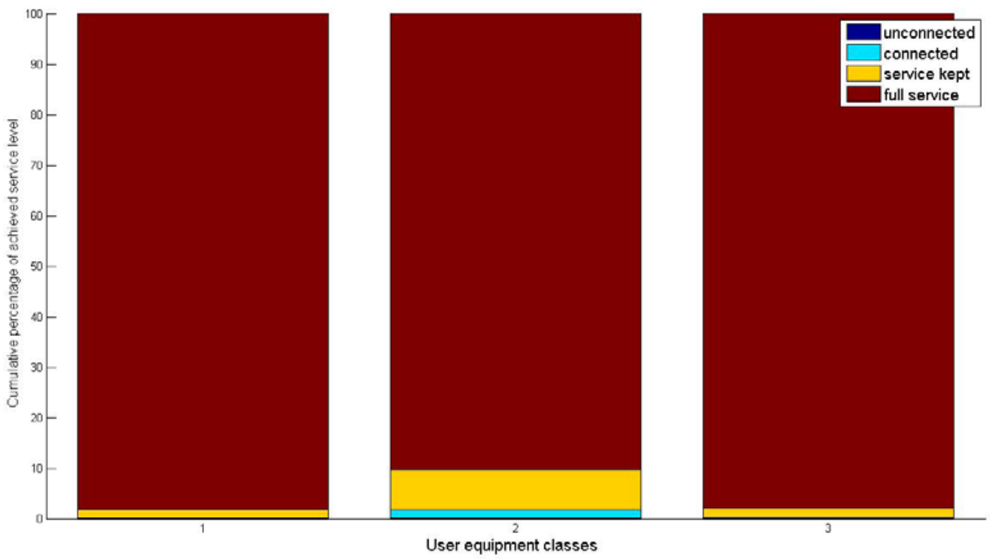


Figure 3-11: UC1 achieved service levels for different UE classes (analysis 2).

Therefore, based on the analysis of this case, it could be a valid combination of BW requirements for deploying dense urban networks (UC1) with a reasonable level of service.

UC3 Broadband Access Everywhere

This scenario is also composed by 37 BS, but in this case the ISD is much bigger: 1732 m (20% in angular and distance error is also used). This scenario is based on the use of a single frequency band with good coverage values, being the value used for the mean Gaussian distribution (accordingly with the outcomes in [MII16-D21]) of 6.6 dB. There are no high density hot spots in this scenario, and only macro layer is used.

The detailed parameters used in the simulation are described in Annex C.2. The value of the BW required to achieve a reasonable QoS as demanded by user services is 1000 MHz. For this BW the following figures show the achieved service levels for different UE classes, and the percentage of BW used by each of the macro layer TRPs.

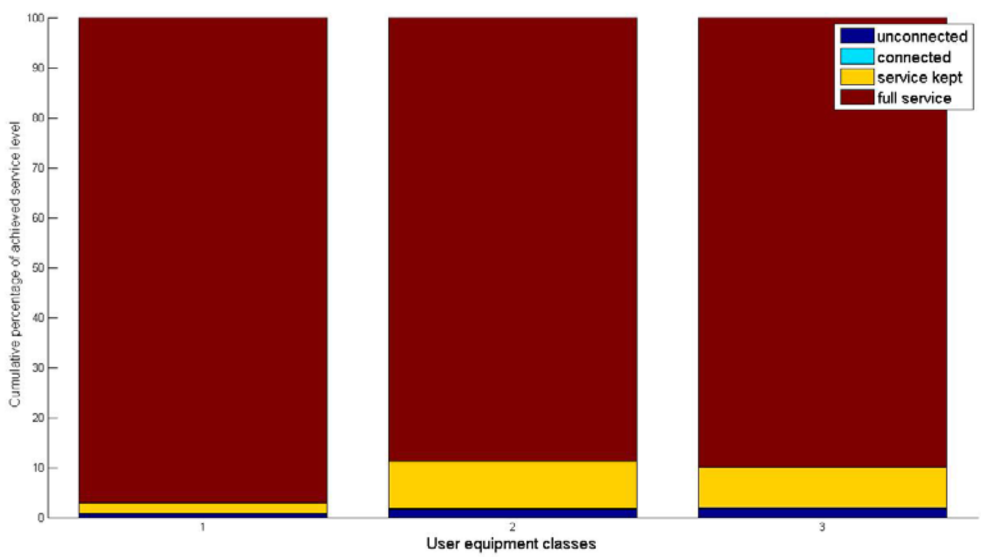


Figure 3-12: UC3 achieved service levels for different UE classes.

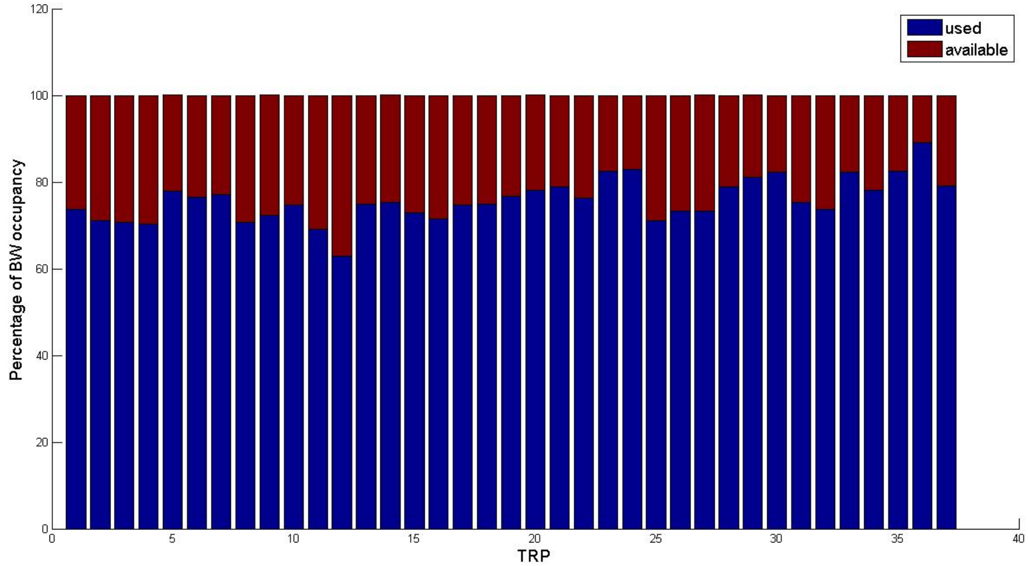


Figure 3-13: UC3 Percentage of BW usage by all BSs.

It is worth to mention that this scenario relates to a good coverage value, i.e. that the available technology will allow a SINR Gaussian distribution with mean value above 6 dB. Therefore, the carrier frequency should perform with good propagation characteristics in this environment, while the frequency bands used for the UC1 scenarios had much lower propagation performance values, and therefore more BW was required and also more TRPs layers and a smaller ISD.

3.2.2 Results for xMBB based on radio spectral efficiency models in section 3.1.4

In the following, the mentioned method is used to estimate the spectrum bandwidth demand of use cases defined by METIS-II, where different band assumptions are also taken into account (see Table 3-5).

Table 3-5: Spectrum bandwidth demand of dense urban information society (UC1) with single band.

UC1 Dense urban information society (Macro-layer with ISD 200m + 3 small cells per sector)	Below 6 GHz only		Above 6 GHz only	
	Downlink	Uplink	Downlink	Uplink
Experienced user throughput (Mbps) required in METIS-II	300	50	300	50
SE per user for 10 user per sector (bps/Hz)	0.86	0.54	0.29-0.86	0.18-0.54
Estimated user number per sector for all operators	53.00		53.00	
Number of operators	3.00		3.00	
Estimated user number per sector per operators	17.67		17.67	
SE per user for above user number per sector (bps/Hz)	0.48	0.31	0.16-0.48	0.10-0.31
Bandwidth (DL/UL, MHz) per operator	619.88	163.58	619.88-1859.65	163.58-490.74
Bandwidth (DL+UL, MHz) per operator	783.46		783.46-2350.39	
Total bandwidth (MHz)	2350.39		2350.39-7051.17	

Note that the required spectrum efficiency in the table is derived taking the two layer co-channel deployment solution into account, in order to minimize the required spectrum bandwidth to meet the requirement of experienced user throughput.

From the table above, it is clear to see that with single band deployment, i.e., with only below or above 6 GHz, would lead to a large number of spectrum bandwidth on either band, e.g., 2.4 GHz for below 6 GHz and about 7 GHz for above 6 GHz. Considering the total amount of bandwidth available below 6 GHz, it seems not feasible to meet the performance requirement with bands only below 6 GHz. For above 6 GHz, the required spectrum bandwidth amount is very large, which might be achieved more easily in bands above 24 GHz, where wider contiguous spectrum might be available. Another deployment scenario is to use spectrum from different bands to take advantage of both the coverage capabilities of bands below 6 GHz and the large amount of potential bandwidth above 6 GHz. To be specific, lower frequency carrier can be deployed for macro layer to provide the basic coverage while the higher frequency carrier can be used to boost the traffic to better meet the user experienced data rate requirement. Note that in UC1, macro layer is deployed below 6 GHz while small cell layer is deployed above 6 GHz, thus the achievable experienced user throughput would be highly related to the association of users between these two layers. Considering the fact that most traffic is consumed in the hotspot area, it is reasonable to assume that 80% users are served by small cell layer to boost the capacity, while the other 20% users are served by the macro layer. The detailed parameters and estimated spectrum bandwidth amount are shown in Table 3-6.

Table 3-6: Spectrum bandwidth demand of dense urban information society (UC1) with multiple bands (both below and above 6 GHz).

UC1 Dense urban information society (Macro-layer with ISD 200m + 3 small cells per sector)	Below 6 GHz		Above 6 GHz	
	Downlink	Uplink	Downlink	Uplink
Experienced user throughput (Mbps) required in METIS-II	300.00	50.00	300.00	50.00
SE per user for 10 user per sector (bps/Hz)	0.18	0.09	0.23-0.68	0.15-0.45
Estimated user number per sector for all operators	53.00		53.00	
Number of operators	3.00		3.00	
Estimated user number per sector per operators	17.67		17.67	
SE per user for above user number per sector (bps/Hz)	0.51	0.25	0.16-0.48	0.11-0.32
Bandwidth (DL/UL, MHz) per operator	588.89	196.30	628.15-1884.44	104.69-314.07
Bandwidth (DL+UL, MHz) per operator	785.19		732.84-2198.52	
Total bandwidth (MHz)	2355.56		2198.52-6595.56	

It is shown that if some traffic was offloaded to below 6 GHz, the needed spectrum bandwidth on each carrier can be reduced accordingly. For example, for the given offloading assumptions, the amounts of bandwidth required for above 6 GHz are between 2.2 GHz and 6.6 GHz. It is expected that further trade-off between different carriers can be achieved with different offload schemes.

With the same approach, we can derive the spectrum bandwidth demand of other use cases, e.g., UC2 and UC3, which are included in Table 3-7, Table 3-8, and Table 3-9.

Table 3-7: Spectrum bandwidth demand of virtual reality office (UC2) with single band.

UC2 Virtual reality office (12 small cell, ISD 20m)	Below 6 GHz only		Above 6 GHz only	
	Downlink	Uplink	Downlink	Uplink
Experienced user throughput (Mbps) required in METIS-II	1000	1000	1000	1000
SE per user for 10 user per sector (bps/Hz)	0.30	0.21	0.10-0.30	0.07 -0.21
Estimated user number per sector for all operators	6.00		6.00	
Number of operators	3.00		3.00	
Estimated user number per sector per operators	2.00		2.00	
SE per user for above user number per sector (bps/Hz)	1.50	1.05	0.50-1.50	0.35-1.05
Bandwidth (DL/UL, MHz) per operator	666.67	952.38	666.67-2000.00	952.38-2857.14
Bandwidth (DL+UL, MHz) per operator	1619.05		1619.05-4857.14	
Total bandwidth (MHz)	4857.14		4857.14-14571.43	

Table 3-8: Spectrum bandwidth demand of virtual reality office (UC2) with multiple bands (both below and above 6 GHz).

UC2 Virtual reality office (12 small cell, ISD 20m)	Below 6 GHz (assumed)		Above 6 GHz (in addition)	
	Downlink	Uplink	Downlink	Uplink
Experienced user throughput (Mbps) required in METIS-II	210.00	73.50	790.00	926.50
SE per user for 10 user per sector (bps/Hz)	0.30	0.21	0.10-0.30	0.07-0.21
Estimated user number per sector for all operators	6.00		6.00	
Number of operators	3.00		3.00	
Estimated user number per sector per operators	2.00		2.00	
SE per user for above user number per sector (bps/Hz)	1.50	1.05	0.50-1.50	0.35-1.05
Bandwidth (DL/UL, MHz) per operator	140.00	70.00	526.67-1580.00	617-67-1853.00
Bandwidth (DL+UL, MHz) per operator	210.00		1144.33-3433.00	
Total bandwidth (MHz)	630.00		3433.00-10299.00	

Table 3-9: Spectrum bandwidth demand of broadband access everywhere (UC3).

UC3 Broadband access everywhere (ISD 1732m)	Below 6 GHz only	
	Downlink	Uplink
Experienced user throughput (Mbps) required in METIS-II	50	25
SE per user for 10 user per sector (bps/Hz)	0.12	0.045
Estimated user number per sector for all operators	9.00	
Number of operators	3.00	
Estimated user number per sector per operators	3.00	
SE per user for above user number per sector (bps/Hz)	0.40	0.15
Bandwidth (DL/UL, MHz) per operator	125.00	166.67
Bandwidth (DL+UL, MHz) per operator	291.67	
Total bandwidth (MHz)	875.00	

In summary, the spectrum bandwidth demand of METIS-II xMBB use cases (other use cases like mMTC and uTC are not considered in this demand estimation) can be illustrated as below. Note that the estimated bandwidth demand is dependent on many factors, e.g., the assumed deployment scenario, user density and spectral efficiency (SE), etc.

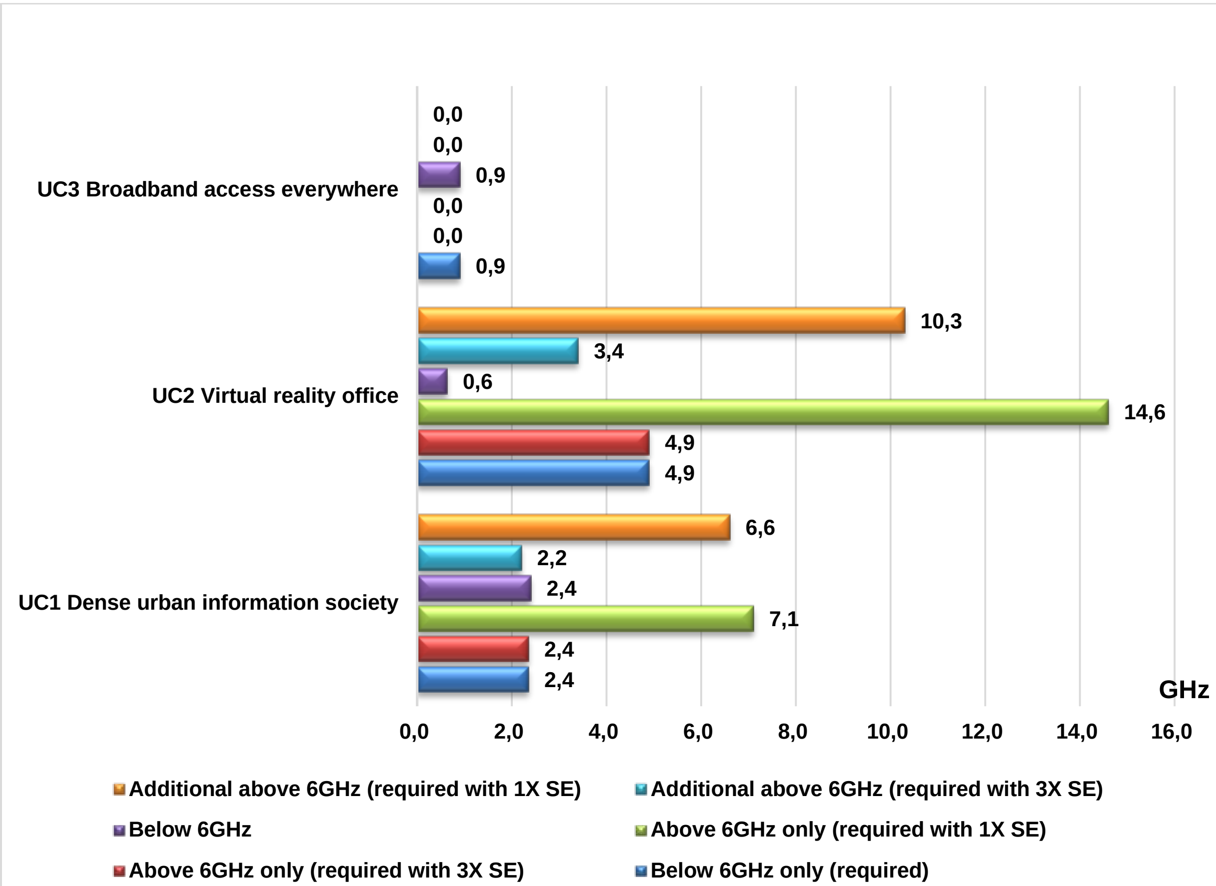


Figure 3-14: Spectrum bandwidth demand of METIS-II xMBB use cases.

3.2.3 Application-based Spectrum bandwidth demand analysis for xMBB

Unlike in the dawn of previous mobile generations, it is very likely that 5G will usher in new applications from its inception while at the same time some of the conventional applications will still remain. The 5G adopters would particularly want to embrace the applications such as immersive multi-media experiences including UHD video, virtual reality experiences and real time mobile gaming.

The application-based methodology needs to take representative application scenarios, e.g., specific deployment settings (e.g., user deployment density, active user rate, etc.) and application parameters (e.g., required data rate for each application and usage pattern) into consideration. As aforementioned, users could have very diverse application requirements from low data rate to extremely high data rate. In this regard, we define the engaging rate μ to indicate the percentage of users engaging in a specific application. For a specific combination of deployment and application settings, the overall spectrum requirement B can be expressed as

$$B = \frac{D_U P_A \sum_i \mu_i R_i}{N_B S}$$

where D_U is the user density, P_A is the user activity rate, μ_i and R_i are the engaging rate and required data rate for application i, respectively, N_B is the cell density in terms of cells per km^2 and S is the spectrum efficiency.

The general procedure of the methodology consists of three major consecutive stages as follows.

1. Service category definitions: Since a UE might require multiple application types, e.g., UHD video streaming, cloud gaming, etc., application categories will be defined using application types (medium and high data rate applications as in dense urban information society use case and super-high data rate application as in virtual reality use case) and connection density. It is worth noting that the data rate model can be either static to address the average requirement or statistical to capture the dynamics of the applications.

2. Application-based estimation: Once the connection density and application data rate by application types are defined, the area traffic capacity which is the total traffic throughput served per geographic area can then be calculated considering application usage patterns (static or statistical). Initial spectrum needs are calculated in the next step by considering system deployment of 5G including Inter-Site Distance (ISD) and spectral efficiencies with considering deployment scenarios. Then, adjustments are made to take into account the large frequency ranges to output the final spectrum needs.

3. Link budget considerations: Due to the hostile propagation condition in mm-wave radio channels, e.g., severe path loss, vulnerability to blockage, etc., the spectrum requirements need to be adjusted.

The most relevant parameters to determine the spectrum requirements are identified as follows:

- Connection density
- Service types: medium data rate application (e.g., 4K UHD and cloud gaming in UC1), high data rate application (e.g., 8K UHD in UC1), super-high data rate application (e.g., virtual reality experiences in UC2)

- Application usage patterns to indicate what percentage of active user/device using a given application type in a given connection density.
- Radio-related parameters, e.g., ISD, spectral efficiency, guard band.

Here we gave an example. Since the spectrum need is proportional to connection density, here we only consider the most crowded scenario, e.g., dense urban area for simplicity. Considered user or device density is assumed to be 1 per 4 m^2. Consequential Connection density depends in user activity factor. With activity factor assumed to be 0.8, we get the connection density of 200 000 /km^2, same as in UC1, i.e., dense urban information society [1].

Multiple applications are considered with data rates ranging from 1 Gbit/s for the Super-high data rate application type, e.g., virtual reality experiences, to 500 Mbits/s for the high data rate application type, e.g., 8K UHD video, and then to 100 Mbits/s for the Medium data rate application type, e.g., 4K UHD video, depending on the information source.

We assume the engaging rates for medium, high and super high data rate applications are 5%, 3% and 2%, respectively as an exemplary case for below 30 GHz bands. Furthermore, we assume that the inter-site distances (ISD) is 100m. The spectrum efficiency in 5G is supposed to be improved to 7.3 bps/Hz/cell via advanced PHY and possibly upper layer techniques as illustrated in [2].

It is also proposed in 3GPP that OFDM-based waveform will be employed in NR Phase-I system design (for xMBB and uMTC applications), which requires around 10% guard band. Based on all the identified parameters and above equation, we can easily calculate the required spectrum need as 3.5 GHz for below 30 GHz spectrum bands.

3.2.4 Results for an example of uMTC using the model in section 3.1.5

In this section, we provide an example of spectrum demand analysis for MTC. This is to illustrate how the methodology proposed in Section 3.1.5 can be used. The numerical example in this section is based on METIS-II UC5 “connected cars” [MII16-D11]. METIS-II UC5 is divided into two parts: traffic efficiency and safety (uMTC-related) and real-time remote computing for mobile terminals (xMBB-related). We will focus on the former part of the UC5. Note that the bandwidth demand estimate can change significantly depending on the system design assumptions. Thus, it is important to emphasize that our aim is not to provide a definite value of bandwidth demand for METIS-II UC5. Instead, we intend to show how different assumptions affect the spectrum demand for this UC5.

Firstly, we extract service specific parameters from the use case description (see Table 3-10).

Table 3-10: Parameters for analysis of METIS-II UC5 (traffic efficiency and safety part).

Notation	Value	Justification
L_{pkt}	1600 Byte	Table C-10 in [MII16-D11]
R_{gen}	10 packets/sec	Table C-10 in [MII16-D11]
D_{req}	3 ms	End-to-end one-way latency requirement is 5 ms. We assume that each node spends 1 ms for processing.
N_{dev}	Poisson distributed with mean 123.44	According to [MII16-D21] (page 46), a synthetic 6-lane highway can be modelled where vehicles are dropped by a spatial Poisson process with an average inter-vehicle distance of 97.22 m. Considering the communication range of 1 km [MII16-D11], it leads to 123.44 vehicles on average in the boundary of 2 km. Different communication range gives different N_{dev}.

Then, we need to make further assumptions to continue the numerical analysis.

- We assume that S_{mcs} = 2 bps/Hz (e.g., QPSK). Modulation and coding should be robust enough to ensure the reliability requirement in the radio link. METIS-II UC 5 targets the service reliability of 99.999%. In this example, we assume that QPSK (or higher-order modulation with higher coding rate) enables error-free packet reception unless collision occurs.
- We assume uncoordinated medium access contention based on slotted ALOHA. No retransmission is made due to stringent delay requirement. However, packet reception failure due to packet losses are allowed with a probability P_{fail}.
- Packet loss only occurs due to a collision in the medium access. We further assume that a collision always causes a packet loss.

A challenge in the numerical analysis is the determination of medium access efficiency, η_{MA}. Let us define the medium occupancy ratio, M_{ocp}, as the portion of time that a device (vehicle) occupies the medium.

$$M_{ocp} = \frac{L_{pkt} R_{gen}}{S_{mcs} W_{MA}}.$$

Let N_{slot} be the number of slots to serve all vehicles. Then, $N_{slot} = 1/M_{ocp}$. We can define η_{MA} as N_{dev}/N_{slot}, where N_{slot} is calculated from the following equation.

$$P_{fail} = \sum_{N_{dev}} \left[1 - \left(\frac{N_{slot} - 1}{N_{slot}} \right)^{N_{dev}-1} \middle| N_{dev} = n \right] \Pr\left(N_{dev} = n\right).$$

It is not obvious which value of P_{fail} will be allowed to achieve the service reliability of 99.999%, we obtain η_{MA} of about 1.02%. Then, it gives W_{MA} of 780 MHz, which is considerably higher than W_{delay} of 2.13 MHz.

The spectrum demand estimation is extremely sensitive to the assumption of the parameters, as shown in the following figures. Figure 3-15 illustrates the impact of the V2V communication range. METIS-II UC5 defines three different ranges: 50 m, 500 m, and 1 km. The corresponding average number of vehicles contending for the medium has a substantial impact on the spectrum demand. In the figure, the communication ranges of 50 m, 500 m, and 1 km correspond to N_{dev} =6, N_{dev} =62, and N_{dev} =123, respectively. Figure 3-16 depicts how the robustness to the packet collision affects the spectrum demand. If the packet reception failure target is relaxed from 1% to 10%, the spectrum demand is reduced by ten times. These figures demonstrate that it is essential to define the parameters properly when applying the proposed methodology.

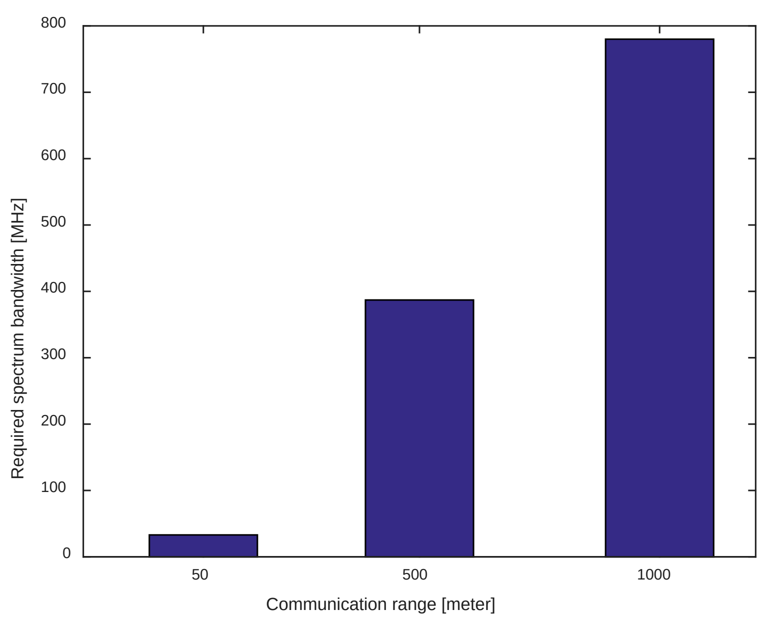


Figure 3-15: Spectrum demand of METIS-II UC5 for different communication ranges.

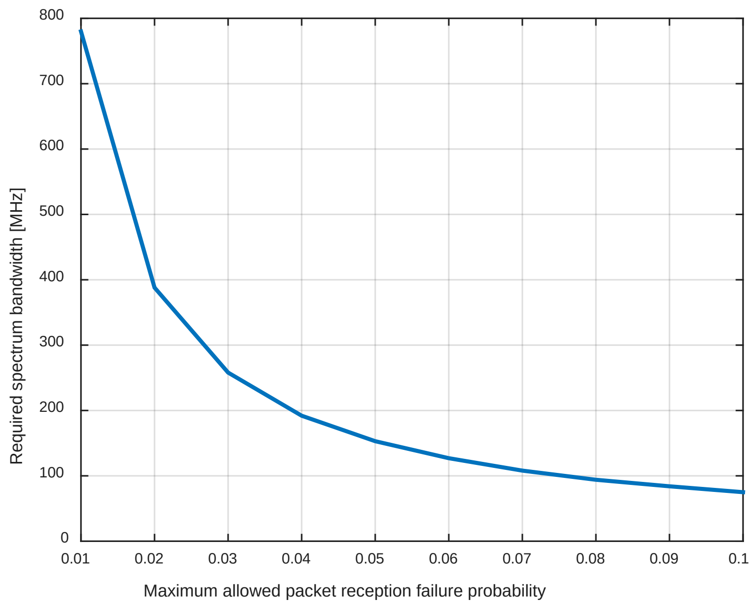


Figure 3-16: Spectrum demand of METIS-II UC5 as a function of the allowed packet reception failure probability.

4 Concepts and technical enablers for flexible spectrum management

4.1 Standardized methods for spectrum sharing

Economies of scale are a key factor for the mobile broadband industry. Therefore, the identification of spectrum opportunities without consideration of wider industry and standardization support may not lead to successful commercial deployment. Thus, all concepts for spectrum sharing should first and foremost focus on the bands that are globally harmonized (or at least can offer good potential for global harmonization) and which are subject to international standardization activities.

4.1.1 License Shared Access

In [RSPG13-538] license shared access (LSA) is defined as follows:

> *"A regulatory approach aiming to facilitate the introduction of radiocommunication systems operated by a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users. Under the Licensed Shared Access (LSA) approach, the additional users are authorised to use the spectrum (or part of the spectrum) in accordance with sharing rules included in their rights of use of spectrum, thereby allowing all the authorised users, including incumbents, to provide a certain Quality of Service (QoS)".*

LSA could be a means for MNOs for accessing additional spectrum in specific bands, within specified geographical, time or technical limits, by complementing the traditional exclusive access based on individual authorisation. Thus, LSA would enable the sharing of spectrum between MNOs and non-MNOs incumbent spectrum users in the case that refarming of spectrum is impracticable due to incumbent use.

In order to adapt to national circumstances, the implementation of LSA is likely to differ from country to country, but a dialogue involving the National Regulatory Authority (NRA), the incumbent(s) and prospective LSA licensees, in order to define the sharing framework and issuing an individual right of use to the LSA Licensee is necessary in any case. The regulatory process defined in [ECC14-R205] is shown in Figure 4-1.

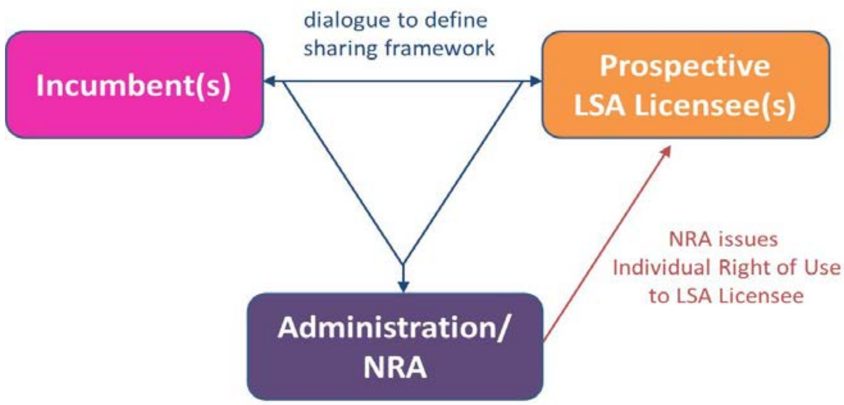


Figure 4-1: Regulatory process required prior to the introduction of LSA.

4.1.2 Citizens Broadband Radio Service

In the US, a new spectrum sharing approach called Citizens Broadband Radio Service (CBRS) to enable deployment of relatively low powered network technologies in the band 3550-3700 MHz has been introduced by [FCC15-47]. CBRS introduces a 3-tier spectrum sharing method, which differentiates three hierarchies of spectrum users:

1. **Incumbent users:** represent the highest tier and receive interference protection from all other spectrum resource users.
2. **Priority Access License (PAL) users:** represent the second tier and receive interference protection from other PAL users and lower tier users.
3. **General Authorized Access (GAA) users:** represent the lowest tier and receive no interference protection; i.e. GAA users have to accept that there is no guaranteed interference protection from PAL users and/or other GAA users.

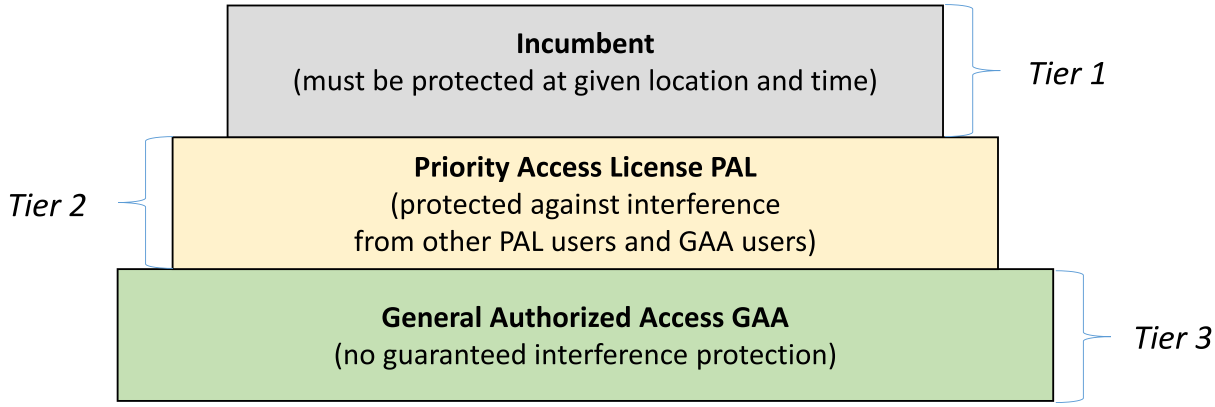


Figure 4-2: CBRS 3-tier model for 3.5 GHz band.

CBRS allows providing defined spectrum to run wireless/mobile services, but adds additional complexity due to the required protection of the higher tiers, e.g. sensing to detect the respective incumbent services (Tier 1).

4.2 Concepts for spectrum management and sharing under research

4.2.1 COHERENT spectrum management and coordination & control system

The H2020 project Coherent [COH16-D41] proposes a three-plane architecture concept, which consists of a spectrum management plane (spectrum management application), a coordination and control plane, and an infrastructure plane (or equivalently data plane). The key role in this architecture is performed by the central controller & coordinator which utilizes network graphs for spectrum usage, based on high-level directives obtained from the spectrum management plane.

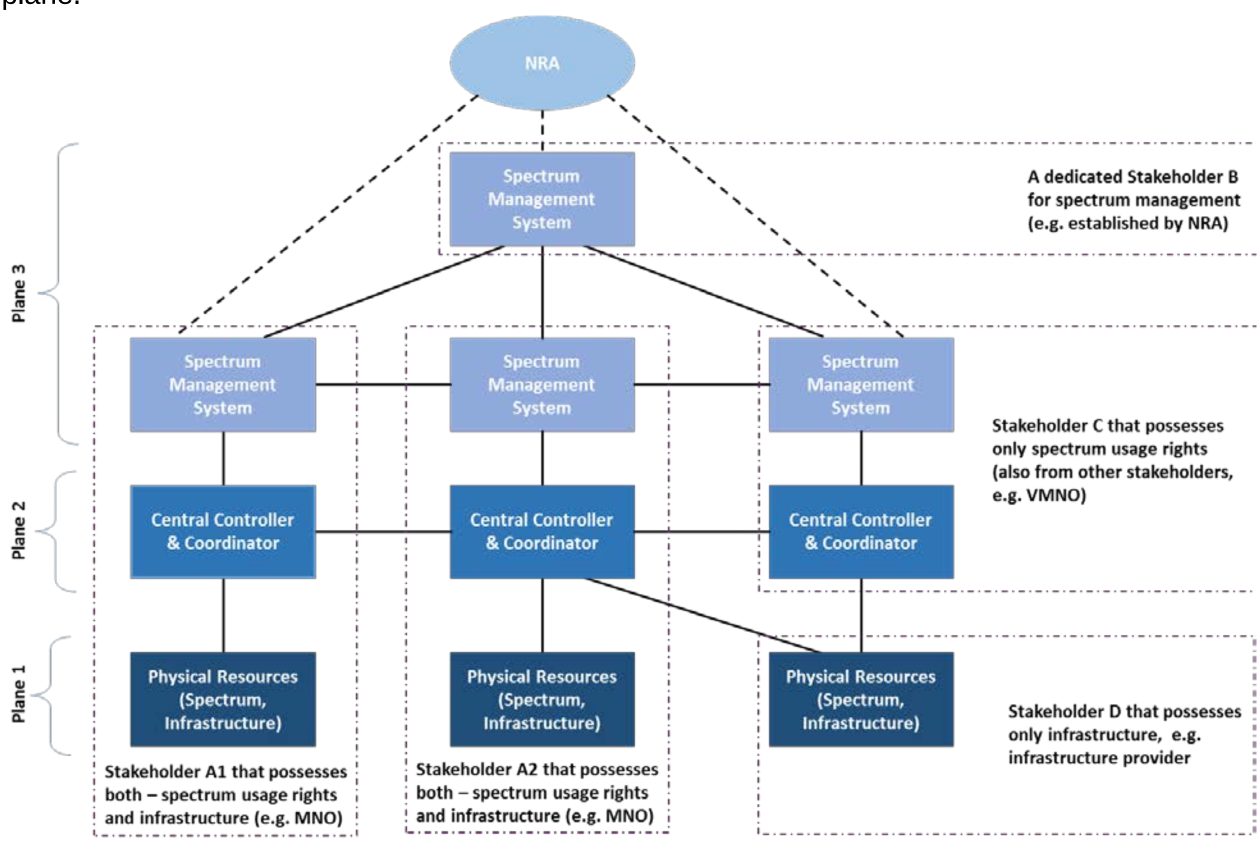


Figure 4-3: COHERENT Spectrum Management and Coordination & Control System [COH16-D41].

Figure 4-3 shows the general principle of the three-plane architecture, its flexibility to support deployments in multi-operator (represented by the stakeholders) environments, and the interfaces to interconnect the three planes.

A stakeholder may operate a single plane, i.e. a mobile network which is described by physical resources building the network (stakeholder D) or a combination of planes, e.g. to act as spectrum usage rights administrator (stakeholder C), spectrum manager on behalf of the NRA (stakeholder B), or as a mobile network operator (stakeholder A1, A2).

The applicability of the Coherent concept highly depends on the willingness of the stakeholders to share sensitive information (e.g. network graphs describing the load and interference when shared spectrum is used by the physical resources). The Coherent concept is still under discussion expected to be finalized end 2017.

4.2.2 METIS-II enhanced concept for spectrum management and spectrum sharing

The concept for spectrum management and spectrum sharing for 5G mobile networks, based on the relation between spectrum authorization modes and spectrum usage scenarios, has been developed in the METIS project [MET14-D53], [MET15-D54]. This concept is enhanced in order to cover also radio spectrum already designated to potential new 5G user groups (e.g. for vertical industry applications like ITS or PPDR), by splitting the former “primary user mode” into “exclusive user mode” and “service dedicated (ITS, PPDR,...) user mode” (see Figure 4-4).

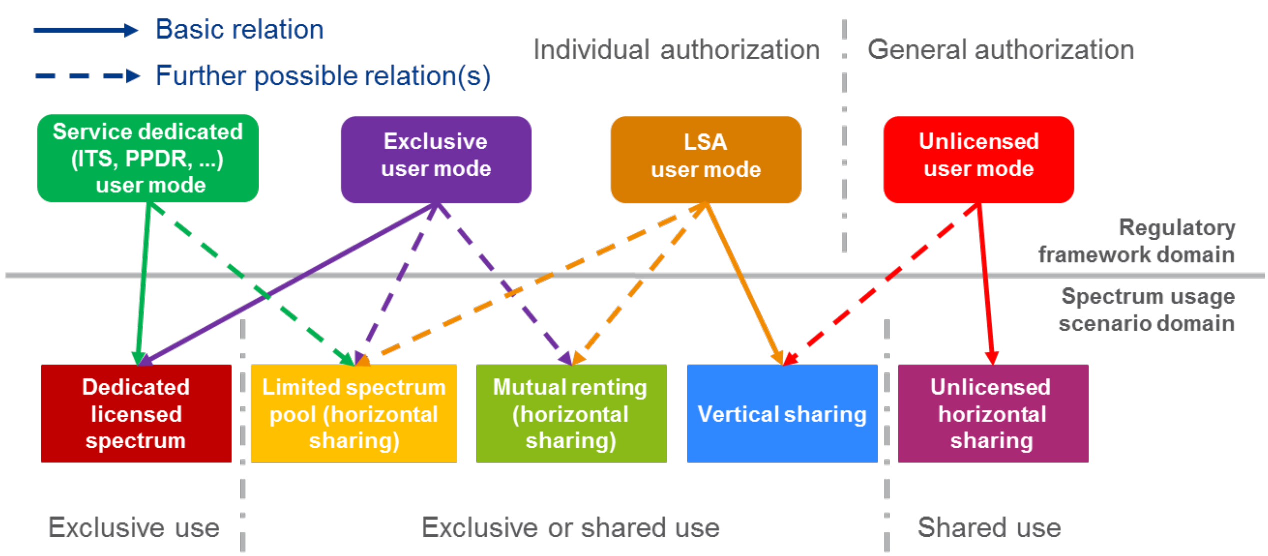


Figure 4-4: Enhanced concept for spectrum management and spectrum sharing for 5G mobile networks.

As illustrated in Figure 4-4, four different user modes can be defined under which 5G radio access systems are expected to operate, namely “service dedicated user mode”, “exclusive user mode”, “LSA user mode” and “unlicensed user mode”. The use of radio spectrum can be authorized in two ways, first by “individual authorization” in the form of awarding licenses, and second by “general authorization” also referred to as license-exempt or unlicensed. The relationship between the user modes and the authorization schemes is visible in the upper part of Figure 4-4, named “regulatory framework domain”.

Spectrum usage rights awarded by “individual authorization” are exclusive at a given location and/or time. The “service dedicated user mode” refers to spectrum designated to services other than MFCN, which are intended to be integrated into the 5G eco system (e.g. ITS or PPDR). This spectrum is to be used only for the dedicated services and applications. Spectrum designated to MFCN falls into the “exclusive user mode”. In the “LSA user mode” a non-MFCN license holder (incumbent) would share spectrum access rights with one (or more) MNOs (LSA licensee) which can use the spectrum under defined conditions subject to an individual agreement and permission by the relevant regulatory authority.

These three user modes can occur in their basic form (continuous lines), or as evolution of current approaches in the form of “limited spectrum pool” or “mutual renting” (dashed lines), see Figure 4-4.

- Limited spectrum pool is used in spectrum usage scenarios where a limited number of known operators obtain authorizations to access a spectrum band dynamically. It is envisioned that mutual agreements between licensees are such that the long term share of an individual operator has a predictable minimum value.
- Mutual renting allows that an operator to rent at least part of its licensed spectrum resources to another operator, based on a mutually agreed rules. While the spectrum ownership stays unchanged, the rules may define spectrum usage restrictions and spectrum owner protections. Mutual renting is able to provide both static (i.e. like exclusive use), and/or dynamic shared spectrum.

Depending on the duration (static or dynamic) of the spectrum access, the spectrum usage scenarios “limited spectrum pool”, “mutual renting” and “vertical sharing” may be considered as exclusive use or shared use.

In the “unlicensed user mode” spectrum access and usage rights are granted by general authorization, i.e. without an individual license but subject to certain technical restrictions or conditions like limited transmit power or functional features like duty cycle or listen before talk. In this mode, users cannot claim protection and may be interfered by other users.

Spectrum sharing between systems of different priority, e.g. if incumbent users have to be protected in the “LSA user mode”, is referred to as “vertical sharing”, and sharing between systems of equal priority is called “horizontal sharing”. For example, 5 GHz WLAN systems need to ensure protection of the incumbent radar systems (vertical sharing), and also to coexist with other WLAN systems (horizontal sharing).

In order to achieve high spectrum usage efficiency, 5G systems may preferably support all spectrum usage scenarios shown in Figure 4-4, noting that several scenarios may occur simultaneously.

4.3 Technical enablers for advanced spectrum management and sharing

Technical enablers facilitating advanced spectrum management and sharing would encompass for example

- enhanced geolocation databases, being able to manage access between opportunistic spectrum users.
- spectrum sensing, i.e. devices being able to listen for other nearby spectrum users and determine whether it is possible to transmit.
- spectrum agile equipment, i.e. equipment being able to tune across a wide range of spectrum bands.
- beamforming, e.g. zero forcing beamforming being capable to protect the incumbent user from interferences and to cancel the self-interference among secondary users.

The METIS project has proposed innovative Technology Components (TeCs) which have the potential to enable the adoption of new mechanisms for spectrum management and spectrum sharing [MET15-D54]. These TeCs are briefly described in Annex A. Further technical enablers are introduced is the following sub-sections.

4.3.1 Application Context Aware Local Service Provisioning

One key aspect for the wide adoption and deployment of 5G technologies, especially the diverse set of 5G features, would be the cross-industry collaboration of vertical industries. This would require new features enabling the fast and easy local deployment of services through networks that are confined to a relatively small local area. In order to enable this, it is important that a local network (LN) could be tailored quickly to provide specific services which target advanced 5G features such as extreme mobile broadband data rates, with relatively high reliability and/or low-latency.

By this technical enabler, an application context aware local network LN connectivity and operation is considered, where the 5G user can have multi-operator / multi-network (both with the LN and wide area network (WAN)) simultaneously. The WAN connectivity is provisioned through the mechanisms available today, and which are enhanced to support 5G features and capabilities. For the LN connectivity, the application within the UE interacts with the 5G radio access network radio, in order to connect with the LN. An overview of the application context aware multi-operator multi-connectivity is as shown in Figure 4-5.

The main idea is that the application within the UE for LN connectivity (called LNApp) provides the basic connectivity parameters to the 5G user, in order to connect to the LN. For the cell search procedure, the LNApp initiates the process and provides appropriate frequency bands to be searched for LN connectivity. The LNApp could interwork with dynamic spectrum access algorithms, in order to provide availability for of most suitable spectrum (at that spot and time) and location independent connectivity to the user. Other LN connectivity procedures such as cell selection and charging could also be working through the LNApp function within the UE, with the cell selection parameters provided by the application within the UE. For user authentication and charging, the relevant parameters could also be provided by the LNApp which are then sent to the core network (CN), instead of the conventional approaches used for WAN connectivity. The concept enables the fast and efficient deployment of LNs, and the provisioning of specialized use cases and 5G features to the end users.

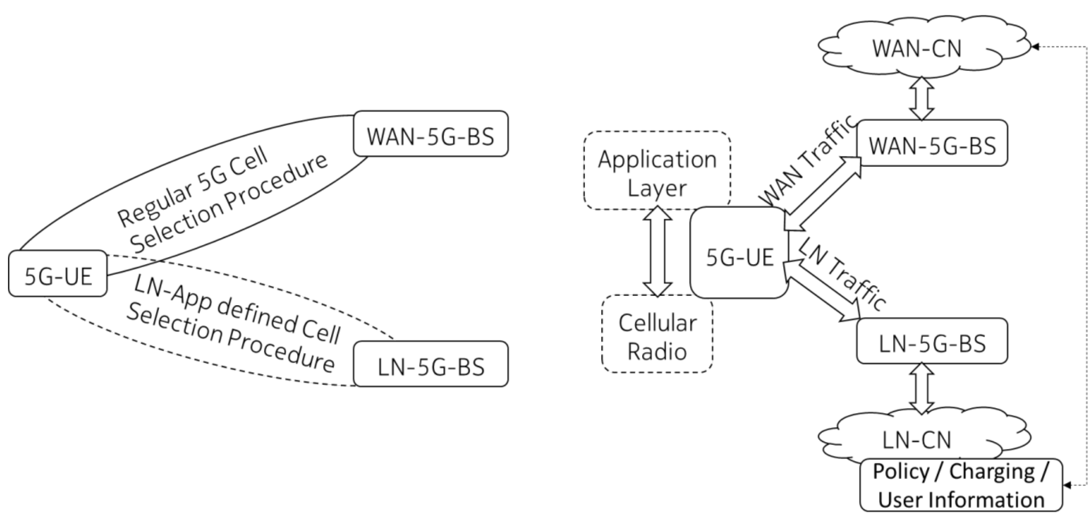


Figure 4-5: Overview of the application context aware concept.

The use cases that such LNs could target include high-performance gaming arenas, virtual or augmented reality arenas, ultra-low latency robotics arena, etc., where the 5G users could be served with new 5G services which the WANs would not be able to support, with possibly new business models (including new players entering the RAN ecosystem [MII16-D11]). Thus, the main idea behind LNs are to enable local mobile / nomadic operation of networks, using for e.g., ultra-dense indoor or outdoor deployment of small cells.

4.3.2 QoS driven Scheduler for Inter-Operator Spectrum Sharing

The ambitious service targets envisioned in 5G systems are demanding denser network deployment and large contiguous spectrum bandwidths for ubiquitous service provisioning. A shared network paradigm is an attractive deployment solution for multiple mobile operators in order to improve system spectral efficiency and service coverage with reduced operational and investment costs.

Spectrum sharing is a promising technique to enhance the utilization of spectrum in 5G systems. One of the stringent requirements for applying spectrum sharing in a multi-operator scenario is fulfilling the Quality of Service (QoS) variants among the shared parties. In such cases, since the presence of aggressive service types or users might lead to unfair sharing, a QoS based scheduler that fairly enables the common spectrum usage among the key players and maximizes the spectrum utilization efficiency of the system is highly required. Moreover, maintaining resource fairness and simultaneously guaranteeing the needed QoS, for example data rate, pose a challenge in such a sharing environment.

In this section, a QoS based multi-operator (MO) scheduler is proposed as a key enabler for spectrum sharing within inter-operator 5G networks. The proposed scheduling mechanism framework deals with the different QoS requirements for various services by taking pre-defined Service Level Agreements (SLA) into account. The SLA includes the QoS parameters, policies, constraints and list of conditions on how to cooperate and utilize the shared system resources.

Considering the 5G wireless network, each participating operator may provide specific service types which lead to heterogeneous SLAs in the system. One scenario could be an operator (OP-1) supports low power massive machine type communications (mMTC) while the other operator (OP-2) is providing ultra-broadband services. Accordingly, OP-1 could be interested to have an energy efficient sharing strategy and maintaining a low rate for a short packet data communication while OP-2 has a stringent high data rate requirement. Some of the SLAs can be resource fairness, rate fairness and power consumption. In addition to the SLAs, the MO-scheduler is designed with the objective of maintaining the spectral and energy efficiency requirements of the individual operators. To make such MO spectrum sharing paradigm more attractive; hence, the scheduler is multi-objective with diverse constraints.

The scheduler assumes a system architecture having multi-operator common radio resource management. Besides, a full sharing scenario is considered where both the RAN and the spectrum are shared. The proposed strategy is a general spectrum sharing framework that is applicable both for licensed and unlicensed band usage. The MO-scheduler architecture is presented in Figure 4-6.

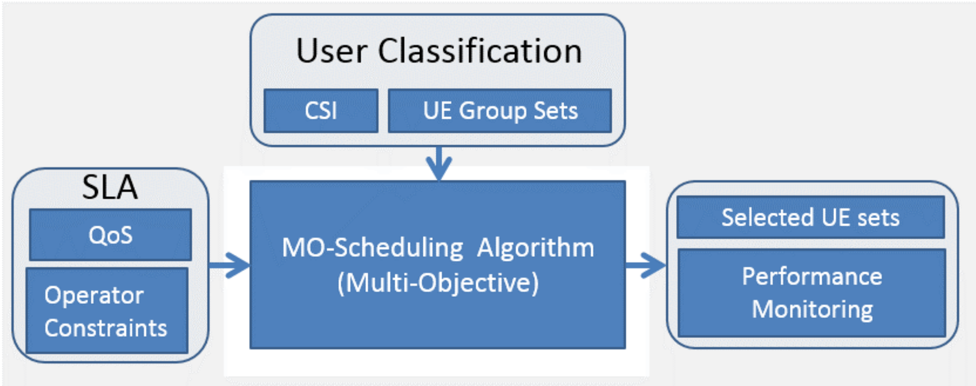


Figure 4-6: MO-Scheduler architecture.

The description of the functional blocks presented in Figure 4-6 is summarized as follows:

User Classification: at least one user from each operator is selected to form the candidate UE group set which share the same time-frequency slot. The selection and the grouping are done based on the channel state information (CSI) reports.

Service Level Agreement (SLA): provides list of predefined agreements and constraints on the QoS, resource share, minimum data rate needs to be guaranteed, power consumption, and spectral and energy efficiency performance constraints of the individual operators.

Performance Monitoring: evaluates the spectral and energy efficiency performance of the system.

One of the novelties of the proposed MO-scheduler is the application of Multi-User-MIMO (MU-MIMO) and beamforming techniques within inter-operator domain while ensuring maximum resource share fairness. By applying multi-operator MU-MIMO, the traffics of several UEs from all participating operators are spatially multiplexed on the same radio resource during each scheduling time period. MU-MIMO assumes a closed-loop feedback system where the CSI of each active user is available at the serving base station (BS) and the intra-cell interference is perfectly cancelled out using zero-forcing. Figure 4-7 (a) demonstrates a single BS shared among three operators. Figure 4-7 (b) illustrates how the SLAs are guaranteed by controlling the amount of transmit power allocated to the UEs of each operator that are spatially multiplexed.

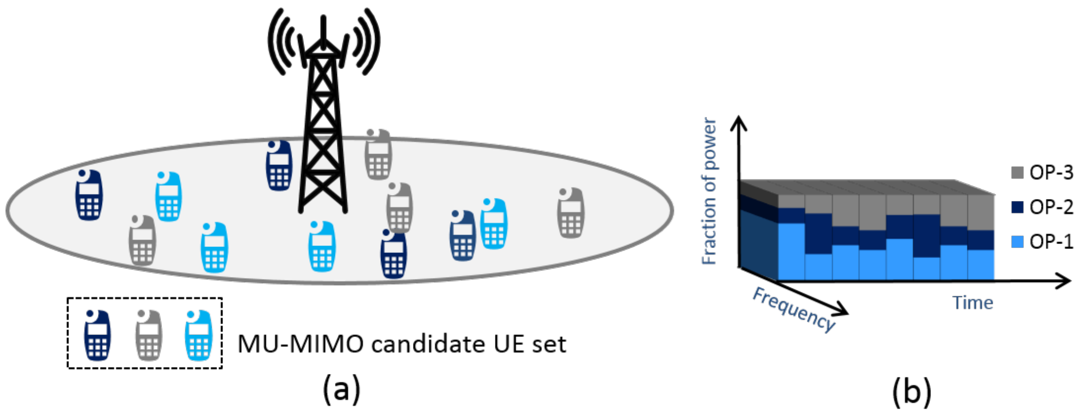


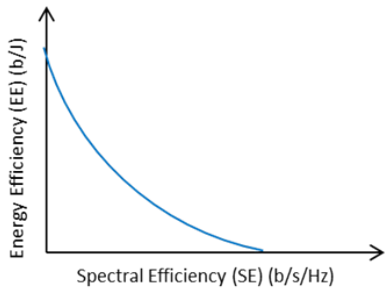
Figure 4-7: (a) Multi-Operator MU-MIMO; (b) Flexible resource sharing scheme.

Multi-Objective Sharing: the MO-scheduler takes individual operator's QoS requirements and constraints into account enabling effective sharing of spectrum among the partners by satisfying the expected desires. These parameters are implicitly integrated into the scheduling algorithm performance evaluation criteria and the decision is taken by looking into a system utility that can be adapted according to the desired sharing business cases reflected by each operator's constraints. Spectral efficiency (SE) and energy efficiency (EE) performances are the two business show cases discussed here. The scheduler decides on an optimal system operating point for any combinations of operator's specific constraints by controlling the transmission power, as the time-frequency resources are fully shared utilizing MU-MIMO. In fact, maximization of each utility corresponding to SE and EE cannot be simultaneously achieved, hence, it is highly challenging owing to their intrinsic contradicting dependency with respect to the transmit power level. The multi-objective sharing technique, therefore, defines a framework to find a pareto-optimal solution determining the feasible operating point maximizing the combined system utility.

The developed multi-objective sharing solution can be described in a simplified generic form as a convex optimization problem combining the SE and EE utilities:

$$\max_{X \in \chi} \quad \beta\, EE(X) + (1-\beta) SE(X),$$

In the objective function given above, χ is a convex vector set of $X = \{x_i\}$ where x_i is a function of the SINR of each candidate UE i in X and $I = |X|$ the number of candidate UEs in set X which are sharing same time-frequency resource via MU-MIMO. β is a weighting variable that determines the operating point prioritizing whether the SE or EE performance of the system is desired. The relationship behaviour explained in the equation above can as well be graphically illustrated in Figure 4-8 (a) showing the feasible system operating region. In addition, the figure clearly depicts the fact that increasing one objective is not feasible without impacting the other one.



(a)

Summary of Multi-Objective Sharing Solutions: Heterogeneous requirements of multiple operators			
SLA Study Case		QoS	Operator Constraints
		Data Rate	Energy Efficiency
1	OP-1	X	-
	OP-2	X	-
2	OP-1	-	X
	Op-2	-	X
3	OP-1	X	X
	Op-2(site owner)	X	-
4	OP-1	X	
	OP-2	X	
	OP-3 (site owner)	-	X

(b)

Figure 4-8: (a) SE vs EE relationship; (b) Study case scenarios and summary of multi-objective sharing requirements.

Discussion and Performance Analysis

The various case scenarios which have been investigated in this study are summarized Figure 4-8 (b). In cases 1 and 2, the participating operators are both interested to guarantee a minimum data rate and EE, respectively. In case 3 one of the operators is the site-owner who would like to maximize its SE as much as possible as well while the other operator puts EE constraint on top of the minimum data rate requirement, as part of the sharing business model considered. In case 4, OP-3 is only network provider and therefore interested in minimizing the energy consumption of the system while guaranteeing the promised data rate to the other operators.

Simulations have been carried out for different study case scenarios comprising of different operator constraints. Uniform user distribution and full buffer traffic model is considered. The channel realization assumes perfect CSI feedback for each user. The system performance is discussed using the plot from one specific study case scenario considering two participating operators where OP-1 has EE efficiency constraints (EE_{OP-1}) whereas OP-2 has a minimum data rate requirement ($Rate_{OP-2}$). The results observed for this selected scenario are presented in Figure 4-9.

Figure 4-9 (a) depicts the EE and the SE performance of the system for different weighting values. It can be observed that, the SE and EE values remain steady for $\beta<0.5$ as the algorithm prioritize SE maximization once the EE for OP-1 is maintained to its minimum. This is clearly visible at the individual operator performance with the same behaviour in Figure 4-9 (b) for the same weighting range.

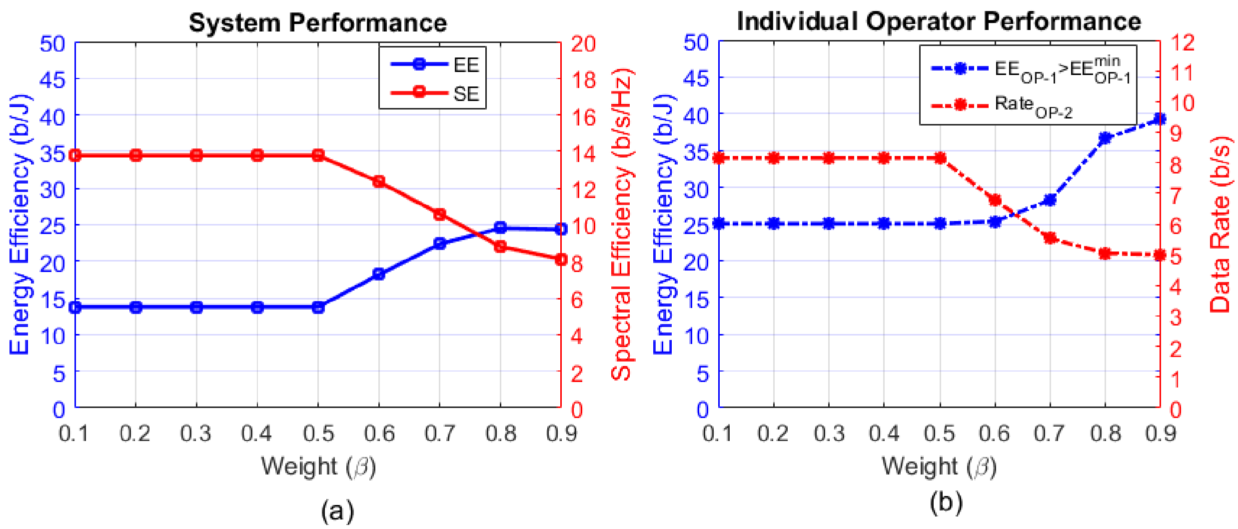


Figure 4-9: MO-Spectrum sharing: performance comparison.

On the other hand, for β>0.5, EE is highly prioritized and up to 67% EE improvement is gained. This is achieved by reducing the transmission power at the cost of the SE performance degradation. Despite the high EE value, the data rate requirement for OP-2 is still maintained above the desired threshold as depicted in Figure 4-9 (b).

4.3.3 Tuning ranges

A key aspect for 5G spectrum deliberations is to achieve global (or regional) harmonization to enable economies of scale benefits for 5G equipment.

Sufficient harmonization does not only rely on having exactly the same spectrum available in different regions, which may be anyhow very difficult to achieve due to differing situations in different countries with regard to incumbent spectrum users and usage conditions. Therefore, in order to maximize the addressable market, consideration is being given to the idea of tuning ranges, i.e. the same equipment could be used in (near) adjacent frequency bands. In Figure 4-10, it is illustrated how a tuning range could provide spectrum harmonization for a single device implementation in the range 24.25 – 29.5 GHz to serve different frequency availability situations in different countries, territories or markets.

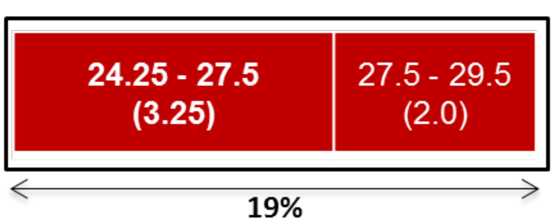


Figure 4-10: Tuning range example for 24.25 – 29.5 GHz.

Another possible tuning range could apply to the band 37 – 43.5 GHz (see Figure 4-11).

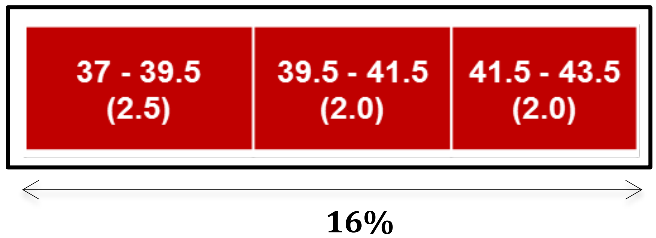


Figure 4-11: Tuning range example for 37 – 43.5 GHz.

Regarding the size of the tuning range, wideband beamforming architectures are proposed to work in wide ranges such as 17-29 GHz and 46-68 GHz bands [JSS17].

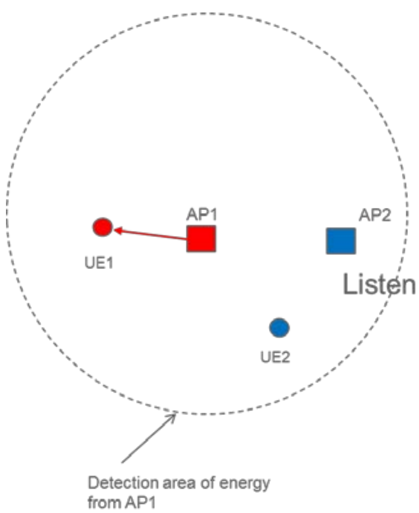
The frequency tuning capability both for base stations and terminals depends on two aspects: 1) development of RF components and 2) the advanced antenna systems of 5G with implementation of a large number of separated bands. Both aspects may add significant or even insurmountable complexity to the design.

The continued scaling of digital CMOS technology has enabled components with record figures of merit. One of the critical components, the voltage controlled oscillator (VCO), is required to have low phase noise while maintaining wide a tuning range to satisfy multiband/multi-channel standards and achieve low bit error rates (BERs) [KL07] [Wu13]. A tuned wideband VCO is implemented in 0.13 µm CMOS technology [KL07] and the frequency is continuously tuneable within the range 23-29.4 GHz with a differential-mode tuning range of 23.6%. In [ZMY15], a mm-wave dual-mode VCO topology with switchable coupled VCO-cores for wide frequency tuning range and low phase noise application is presented. This VCO exhibits a wide tuning range of more than 10 GHz and low phase noise over the entire tuning range. Tuneable negative capacitance structures are analysed and demonstrated to extend the tuning range significantly with minimal impact on phase noise, power consumption or chip area [WQM+13] and [Wu13]. Researchers report a VCO design that overcomes the fundamental trade-off between excess phase noise and high output swing in silicon-germanium VCOs, and hence achieves around 30% tuning range at around 30 GHz and low phase noise simultaneously at minimal power consumption. An ultra-wide band VCO with very high frequency tuning range (>50%) at mm-wave frequencies has also been developed by [DMW17].

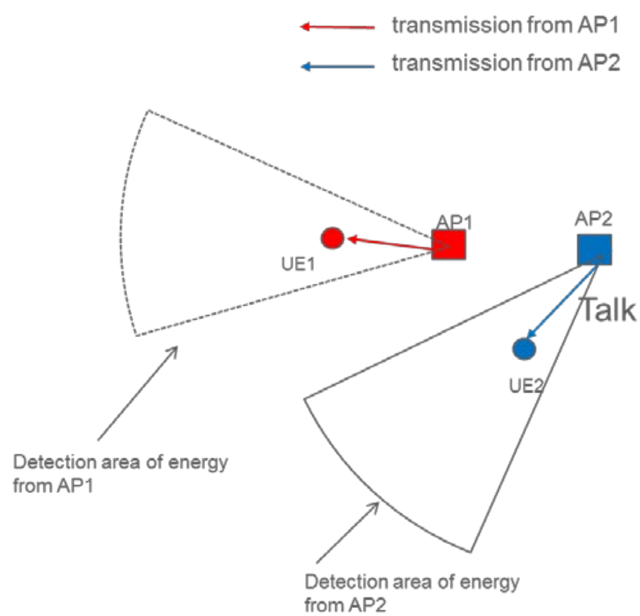
4.3.4 Studies on listen before talk with high gain beamforming

5G is aimed to be deployed in dedicated licensed spectrum as well as in shared spectrum. As a consequence, 5G mobile system should be able to operate with other 5G systems and/or different technologies, such as LTE and Wi-Fi, within the same frequency band. The main purpose of this study is to provide initial thinking on how to design 5G to operate well in shared spectrum, taking into account new 5G features' impact. Listen-before-talk (LBT), together with high gain beamforming technologies, is considered as an enabler to support horizontal spectrum sharing.

The key idea of LBT is that the source node (SN) listens to check the channel status before it actually transmits to the destination node (DN). In other words, the default mode of LBT for SN is 'not to send' and data is sent only when it is confirmed that the channel is available by listening. In addition, a back-off counter is introduced for LBT. The counter is generated randomly when SN wants to transmit data and decreases if the channel is sensed idle. When it expires, SN could start to transmit data. Due to high gain beamforming available in 5G systems, directional beamforming pointing towards the DN is used during the sensing power phase. In this case, compared to traditional LBT without beamforming, different oriented directions may result in different receiving powers as illustrated in Figure 4-12.



a) LBT without beamforming: when AP1 transmits, AP2 does not transmit since it detects energy above threshold from AP1.



b) Directional LBT: AP1 and AP2 do not interfere (detect) each other so that both transmit.

Figure 4-12: Illustration of directional LBT

AP1 is transmitting data to UE1 while AP2 is listening. Note that the dotted line indicates the detection area of energy from AP1. Without beamforming (Figure 4-12 a)) AP2 considers the channel is busy while AP1 transmits. In contrary, directional LBT (Figure 4-12 b)) allows spatial channel reuse in this situation so that AP2 cannot detect energy from AP1 (or AP1 does not interfere to AP2) and AP2 can conclude that the channel is idle. This enables that both AP1 and AP2 can transmit at the same time in Figure 4-12 b).

Evaluation assumptions

For evaluations, we consider a dense urban scenario with micro cell deployment. This scenario is inspired by the fact that shared spectrum is usually complementary to licensed operation in high capacity demand case, e.g. in a crowded shopping centre. 61 buildings are placed in the simulation area, and two networks are deployed in this area. Each network consists of 4 APs and 40 UEs for downlink only traffic. The APs are wall mounted and the UEs are distributed randomly outdoor in the streets. One deployment example is shown in Figure 4-13, with APs and UEs in blue colour for one network, and in red colour for the other one.

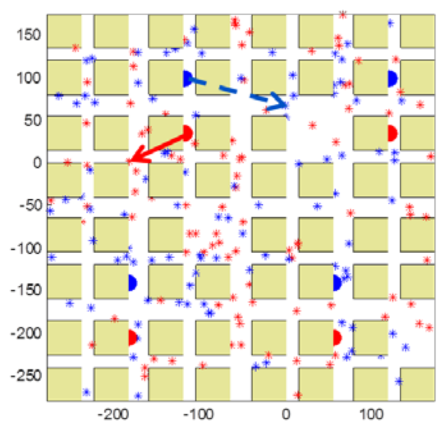


Figure 4-13: Deployment in dense urban Micro scenario.

In the simulations, the BS antenna is assumed to be a rectangular array with *M* x *N* dual-polarized elements, where *M* is the number of columns and *N* is the number of rows. The propagation model is composed of several sub-models taking into account free space propagation in line-of-sight, diffraction modelling in non-line-of-sight, and building penetration loss (BPL). The basis for each of these sub-models has been taken by selecting appropriate models described in the COST 231 Final Report [ECC99]. The models have been further updated to include relevant frequency-dependency, mainly based on measurements and estimations performed by different sources [MII16-D31].

For the evaluation purpose, the transmit power is fixed at 30 dBm, and a channel bandwidth of 100 MHz with the carrier frequency of 15 GHz is chosen. We assume downlink only traffic in this scenario. Four different schemes were compared as described below:

- Naïve scheme (No LBT): two networks schedule the data transmission independently without coordination or sensing.
- Naïve scheme with directional antenna at AP (No LBT): two networks schedule the data transmission independently without coordination or sensing. However, the directional antenna can suppress interference at receivers.

- LBT scheme: In the evaluation, the energy detection threshold is set -62 dBm. The random back-off counter will be generated between 0 and 16. Due to LBT and random back-off, the collision or erroneous transmission can be avoided.
- LBT scheme with directional antenna at AP: This is same as the LBT scheme, but it uses directional antenna which affects both LBT at AP and interference at UE.

Evaluation results

Figure 4-14 shows user throughput and system throughput at a different per user load level. In principle, the higher load causes lower throughput per user but increases overall system throughput which is measured by aggregating bits from multiple users in a whole system.

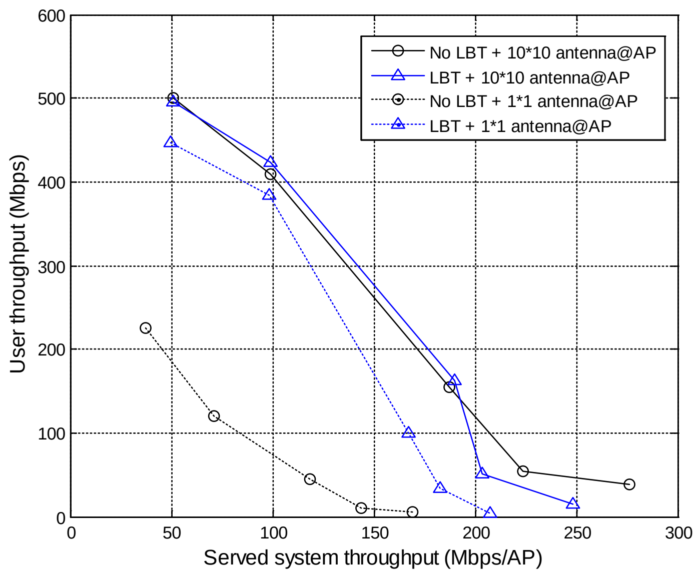


Figure 4-14: System-level performance of the beamforming impact to LBT systems.

The dashed curves in Figure 4-14 show that without beamforming (1*1 antenna@AP), LBT performs better than naive schemes. However, with beamforming (10*10 antenna@AP) as shown in solid lines, LBT has a similar performance than the naive scheme. This implies that there is the potential of using high gain beamforming for inter-network spectrum sharing without the necessary use of LBT at high frequency range. However, this remains to be further studied, e.g., investigations in different scenarios and frequency ranges.

4.3.5 A cooperative system concept for broadcast and unicast delivery

5G has a vision of broadband access everywhere, which refers to ubiquitous mobile broadband provisioning in suburban and remote rural areas [MII16-D11]. Challenges for achieving the vision are not only related to technologies but also to economics. Therefore, it is imperative to develop an extremely low-cost solution for wide areas with low population density. For this, it is desirable to utilize frequency bands with good propagation characteristics, and to reuse existing infrastructure, e.g., radio towers, as much as possible.

The UHF frequency band, particularly the range 470-694 MHz, has been considered a valuable spectrum resource for coverage-limited services due to its excellent propagation characteristics. Since the band is currently used by the digital terrestrial television (DTT) broadcasting system, shared use between DTT and 5G is of interest. In the past years, the most extensively investigated concept was accessing the geographically unused TV channels in a secondary manner, so called TV white spaces (TVWS) [ZRS+13]. However, TVWS assumes that the DTT system is non-cooperative, and only to be protected. The potential of cooperative broadcast and unicast systems design for downlink delivery has yet to be investigated.

A cooperative system can benefit from the well-established TV coverage. In rural areas, one may find often houses with poor broadband access while TV reception is feasible. By utilizing the existing TV transmission towers, it would be possible to extend the availability of broadband services to the level of TV coverage without incurring significant cost.

In this section, we introduce a novel concept of wideband DTT based on reuse one, namely WiB (wideband reuse one), and describe how it can extend the broadband availability. WiB was originally developed as a new system concept for DTT [SGK16]. As illustrated in Figure 4-15, it is radically different from conventional DTT, such that the whole UHF frequency band allocated to DTT (470-694 MHz) is utilized by all transmitter sites (reuse-1) while the transmit power is spread out equally across the spectrum. The interference between the sites is handled by the use of a robust transmission mode (e.g., QPSK with ½ code rate), directional discrimination of the receiving antenna, and interference cancellation methods. With WiB one can achieve a significant reduction of energy consumption and operational cost, and 40-60% capacity increase for the same coverage compared to the current DVB-T2. WiB gives the flexibility of content distribution at each site [SGK16], and it requires about 90% less total transmit power by using all frequencies with low-order modulation.

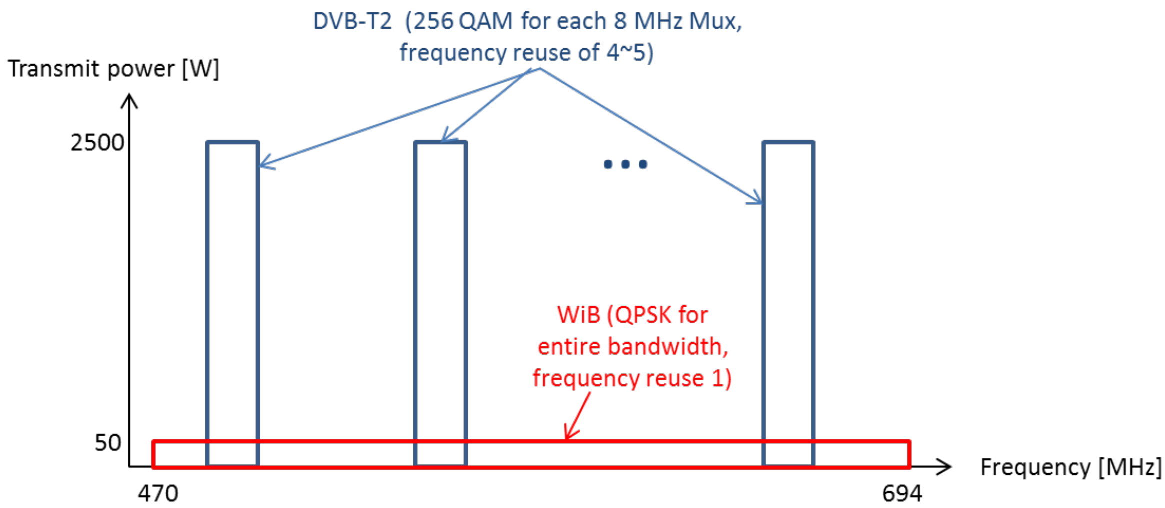


Figure 4-15: WiB concept.

WiB would facilitate efficient coexistence of DTT and unicast downlink signals in the same time and frequency domain by means of superposition coding, also known as non-orthogonal multiple access (NOMA) or layer division multiplexing (LDM). A second layer of unicast downlink signal can be added, superimposed on the basic WiB broadcast signal, and transmitted with a controlled power level difference relative to the basic signal, i.e., injection level. It is reasonable to assign a stronger power to the broadcast signal so that the broadcast contents can be demodulated by any user in the coverage area who wants to receive TV contents without broadband services, which makes the broadcasting layer agnostic to the unicast signals. It is to be noted that the WiB broadcast has a fairly low SINR target due to the low-order modulation. Thus, an injection level of 4-5 dB is considered sufficient for a successful reception of broadcast signals.

For example, in a rural area without broadband access, the aim is to provide fixed wireless access (FWA) in the UHF spectrum band while maintaining the broadcasting services. As for the unicast downlink, one can consider using highly sectorised antennas serving multiple houses simultaneously. Furthermore, the use of a large number of antenna arrays can enable massive MIMO. The typical height of a TV tower is about 200-300 meters, and it is possible to build a cylinder of antenna arrays of more than 10 meters on the top of the tower. The uplink can be provided by means of TDD as illustrated in Figure 4-16. The WiB broadcast and the superimposed unicast downlink signals can be transmitted in a discontinuous manner, alternating with uplink in time domain. Synchronization between the neighbouring sites would be needed to avoid interference between the downlink and uplink. Note that the concept proposed in this section can be considered as an air interface variant which takes part in the overall 5G RAN architecture.

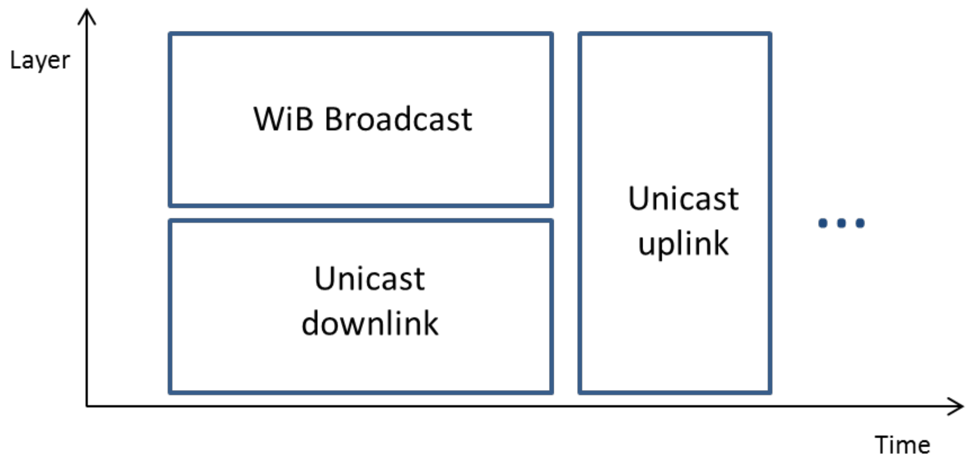


Figure 4-16: Uplink service provisioning by means of TDD.

For simulation experiments, we further assume the following assumptions were met:

- TV coverage is already established with a towers inter-site distance of 60 km.
- Houses are re-using the TV reception rooftop antenna in order to save costs.
- A tower is equipped with 2304 antenna elements, and it serves 320 users who are uniformly distributed over the site area.
- The downlink accounts for 80% of time resources.

The above assumptions lead to a downlink capacity of 93.6 Gbps which corresponds to the traffic volume density of 33.1 Mbps per km^2. The fifth-percentile user throughput is 67.8 Mbps when 320 users are uniformly distributed in the coverage area of each TV transmitter.

4.3.6 Self-backhauling in 5G bands

For 5G use cases, and noting the foreseen need for cell densification, effective and low latency backhauling is required. The use of bands above 6 GHz and especially high millimetre wave spectrum for 5G would provide the unique opportunity for using in-band self-backhauling (sBH), where access (BS-UE) and the backhaul (BS-BS or BS-Network) use the same wireless channel/spectrum. The same channel/spectrum can be shared in time, frequency or space; or a combination of those three aspects. In higher bands with MIMO antennas providing “pencil-shape” beamforming, the reuse of time, frequency and/or space resources between access and backhaul can be done more efficiently and with higher precision than in lower bands.

Generic concept and foreseen scenarios enabled by sBH

By implementing sBH, access and backhaul links would dynamically share the same wireless channel resources. The generic concept is considered in Figure 4-17.

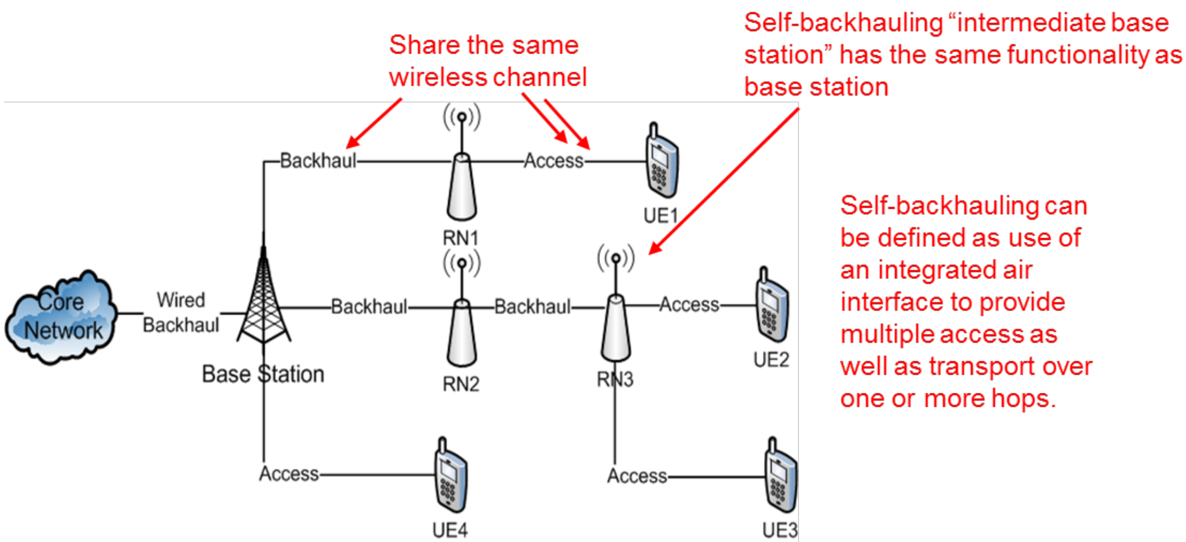


Figure 4-17: Generic concept of sBH.

By implementing sBH, faster deployments for overall infrastructure could be enabled as sBH would obviate the need for other backhaul (like fibre) connectivity at every 5G Access Point (AP). Also, Macro-to-pico deployments (including O2I deployments) from above rooftop to below can be done, and sBH could also enable successive links along a roadway or an open space. These scenarios are illustrated in Figure 4-18.

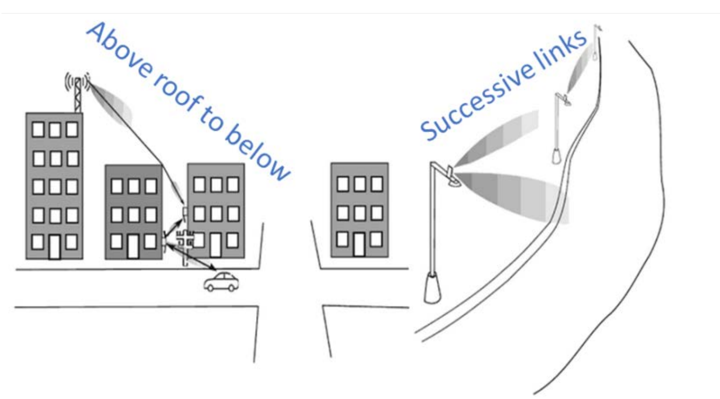


Figure 4-18: Scenarios enabled by sBH.

Parameters and assumptions used for simulation of sBH network topology and protocol

In this study done at 73 GHz, a Master-Slave Protocol was used with the following nodes:

- Anchor Base Station (a.k.a. Egress Node): The master radio controls the overall timing of the network and is always the parent device for other multi-hop radios.
- Intermediate Base Station (Non-egress Node): It acts as both a parent and a child. It receives data packets from its parent, then re-transmits the data packet to the children within the its network.
- User Equipment: A radio in slave mode does not re-transmit the data packet on the radio link. A slave device does not directly communicate with another slave device.

The feasibility and performance of a multi-hop sBH was assessed with simplified route selection and scheduling algorithms

  - Min number of hops
  - Minimum Path Loss per hop = 120 dB
  - Routing tree is iteratively constructed to the nearest egress node

- Scheduling Algorithm (multi-hop extension of the classical Proportional Fair (PF)-based algorithm)
  - Across all pending packets, find the packet with the highest PF priority (UL/DL, BH/Access)
  - Schedule the corresponding link/hop
  - Under the half-duplex and other interference constraints, eliminate packets on the interfering links
  - Find the next highest priority packet, schedule the corresponding link, eliminate the interfering links/packets, etc.
  - Scheduling approach with the highest priority packet in the network scheduled first
  - The algorithm provides and upper bound on a true distributed scheduling algorithm

In the simulations, the parameters given in Table 4-1 were used:

Table 4-1: Simulation parameters.

	Parameter	Value
Antenna/RF	TX Power	BS: P_t = 28 dBm (7 dBm per element) UE: P_t = 16 dBm (7 dBm per element)
	Antenna	BS: OMNI, N_{ant} = 64, 8×8×2 array, max gain 19 dB UE: N_{ant} = 4, 2×2×2 array, max gain 7 dB (UEs oriented towards the serving AP)
	Noise Figure	BS: NF_{TX} = 5 dB UE: NF_{TX} = 10 dB
Channel	Carrier Freq.	f_c =73 GHz
	Bandwidth	BW = 2 GHz
	Path Loss (access link)	PLE_{LOS} = 2.1, σ_{LOS} = 5.2 dB PLE_{NLOS} = 3.4, σ_{NLOS} =7.6 dB 100% UEs outdoors
General	# of Nodes	n_{BS}=25 or 9, n_{UE} =300 (all UEs are UL)
	Traffic	FTP Model (arrival rate =12 UE/sec/sector)
	Area	500 m × 500 m
Simulation	Simulation Time	1s
	Slot Duration	0.1 ms
	File size	150 Mb
	Allocation Size	132480 REs/TTI
	Load Fraction	10%
	# of Polarization	2
	Mean Access SNR	20 dB
	Mean UE FB Throughput	1.5 Gbps
	Mean Sector Throughput	18 Gbps

In the simulations, the following formula was used to calculate the path loss at 73 GHz [(*T.S. Rappaport, IEEE ICC-2014*)]:

$$PL[dB](d) = 20\log_{10}\left(\frac{4\pi d_o}{\lambda}\right) + 10n\log_{10}(d/d_o) + X$$

The calculated path loss parameters are shown in Table 4-2.

Table 4-2: Path loss parameters at 73 GHz.

Link direction	AP-to-UE		AP-to-AP		UE-to-UE	
Link type	LOS	NLOS	LOS	NLOS	LOS	NLOS
Path Loss Exponent *n*	2.1	3.3	2.1	3.5	2.1	3.3
Shadow Fading *X*	4.9 dB	7.6 dB	4.2 dB	7.9 dB	5.0 dB	7.6 dB

Additionally, for NLoS probability, the following model from [*T.A Thomas and F.W. Vook, IEEE PIMRC-2014*] was used, where it was assumed that all links with obstructed paths are NLoS, and in addition all AP-to-UE and UE-to-UE links with unobstructed paths are NLoS according to the following probability:

$$P_{NLOS} = \min\{0.0078d + 0.1, 0.8\}$$

This additional NLoS probability models clutter blockage effects, such as cars, trees, foliage, etc. All AP-to-AP links were assumed above the clutter and the probabilistic blockage was not applied on these links.

The network topology used in the simulations is shown in Figure 4-19, which roughly captures the effects of a mmWave deployment (in this study 73 GHz was used) along city blocks:

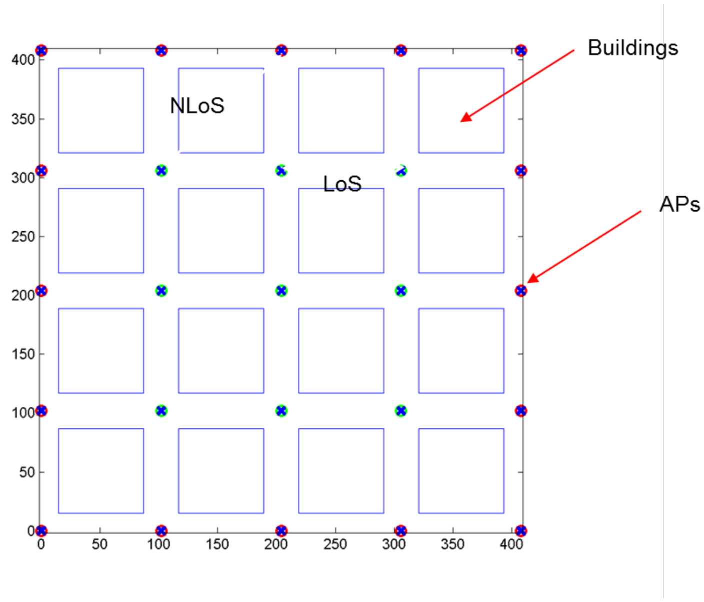


Figure 4-19: Network topology used in the simulations.

Results of the simulations

With the different number (1,2,3,9) of egress nodes (EN), the routing trees as illustrated in Figure 4-20 could be discovered.

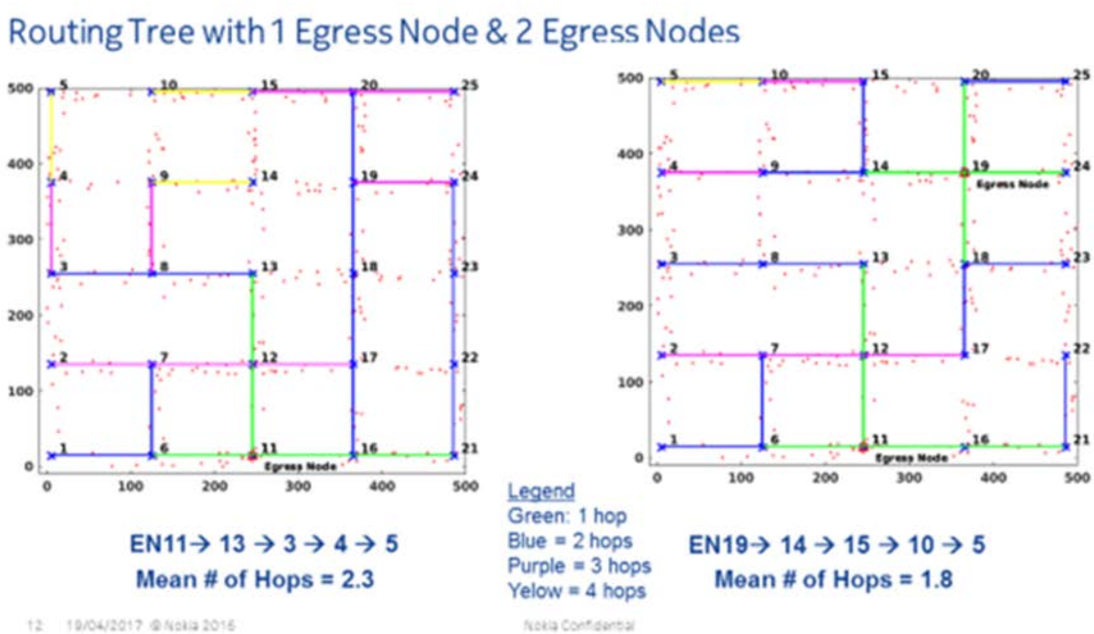


Figure 4-20: Routing trees in dependence of egress nodes.

The SNR comparison as illustrated in Figure 4-21 was performed for both uplink and downlink:

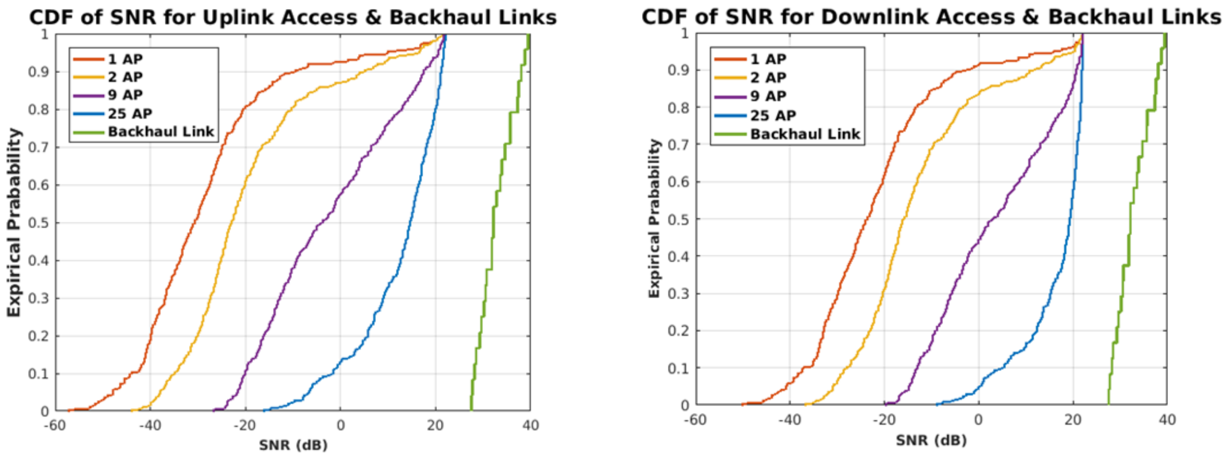
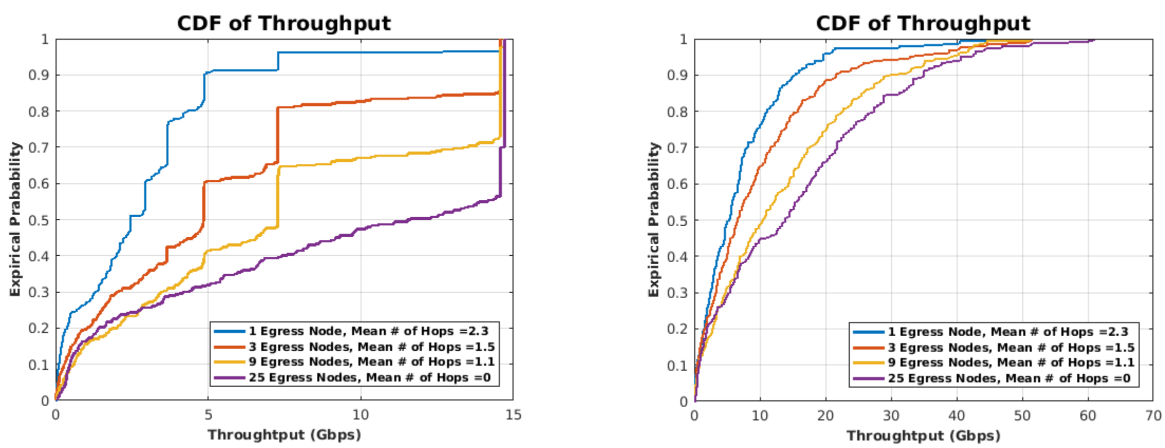


Figure 4-21: SNR comparison for uplink and downlink.

The CDF (Cumulative Distribution Function) of throughput with 25 Access Points is described in Figure 4-22 (the former is when Spectral Efficiency (SE) limit is set to 5.5 and the latter without any limit): The SE limit of 5.5 assumes the highest possible Modulation and Coding Set (MCS) of 64 QAM and coding rate 0.92 per MIMO stream.



Uplink Downlink

Figure 4-22: CDF of throughput for 25 AP and 25 EN.

The CDFs of throughput in Figure 4-23 indicate that the median (50% probability) UE throughput increases from 0.8 Gbps to 6 Gbps, when 25 AP maintain sBH connection to one of the 9 EN, as compared to the case where only 9 AP are deployed in the simulated network.

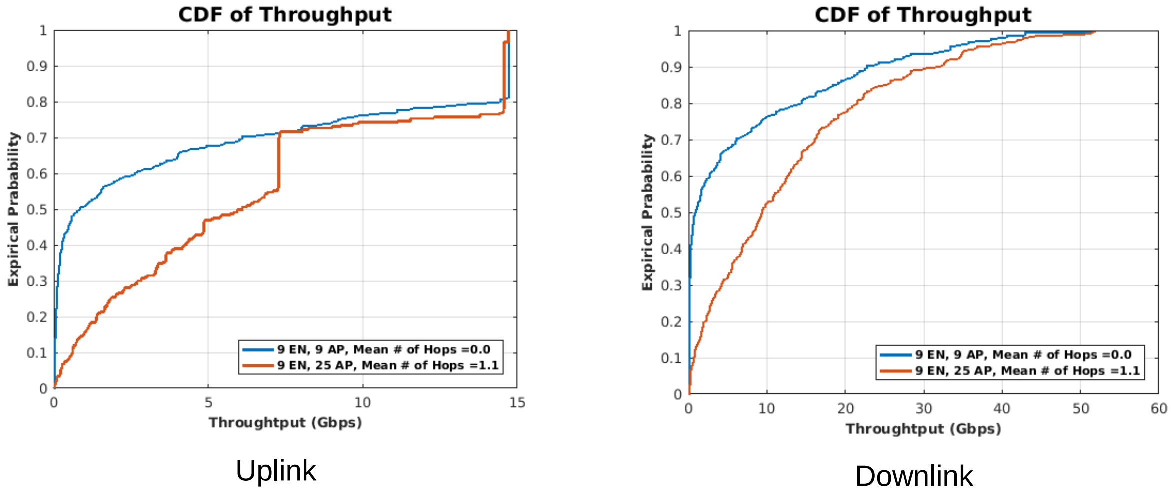


Figure 4-23: CDF of throughput for 25 AP and 9 EN.

As a summary of these sBH simulations done at 73 GHz, one can say that the best ("the maximum") case is 25 AP and 25 EN, but this leads to a significant increase in deployment efforts. The case with 9 EN and 25 AP results in a topology with an average number of 1.1 sBH hops, but it provides a significant increase in the UE median throughput compared to the case of no sBH hops (9 EN with 9 AP).

4.3.7 Geographically limited Licensed Shared Access

With the use of frequency bands above 6 GHz and with the support of appropriate spectrum regulatory regimes to facilitate guaranteed QoS, geographical limited / local licenses could cater to a diverse set of deployment paradigms and use cases, leveraging on the wide and economical availability of unified 5G ecosystem.

5G in higher frequency bands is assumed to be deployed using a beam-based system design, where the whole coverage area is achieved using a finite set of analogue beams, with fixed directionality. Such beams are uniquely identified using beam IDs, similar to the use of cell IDs in legacy systems to maximize frequency reuse and ensuring coverage precision. The basic scenario of such deployments with three local networks (LN) is as shown in Figure 4-24.

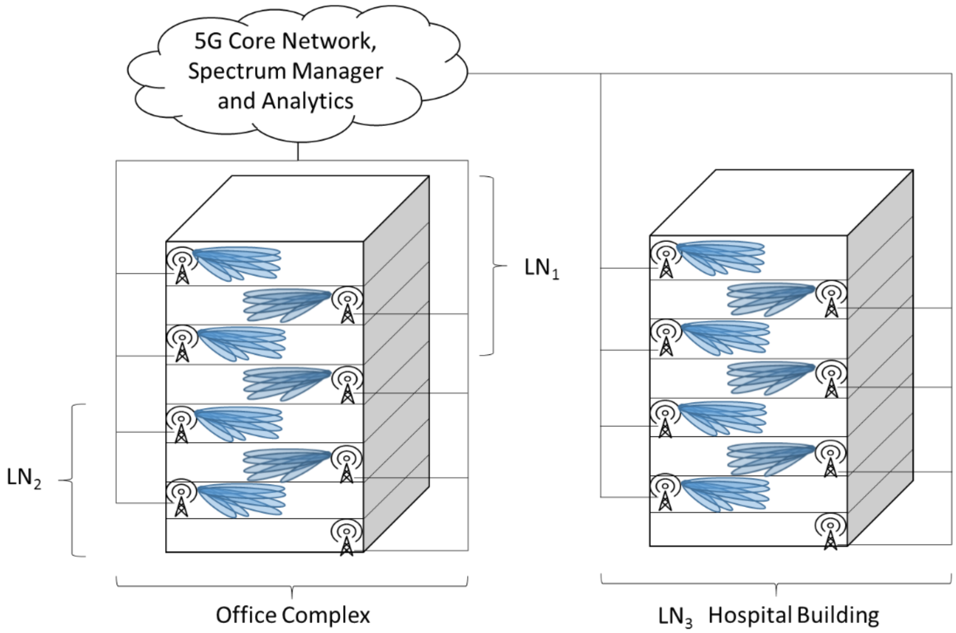


Figure 4-24: Basic 5G beam-based local network scenario.

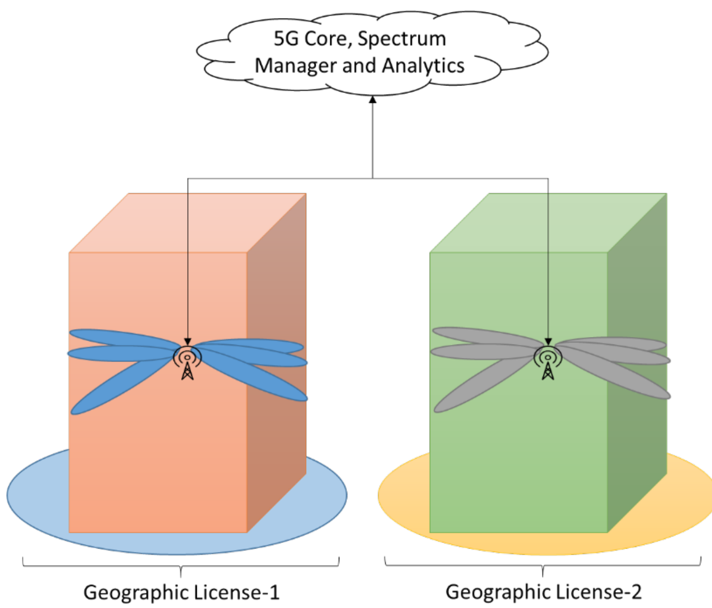


Figure 4-25: Scenario considered with geographic licenses.

The overall scenario considered in this concept with geographical licensing is as shown in Figure 4-25. Here we consider the coexistence of multiple LNs with geographically limited co-primary licenses which are centrally allocated through a spectrum manager. The spectrum manager could be located in the cloud, through which the LNs could independently request for spectrum, based on the geographical information provided by the base stations belonging to the LN. The spectrum assignment could be done statically with renewals done at finite time intervals or dynamically with assignment paradigms renewed depending on the real-time changes in network operational parameters. Here we are agnostic in terms of the next generation core network (5G-Core) and other network analytic tools that need to be deployed in order to ensure the functioning of the LNs.

An example illustration of the potential operation of the proposed method is as shown in Figure 4-26. Here the base stations of LN_1 and LN_2 coordinate with the spectrum manager and 5G-Core for coordinating the beam-based system design. Depending on the spectrum provided to both LNs, the spectrum manager can inform the LNs regarding its operational parameters including the beam IDs that can be activated, thereby optimizing the interference caused by co-primary users to each other. The only information the spectrum manager would require from LNs would be the geographical location of the BSs ([x,y,z] information). Alternatively, the spectrum manager could provide the spectrum usage limitations to the LN BSs, so that the BSs can optimize their radio transmission parameters accordingly, with the optimizations monitored by the spectrum manager.

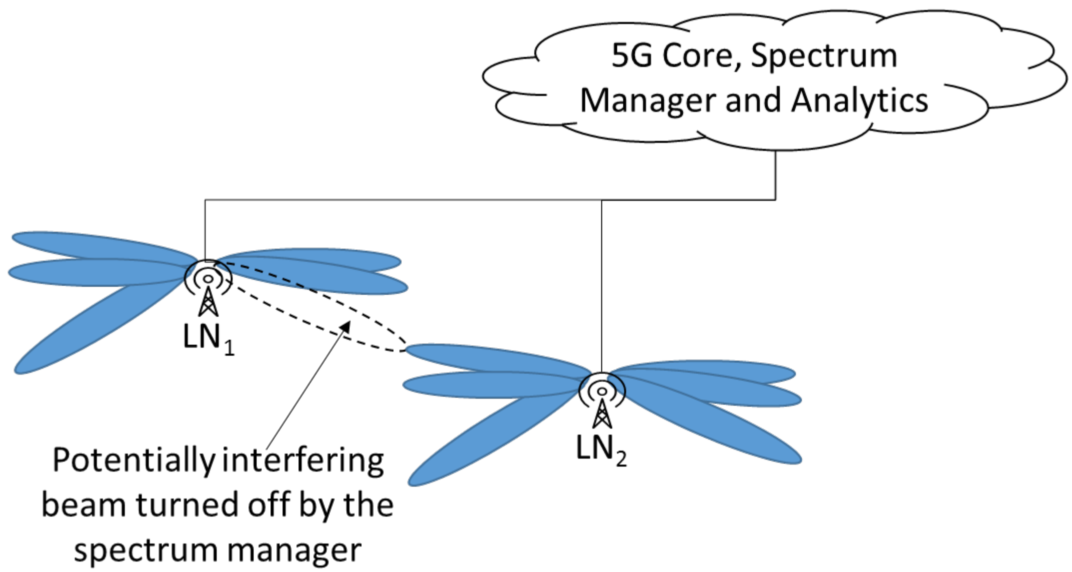


Figure 4-26: Potential operation of geographical licensing.

The geographical licensing concept could be based on e.g. LSA and is applicable to traditional MNO network operations, but could also facilitate new players in the 5G e.g. in a vertical industry sector.

4.4 Technical enabler analysis

In Table 4-3, the technical enablers introduced in section 4.3 are roughly analysed with regard to selected aspects: spectrum usage KPIs, METIS-II use cases, spectrum ranges and deployment scenarios.

Table 4-3: Analysis of technical enablers.

Technical Enablers N.A. = Not Applicable		Application Context Aware Local Service Provisioning	QoS driven Scheduler for Inter-Operator Spectrum Sharing	Tuning ranges (in mmW spectrum)	Studies on listen before talk with high gain beam-forming	Cooperative system concept for broadcast and unicast delivery in UHF band	Self-backhauling in 5G bands	Geo-graphically limited Licensed Shared Access
Applied spectrum usage KPIs	Availability	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Capacity	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Coverage	No	No	No	No	Yes	No	No
	Increase of spectrum per operator	Yes	Yes	Yes	Yes	Yes	N.A.	Yes
	Relative spectrum occupation rate	No	Yes	No	Yes	Yes	Yes	Yes
Applied METIS-II Use Cases	Dense urban information society	Yes	Yes	Yes	Yes	No	Yes	Yes
	Virtual reality office	Yes	Yes	Yes	Yes	No	No	Yes
	Broadband access everywhere	No	Yes	No	Yes	Yes	No	Yes
	Massive distribution of sensors and actuators	No	Yes	No	No	No	No	No
	Connected cars	No	Yes	No	No	No	No	No
Spectrum ranges supported	< 1 GHz	No	Yes	No	No	Yes	No	No
	1 - 3 GHz	No	Yes	No	No	No	No	No
	3 - 30 GHz	Yes	Yes	Yes	Yes	No	No	Yes
	> 30 GHz	Yes	Yes	Yes	Yes	No	Yes	Yes
Network Deployment Scenarios supported	Rural Macro	No	No	No	No	Yes	No	No
	Urban Macro	No	No	No	No	No	No	No
	Outdoor Small Cell	Yes	Yes	Yes	Yes	No	Yes	Yes
	Indoor Small Cell	Yes	Yes	Yes	Yes	No	No	Yes
	Nomadic Node	No	No	No	No	No	No	No
	D2D	No	No	No	No	No	No	No

5 5G spectrum management architecture

In order to enable innovative spectrum management, a number of technical requirements have to be fulfilled. It can be differentiated between requirements outside the Mobile Network Operator (MNO) domain and inside the MNO domain. In the latter case, a further classification on whether the requirements are related to the MNO spectrum management or dedicated to other network entities is meaningful.

5.1 Requirements outside the MNO domain

Requirements outside the MNO domain are basically in the regulator domain. In particular, a “Spectrum Management System” (SMS) entity that would perform the respective spectrum resource request and protection evaluations and decisions based on regulatory terms and rules is needed. The regulatory terms and rules may also contain complementary rules of bilateral sharing arrangements between Incumbents as spectrum resource owners and MNOs as spectrum resource users.

The SMS architecture for METIS-II is based on the LSA architecture reference model defined in [ETSI15-103235] which is shown in Figure 5-1.

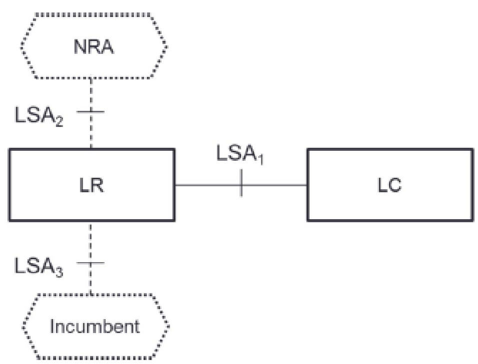


Figure 5-1: LSA Architecture Reference Model [ETSI15-103235].

This LSA architecture is extended according to the principles identified in [MET15-D54]. The main extensions are as follows:

- The SMS is an extended LSA Repository (LR) which allows
  - to support several additional sharing methods like limited spectrum pool, etc.,

  - o to manage spectrum resource user authorization more flexible to support the limited spectrum pool and mutual renting options.
- The LSA_1 interface between the LR and the LSA Controller (LC) is extended to provide beside the LSA Spectrum Resource Availability Information (LSRAI) the dynamic request of spectrum resource grants and the release of no longer used spectrum resource grants in the MNO domain.
- The LSA_3 interface between the incumbent and the LR is extended to support more dynamic sharing with multiple MNOs via a limited spectrum pool.

The biggest advantage of the proposed SMS architecture is that it follows the proven and standardized LSA concept. With the new extensions, the SMS is also prepared to introduce further spectrum sharing/usage methods like CBRS or LSA via limited spectrum pools quite simple by adding a new spectrum resource database and setting respective spectrum resource protection rules. Both can then be linked to an existing licensing or registration scheme. Figure 5-2 shows the functional blocks forming the SMS.

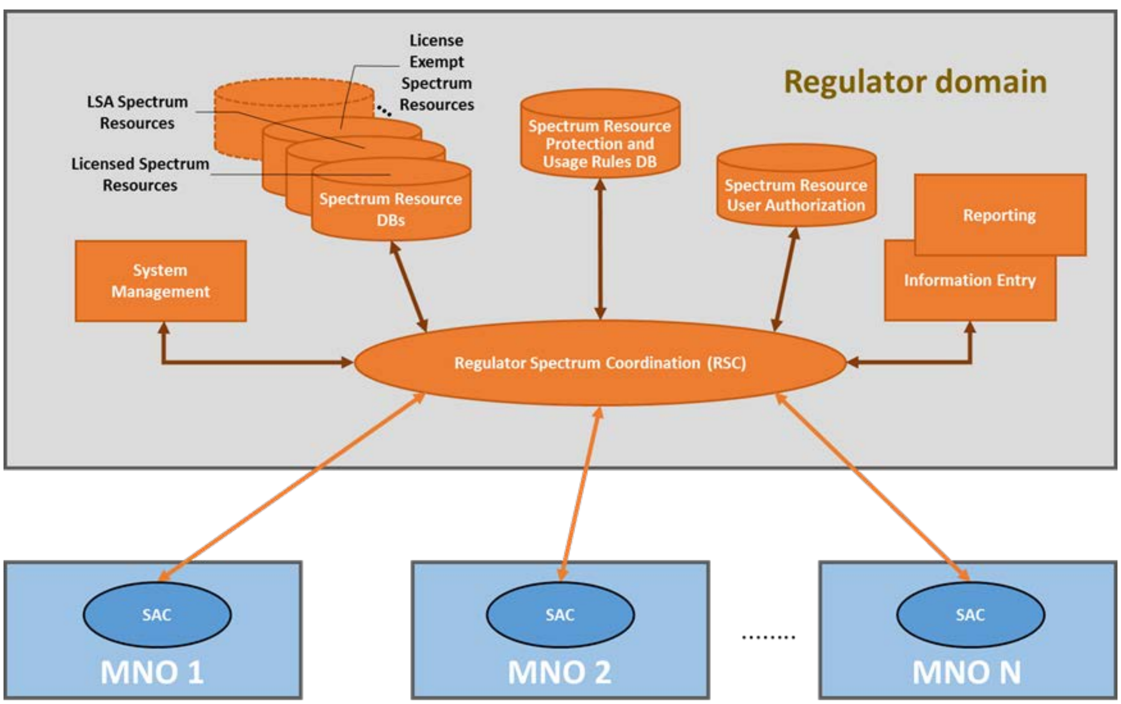


Figure 5-2: Spectrum Management System (SMS) in the Regulator domain.

The “Regulator Spectrum Coordination” (RSC) handles the communication with the MNO domains and is supported by further functional blocks:

- a variety of spectrum resource databases to organize spectrum resources in terms of different authorization types,
- the spectrum resource protection and usage rules database which realizes spectrum frameworks (e.g. sharing framework for LSA) and optional sharing arrangements,
- the spectrum resource user authorization entity containing MNOs licensing and registration information,
- the information entry allowing involved parties to provide information relevant for the regulator domain in a secure way,
- the reporting entity which provides reports regarding the spectrum resources for involved parties (e.g. regulator, incumbent(s), and/or spectrum resource users) on an on-demand or scheduled basis,
- the system management providing functions to perform operation administration, and maintenance tasks.

Finally the regulator domain contains various support functions (not shown in Figure 5-2) in order to support multiple deployment options in the regulator domain, e.g. each functional block may be split and distributed to different operation domains, e.g. the national regulator, a third party, and/or an incumbent domain.

5.2 Holistic Spectrum Management Architecture

Main challenges of spectrum management in future 5G networks are to integrate numerous of frequency bands from within a wide range of spectrum under the appropriate spectrum access condition (licensed / shared / licence-exempt), and to cope with the diverse spectrum requirements from different user groups. These challenges are proposed to be addressed by a holistic spectrum management architecture comprising a central “Spectrum Assignment Coordination” (SAC) entity which takes the final assignment decision, supported by a “Service-specific Spectrum Requirements” (SSR) entity and a “Spectrum Resource Storage” (SRS) entity for providing information on service specific requirements and spectrum availability, the “Spectrum Usage Rules” (SUR) entity encompassing “Spectrum Access Modes” (SAM) and “Network Deployment Scenarios” (NDS) based on operator spectrum policy, and the corresponding spectrum usage tools “Spectrum Sharing Enablers” (SSE) entity and “Inter-operator Coordination Functions” (ICF) entity in order to perform this task. Interfaces between the SAC and external entities, e.g. SAC entities at other operators (Inter-Operator Interface - IOIF) and a “Regulatory Spectrum Coordination” (RSC) entity at the regulator (Operator-Regulator Interface - ORIF) are required in order to facilitate cross-operator operation and data exchange on spectrum requests and assignments as well as regulatory requirements. The SAC is further connected with the operator's Radio Resource Management (RRM) via the "SR-IF" interface. A graphical illustration of this holistic spectrum management architecture is shown in Figure 5-3.

In the following subsections, the different functional entities within the "Operator Spectrum Management" as well as interfaces to external and internal functional entities are described. The processing of relevant information in the central SAC in interaction with the functional entities within the "Operator Spectrum Management" is illustrated for dedicated use cases and applications. The interworking between the SAC and the functional entities outside the "Operator Spectrum Management" is shown by message sequence charts for representative spectrum usage scenarios.

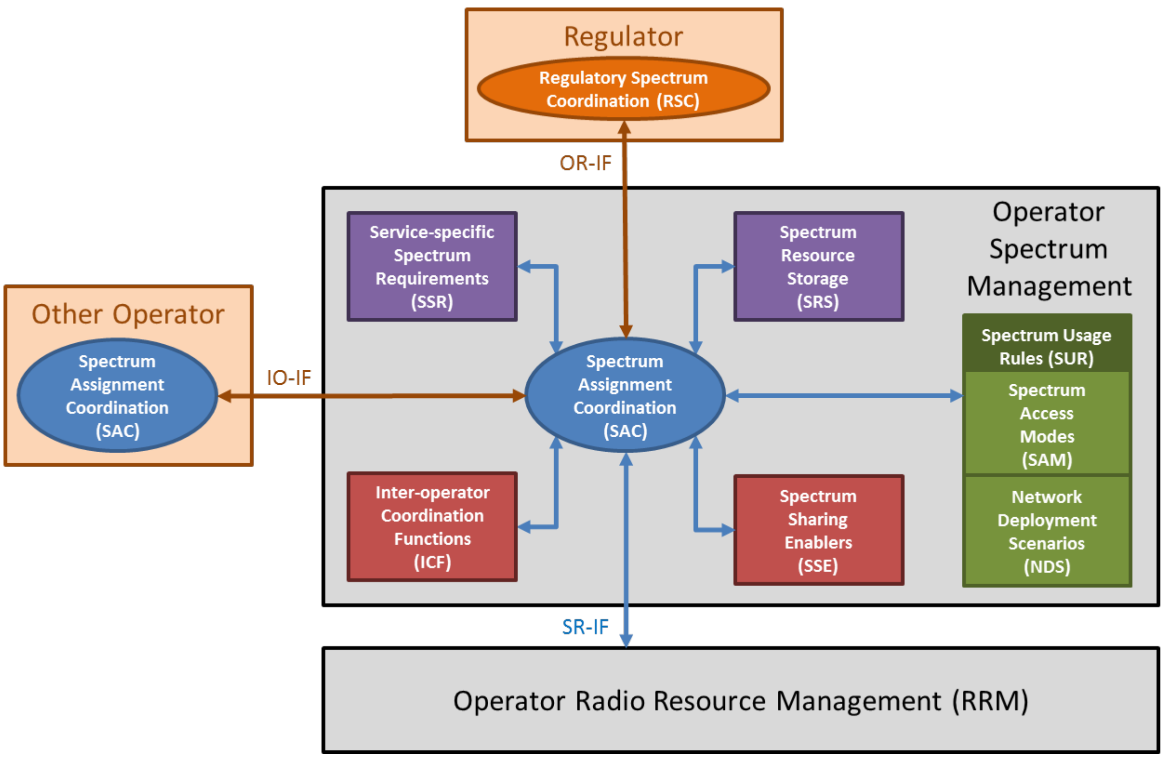


Figure 5-3: Holistic Spectrum Management architecture: Operator Spectrum Management comprising a central "Spectrum Assignment Coordination" (SAC) entity with interfaces to internal and external functional entities.

5.2.1 Spectrum Assignment Coordination

The "Spectrum Assignment Coordination" (SAC) entity is processing information from internal and external functional entities and takes finally the spectrum assignment decision for a dedicated use case, service or application. This assignment decision is communicated to the Radio Resource Management which is responsible for using the assigned spectrum resources in the most efficient manner, by controlling relevant parameters such as transmit power, modulation scheme, resource block allocation, etc.

5.2.2 Service-specific Spectrum Requirements

The “Service-specific Spectrum Requirements” (SSR) entity represents a database containing information on requirements related to the specific use case, service or application for which a spectrum assignment is requested. These requirements include

- Availability
- Capacity
- Coverage
- Mobility
- Reliability

and are to be taken into account in the spectrum assignment decision process.

5.2.3 Spectrum Resource Storage

The “Spectrum Resource Storage” (SRS) entity is a database being aware of all spectrum bands available in the operator’s mobile network. This comprises bands individually licensed to the operator, but also other spectrum usage options like shared access to license-exempt bands or to LSA bands, and also bands dedicated to a specific service or application like ITS or PPDR. In addition bands available based on inter-operator co-operation, e.g. mutual renting including cross-operator D2D communications or limited spectrum pool (see “Inter-operator Coordination Functions”), might be covered.

Spectrum bands are to be selected subject to the “Service-specific Spectrum Requirements”, but also the “Network Deployment Scenarios” play a major role in this context. One can for instance distinguish roughly between spectrum bands

- below 1 GHz for rural coverage,
- between 1 GHz and 3 GHz for urban coverage,
- between 3 GHz and 30 GHz for outdoor and indoor capacity increase,
- above 30 GHz for mainly indoor capacity increase.

5.2.4 Spectrum Usage Rules

The “Spectrum Usage Rules” (SUR) entity is encompassing two databases, namely the “Spectrum Access Modes” (SAM) entity and the “Network Deployment Scenarios” (NDS) entity. These entities contain the information of the overall operator spectrum policy with regard to spectrum access and network deployment.

Spectrum Access Modes

Subject to the "User-specific Spectrum Requirements", in particular with respect to availability and reliability, the corresponding spectrum access mode is selected. Also the overall operator spectrum policy plays a fundamental role. Spectrum access modes comprise

- Exclusive spectrum access
  - Dedicated licensed spectrum
  - Service dedicated licensed spectrum (e.g. ITS, PPDR, …)
  - Static shared spectrum (e.g. LSA without time constraints for usage during the license period)
- Shared spectrum access
  - Limited Spectrum Pool for exclusive spectrum, service dedicated spectrum, LSA spectrum
  - Mutual Renting of exclusive spectrum, LSA spectrum
  - License-exempt spectrum (e.g. LAA, WLAN, …)

Network Deployment Scenarios

According to the user's location, the available network deployment scenario has to be taken into account for the "spectrum assignment decision". Possible network deployment scenarios encompass

- Rural Macro Cell (RMC)
- Urban Macro Cell (UMC)
- Outdoor Small Cell (OSC)
- Indoor Small Cell (ISC)
- Nomadic Node (NN)
- Device-to-Device (D2D), incl. V2V, M2M, …

5.2.5 Spectrum Sharing Enablers

The "Spectrum Sharing Enablers" (SSE) entity is required to facilitate operation in shared spectrum bands, for example access to license-exempt bands or LSA bands. In such a case, following functionalities need to be activated:

- Mitigation techniques for license-exempt band usage (e.g. LBT, DCS/DFS, TPC, Duty-Cycle, …)
- LSA operation support (incl. LSA Controller functionality)

It has to be mentioned that these functionalities are implemented only if the operator's spectrum usage rules include the shared use of spectrum. In the case of LSA also a respective license is required.

5.2.6 Inter-operator Coordination Functions

The "Inter-operator Coordination Functions" (ICF) entity enables mutual spectrum utilization among different mobile network operators. The following common usage scenarios can be envisaged:

- **Mutual renting**; whereby an operator rents unused resources to other operators as long as not needed for the own network,
- **Limited spectrum pool**. In this case the regulator awards authorization to several operators to access a spectrum band. This allows participating operators to use up to the whole band on a shared basis according the rules to which resources are distributed among licensees inside the spectrum pool.
- **Cross-operator D2D operation.** This implies in-band overlay spectrum between operators sharing where a part of cellular uplink spectrum is allocated exclusively to D2D communication. Depending on the amount of D2D users and cellular users, the spectrum is automatically divided among them.

The dedicated selection is subject to operational requirements. It has to be mentioned that these functionalities are implemented only if the operator's spectrum usage rules include the inter operator use of spectrum. Thus, corresponding contracts with other operators, and in the case of limited spectrum pool also a respective license, are a prerequisite.

5.2.7 Interfaces

Interface between the Operator and the Regulator (OR-IF)

The OR-IF enables the exchange of data on spectrum requests and assignments and on regulatory requirements between the SAC and the "Regulatory Spectrum Coordination" (RSC) entity at the regulator. This interface is used for operation in e.g. License Shared Access (LSA) mode and within service dedicated spectrum (ITS, PPDR, …).

Inter-Operator Interface (IO-IF)

The IO-IF connects "Spectrum Assignment Coordination" (SAC) entities of different operators and thus facilitates the exchange of data necessary for inter-operator coordination. This interface is used in cases where mutual renting, limited spectrum pool and cross-operator D2D operation is applied.

Interface between the Operator Spectrum Management and the Radio Resource Management (SR-IF)

Over the SR-IF data on spectrum assignment, resource availability and interference is exchanged. In particular, the SAC informs the RRM about the respective spectrum assignment decisions in response to a respective request, and the SAC receives information from the RRM on the actual resource usage and about the interference situation.

5.2.8 Use cases and applications

The practicability of the proposed “Operator Spectrum Management” is demonstrated for dedicated applications which can be collated to the five use cases selected by METIS-II:

- **Use Case 1: Dense urban information society**; covering connectivity by humans and machines in dense urban environments at any place and at any time, including both indoor and outdoor environments.
- **Use Case 2: Virtual reality office**; facilitating interactive video communication for personal as well as professional use.
- **Use Case 3: Broadband access everywhere**; supporting a minimum experienced user throughput which is guaranteed everywhere.
- **Use Case 4: Massive distribution of sensors and actuators**; coping with the massive deployment of low cost and of low energy consumption devices.
- **Use Case 5: Connected cars**; enabling traffic safety and efficiency, and real-time remote services.

Table 5-1 illustrates an exemplary mapping of relevant information available in the functional entities within the “Operator Spectrum Management” for dedicated use cases and applications, which is to be processed by the SAC. The options which do not apply to the selected use cases/applications are crossed out in the respective columns; e.g. RMC and NN is not relevant in the NDS for the use case “Dense Urban Information Society”. As a result, the SAC takes a spectrum assignment decision to be communicated to the “Operator Radio Resource Management”, or initiates further coordination with the functional entities outside the “Operator Spectrum Management”, i.e. with another operator or with the regulator, before a final spectrum assignment decision is taken.

For example, when the mMTC use case “massive distribution of sensors and actuators” for the application “smart grid in rural areas” (fourth row in Table 5-1) is considered, availability and coverage as service-specific communication requirements are stored within the SSR, and the use of frequency bands below 1 GHz is indicated within the SRS. Within the SAM exclusive spectrum access as spectrum access mode applies which might also be shared by limited spectrum pool or mutual renting, and RMC and D2D as network deployment scenarios within the NDS are relevant. The SSE is not involved as the use of unlicensed or LSA spectrum does not apply. For assigning dedicated exclusive frequency spectrum below 1 GHz, the following factors may be taken into account: availability of a corresponding license, available infrastructure in the desired coverage area, technological support of the specific communication service, current utilization of the frequency spectrum, etc.

As another example, for the uMTC use case “connected cars” and the application “traffic safety” (part of fifth row in Table 5-1), availability, coverage, mobility and reliability as service-specific communication requirements are stored within the SSR, and the use of frequency bands from below 1 GHz up to above 30 GHz is indicated within the SRS. Within the SAM a service dedicated spectrum access as spectrum access mode may apply for traffic safety applications which could also be part of a limited spectrum pool. Irrespective of further information in the mapping table applying for both, traffic efficiency and traffic safety or only to traffic safety, the ITS spectrum band 5875-5905 MHz would be the respective option, i.e. further coordination with the regulator is required (see Figure 5-6).

Table 5-1: Illustration of mapping the relevant information and spectrum usage options (as described in sections 5.2.2 to 5.2.6) in the Spectrum Assignment Coordination (SAC) entity for dedicated use cases and applications.

Service	Use Case	Application	SSR	SRS	SAM	NDS	SSE	ICF
xMBB	Dense Urban Information Society	public cloud services & device-centric services	~~Availability~~ Capacity Coverage Mobility Reliability	< 1 GHz 1 - 3 GHz 3 - 30 GHz > 30 GHz	Exclusive spectrum access - Dedicated licensed spectrum - ~~Service dedicated licensed spectrum (e.g. ITS, PPDR, …)~~ - Static shared spectrum (e.g. LSA without time constraints for usage during the license period) Shared spectrum access - Limited Spectrum Pool for exclusive spectrum, ~~service dedicated spectrum,~~ LSA spectrum - Mutual Renting of exclusive spectrum, LSA spectrum - License-exempt spectrum (e.g. LAA, WLAN, …)	~~Rural Macro Cell (RMC)~~ Urban Macro Cell (UMC) Outdoor Small Cell (OSC) Indoor Small Cell (ISC) ~~Nomadic Node (NN)~~ Device-to-Device (D2D), incl. V2V, M2M, …	Mitigation techniques for license-exempt band usage (e.g. LBT, DCS/DFS, TPC, Duty-Cycle, …) LSA operation support (incl. GLDB support)	Mutual renting Limited spectrum pool Cross-operator D2D
xMBB	Virtual Reality Office	high resolution 3D scene interactions	~~Availability~~ Capacity ~~Coverage~~ ~~Mobility~~ Reliability	~~< 1 GHz~~ ~~1 - 3 GHz~~ 3 - 30 GHz > 30 GHz	Exclusive spectrum access - Dedicated licensed spectrum - ~~Service dedicated licensed spectrum (e.g. ITS, PPDR, …)~~ - Static shared spectrum (e.g. LSA without time constraints for usage during the license period) Shared spectrum access - Limited Spectrum Pool for exclusive spectrum, ~~service dedicated spectrum,~~ LSA spectrum - Mutual Renting of exclusive spectrum, LSA spectrum - License-exempt spectrum (e.g. LAA, WLAN, …)	~~Rural Macro Cell (RMC)~~ ~~Urban Macro Cell (UMC)~~ Outdoor Small Cell (OSC) Indoor Small Cell (ISC) ~~Nomadic Node (NN)~~ ~~Device-to-Device (D2D), incl. V2V, M2M, …~~	Mitigation techniques for license-exempt band usage (e.g. LBT, DCS/DFS, TPC, Duty-Cycle, …) LSA operation support (incl. GLDB support)	Mutual renting Limited spectrum pool ~~Cross-operator D2D~~
xMBB	Broadband Access Everywhere	user experience > 50 Mbps (DL)	~~Availability~~ Capacity Coverage Mobility ~~Reliability~~	< 1 GHz 1 - 3 GHz 3 - 30 GHz > 30 GHz	Exclusive spectrum access - Dedicated licensed spectrum - ~~Service dedicated licensed spectrum (e.g. ITS, PPDR, …)~~ - Static shared spectrum (e.g. LSA without time constraints for usage during the license period) Shared spectrum access - Limited Spectrum Pool for exclusive spectrum, ~~service dedicated spectrum,~~ LSA spectrum - Mutual Renting of exclusive spectrum, LSA spectrum - License-exempt spectrum (e.g. LAA, WLAN, …)	Rural Macro Cell (RMC) Urban Macro Cell (UMC) Outdoor Small Cell (OSC) Indoor Small Cell (ISC) Nomadic Node (NN) ~~Device-to-Device (D2D), incl. V2V, M2M, …~~	Mitigation techniques for license-exempt band usage (e.g. LBT, DCS/DFS, TPC, Duty-Cycle, …) LSA operation support (incl. GLDB support)	Mutual renting Limited spectrum pool ~~Cross-operator D2D~~
mMTC	Massive Distribution of Sensors and Actuators	smart grid in rural area	Availability ~~Capacity~~ Coverage ~~Mobility~~ ~~Reliability~~	< 1 GHz ~~1 - 3 GHz~~ ~~3 - 30 GHz~~ ~~> 30 GHz~~	Exclusive spectrum access - Dedicated licensed spectrum ~~- Service dedicated licensed spectrum (e.g. ITS, PPDR, …)~~ ~~- Static shared spectrum (e.g. LSA without time constraints for usage during the license period)~~ Shared spectrum access - Limited Spectrum Pool for exclusive spectrum, ~~service dedicated spectrum, LSA spectrum~~ - Mutual Renting of exclusive spectrum, ~~LSA spectrum~~ ~~- License-exempt spectrum (e.g. LAA, WLAN, …)~~	Rural Macro Cell (RMC) ~~Urban Macro Cell (UMC)~~ ~~Outdoor Small Cell (OSC)~~ ~~Indoor Small Cell (ISC)~~ ~~Nomadic Node (NN)~~ Device-to-Device (D2D), incl. V2V, M2M, …	~~Mitigation techniques for license-exempt band usage (e.g. LBT, DCS/DFS, TPC, Duty-Cycle, …)~~ ~~LSA operation support (incl. GLDB support)~~	Mutual renting Limited spectrum pool ~~Cross-operator D2D~~
uMTC	Connected Cars	traffic eficiency and safety	Availability ~~Capacity~~ Coverage Mobility Reliability	< 1 GHz 1 - 3 GHz 3 - 30 GHz > 30 GHz	Exclusive spectrum access ~~- Dedicated licensed spectrum~~ - Service dedicated licensed spectrum (e.g. ITS, PPDR, …) - ~~Static shared spectrum (e.g. LSA without time constraints for usage during the license period)~~ Shared spectrum access - Limited Spectrum Pool for ~~exclusive spectrum,~~ service dedicated spectrum~~, LSA spectrum~~ ~~- Mutual Renting of exclusive spectrum, LSA spectrum~~ ~~- License-exempt spectrum (e.g. LAA, WLAN, …)~~	Rural Macro Cell (RMC) Urban Macro Cell (UMC) Outdoor Small Cell (OSC) ~~Indoor Small Cell (ISC)~~ ~~Nomadic Node (NN)~~ Device-to-Device (D2D), incl. V2V, M2M, …	~~Mitigation techniques for license-exempt band usage (e.g. LBT, DCS/DFS, TPC, Duty-Cycle, …)~~ ~~LSA operation support (incl. GLDB support)~~	~~Mutual renting~~ Limited spectrum pool Cross-operator D2D
xMBB	Connected Cars	real-time remote computing	Availability ~~Capacity~~ Coverage Mobility Reliability	~~< 1 GHz~~ ~~1 - 3 GHz~~ 3 - 30 GHz > 30 GHz	Exclusive spectrum access - Dedicated licensed spectrum - ~~Service dedicated licensed spectrum (e.g. ITS, PPDR, …)~~ - Static shared spectrum (e.g. LSA without time constraints for usage during the license period) Shared spectrum access - Limited Spectrum Pool for exclusive spectrum, ~~service dedicated spectrum,~~ LSA spectrum - Mutual Renting of exclusive spectrum, LSA spectrum - License-exempt spectrum (e.g. LAA, WLAN, …)	Rural Macro Cell (RMC) Urban Macro Cell (UMC) Outdoor Small Cell (OSC) ~~Indoor Small Cell (ISC)~~ Nomadic Node (NN) ~~Device-to-Device (D2D), incl. V2V, M2M, …~~	Mitigation techniques for license-exempt band usage (e.g. LBT, DCS/DFS, TPC, Duty-Cycle, …) LSA operation support (incl. GLDB support)	Mutual renting Limited spectrum pool ~~Cross-operator D2D~~

5.2.9 Spectrum usage scenarios

The SAC processing depends on the spectrum usage scenarios to be supported, and the availability of respective spectrum authorizations and spectrum access modes. In general it requires a flexible interworking between the SAC and the functional entities outside the "Operator Spectrum Management". This flexibility is shown by message sequence charts for representative spectrum usage scenarios. The spectrum usage scenarios selected for this purpose are:

- Spectrum usage in dense urban environment
- Spectrum usage for smart grid in rural area
- Spectrum usage for traffic efficiency and safety applications

Figure 5-4 describes the spectrum assignment in a dense urban environment. The SAC receives the request for spectrum assignment. The processing in the SAC in interaction with the functional entities within the "Operator Spectrum Management" reveals that a large amount of additional spectrum is needed, and that also cross-operator D2D operation (for M2M communication) is required. Therefore, a request is send to the RSC at the regulator for the designation of LSA spectrum which is answered positively with a corresponding spectrum designation. The request for renting currently unused spectrum from another operator is rejected. In addition the SAC of the other operator is informed about the usage of spectrum out of a limited spectrum pool and cross-operator D2D operation within mutual agreed spectrum band(s) which is acknowledged. Thus the SAC takes the decision to assign exclusively licensed, license-exempt and LSA spectrum for usage in all bands available for outdoor and indoor cells, including cross-operator D2D operation for M2M communications.

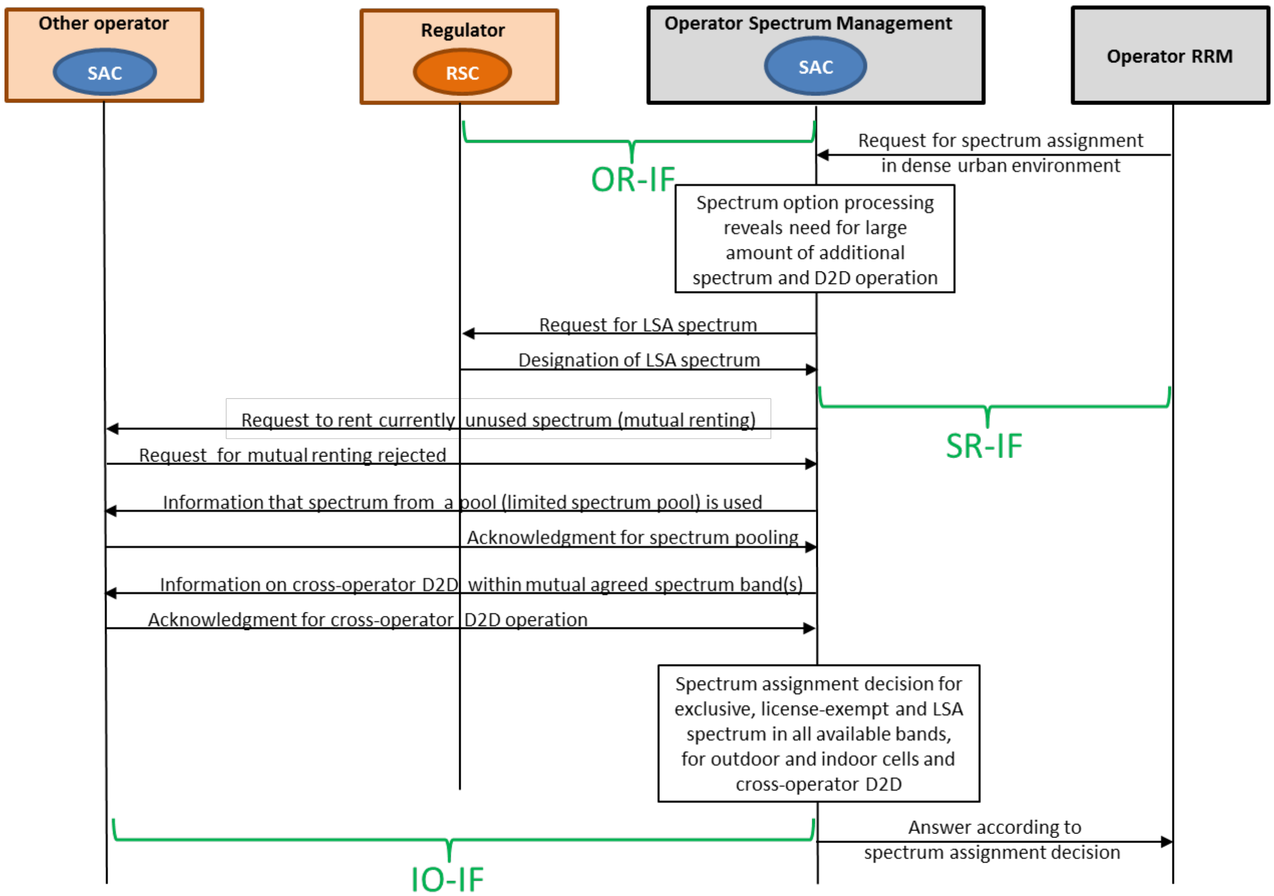


Figure 5-4: Message sequence chart example for spectrum assignment in dense urban environment.

Figure 5-5 describes the spectrum assignment for smart grid in a rural area. The SAC receives the request for spectrum assignment. The processing in the SAC in interaction with the functional entities within the “Operator Spectrum Management” results in the decision to assign exclusively licensed spectrum below 1 GHz for this usage scenario, for rural macro cell operation and optional D2D operation in the case of communication directly between MTC devices.

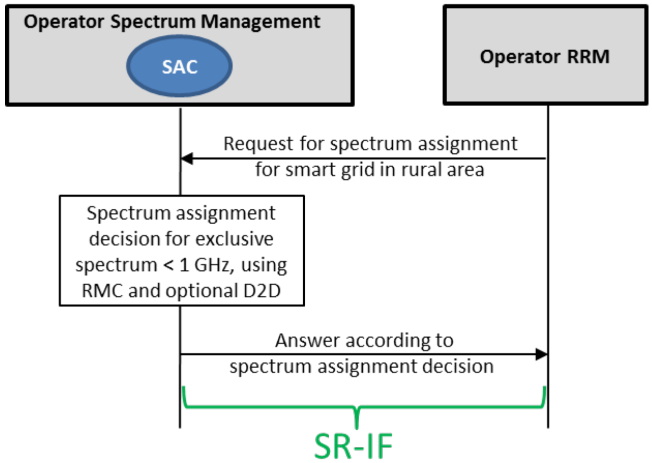


Figure 5-5: Message sequence chart example for spectrum assignment for smart grid in rural area.

Figure 5-6 describes the spectrum assignment for traffic efficiency and safety applications. The SAC receives the request for spectrum assignment. The processing in the SAC in interaction with the functional entities within the “Operator Spectrum Management” reveals that service dedicated spectrum (ITS spectrum in this case) and also cross-operator D2D operation (for V2V communication) is required. Therefore, a request is send to the RAC at the regulator for the designation of ITS spectrum which is answered positively. In addition the SAC of another operator is informed about cross-operator D2D operation within mutual agreed spectrum band(s) which is acknowledged. Thus the SAC takes the decision to assign exclusively licensed and ITS spectrum for usage in all bands available for outdoor cells, including cross-operator D2D operation for V2V communications.

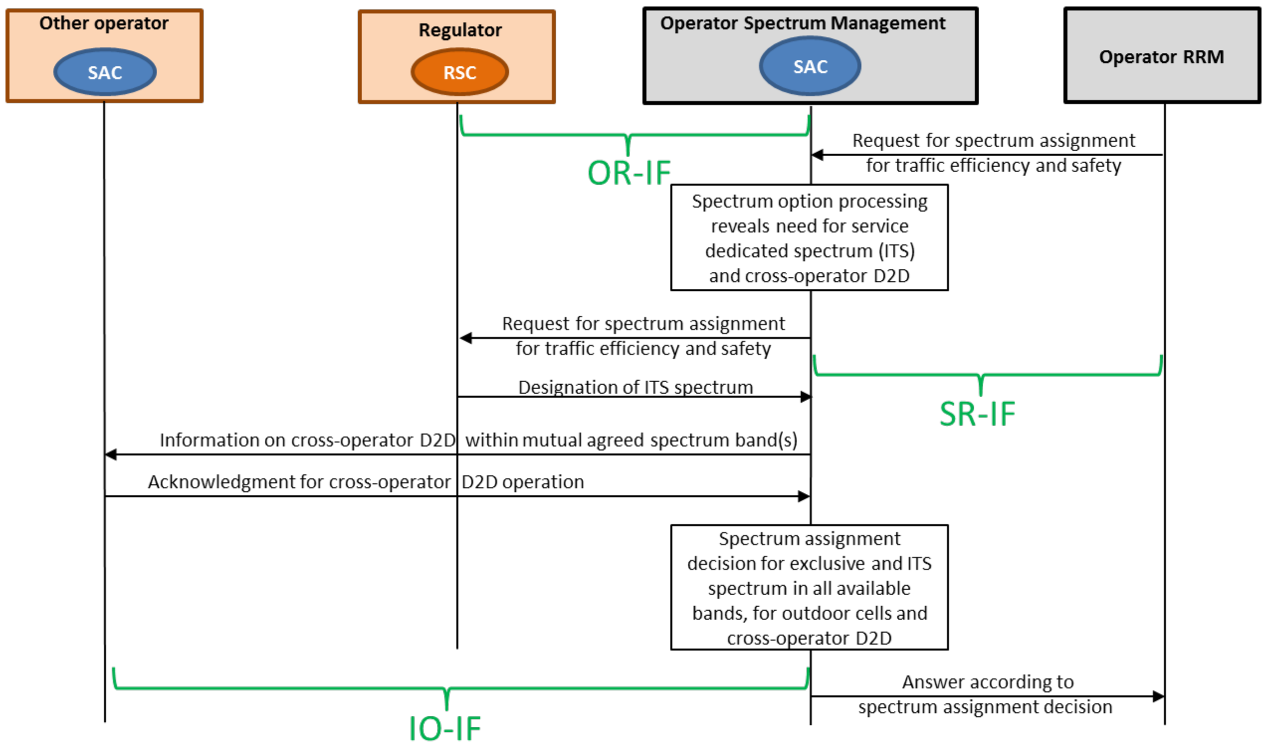


Figure 5-6: Message sequence chart example for spectrum assignment for traffic efficiency and safety applications.

5.3 Implementation options for the operator spectrum management architecture

In the following, options for implementing the functional spectrum management architecture presented in section 5.2 are considered. Herewith, it is focused on the implementation of the Spectrum Assignment Coordination (SAC) entity, as the other spectrum management entities may be either connected directly to the SAC or already part of the Operations Support System (OSS).

5.3.1 Implementation of the SAC into the 3GPP OAM system

The SAC within the operator spectrum management architecture may interact with the "Operation, Administration, and Maintenance" (OAM) system in the MNO domain at the Network Management (NM) level, similar to the implementation option for the LSA controller recommended in [3GPP16-32855]. The interaction at Element Management (EM) / Domain Management (DM) level is not considered.

The main advantage of the SAC being implemented at the NM level is that it can be connected to NM level applications (including the existing network planning and administration tools). Thus, the activities to use spectrum resources are part of the existing processes of managing the Radio Access Network (RAN). This implementation is illustrated in Figure 5-7, by showing two MNO domains and the NRA domain.

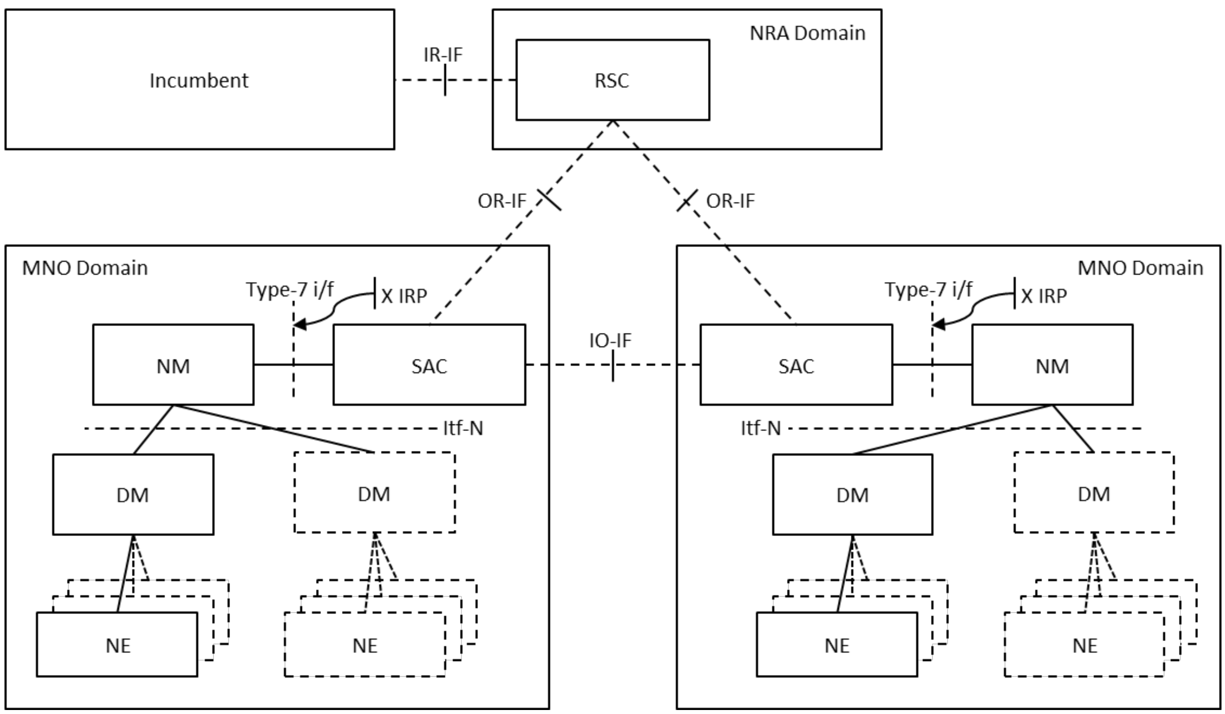


Figure 5-7: Interaction between SAC and NM by showing two MNO domains.

The SAC and the NM may interact by using Type-7 interface. According to the description of Type-7 interface in [3GPP16-32101], the SAC is then a kind of NM Layer Service. The SAC is the Service Provider, and the NM is the Service Consumer. It is assumed that the spectrum assignment related NM operations towards the NEs (e.g. Transmission Reception Points (TRP), or network functions (NF) in virtualized networks (see section 5.3.2)) are performed using the existing Integration Reference Points (IRPs) already defined by 3GPP.

Network reconfiguration performed within the SAC

It is assumed that the SAC is responsible for processing the Spectrum Resource Availability Information (SRAI).

The SRAI is received by the SAC from the RSC or another SAC. Using this information, the SAC determines configuration constraints (e.g., frequency band(s), signal bandwidth, maximum transmission power, antenna parameters) for cells utilizing shared spectrum resources, and provides this information to the OAM. The OAM then utilizes these configuration constraints provided by the SAC in its "normal" operation (e.g., Self-Organizing Network (SON) and Configuration Management (CM) functions). Figure 5-8 shows the functional split between the SAC and the OAM.

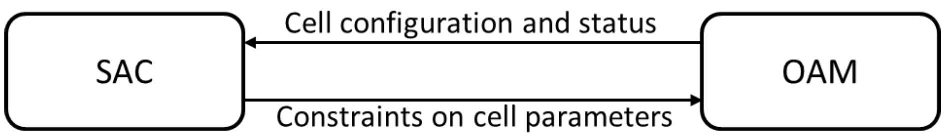


Figure 5-8: Functional split between SAC and OAM.

The functionalities fulfilled by the SAC and the OAM are as follows:

- The SAC determines and provides constraints on cell parameters (e.g., maximum transmission power) upon receiving SRAI from the RSC or another SAC, and upon receiving a notification from the NM describing a change in network deployment.
- The OAM utilizes the constraints on cell parameters received from the SAC in its normal operation (e.g., SON and CM functions) and provides the information for utilizing the spectrum resources (e.g., applied transmission power) to the SAC.

5.3.2 Implementation of the SAC into virtualized networks

Figure 5-9 illustrates the 3GPP management architecture which manages both, virtualized and non-virtualized network functions, and also clarifies the relationship between 3GPP management framework and NFV-MANO framework [ETSI14-NFV-MAN]. Assuming the SAC being implemented at the NM level (green box in Figure 5-9) or even being part of the NM, no specific modification of the standardized interactions between the NM and other entities are considered to be required.

The 3GPP CM has the system modification functions and system monitoring functions in order to support the operations of NE. The NFV configuration management includes the configuration of VNF application specific parameters and the configuration of VNF deployment specific parameters. If VNF deployment specific parameters or VNF application specific parameters are changed, this parameter change should be notified to the NM by using CM capabilities.

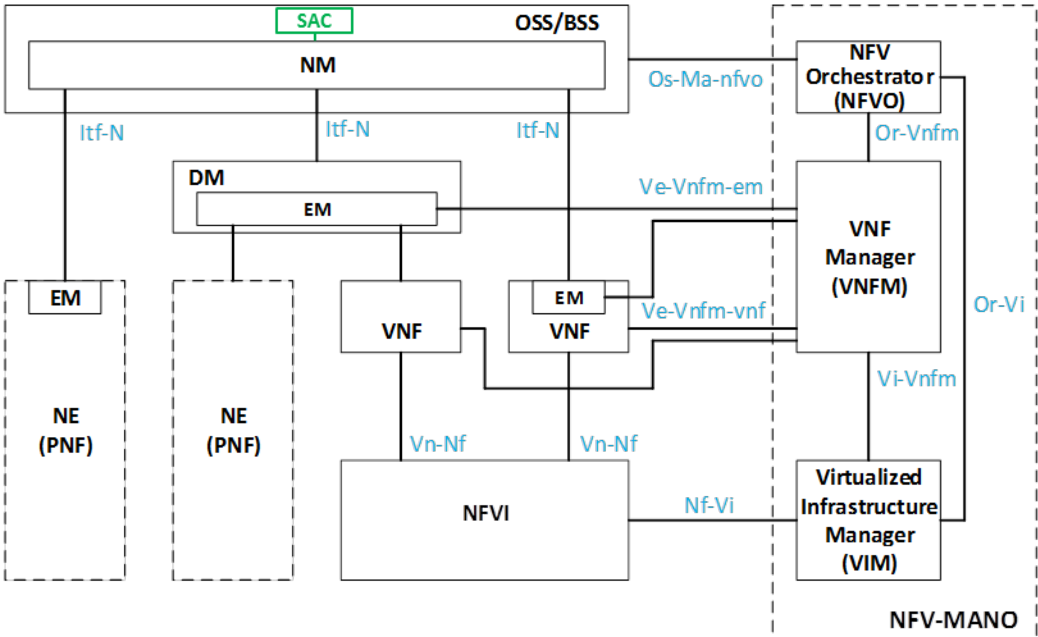


Figure 5-9: Mixed network management mapping relationship between 3GPP and NFV-MANO architectural framework [3GPP15-32842], SAC added as green box.

The constraints on cell parameters received by the NM from the SAC may be further processed similar to the use case "NFV configuration management" described in [3GPP15-32842]:

1. NM sends the configuration request to NFVO over the interface "Os-Ma-nfvo". NFVO interprets it into a specific VNF lifecycle management request and sends the request to VNFM over the interface "Or-Vnfm".
2. VNFM receives this request and implements the corresponding operation to the VNF and completes configuration of VNF deployment specific parameters over the interface "Ve-Vnfm-vnf".
3. After the VNF deployment specific parameters are configured by VNFM, VNF is created, terminated or updated and the resource of the VNF is changed.
4. After the completion of the configuration, VNFM returns the success response to EM with necessary VNF change notification over the interface "Ve-Vnfm-vnf".
5. EM performs post-operation activities (e.g. adjusting neighbour nodes of the affected VNF, configuring the VNF with application specific parameters).
6. EM notifies NM of all needed VNF resource changes through CM capabilities over the interface "Itf-N".

From the functional areas defined in [3GPP15-32842] and [ETSI14-NFV-MAN], the "Virtualized Resource Management" (VRM) and the "Policy Administration" are considered as most relevant for spectrum management. For example, the NM may need to trigger certain VRM functions over the interface "Os-Ma-nfvo", allowing the agile resource management of 5G RAN to apply dedicated resources (i.e. spectrum, infrastructure, processing power, etc.) for flexible spectrum usage [MII17-D52]. Furthermore, VRM data may need to be correlated with VNF application specific data over the interface “Itf-N”. Concerning policy administration, the NM may need to configure VRM policies over the interface “Os-Ma-nfvo” which may be forwarded over the interfaces “Or-Vnfm” and “Or-Vi”.

5.3.3 Implementation of the SAC into a SON architecture

Self-Organizing Networks (SON) technology enables the autonomic organization of network elements and functions, respectively, as well as optimization of network performance by supporting the implementation of complex solutions in a flexible manner. In [3GPP17-32501] it is described how concepts of self-configuration work and which IRP requirements are to be met in order to support respective functionalities. The flexible spectrum management concept introduced in section 5.2 could be implemented in a similar manner, e.g. like the Self-Configuration Monitoring and Management Function.

Thus, the SAC entity may be considered as a “Self-Configuration Spectrum Assignment Function” (SC_SACF). The respective functional architecture, i.e. the implementation of the SAC into the 3GPP SON concept according to the Self-Configuration Reference Model, is illustrated in Figure 5-10, showing the three levels of the network management, namely NM, DM/EM and NE.

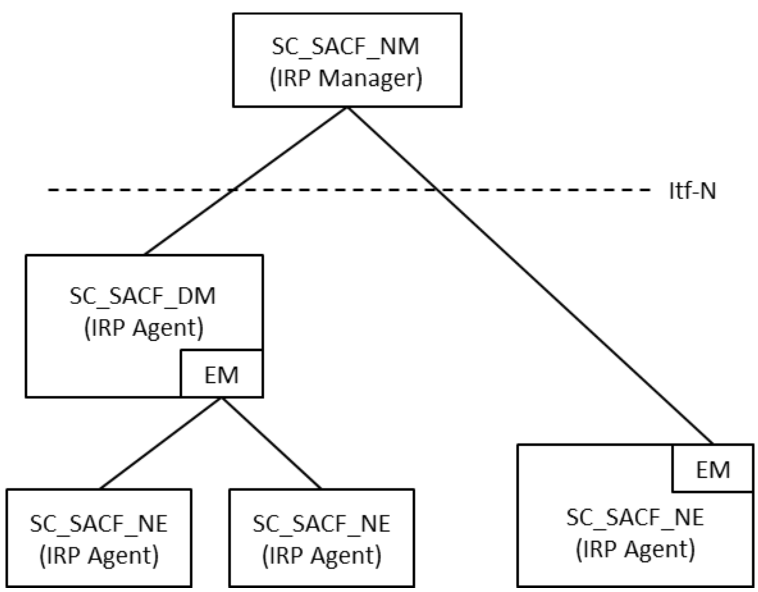


Figure 5-10: Implementation of the SAC into the 3GPP SON concept according to the Self-Configuration Reference Model [3GPP17-32501].

The SC_SACF_NM functional block represents the NM portion (i.e. policy, control and monitor functions) of SC_SACF, as well as the related IRP Manager functionality. It takes the spectrum assignment decision for a dedicated use case, service or application, after processing of relevant information from other functional entities. This assignment decision is communicated to the SC_DM/(EM) and the SC_SACF_NE functional blocks. These blocks are representing the portion of the SC_SACF operating below the Itf-N, as well as related IRP Agent functionality. The SC_SACF_NE functional block (where the SON algorithms are located) is responsible for the respective configurations of cell parameters according to the decision made by the SC_SACF.

The communication between the functional blocks may happen according to the already specified concept of “Automatic Radio Configuration Data handling Function” (ARCF). As ARCF data requires overarching coordination, it cannot be generated below Itf-N. Thus, the ARCF data handling for the SC_SACF includes the preparation of ARCF data in the SC_SACF_NM functional block, the transfer of ARCF data from the IRP Manager (SC_SACF) to the IRP Agent(s) (SC_DM/(EM) and SC_SACF_NE) and the validation of the syntax and semantics of the ARCF data in the IRP Agent(s).

6 Conclusions

5G networks need to support extreme data rates in mobile broadband applications for the public, but also services with high reliability requirements in vertical industry sectors like automotive or energy. The resulting diverging requirements can be roughly grouped into three service categories: Extreme Mobile Broadband (xMBB), Massive Machine-Type Communications (mMTC), and Ultra-reliable Machine-Type Communications (uMTC).

For xMBB usage scenarios, a mixture of frequency spectrum comprising lower bands for coverage and low traffic, and higher bands with large contiguous bandwidth to cope with extreme traffic demand, including wireless backhaul solutions, is required. Exclusive licensed spectrum is essential to guarantee coverage and service quality, supplemented by spectrum access with other licensing regimes (e.g. Licensed Shared Access (LSA) or license-exempt access) to increase the overall spectrum availability. For most mMTC applications, frequency spectrum below 6 GHz is more suitable and spectrum below 1 GHz is needed in particular when large coverage areas and outdoor to indoor penetration are needed. Exclusive licensed spectrum is the preferred option. However, other licensing regimes might be considered depending on the specific application requirements. For uMTC services, licensed spectrum is considered as most appropriate. For automotive traffic efficiency and safety communications, the frequency spectrum harmonized for Intelligent Transport Systems (ITS) is an option. For high-speed applications (like high-speed trains) and rural environments spectrum below 1 GHz is particularly suited.

The spectrum bandwidth demand for 5G services depends on a number of factors, including the use case, the applications used, the deployment scenario, the frequency band, user density and spectrum efficiency, etc. For example, with specific assumptions a total bandwidth demand of 2.4 - 7.1 GHz has been estimated for the xMBB use case “dense urban information society”. It is evident that a significant amount of additional spectrum needs to be made available for 5G, if possible harmonized world-wide. This is addressed by a group in ITU-R which is conducting sharing and compatibility studies for a number of frequency bands in the range 24-86 GHz in order to prepare for a possible identification for 5G/IMT-2020 at the World Radiocommunication Conference in 2019 (WRC-19).

Thus, 5G systems need to be able to support numerous operational bandwidths in miscellaneous deployment scenarios, and covering bands from below 1 GHz up to almost 100 GHz. Based on several initiatives and trials in different countries, first 5G implementations are expected to take place in the 3.4-3.8 GHz range and in the 26 GHz and 28 GHz bands.

The concept for spectrum management and spectrum sharing for 5G mobile networks developed in the METIS project has been enhanced in order to cover also radio spectrum already designated to potential new 5G user groups, e.g. for vertical industry applications like ITS or PPDR. To enable the spectrum management concept, a holistic architecture is introduced, embracing the regulator domain as well as the operator domain. In the regulator domain, a “Spectrum Management System” (SMS), based on the LSA approach and extended to support several additional sharing methods like e.g. limited spectrum pool, would perform the respective spectrum resource request and protection evaluations and decisions based on regulatory terms and rules. The operator domain comprises a central “Spectrum Assignment Coordination” (SAC) entity which takes the final assignment decision, supported by a number of further entities. The SAC functionality may be implemented into the network management & orchestration (MANO) framework of the 5G system.

7 References

[3GPP15-32842] 3GPP TR 32.842 V13.1.0, "Telecommunication management; Study on network management of virtualized networks", December 2015

[3GPP16-32101] 3GPP TS 32.101 V13.0.0, "Telecommunication management; Principles and high level requirements", January 2016

[3GPP16-32855] 3GPP TR 32.855 V14.0.0, "Telecommunication management; Study on OAM support for Licensed Shared Access (LSA)", March 2016

[3GPP17-32501] 3GPP TS 32.501 V14.0.0, "Telecommunication management; Self-configuration of network elements; Concepts and requirements", April 2017

[All16] Monica Alleven, "Samsung touts breakthrough in 5G-ready antenna, power amplifier at 28 GHz," online at http://www.fiercewireless.com/tech/samsung-touts-breakthrough-5g-ready-antenna-power-amplifier-at-28-ghz, 30 Jun. 2016.

[COH16-D41] ICT-671639 Coherent, Deliverable D4.1, "Report on enhanced LSA, intra-operator spectrum sharing and micro-area spectrum sharing", June 2016.

[DC99] E. Damosso and L. M. Correia, COST231 Final Report, "Digital Mobile Radio Towards Future Generation Systems Communications", 1999.

[DMW17] Davis Millimeter Wave Research Center Technical report, 2017.

[ECC11-DEC06] ECC/DEC/(11)06, "Harmonised frequency arrangements for MFCN operating in the bands 3400-3600 MHz/3600-3800 MHz", December 2011.

[ECC12-R173] ECC Report 173, "Fixed Service in Europe - Current use and future trends post 2011", April 2012.

[ECC14-R205] ECC Report 205, "Licensed Shared Access (LSA)", February 2014.

[ECC16-110A17] Document ECC(16)110 Annex 17, "CEPT roadmap for 5G", November 2016

[ETSI14-NFV-MAN] ETSI GS NFV-MAN 001 V1.1.1, „Network Functions Virtualisation (NFV); Management and Orchestration", December 2014

[ETSI15-103235] ETSI TS 103 235 V1.1.1, "Reconfigurable Radio Systems (RRS); System architecture and high level procedures for operation of Licensed Shared Access (LSA) in the 2 300 MHz - 2 400 MHz band", October 2015

[EU16-COM588] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, COM(2016) 588, "5G for Europe: An Action Plan", September 2016.

[FCC15-47] US Federal Communications Commission (FCC), "Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band", April 2015.

[FCC16-89] US Federal Communications Commission (FCC), "Use of Spectrum Bands Above 24 GHz for Mobile Radio Services," November 2016.

[Goo16] Diana Goovaerts, "Samsung Applies to Conduct 28 GHz 5G Tests Near Verizon HQ," online at https://www.wirelessweek.com/news/2016/08/samsung-applies-conduct-28-ghz-5g-tests-near-verizon-hq, 2016.

[GSA16] A GSA Executive Report from Ericsson, Intel, Huawei, Nokia and Qualcomm, "The case for new 5G spectrum", November 2016.

[ITU06-1046] ITU-R Recommendation SM.1046-2, "Definition of spectrum use and efficiency of a radio system", May 2006.

[ITU13-1768] ITU-R Report M.1768, "Methodology for calculation of spectrum requirements for the terrestrial component of International Mobile Telecommunications", April, 2013.

[ITU13-2290] ITU-R Report M.2290-0, "Future spectrum requirements estimate for terrestrial IMT", December 2013

[ITU15-2083] ITU-R Report M.2083, "IMT vision – framework and overall objectives of the future development of IMT for 2020 and beyond", September, 2015.

[ITU17-WP5D] ITU-R Working Party 5D, LIAISON STATEMENT TO TASK GROUP 5/1, "SPECTRUM NEEDS AND CHARACTERISTICS FOR THE TERRESTRIAL COMPONENT OF IMT IN THE FREQUENCY RANGE BETWEEN 24.25 GHz AND 86 GHz", February 2017

[KL07] Ka Chun Kwok and J. R. Long, "A 23-to-29 GHz transconductor-tuned VCO MMIC in 0.13 m CMOS. Solid-State Circuits," IEEE Journal of, 42(12):2878–2886, Dec. 2007.

[KRB15] Chang Wook Kim, Jihoon Ryoo and Milind Madhav Buddhikot, "Design and Implementation of an End-to-End Architecture for 3.5 GHz Shared Spectrum", 7th IEEE Dynamic Spectrum Access Networks (DySPAN), Stockholm, Sweden, Sep29-Oct02 2015.

[MET14-D53] ICT-317669-METIS, Deliverable D5.3 Version 1, "Description of the spectrum needs and usage principles", August 2014.

[MET15-D54] ICT-317669-METIS, Deliverable D5.4 Version 1, "Future spectrum system concept", April 2015.

[MET15-D61] ICT-317669-METIS, Deliverable D6.1 Version 1, "Simulation guidelines", October 2013.

[MET15-D64] ICT-317669 METIS, Deliverable 6.4 Version 2 "Final report on architecture", January 2015.

[Mey17] Dan Meyer, "T-Mobile 5G plans ensnare Samsung into 28 GHz trial," online at http://www.rcrwireless.com/20160907/carriers/t-mobile-5g-plans-ensnare-samsung-28-ghz-trial-tag2, visited at 11 Jan. 2017.

[MII16-D11] ICT-671680 METIS-II, Deliverable D1.1 Version 1, "Refined scenarios and requirements, consolidated use cases, and qualitative techno-economic feasibility assessment", January 2016.

[MII16-D21] ICT-671680 METIS-II, Deliverable D2.1 Version 1, "Performance evaluation framework", January 2016

[MII16-D31] ICT-671680 METIS-II, Deliverable D3.1 Version 1, "5G spectrum scenarios, requirements and technical aspects for bands above 6 GHz", May 2016.

[MII17-D52] ICT-671680 METIS-II, Deliverable D5.2, Version 1, "Final Considerations on Synchronous Control Functions and Agile Resource Management for 5G", March 2017.

[Moo16] Patrick Moorhead, "How The Snapdragon X50, World's First 5G Modem, Puts Qualcomm Ahead Of The Curve," online at http://www.forbes.com/sites/patrickmoorhead/2016/10/17/qualcomm-unveils-the-worlds-first-5g-modem-snapdragon-x50-for-28-ghz-mmwave-networks/#28dc010f3896, 17 Oct. 2016.

[MZS+16] G. Miao, J. Zander, K. W. Sung, and S. B. Slimane, Fundamentals of Mobile Data Networks, Cambridge University Press, 2016.

[NEC16] NEC Press release, "NEC develops 5G massive-element active antenna system that supports 28GHz band," online at http://www.nec.com/en/press/201611/global_20161116_01.html, 16 Nov. 2016.

[Pea16] James Pearce, "Nokia and T-Mobile conclude preliminary 5G tests on 28GHz," online at http://www.capacitymedia.com/Article/3587158/Nokia-and-T-Mobile-conclude-preliminary-5G-tests-on-28GHz.html, 21 Sept. 2016.

[PKS17] Jeyanandh Paramesh, Sandipan Kundu, Shadi Saberi, "Wideband Millimeter-wave Beamforming Receivers in Silicon," online at https://users.ece.cmu.edu/~paramesh/WSO_5GMIMO_Paramesh.pdf

[RSCOM16-40rev3] RADIO SPECTRUM COMMITTEE, "Mandate to CEPT to develop harmonised technical conditions for spectrum use in support of the introduction of next-generation (5G) terrestrial wireless systems in the Union", December 2016.

[RSPG13-538] RSPG Opinion on "Licensed Shared Access", November 2013.

[RSPG16-032] RADIO SPECTRUM POLICY GROUP Opinion on spectrum related aspects for next-generation wireless systems (5G), "STRATEGIC ROADMAP TOWARDS 5G FOR EUROPE", November 2016.

[Sam16] Samsung News, "SK Telecom and Samsung Electronics Complete Field Trial of Handover between mmWave 5G Base Stations," online at https://news.samsung.com/global/sk-telecom-and-samsung-electronics-complete-field-trial-of-handover-between-mmwave-5g-base-stations, 20 Sept. 2016.

[SGK16] E. Stare, J. J. Gimenez, and P. Klenner, "WiB – A New System Concept for Digital Terrestrial Television (DTT)," in IBC 2016, Amsterdam, Netherland, September 2016. [Best Paper Award]

[TMO17]	T-Mobile US, Nokia test 5G using 28GHz spectrum, online at https://www.telegeography.com/products/commsupdate/articles/2016/09/23/t-mobile-us-nokia-test-5g-using-28ghz-spectrum/ visited at 11 Jan. 2017.
[US17-MNA]	https://www.congress.gov/bill/115th-congress/senate-bill/19, March 2017.
[WQM+13]	Qiyang Wu, Tony Quach, Aji Mattamana, Salma Elabd, Steven R. Dooley, Jamin J McCue, Pompei L. Orlando, Gregory L. Creech, and Waleed Khalil, “10mW 37.8GHz Current-Redistribution BiCMOS VCO with an Average FOMT of -193.5dBc/Hz,” ISSCC 2013 / SESSION 8 / MILLIMETER-WAVE TECHNIQUES / 8.8.
[Wu13]	Qiyang Wu, Analysis and Design of Wide Tuning Range Low Phase Noise mm-wave LC-VCOs, PhD Dissertation, 2013.
[ZMY15]	Qiong Zou, Kaixue Ma, and Kiat Seng Yeo, “A Low Phase Noise and Wide Tuning Range Millimeter-Wave VCO Using Switchable Coupled VCO-Cores,” IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—I: REGULAR PAPERS, VOL. 62, NO. 2, pp. 554-563, FEBRUARY 2015.
[ZRS+13]	J. Zander, L. K. Rasmussen, K. W. Sung, P. Mähönen, M. Petrova, R. Jäntti, and J. Kronander, "On the Scalability of Cognitive Radio: Assessing the Commercial Viability of Secondary Spectrum Access," IEEE Wireless Communications, vol. 20, no. 2, pp. 28-35, April 2013.
[ZTE17]	ZTE, ZTE Microelectronics, “Calibration results for Phase 1 NR MIMO system level calibration”, 3GPP TSG RAN WG1 Meeting document R1-1704420, April 2017.

A Technology Components from METIS-I

The METIS project has proposed innovative Technology Components (TeCs) which have the potential to enable the adoption of new mechanisms for spectrum management and spectrum sharing [MET15-D54]. Some of these TeCs could be implemented in the holistic spectrum management architecture described in section 5.2. The TeCs are briefly considered in the following sub-sections.

A.1 TeC02 - Flexible spectrum use for moving networks

TeC02 provides mechanisms for the flexible use of spectrum when a vehicular node changes its purpose from a relay node to a base station, and vice versa. Depending on the desired behaviour (e.g., in-vehicle coverage or coverage extension outside the vehicle) this TeC enables better spectrum utilization in xMBB and dynamic RAN.

TeC02 can be applied to all spectrum environments but it is especially useful in diverse multi-operator, multi-RAT environments with mixture of licensed and license exempt spectrum and when the mobile node is moving over different spectrum access and regulatory areas.

A.2 TeC03 - Inter-operator separation rule for non-cooperative spectrum sharing

TeC03 is essentially about making a rule for necessary separation between operators in order to prevent cooperation. The required inter-operator separation is measured in terms of base station density with and without inter-operator coordination.

TeC03 can be applied when spectrum is to be shared by operators geographically non-overlapping. As an example, one can imagine neighbouring buildings where each building is served by a different network operator.

A.3 TeC04 - Coordinated multi-carrier waveform based sharing technique

TeC04 addresses flexible spectrum sharing between operators based on multi-carrier waveform and centralized spectrum coordination. Two or more operators obtain a certain spectrum band for shared usage in a certain time period. The spectrum band can be contiguous or non-contiguous. Prior to the shared spectrum usage, a common “subcarrier grid" is determined that defines the maximum total number of subcarriers. During the shared usage, each operator only activates the determined subset of subcarriers.

TeC04 can be applied for example to co-primary inter-operator spectrum sharing, and coexistence in LSA mode.

A.4 TeC05 - Co-ordination protocol for interaction between operators supporting the use of limited spectrum pool and mutual renting

TeC05 constructs a protocol based on asking and receiving spectrum usage favours by the operators, and keeping a book of the favours. A spectrum favour is exchanged if one operator asks for it and the other is willing to accept it.

TeC05 can be applied for example to co-primary inter-operator spectrum sharing, and coexistence in LSA mode.

A.5 TeC06 - Geo-location based interference management in environments with non-uniform user density and terrain-based propagation

TeC06 proposes a model for computing the aggregate interference level in environments with correlated fading, e.g. due to terrain-based propagation, and non-uniform density of the users. According to the model, the deployment area is divided into multiple disjoint clusters and the aggregate interference from each cluster is described in a simplified way, e.g. using a Poisson point process model. As a result, a geolocation database will be able to handle spectrum access requests with reduced complexity.

TeC06 can be applied for instance in LSA mode. It will facilitate the computation of aggregate interference generated from the spectrum licensees to the incumbent.

A.6 TeC08 - Modelling aggregate interference from in-car BS to indoor femto-cells

TeC07 proposes a model that can be used to assess the outage probability at femto-cells due to the interference generated from car base stations for two relevant spectrum sharing scenarios: (i) communication from mounted antennas on the roof of the vehicles to the infrastructure network utilizes the same spectrum as indoor femto-cells (ii) in-vehicle communication utilizes the same spectrum as indoor femto-cells while vehicular to infrastructure communication is allocated at different spectrum.

TeC07 is applicable for sharing between moving networks and indoor femto-cells. The proposed model can be used by a spectrum allocation database: according to the density of vehicles, the database evaluates the outage probability at the femto-cells and decides whether to allocate vehicular and femto-cell transmissions the same spectrum.

A.7 TeC09 - Inter-UDN coordinated spectrum sharing

Based on the high gain beam forming feature, a link-specific coordination context scheme is proposed to avoid the severe interference between different networks.

Such protocols are methods to enable spectrum sharing between resource-compatible networks that implement the same coordination protocol. The proposed scheme can efficiently utilize the high-gain beam forming feature in high frequency bands to enable more aggressive resource reuse between different networks.

A.8 TeC12 - Spectrum opportunity detection and assessment

TeC12 is based will help to obtain spectrum by negotiating access, and also assessing the use of spectrum (in terms of sharing). The functionality includes detection mechanisms and the results of the mechanisms serve as the decision basis for the spectrum assessment.

TeC12 is a central function that will enable the operator's network to operate using one or all the spectrum usage scenarios (dedicated limited spectrum pool, mutual renting, vertical sharing and unlicensed horizontal sharing). TeC12 will enhance the current operator's network given that if the network suffer high traffic load it can alleviate the problem by acquiring (renting, trading) more spectrum from other sources.

A.9 TeC14 - Spectrum sharing and mode selection for overlay D2D communication

TeC14 proposes a scheme for allocating spectrum for multi-operator D2D communication, i.e., the two ends in a D2D pair have subscriptions with different mobile network operators. It also proposes a mode selection scheme for multi-operator D2D users. It is assumed that the D2D communication takes place over dedicated cellular spectral resources contributed from both operators, i.e., in-band overlay multi-operator D2D.

TeC14 is applicable to e.g., vehicle-to-vehicle communication, and other D2D scenarios.

A.10 TeC17 - Ontologies as tool for spectrum decision making

TeC17 provides a spectrum selection scheme to evaluate spectrum offers for different spectrum sharing schemes. TeC17 covers multiple cases of spectrum offers coming both from Incumbent Users (LSA mode) and/or other MNOs (Co-primary mode).

A.11 TeC18 - Reinforcement learning scheme for adaptive spectrum sharing

TeC18 is a reasoning scheme based on fuzzy logic for identifying which is the most suitable spectrum for covering MNO's needs in a specific location, time, and date. The fuzzy logic controllers will incorporate the operator's renting strategy to maximize his revenues while covering the users' needs. The proposed algorithm is focused on LSA sharing scheme and Co-primary sharing but could be easily extended to other sharing schemes (e.g., general authorization schemes).

A.12 TeC19 - Base Station clustering for inter-operator spectrum sharing under realistic network deployment

TeC19 allows flexible inter-operator spectrum sharing and can reduce inter-operator co-channel interference while adapting the spectrum partition and allocation to the spectrum demands of the operators. TeC19 consists of dynamic clustering of the BSs of different operators in a certain location. Within each cluster, a spectrum partition pattern is determined and used.

A.13 Prepared and database assisted ultra-reliable communication for V2V

TeC20 improves the availability and reliability of ultra-reliable communication between nodes with restricted mobility trajectories (e.g. V2V communication for traffic safety between cars). TeC20 is also suitable for V2I communication.

TeC20 is applicable for all kinds of spectrum access and sharing schemes. If fast spectrum re-allocations or fast access to extra spectrum is needed, the scheme needs support for such access mechanisms.

A.14 TeC21 - Physical cell identity allocation in inter-operator spectrum sharing heterogeneous networks

This TeC comprises of Physical Cell Identity assignment algorithms for densely deployed heterogeneous networks, in a multi-operator spectrum sharing scenario. The aim is to achieve PCI assignment that is conflict-free and confusion-free, jointly for multiple operators, in a self-organized way.

A.15 TeC22 - Multi-operator D2D communication

TeC22 includes two aspects: (i) multi-operator D2D discovery and communication considering the scenario where the involved devices are subscribers from different mobile network operators (ii) to propose a joint spectrum allocation and mode selection scheme for multi-operator D2D without proprietary information exchange between the two operators and/or to other parties. In this perspective, TeC22 offers a complete multi-operator D2D support.

B Spectrum demand calculation procedure for UC1

In section 3.2, the spectrum demand analysis of xMBB use cases was provided, together with estimated spectrum bandwidth amount based on different deployment solutions. In the following, the detailed assumptions and calculation procedures of spectrum demand analysis are provided, taking UC1 as an example. In UC1, basically we have two layers deployed on the same area, and in general two deployment solutions can be considered, i.e., co-channel and orthogonal-channel deployment. With co-channel deployment, the same spectrum bandwidth (including either below or above 6 GHz) is deployed on macro and small cell layers, while for orthogonal-channel deployment, below 6 GHz and above 6 GHz are deployed for macro layer and small cell layer, respectively. The following symbols are defined to simplify the notation.

SE_{M_REQ}: the required 5th percentile user spectral efficiency of macro layer (with 10 users per cell)

SE_{SC_REQ}: the required 5th percentile user spectral efficiency of small cell layer (with 10 users per cell)

C_{REQ}: the required experienced user throughput.

SE_M: the estimated 5th percentile user spectral efficiency of macro layer.

SE_{SC}: the estimated 5th percentile user spectral efficiency of small cell layer.

N: the number of active users per sector (including both macro and small cell layers).

M: the number of small cells per macro cell.

α : the ratio of users associated with the small cell layer.

B_M: the estimated spectrum bandwidth demand of macro layer.

B_{SC}: the estimated spectrum bandwidth demand of small cell layer.

C: the estimated experienced user throughput.

B.1 UC1 with co-channel deployment

Since a certain user can be associated with either macro layer or small cell layer, the experienced user throughput should be the minimum of the estimated throughput on these layers, e.g.,

$$\mathrm{C} = \min(\mathrm{SE}_M * B_M, SE_{SC} * B_{SC}) = \min(\frac{\mathrm{SE}_{M\_REQ} * 10}{N * (1-\alpha)} * B_M, \frac{SE_{SC\_REQ} * 10}{N * \alpha / M} * B_{SC})$$

As macro and small cell layers are deployed on the same carrier frequency, it is reasonable to assume that they can fully reuse the bandwidth, i.e., $B_M = B_{SC} = B$.

It is observed that the user association ratio α has a direct impact on the eventual experienced user throughput, and in order to minimize the required spectrum bandwidth, the optimal association ratio should meet the following requirement.

$$\alpha^* = \arg\max C = \arg\max[\min(\frac{\mathrm{SE}_{M\_REQ} * 10}{N * (1-\alpha)} * B, \frac{SE_{SC\_REQ} * 10}{N * \alpha / M} * B)]$$

The maximum throughput can be achieved when the separate throughput are the same, thus the optimal association ratio can be derived as below.

$$\alpha^* = \frac{\mathrm{SE}_{SC\_REQ} * M}{SE_{M\_REQ} + SE_{SC\_REQ} * M}$$

In this way, the estimated experienced user throughput can be rewritten as

$$\mathrm{C} = \frac{(SE_{M\_REQ} + SE_{SC_{REQ}} * M) * 10}{N} * B$$

Here $SE_M + SE_{SC_{REQ}} * M$ can be regarded as the equivalent spectrum efficiency of the two layers, thus the required spectrum bandwidth to meet the target throughput, i.e., C_{REQ}, can be derived as

$$\mathrm{B}_M = B_{SC} = \frac{N * C_{REQ}}{(SE_{M\_REQ} + SE_{SC_{REQ}} * M) * 10}$$

B.2 UC1 with orthogonal-channel deployment

For orthogonal-channel deployment, as different amount of spectrum bandwidth can be allocated on each layer, it is quite difficult to derive the optimal user association ratio for one layer. Based on the above analysis, for a different user association ratio, the required spectrum bandwidth on each layer would be different. However, in order to minimize the total spectrum requirement of the two layers, the achievable experienced user throughput of each layer should still be the same. Regarding that principle, we can derive the spectrum bandwidth demand of macro layer and small cell layer as below, respectively.

$$\mathrm{B}_M = \frac{N * (1-\alpha) * C_{REQ}}{SE_{M\_REQ} * 10}$$

$$\mathrm{B}_{SC} = \frac{N * \alpha * C_{REQ}}{SE_{SC_{REQ}} * M * 10}$$

C Spectrum demand calculation analysis parameters for local environments

This Annex include the full list of parameter used for spectrum demand evaluation for local environment, accordingly with section 3.1.3, as well as the values finally adopted for different UCs evaluated, accordingly with METIS-II scenario definitions.

Table C-1: Simulation control parameters

Abbreviation	Parameter	Details
N_iter	Number of iterations	The number of different Monte Carlo analyses, each one carried out with a different scenario layout.
N_slot	Number of time slots	Different time slots for each iteration allow the statistical variation of UEs required throughput and the achievable SINR.
BW_av	Bandwidth available	Several carrier frequencies are considered, each one with a different value of available bandwidth (assigned for the radiocommunication system being evaluated), even if not all UEs and TRP will be able to use all carrier frequencies considered (as an example sensors are considered as a single carrier frequency equipment).

Table C-2: UE and TRPs characterization

Abbreviation		Parameter	Details
Class_UE		UE Classes	Definition of different UEs characteristics, as performance at different carrier frequencies, probability of different type of sessions, etc. (values usually associated to sensors, computers, mobile phones, etc.).
For each UE class the scenario, and each carrier frequency considered, the values of the following parameters are different	Alpha	Degradation coefficient	This value determines the degradation of the UE achievable throughput compared with Shannon law.
	Eff_esp	Maximum achievable spectral efficiency	This value will depend on the RF characteristics of the UE as the number of antennas, and establish a limit for the spectral efficiency achievable.
	Min_SINR	Minimum SINR	Value of the minimum SINR below which the UE cannot be reached.
	P_QCI	Probability of QCI session	Value of the probability that the UE is willing to establish a session with any of the different QCI considered in the scenario.
SINR_m		SINR Mean Value	For each BS and SC (for high or ultra-high density), and for each carrier frequency, this value indicates the mean value of the Gaussian distribution of the TRP achievable SINR.
SINR_sd		SINR standard deviation	For each BS and SC (for high or ultra-high density), and for each carrier frequency, this value indicates the standard deviation value of the Gaussian distribution of the TRP SINR.
SINR_m_v		SINR Mean variation	Once the SINR are assigned for different UE-TRP links, an additional Gaussian variation of the achievable SINR value is set up, to take into account particularities as indoor situations or random reflections.
Eff_esp_min		Minimum value of spectral efficiency to schedule resources	For each BS and SC, this value indicates the minimum spectral efficiency in which TRP will assign bandwidth to a UE-TRP link.

Table C-3: Sessions characterization and targeted QoS

Abbreviation	Parameter	Details
Thpt_stat_model	Throughput statistical model	For each session, depending on the QCI, a different throughput statistical model is established, being Gaussian and Poisson models the most used in the simulation, with mean values according to the QCI.
Thr_min	Minimum Throughput	Minimum value of the throughput that needs to be achieved to consider that the UE keeps the connectivity of the UE-TRP link.
Thr_serv_rate	Throughput service rate	This value is the rate between the throughput required for the full service, and the throughput with which it is considered that the service is maintained with limited degradation.

Table C-4: Physical deployment of UEs and TRPs

Abbreviation	Parameter	Details
ISD	Inter Site Distance	Average distance between BSs present in the scenario.
NL	Number of Layers	The BSs in the scenario will be deployed in several layers around a central BS (located in the x=0 y =0 position) being the number of layers selectable
Ang_err	Angular error	Value of the random angular error between the actual BS position and the one that would be assigned to it in case of regular grid.
Dist_error	Distance error	Value of the random distance error between the actual BS position and the one that would be assigned to it in case of regular grid.
BS_min_dist	BS-BS minimum distance	Minimum distance that is permitted between two BSs in the scenario.
UE_dens	UE density	Value of the UE density for the overall scenario, composed by all the BS Voronoi cells.
High_dent_R	Radius of high density areas	Radius of the different areas of high density considered in the scenario.
Dist_SC_high	Distance between SC and high density area	This value indicates the average random value of the distance between a high density area and a SC. If the distance is zero it is considered that there is no specific SC for the high density area.
min_dist_high	Minimum distance between high density area	This value is also used as the minimum distance between the high density area and any BS.
UE_dens_high	Density of UEs in high density area	Since high density areas are inside the main scenarios this UEs are additional to the ones already presented in this area due to main scenario density (UE_dens).
Ultra-high_dent_R	Radius of high density areas	The radius of the different areas of ultra-high density considered in the scenario.
Dist_SC_ultra-high	Distance between SC and ultra-high density area	This value indicates the average random value of the distance between a ultra-high density area and a SC. If the distance is zero it is considered that there is no specific SC for the ultra-high density area.
min_dist_ultra-high	Minimum distance between high density area	This value is also used as the minimum distance between the ultra-high density area and any BS or SC of high density.
UE_dens_ultra-high	Density of UEs in ultra-high density area	Since high density areas are inside the main scenarios this UEs are additional to the ones already presented in this area due to main scenario density (UE_dens).

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Table C-5: Simulation control parameters

Parameter	Value
N_iter	20
N_slot	10
BW_av	Different options considered

Table C-6: UE and TRPs characterization

Parameter	Value
Class_UE	1, 2, 3
Alpha (f1)	UEClass 1 = 0.85 ; UEClass 2 = 0.85 ; UEClass 3 = 0.85
Alpha (f2)	UEClass 1 = 0.9 ; UEClass 2 = 0.9 ; UEClass 3 = 0.9
Eff_esp (f1)	UEClass 1 = 3 ; UEClass 2 = 6 ; UEClass 3 = 2
Eff_esp (f2)	UEClass 1 = 3 ; UEClass 2 = 6 ; UEClass 3 = 2
SINR_m (f1) (dB)	UEClass 1 = -20 ; UEClass 2 = -20 ; UEClass 3 = -20
SINR_m (f2) (dB)	UEClass 1 = -20 ; UEClass 2 = -20 ; UEClass 3 = -20
P_QCI (1)	UEClass 1 = 0.3 ; UEClass 2 = 0.2 ; UEClass 3 = 0.1
P_QCI (2)	UEClass 1 = 0.4 ; UEClass 2 = 0.5; UEClass 3 = 0.2
P_QCI (3)	UEClass 1 = 0.2 ; UEClass 2 = 0.2; UEClass 3 = 0.4
P_QCI (4)	UEClass 1 = 0.1 ; UEClass 2 = 0.1 ; UEClass 3 = 0.3
SINR_m BS (f1) (dB)	2
SINR_m BS (f2) (dB)	-2
SINR_sd BS (f1) (dB)	6.2
SINR_sd BS (f2) (dB)	6
SINR_sd BS (f2) (dB)	6
SINR_m_v BS(f1) (dB)	4
SINR_m_v BS(f2) (dB)	4
SINR_m_v SC(f2) (dB)	6
Eff_esp_min BS (bps/Hz)	0.002
Eff_esp_min SC (bps/Hz)	0.002

Table C-7: Sessions characterization and targeted QoS

Parameter	**Value**
Thpt_stat_model QCI(1)	Gaussian mean value 300 Mbps (limited to 400 Mbps)
Thpt_stat_model QCI(2)	Gaussian mean value 30 Mbps (limited to 100 Mbps)
Thpt_stat_model QCI(3)	Gaussian mean value 1 Mbps (limited to 20 Mbps)
Thpt_stat_model QCI(4)	Poisson lambda 1Mbps (limited to 10Mbps)
Thr_min QCI(1) (Mbps)	1.5
Thr_min QCI(2) (Mbps)	1
Thr_min QCI(3) (Mbps)	0.2
Thr_min QCI(4) (Mbps)	0.2
Thr_serv_rate QCI(1)	50 %
Thr_serv_rate QCI(2)	50 %
Thr_serv_rate QCI(3)	70 %
Thr_serv_rate QCI(4)	50 %

Table C-8: Physical deployment of UEs and TRPs

Parameter	**Value**
ISD (m)	200
NL	3
Ang_err	20 %
Dist_error	20 %
BS_min_dist (m)	140
UE_dens (UE/km^2)	250
High_dent_R (m)	60
Dist_SC_high (m)	15
min_dist_high (m)	55
UE_dens_high (UE/km^2)	300

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Table C-9: Simulation control parameters

Parameter	Value
N_iter	20
N_slot	10
BW_av	1000 MHz

Table C-10: UE and TRPs characterization

Parameter	Value
Class_UE	1, 2, 3
Alpha	UEClass 1 = 0.8 ; UEClass 2 = 0.7 ; UEClass 3 = 0.6
Eff_esp	UEClass 1 = 8 ; UEClass 2 = 6 ; UEClass 3 = 2
SINR_m (dB)	UEClass 1 = -20 ; UEClass 2 = -20 ; UEClass 3 = -20
P_QCI (1)	UEClass 1 = 0.3 ; UEClass 2 = 0.2 ; UEClass 3 = 0.1
P_QCI (2)	UEClass 1 = 0.4; UEClass 2 = 0.5 UEClass 3 = 0.2
P_QCI (3)	UEClass 1 = 0.2 ; UEClass 2 = 0.2 ; UEClass 3 = 0.4
P_QCI (4)	UEClass 1 = 0.1; UEClass 2 = 0.1 ; UEClass 3 = 0.3
SINR_m BS (dB)	6.6
SINR_sd BS (dB)	9
SINR_m_v BS (dB)	8
Eff_esp_min BS (bps/Hz)	0.002

Table C-11: Sessions characterization and targeted QoS

Parameter	**Value**
Thpt_stat_model QCI(1)	Gaussian mean value 30 Mbps (limited to 100 Mbps)
Thpt_stat_model QCI(2)	Gaussian mean value 30 Mbps (limited to 100 Mbps)
Thpt_stat_model QCI(3)	Gaussian mean value 1 Mbps (limited to 20 Mbps)
Thpt_stat_model QCI(4)	Poisson lambda Mbps 8 Mbps (limited to 20 Mbps)
Thr_min QCI(1) (Mbps)	1
Thr_min QCI(2) (Mbps)	1
Thr_min QCI(3) (Mbps)	0.2
Thr_min QCI(4) (Mbps)	0.2
Thr_serv_rate QCI(1)	50 %
Thr_serv_rate QCI(2)	50 %
Thr_serv_rate QCI(3)	70 %
Thr_serv_rate QCI(4)	50 %

Table C-12: Physical deployment of UEs and TRPs

Parameter	**Value**
ISD (m)	1732
NL	3
Ang_err	20%
Dist_error	20 %
UE_dens (UE/km^2)	5 UE/km^2