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Deliverable D5.1

Intermediate description of the spectrum needs and usage principles

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Abstract:

This document explains and analyses the expected spectrum scenarios addressed in METIS.

In a bottom-up process, several spectrum bands are investigated and potential bands for future mobile communications use are explored. An analysis of spectrum access schemes and authorization regimes is provided, allowing to open up new spectrum usage options and to increase the overall spectrum efficiency. Implementation aspects resulting from these new spectrum authorization regimes are discussed in detail. A "Spectrum Sharing Tool Box" is introduced that provides a framework for the efficient implementation of the defined sharing concepts.

In a top-down process, the scenarios and test cases defined in METIS deliverable D1.1 are reviewed from a spectrum need and usage point of view. Linking the test cases to the METIS radio access concepts and horizontal topics that are most promising for their implementation allows a first mapping of the test case specific spectrum needs onto new and existing spectrum options, in particular those that might become available under new spectrum sharing regimes. The analysis clearly highlights the importance of making new spectrum usage options available. Without these new options many of the upcoming applications depending on wireless connectivity cannot be implemented. The analysis also indicates that not only more spectrum and more efficient spectrum usage concepts are required but that the broader range of application requirements will in addition result in new challenges on spectrum engineering with respect to guaranteeing co-existence, compatibility, and coverage.

It should be noted that deliverable D5.1 presents initial results of the METIS spectrum investigations, i.e., all aspects presented here are under discussion.

Keywords:

Radio Frequency Spectrum; Individual / General Authorisation; Shared Spectrum Access; Spectrum Sharing Tool Box; Spectrum Demand; Licensed Shared Access (LSA); Higher Frequencies; Millimetre Wave (MMW) bands; Spectrum Usage.

Contents

List of Abbreviations, Acronyms, and Definitions

3GPP	The 3rd Generation Partnership Project
AEHF	Advanced Extremely High Frequency Services
ASA	Authorized Shared Access
BS	Base Station
BWA	Broadband Wireless Access
CAPEX	Capital Expenditure
CCIR	Comité consultatif international pour la radio
CDMA	Code Division Multiple Access
CEPT	The European Conference of Postal and Telecommunications Administrations
CTS	Clear To Send frame
CUS	Collective Use of Spectrum
D2D	Device-to-Device
DCS	Dynamic Channel Selection
DEC	Decision
DECT	Digital Enhanced Cordless Telecommunications
DFS	Dynamic Frequency Selection
DSRC	Dedicated Short-Range Communications
DT	Deutsche Telekom
ECA	European Common Allocation
ECC	Electronic Communication Committee
ECO	European Communications Office
EESS	Earth Exploration Satellite Service
EFIS	ECO Frequency Information System
ERC	European Radio Committee
ERI	Ericsson A.B.
ETCS	European Train Control System
EU	European Union
FBMC	Filter Bank Multicarrier
FDD	Frequency-Division

	Duplexing
FS	Fixed Service
FSS	Fixed Satellite Service
GBSAR	Ground Based Synthetic Aperture Radar
GLDB	Geo-location Database
GSM	Global System for Mobile Communications
HTs	Horizontal Topics
HWDU	Huawei
ICT	Information & Communication Technology
IEEE	The Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
ISM	The industrial, scientific and medical
ISS	Inter Satellite Service
ITS	Intelligent Transport Systems
ITU	International Telecommunication Union
LOS	Line-of-sight
LRTC	Least Restrictive Technical Conditions
LSA	Licensed Shared Access
LTE	Long Term Evolution
MAC	Medium Access Control
MBB	Mobile Broadband
MGWS	Multi Gigabit Wireless Systems
MIMO	Multiple-Input and Multiple-Output
MMC	Massive Machine Communications
MMW	Millimetre Waves
MN	Moving Networks
MNO	Mobile Network Operators
MTC	Massive Machine Type Communication
MWS	Multimedia Wireless Systems
NATO	The North Atlantic Treaty Organization

NKUA	National and Kapodistrian University of Athens
NLOS	Non- line-of-sight
NRA	National Regulatory
NSN	Nokia Siemens Networks
OPEX	Operational Expenditure
PMSE	Programme Making and Special Events
PPDR	Public Protection & Disaster Relief
QoS	Quality of Service
RAS	Radio Astronomy Service
RAT	Radio Access Technology
REC	Recommendation
RF	Radio Frequency
RSPG	The Radio Spectrum Policy Group
RTS	Request to Send frame
SAB	Services Ancillary to Broadcasting
SAO	Spectrum Authorization Options
SAP	Services Ancillary to Programme making
SRD	Short Range Devices
TC	Test Case
TDD	Time-division duplexing
TDMA	Time division multiple access
TID	Telefónica ID
TV	Television
TVWS	Television White Space
UDN	Ultra Dense Networks
UE	User Equipment
UHF	Ultra High Frequency
UK	United Kingdom
UKL	University of Kaiserslautern
URC	Ultra Reliable Communications
USA	United States of America
V2V	Vehicle to Vehicle
V2VRU	Vehicle to Vulnerable Road User
WLAN	Wireless Local Area Network

WP1	Work Package 1
WRC	World Radio Conference
VRU	Vulnerable Road User

1 Introduction

Spectrum is a key prerequisite for any radio access network. The availability of spectrum and the efficiency of its usage fundamentally affect the achievable network capacity and performance. This deliverable exclusively focuses on spectrum related aspects and addresses selected challenges related to the potential of new spectrum resources, the efficiency of their usage, the spectrum authorisation regimes and their implementation, as well as spectrum usage options in the context of the METIS test cases defined in METIS deliverable D1.1 [17].

What METIS is about

The METIS objective is to respond to societal challenges for the year 2020 and beyond by laying the foundation for the next generation of mobile and wireless communication systems. METIS is a consortium of 29 partners spanning telecommunications manufacturers, network operators, the automotive industry and academia.

Societal development will lead to changes in the way mobile and wireless communication systems are used. The advent of the Internet of Things and other innovative applications will see tens of billions of connected devices and an unprecedented diversity of requirements and use cases associated with wireless connectivity.

METIS will respond to the increase in traffic volume by increasing the capacity and by improving the energy efficiency, the cost and the spectrum utilization. Besides evolving today's public network technology, new radio access concepts will be introduced and efficiently integrated. This approach will, on the one hand, support the dramatic increase in mobile data volume foreseen by 2020 and will, on the other hand, support services and applications that cannot yet benefit from the economy of scale effects.

Spectrum resources and the efficiency of their usage are crucial ingredients for the overall METIS approach.

The METIS approach

METIS has analysed the above mentioned challenges regarding mobile and wireless infrastructure for beyond 2020 in detail. In order to illustrate the challenges, five scenarios were defined and described in METIS deliverable D1.1:

a) "Amazingly fast" focusing on providing high data-rates for future mobile broadband users so as to experience instantaneous connectivity without delays,

b) "Great service in a crowd" focusing on providing reasonable mobile broadband experience even in the very crowded areas and conditions,

c) "Ubiquitous things communicating" focusing on efficient handling of a very large number of devices (including e.g. machine type of devices, and sensors) with widely varying requirements,

d) "Best experience follows you" focusing on end-users on the move with high levels of experience, and

e) "Super real-time and reliable connections" focusing on new applications and use cases with very strict requirements on latency and reliability.

Based on these scenarios more detailed "test cases" are defined in deliverable D1.1. Each test case typically contains challenges from one or more scenarios. The aim of the test cases is to provide distinct problem descriptions, requirements, and Key Performance Indicators (KPIs) from the end-user perspective. They will be used by the METIS project as a basis for designing and evaluating technical solutions.

Figure 1 shows the mapping of the test cases on the scenarios.[1]

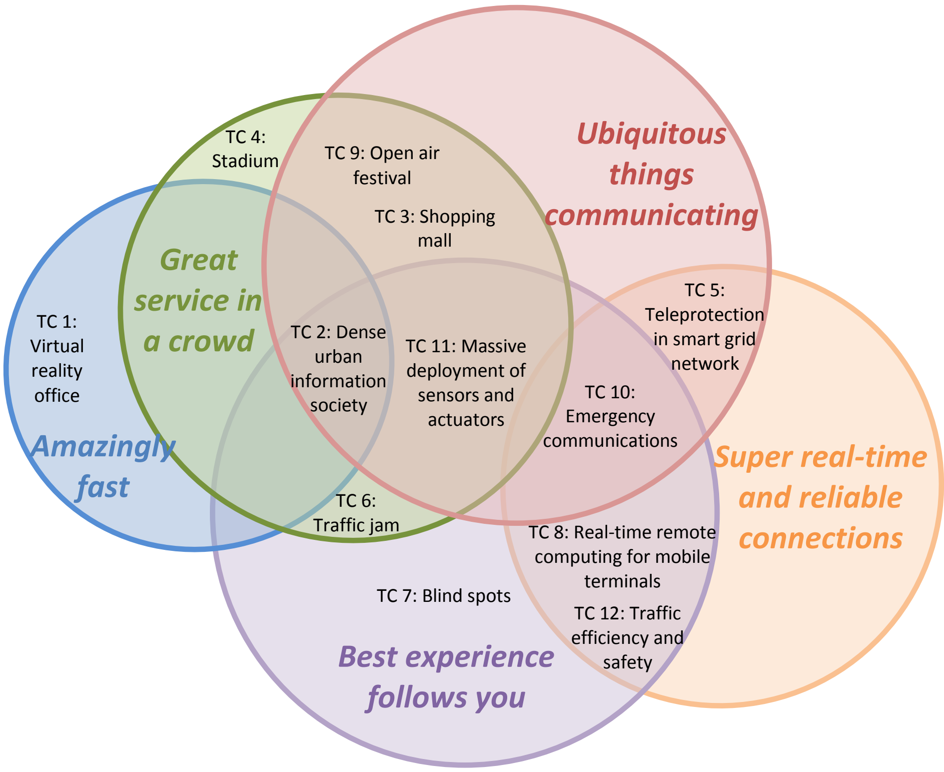


Figure 1 – Twelve test cases mapped onto the five scenarios

In order to develop technical solutions METIS has defined Horizontal Topics (HTs) that will provide the new functionality needed to address the user requirements efficiently. HTs defined up to now are Device-to-Device (D2D) integration, Ultra Reliable Communications (URC), Ultra Dense Networks (UDN), Moving Networks (MN), and Massive Machine Communications (MMC). Their implementation will result in specific requirements on spectrum usage. In addition to the HTs, optimisation of 4G concepts, new spectrum usage options, and a revision of the system architecture will be addressed. The various technical components and solutions will be integrated into a unified METIS concept that addresses the fundamental challenges of the beyond 2020 information society.

Although the test cases, which will be reviewed in Section 5 of this document from a spectrum point of view, are rather specific, the solutions derived therefrom are expected to address a much wider range of problems relevant for the same fundamental challenges that the test cases are based on. The concrete test case KPIs shall give directions for research and a measure of success for METIS. Based on the test cases, METIS will propose candidate solutions as described above and map the end-user KPIs to solution-specific KPIs.

[1] For details on the test cases see Section 5.3. That section contains a brief overview and analysis from a spectrum perspective for each test case.

1.1 How spectrum is addressed in METIS

In METIS deliverable D1.1 some initial spectrum requirements are already considered. In general, the availability and usage options for spectrum are fundamental for the implementation of any radio technology.

In order to study the potential of additional spectrum, the following challenges are addressed:

- Study new bands, in particular by extending the spectrum range for mobile communications to yet rarely used higher frequency bands,
- development of new spectrum sharing concepts that help to improve spectrum usage efficiency,
- provision of enablers for the efficient use of the new METIS radio concepts that guarantee coexistence and interference management, and
- design of an overall spectrum management concept.

Following the approach outlined above, METIS will combine a requirement based top-down design with a technology driven bottom-up approach.

Where needed, METIS will not only investigate the technical challenges but also address the relevant regulatory dimension of shared spectrum usage. Section 3 of this deliverable will already provide an initial analysis of spectrum authorization regimes.

All results presented in this deliverable are initial and preliminary. Future deliverables will provide more detailed results and a quantitative analysis of the mapping between the top-down requirements and the bottom-up technical options developed in METIS.

1.2 Objective and structure of this document

Deliverable D5.1 is an intermediary deliverable in preparation of the major deliverable D5.3 with tentative title “Description of the spectrum needs and usage principles”. D5.1 covers:

- potential options related to spectrum,
- spectrum usage scenarios including spectrum authorization regimes,
- implementation aspects of spectrum usage concepts including the introduction of a Spectrum Sharing Tool Box,
- an initial analysis of test-case-specific spectrum needs and how they can be addressed using the METIS HTs including first results on metrics that can be used to evaluate the efficiency of spectrum usage.

The work flow in this deliverable is illustrated in

Figure 2.

The rest of the document is structured as follows: In Section 2, an initial analysis of future spectrum bands is provided. Spectrum sharing concepts and regulatory regimes that allow increasing the spectrum usage efficiency are discussed in Section 3. The resulting requirements on the implementation and technical enablers are summarized in Section 4. Here, as a major result the METIS "Spectrum Sharing Tool Box" approach is introduced that helps addressing a wide range of spectrum usage scenarios and various promising spectrum sharing options. Based on the findings of the sections above, in Section 5 it is finally discussed what the test case specific spectrum needs are and how the HTs can address these needs. The METIS test cases are defined by METIS WP1 and described in D1.1. Section 6 provides initial conclusions and an outlook.

Besides a first assessment on how the spectrum needs of the METIS test cases can be addressed, this deliverable also provides input to the overall technical concept development in

METIS (green part in Figure 2), in particular the requirements defined in Section 4 and the technical options provided by the spectrum tool box.

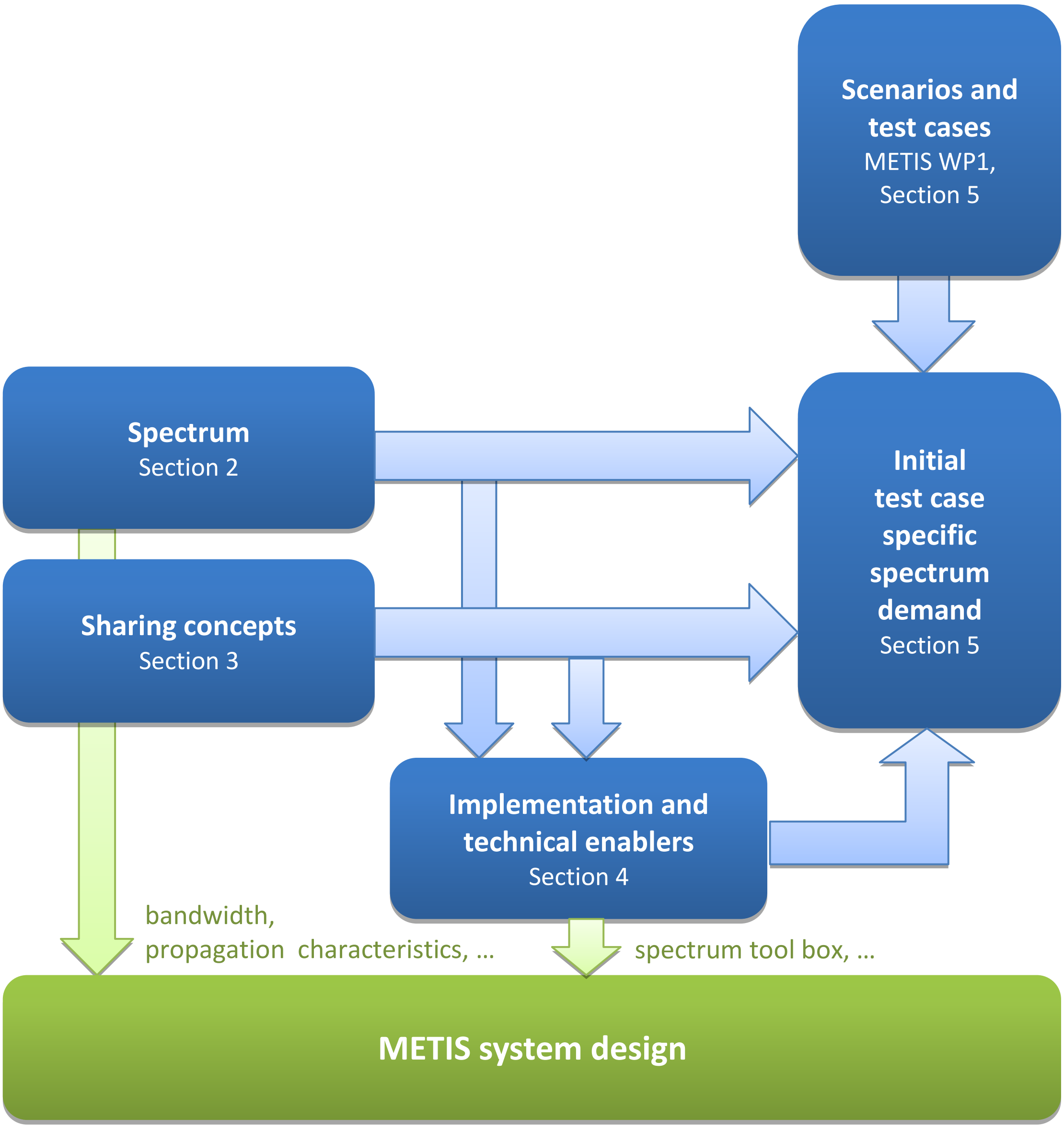


Figure 2 – Work flow and interaction of sections in deliverable D5.1

2 Investigation of Spectrum Bands

This section provides an initial analysis of spectrum bands. The main focus of this section is on exploring additional spectrum options that can help to meet future METIS challenges. For the sake of completeness, and to provide some example cases, some relevant frequency bands already in use or under current discussion will be reviewed as well.

The analysis presented here is preliminary and will have to be revised when the METIS concepts and overall system approach is defined in more detail. Five frequency ranges are discussed separately and – depending on their relevance - on different levels of detail:

- 380 – 5925 MHz,
- 5.925 – 40.5 GHz,
- 40.5 – 95 GHz,
- 95 – 275 GHz.

This classification has been chosen following the breakdown of the existing service allocations in the ITU-R Radio Regulations [29] and the CEPT ECA table [30].

Hereafter, the above defined bands are discussed and the most promising options for the future METIS work are identified. For the selection process, three questions are addressed:

- How is spectrum used currently?
- Can we make efficient use of a given frequency range from a technical as well as from an economic point of view, fulfilling METIS requirements as defined in METIS D1.1 [17]?
- Is spectrum currently available or can it be made available by using new or legacy spectrum authorisation concepts?

Particularly for assessing the second question above, at least a rough understanding of the radio propagation characteristics is required as well as a prediction of RF front ends evolution in the years to come. That is not yet available for all bands.

Furthermore, a deep understanding of the properties of the applicable radio access concepts for example the METIS HTs is necessary. Again, this information is not yet available to the level required for a final assessment. Thus, the analysis provided here will remain preliminary.

2.1 Search criteria

In order to study suitable frequency ranges, in particular in the 5.925 – 40.5 GHz and 40.5 – 95 GHz bands, it is required to define high-level search criteria based on the current (still relatively coarse) understanding of the properties a suitable band should have and of the requirements it should fulfil. The following criteria have been chosen to guide the search for suitable frequency ranges:

- Primary / co-Primary allocation to MOBILE / FIXED in Article 5 of the ITU-R Radio Regulations Service (including bands used for backhaul today)
- Bandwidth: Continuous spectrum of several hundred MHz below 40.5 GHz and at least 1 GHz above 40.5 GHz is seen as a minimum requirement to fulfil user needs
  - In the first round no carrier aggregation capability is assumed, i.e., the bandwidth has to be contiguous. However, if this does not lead to satisfactory results, simple carrier aggregation scenarios to combine a small number of non-contiguous spectrum chunks could be assumed to be supported by METIS in a second step.
  - Bands that can accommodate only one network deployment should not be excluded initially, i.e., no ultimate need to accommodate multiple parallel networks is assumed.

- Paired and unpaired spectrum is considered (both, TDD and FDD networks are options).
- The availability of a suitable existing regulatory framework is seen as benefit.

In the following sections first an overview on current allocations and usage and the visible opportunities is given. The most promising opportunities are then discussed in more detail.

2.2 Frequency range 380 – 5925 MHz

The frequency range 380 – 5925 MHz is currently used by many different services. Possibilities to accommodate additional IMT bands are being considered in the scope of the ITU-R WRC-15 preparation process in detail. Thus, no in depth investigation of this frequency range is necessary within the METIS project.

It should be noted, that any radio access system aiming at providing coverage in an extended area must use this frequency range for technical and economic reasons. Therefore, most of the METIS scenarios and test cases will use at least one RAT in this frequency range. Additionally, in order to fulfil the requirements of the described test cases, the communicating devices must also be equipped with RATs that can access higher frequency ranges, with large bandwidths.

2.3 Frequency range 5.925 – 40.5 GHz

Frequencies above 5.925 GHz are to date rarely used for mobile radio access networks. There is nevertheless considerable use of these frequencies by many other services, including point-to-point and point-to-multipoint microwave links which are often used to provide cellular backhauling.

The key requirement that drives METIS' considerations for this frequency range is the anticipated need for significantly larger contiguous bandwidths compared to what is realistically available below 6 GHz. This is motivated by the envisaged need to support significantly higher data rates.

2.3.1 Spectrum Overview

In Figure 3 the possibility to get access to specific bands according the current service allocations and usages for the frequency range 5.925 – 40.5 GHz is assessed. This figure illustrates the assessment of the relevance (opportunity) of this band for a METIS system.

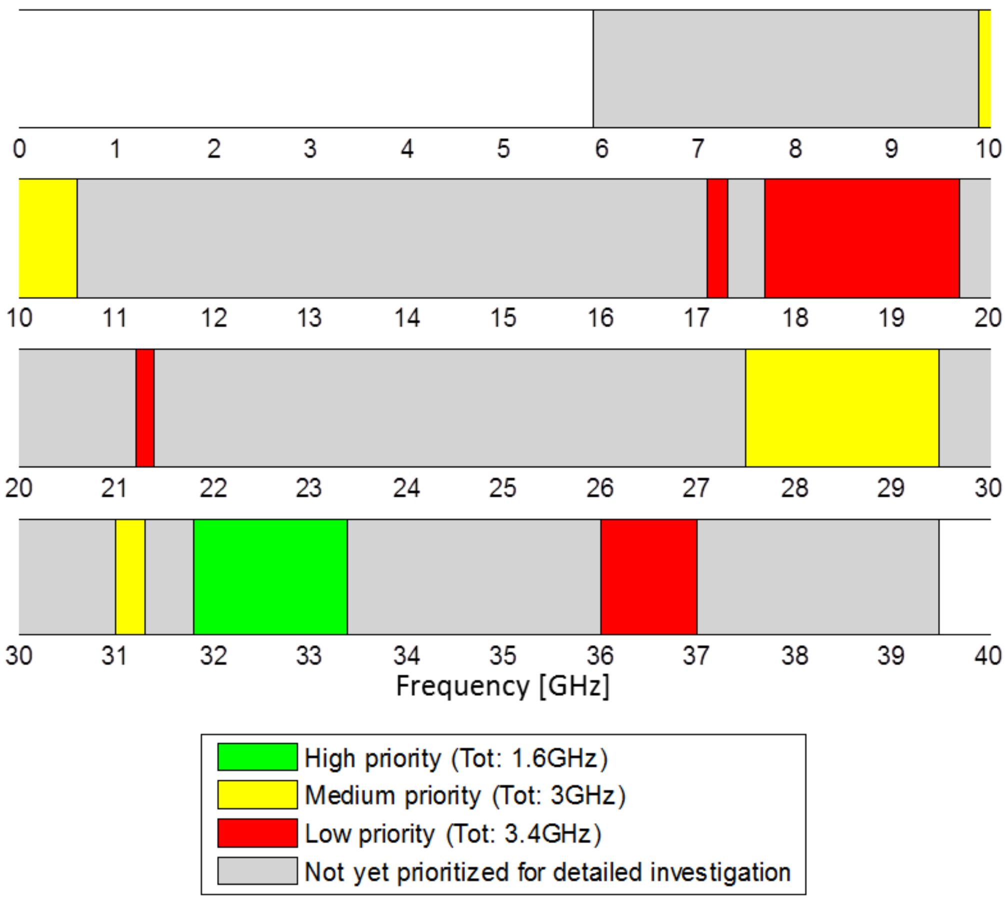


Figure 3 – Spectrum overview 5.925 - 40.5 GHz

2.3.2 Bands in the frequency range 5.925 – 40.5GHz

In the following subsections a number of bands are analysed in more detail with a particular focus on large contiguous spectrum.

2.3.2.1 *Frequency range 9.9 – 10.6 GHz*

Information on current regulation and usage

The services allocated to this frequency range, as they can be found on the ECO Frequency Information System (www.efis.dk), include: FIXED, MOBILE, RADIOLOCATION, AMATEUR.

Radiolocation equipment in this frequency band is historically almost only used in police radar guns (used to measure vehicles speed), and motion detectors for automatic doors.

However, radar guns in this frequency band are almost not in use any longer (and numbers are decreasing year by year) [28]. Due to being easily detectable, they are nowadays more and more replaced by K and Ka band radars or even more recently by laser radars. Similarly, door motion detectors evolve to higher frequencies because new single chip integrations of radar solutions are available for K band [26], with lower cost and better performance. Therefore it is foreseen that in next years, only amateur usage will share this band with fixed and mobile allocations. But even here the trend goes to higher frequencies with larger available bandwidth.

Opportunities for METIS

This band represents a 700 MHz chunk of frequencies at the lower end of the “above 6 GHz” spectrum. Preliminary measurements under line-of-sight (LOS) conditions in a city environment provide evidence that the attenuations approximately follow the free space attenuation (only 0.6 dB additional loss measured at 15 meters distance). In a typical non-LOS scenario with street-trees blocking the direct line of sight only an extra 5 dB loss has to be considered. These values show that there is a good opportunity at this spectrum band with good outdoor propagation characteristics. Also in indoor environments a better performance is expected than at higher frequency bands. Some measurements are available in [27]. Note that a complete migration of radiolocation services into other bands might be advisory since coexistence with radiolocation services is assumed to be challenging.

2.3.2.2 *Frequency range 17.1 – 17.3 GHz*

Information on current regulation and usage

According the ECA table in CEPT the band 17.1 – 17.3 GHz is allocated to the Radiolocation service. The sub-band 17.1-17.2 GHz is allocated to the Mobile service on a secondary basis. The sub-band 17.2-17.3 GHz is in addition allocated to the following services: EARTH EXPLORATION-SATELLITE (active), MOBILE and SPACE RESEARCH (active). The ECA table indicates military radar applications as the main use. Furthermore, usage of the band by unlicensed Short Range Devices (SRD) on the basis of ERC/REC 70-03 is indicated in the ECA table. ERC/REC 70-03 lists the band for radio determination applications (Ground Based Synthetic Aperture Radar, GBSAR).

Opportunities for METIS

Preliminary conclusions achieved in METIS on the deployment of Ultra Dense Networks (UDN) indicate that co-channel secondary usage with radars is challenging at frequencies up to 17 GHz. Based on current regulation and the available information on existing use (in particular military radar) it seems difficult to accommodate additional usage by wireless communication systems in this band unless existing usage turns out to be low or can be re-farmed. Hence this band is of low priority for further investigations within METIS.

2.3.2.3 *Frequency range 17.7 – 19.7 GHz*

Information on current regulation and usage

In CEPT the band is allocated to the FIXED and FIXED-SATELLITE (E/S) service on co-primary basis. The sub-band 18.1 – 18.4 GHz is additionally allocated to the METEOROLOGICAL-SATTELITE (S/E) service on a primary basis. The sub-band 18.6 – 18.8 GHz is additionally allocated to the EARTH EXPLORATION-SATELLITE (passive) service.
For fixed links there is a harmonized European channelling arrangement in ERC/REC 12-03. ERC/DEC/(00)07 regulates the shared use of this frequency range by the fixed service and earth stations of the fixed-satellite service (uplink transmissions from the earth station to the satellite). Coordinated use of the band 17.7-19.7 GHz is permitted on a national basis, i.e., a national administration checks if new stations in either of the two services can be operated without causing problems to already existing stations before issuing an authorization. Uncoordinated FSS earth stations shall not claim protection from stations of the fixed services.

ECC Report 173 states heavy use (about 90000 p2p links) of this frequency range by fixed links. Most links are individually licensed with the majority allocated to fixed and mobile infrastructure. Although moderate congestion is already reported, significantly increased spectrum usage is expected in the following years in many countries.

The FSS usage takes place in the form of e.g. Eutelsat’s Two-way service which uses the 17.7-20.2 GHz band for downlink transmissions [26]. The service has been commercially launched in 2011 and provides 20 Mbit/s downlink and 6 Mbit/s uplink broadband internet access. The service area is Europe and the Middle East.

No information on usage within the METEOROLOGICAL-SATELLITE and EARTH EXPLORATION-SATELLITE services has been found.

Opportunities for METIS

In CEPT the existing widespread use by fixed links, which in some cases seems to approach limitations for additional links, would most likely have to be protected or re-farmed in order to make sharing with mobile broadband systems possible. Since METIS systems will comprise a large number of uncoordinated mobile terminals, sharing with the existing usages seems difficult.

In addition the to-be-expected deployment of uncoordinated FSS earth stations may represent an additional obstacle. On the other hand such stations could be assumed to be deployed predominantly in remote areas where regular ways to access the internet are not available, which would suggest rather low user densities (the satellite capacity indicated in [27] suggests that most likely not more than 1000 users can be served in Germany). This could provide opportunity for sharing with very high capacity mobile access systems predominantly deployed in dense urban areas.

Eventually the intense usage by fixed links dominates the situation for this band and leads to the overall conclusion that this frequency band will not be of prime interest for METIS, unless further investigations show that spectrum can successfully be shared with densely deployed fixed links or the coexistence criteria for such scenarios can be relaxed.

2.3.2.4 *Frequency range 21.2 – 21.4 GHz*

Information on current regulation and usage

According the ECA table the band 21.2 – 21.4 GHz is allocated to the following services: EARTH EXPLORATION-SATELLITE (passive), FIXED, MOBILE and SPACE RESEARCH (passive). Passive systems will be phased out by 2015. The band is part of the frequency range 21.2 – 23.6 GHz which is used by PMSE / SAP/SAB services for unidirectional temporary fixed point-to-point links based on ERC/REC 25-10, which designates this frequency range as a harmonized tuning range for temporary point-to-point video links.

Opportunities for METIS

Given that the tuning range for existing SAP/SAB equipment apparently covers a much wider range, re-purposing of this band for mobile broadband could be feasible. Compatibility with usages in adjacent bands would have to be investigated. Overall this band is of medium priority for further investigations within METIS.

2.3.2.5 *Frequency range 27.5 – 29.5 GHz*

Information on current regulation and usage

In CEPT the band is allocated to the FIXED and FIXE-SATELLITE (E/S) service. The sub-band 28.5-29.5 GHz has an additional allocation to the Earth Exploration-Satellite (E/S) service on a secondary basis, but no corresponding usage is indicated in the ECA table.

In CEPT harmonized regulation exists for fixed links (T/R 13-02). ECC/DEC/(05)01 describes how fixed point-to-point and point-to-multipoint and FSS systems (apparently mostly feeder links for broadcasting satellites) can be separated in frequency, so that only parts of the band can be used without constraints by fixed links. In total 2x504 MHz paired spectrum and 114 MHz unpaired spectrum are available for the fixed service in this band. Uncoordinated FSS earth stations are allowed in the sub-band 28.4445 – 28.8365 GHz.

ECC report 173 states medium use (2600 p2p links and 380 pmp base stations). Both block licensing and individual licensing are used. Some administrations report expectations for increased usage in the future.

Several satellite services using the Ka-band are mentioned in [28].

Opportunities for METIS

The segmentation of the band into ranges that are reserved for FSS and ranges reserved for fixed makes large contiguous allocations beyond a bandwidth of ~500 MHz difficult. Co-channel sharing between fixed links and FSS systems has apparently been found infeasible in the past (cf. ECC/DEC/(05)01). It seems unlikely that METIS systems can enter the band without re-farming at least some of the current usages. This leads to the conclusion that the band is of medium priority for METIS.

2.3.2.6 *Frequency range 31 – 31.3 GHz*

Information on current regulation and usage

According the ECA table the band 31 – 31.3 GHz is allocated to the FIXED and MOBILE services. In addition it is used by the radio astronomy service for continuum observations, but there is no corresponding allocation.

In ECC Report 173 very limited use is indicated for this band, with very few indications (9 administrations out of 31). Licensing regime appears link-by-link. The channel plan follows ECC/REC/(02)02, in addition to national plans. No significant expectations to increase the use in next years are reported.

Opportunities for METIS

The band currently seems to have limited use within CEPT. On the other hand, it is relatively narrow (only 300 MHz bandwidth). Compatibility with services in adjacent bands may require attention. The overall conclusion is that this band is of medium priority (mainly due to its limited size).

2.3.2.7 *Frequency range 31.8 – 33.4 GHz*

Information on current regulation and usage

According the ECA table the band 31.8 – 33.4 GHz is allocated to the FIXED and RADIOLOCATION service, and in addition to the SPACE RESEARCH service below 32.3 GHz and to the INTER-SATELLITE service above 32.3 GHz.

The fixed service is indicated as the common application in usage. In ECC Report 173, it is stated that around 8000 links are active in the 31 countries that responded to the questionnaire. Hop lengths indicated as “typical” are about 3.54 km (0.5 km for those indicated as “minimum”). Use appears mostly for medium and high capacity.
Licenses are assigned mostly by link, although block allocation has been reported by few administrations. The P-P channel plan follows the ERC/REC/(01)02. Even though no P-MP links were reported, the block assignment guidance for P-MP links is provided in ECC/REC/(11)01. 10 countries expect an increase in the usage in coming years (10-50% and more; Finland, Slovakia and Lithuania indicates 100%). No indication of decrease has been reported. Congestion is reported by one administration.

Opportunities for METIS

This band could be appropriate for METIS scenarios being able to share with the fixed service.

2.3.2.8 *Frequency range 36 - 37 GHz*

Information on current regulation and usage

In the ECA table the band 36 – 37 GHz is allocated to the following services: EARTH EXPLORATION-SATELLITE (passive), FIXED, MOBILE, SPACE RESEARCH (passive) and Radio astronomy. It is a harmonised military band for fixed and mobile systems.

According to ECC Report 173 only the Russian Federation indicated the usage of this band, reporting 132 links in operation, P-P, with licensing regime for link and for blocks.
The channel plan is given in the Recommendation ITU-R F. 749.

Opportunities for METIS

As this band is used by passive services it is considered difficult to implement high density networks due to the potential of aggregate interference. A possible coexistence with METIS deployments needs to be investigated in more detail. Also the sharing with the military usages requires further consideration. Overall this band is considered to have low priority for further investigation in METIS.

2.3.2.9 *Frequency range 37 – 39.5 GHz*

Information on current regulation and usage

In CEPT the band is allocated to the FIXED service on a primary basis. The sub-band 37-38 GHz is additionally allocated to the SPACE RESEARCH service. The sub-band 37.5 – 39.5 GHz is allocated to the FIXED-SATELLITE service on a primary basis and the Earth exploration-satellite service on a secondary basis.

ERC T/R 12-01 harmonizes the use of the band for fixed services.

ECC Report 173 reports heavy use of the band for fixed links. About 136000 links are in use by most of the CEPT countries. Individual licensing seems to dominate but in some countries parts of the band are block licensed too.

Opportunities for METIS

Given the heavy use by fixed links, which predominantly serve as backhaul for existing mobile networks, opportunity for accommodating use by METIS access systems appears limited unless coexistence turns out to be very easy. Therefore, the band is considered to be of medium priority for further investigations.

2.3.3 Conclusions on the assessment of frequency bands in the range 9.9 - 37 GHz

The table below summarizes the assessment results of spectrum bands in the frequency range 9.9 - 37 GHz.

Band (GHz)	Size [GHz]	Priority
9.9 - 10.6	0.7	Medium / High
17.1 - 17.3	0.2	Low
17.7 - 19.7	2.0	Low
21.2 - 21.4	0.2	Low
27.5 - 29.5	2.0	Medium
31.0 - 31.3	0.3	Medium
31.8 - 33.4	1.6	High
36 .0 - 37.0	1.0	Low

2.4 Frequency range 40.5 – 95 GHz

Above 40.5 GHz there is considerable use of spectrum bands by many services, including point-to-point and point-to-multipoint microwave links which are often used to provide cellular backhaul. In contrast to the spectrum range below 40.5 GHz there are a few spectrum bands which appear lightly used or even unused in some parts of the world. The unlicensed band at 60 GHz offers already a unique harmonized opportunity with existing regulatory rules that would allow the deployment of systems that correspond well to some METIS scenarios.

2.4.1 Spectrum Overview

In Figure 4 the possibility to get access to specific bands according the current service allocations and usages for the frequency range 40.5 – 95 GHz is assessed. This represents the assessment of the relevance (opportunity) of this band for a METIS system.

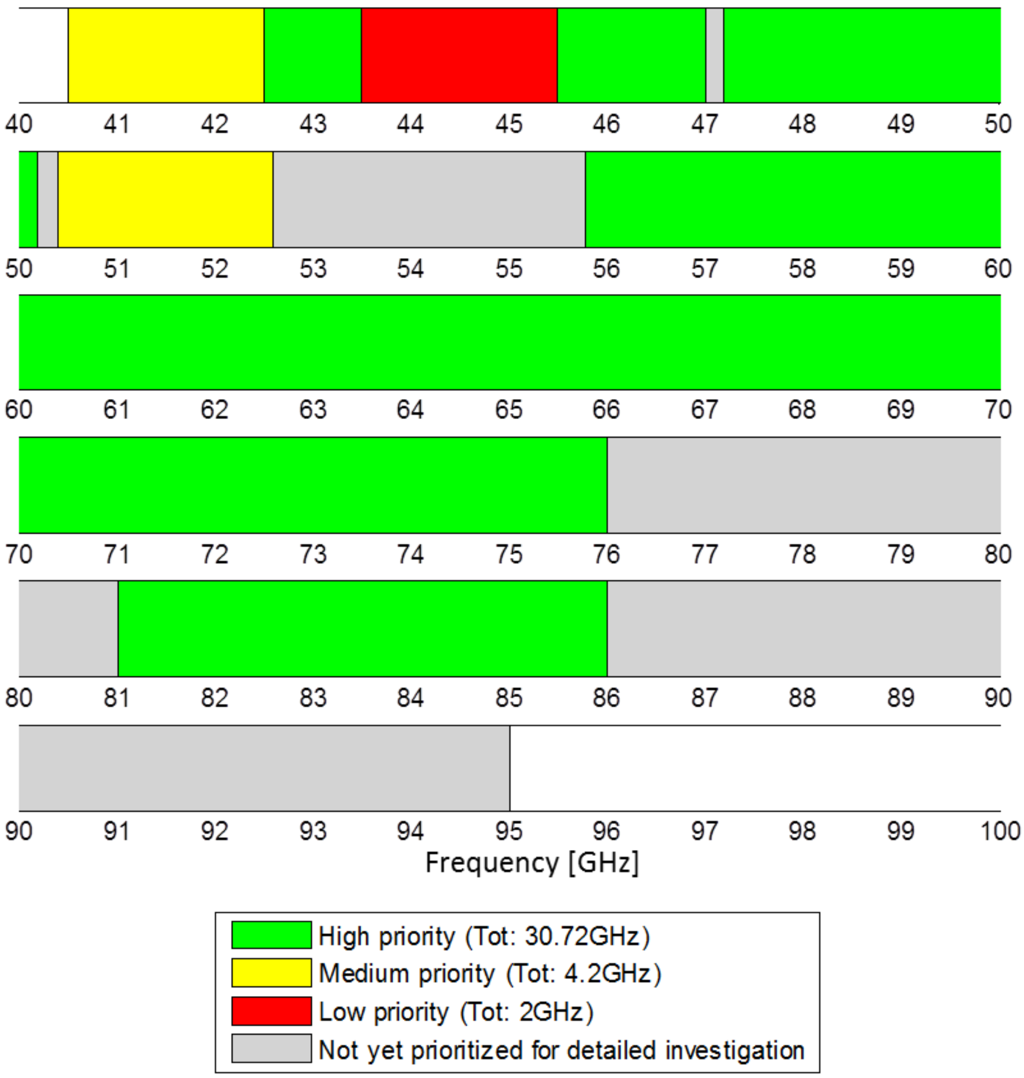


Figure 4 – Spectrum overview 40.5 – 95 GHz

2.4.2 Bands in the frequency range 40 – 95 GHz

The following breakdown of frequency bands is considered and analysed in more detail:

- 40.5 – 43.5 GHz
- 43.5 – 57.0 GHz
- 57.0 – 66.0 GHz
- 66.0 – 71.0 GHz
- 71.0 – 95.0 GHz

2.4.2.1 Frequency band 40.5 - 43.5 GHz

Information on current regulation and utilization

Multimedia Wireless Systems[2] (MWS) in the band 40.5 – 43.5 GHz have been defined in the ERC Decision ERC/DEC/(99)15 as terrestrial point-to-multipoint systems, which have their origin in telecommunication and/or broadcasting, and which provide fixed wireless access directly to the end user for multimedia services.

The introduction of BWA applications in bands below 6 GHz has reduced the economic interest for MWS in the band 40.5 – 43.5 GHz. In the year 2008, very few point-to-multipoint (P-MP) systems were actually deployed in this band and in a number of CEPT countries it was totally unused.

This band has been opened to P-P applications in 2010. Therefore it is just at the beginning of its use (about 100 links have been declared active). Of the 31 countries that have answered to an ECC questionnaire in 2010 (ECC Report 173), 12 foresee use or have just started. However, the need for point-to-point links (P-P) for large data capacity, over short hops, e.g. for transport infrastructures needed in particular for forthcoming LTE–A systems, is rapidly increasing. Historical P-P bands such as 23 GHz and 38 GHz are already crowded and new bandwidth is needed. The band 40.5 – 43.5 GHz, which propagation characteristics are very similar to the 38 GHz, represents its natural extension.

Individually license and block license are present, and both P-P and P-MP are foreseen, great majority of links are addressed to network infrastructure.

Guidelines for the accommodation and assignment of Multimedia Wireless Systems (MWS) and Point-to-Point (P-P) fixed wireless systems in the frequency band 40.5 – 43.5 GHz are given in ECC RECOMMENDATION (01)04 (Revised, Rottach-Egern, February 2010).

Opportunities for METIS

The actual deployment in the band 40.5 – 43.5 GHz seems unchanged compared to 2008. Furthermore, the term “Multimedia Wireless Systems (MWS)” includes applications where “telecommunications operators are wishing to supply broader band two way services to wider markets”, which can be interpreted so that METIS falls within this scope.

Therefore, it is considered possible to deploy METIS within the band 40.5 – 43.5 GHz under the umbrella of the existing regulatory framework. Both, radio access as well as backhaul functionalities are considered feasible. Although some form of spectrum sharing with other services may be necessary, individual licensing for METIS operations is the expected regulatory option within this band.

[2] The term “Multimedia Wireless Systems (MWS)” has been introduced to cater for the phenomena of convergence between terrestrial FS and BS applications, whereby distributors of entertainment services (broadcasters) are wishing to provide interactive services and telecommunications operators are wishing to supply broader band two way services to wider markets.

- Frequency range **40.5 – 42.5 GHz**

  This 2 GHz band has Mobile only as a secondary allocation in Region 1, and no mobile entry in the European Common Allocation (ECA) table where primary allocations are given to the BROADCASTING, BROADCASTING-SATELLITE and FIXED service.

  The importance of this band is considered medium since it is only allocated to the mobile service on a secondary basis in the ITU-R RR and missing in the ECA table. Furthermore, this band is considered to be a rising band for fixed services and it has been identified for high density fixed services in CEPT.

- Frequency range **42.5 – 43.5 GHz**

  This 1 GHz band has MOBILE as a primary allocation and is listed as a possible future MBB band in the ECA table. This makes it a good candidate band for a future METIS system. This band also has FIXED, FIXED-SATELLITE (E/S), and RADIO ASTRONOMY as primary allocations. There are however no indications of significant usage by those services within CEPT in this band. In particular, there are not a lot of fixed links currently deployed in the band. For this reason this is considered a highly relevant candidate band for more detailed investigation.

2.4.2.2 Frequency band 43.5 - 47 GHz

Information on current regulation and usage

From the ITU perspective, this band has primary ITU allocations to MOBILE, MOBILE-SATELLITE, RADIONAVIGATION, and RADIONAVIGATION-SATELLITE in the three regions. However, mobile service may be operated subject to not causing harmful interference to the space radio communication. In this band, satellite links connecting land stations at specified fixed points are also authorized when used in conjunction with the mobile-satellite service or the radio navigation-satellite service.

In Europe the band is divided in two parts:

- Frequency range **43.5 - 45.5 GHz**

  This part of the band is an EU harmonized military band dedicated for satellite uplink and mobile military services. It is also used for military purposes in the US with Advanced Extremely High Frequency Services (AEHF) Military Satellite System. It is a multi-nation military band and seems to be used for mobile users (earth to space) [25].

- Frequency range **45.5 - 47 GHz**

  This band is aligning with the ITU allocation. It is one of the least used bands currently in Europe. No current activities in CEPT are ongoing or to our knowledge planned regarding this band. Further, very few countries have put in recommended services for this band into the EFIS spectrum database [23].

In this range China will possible allow micro-power short range device in unlicensed mode (e.g. 802.11aj being standardized in China). Therefore coexistence with 802.11aj to meet China frequency allocation is needed.

Opportunities for METIS

The range between 43.5-45.5 GHz is currently used for military services. It may be difficult to be allowed to use a METIS system in this part of the band, even when only 2 of 6 proposed military satellites have been launched and the system is yet to reach design efficiency. Therefore it is considered as a low priority band. On the other hand, 45.5 – 47 GHz is non-utilized band, so it is considered a very good candidate for more detailed investigation.

2.4.2.3 Frequency band 47 – 50.2 GHz

Information on current regulation and usage

In ITU-R, this band is divided into small ranges where the primary allocation is for MOBILE, FIXED and FIXED SATELLITE (earth-to-space and/or space-to-earth). The fixed service in the bands 47.2-47.5 GHz and 47.9-48.2 GHz is designated for use by high altitude platform stations. The range 48.94-49.04 GHz is also allocated to the radio astronomy service on a primary basis and is strongly recommended to be protected from harmful interference. ERC-Report 36 provides guidance on sharing between the radio astronomy and fixed services operating within Europe, showing that sharing may be possible.

Europe, USA and China follow the same allocation, excepting Japan where mobile doesn't have an allocation. The band is used for FSS uplink and for mobile service is limited to SAP/SAB applications [31].

Opportunities for METIS

This band is attractive since MOBILE is one of the primary services. The sub-band 48.5 - 50.2 GHz is allocated for fixed links [32] but it is currently not used. For these reasons, this band is considered being a highly relevant candidate band for more detailed investigations.

2.4.2.4 Frequency band 50.4 – 52.6 GHz

Information on current regulation and usage

The band 50.4 – 52.6 GHz is divided into two ranges (50.4 - 51.4 GHz and 51.4 - 52.6 GHz) according to ITU-R. It is primarily allocated to FIXED, FIXED-SATELLITE (E/S) and MOBILE. The adjacent ranges 50.2 - 50.4 and 52.6 - 54.25 GHz are vital for weather forecast. Countries shall not exceed the recommended emission levels in these bands.

The sub-band 50.4 – 51.4 GHz has no primary mobile allocation in CEPT, US and Hong Kong. The range 51.4 - 52.6 GHz is allocated to high density fixed links but there is no actual reported usage of the band, with the exception of 837 links in Switzerland [10]. The links appear block licensed in Switzerland, while a majority of other countries has given indications for link-based licensing. The channel plan follows the Recommendation T/R 12-11 [24]. Three countries report expectations to increase the use in coming years. There is also in Europe an allocation to passive SPACE RESEARCH in this part of the band.

Opportunities for METIS

Even when this band seems to be lightly used, METIS systems will deal with big challenges to get in to this band, since the band has no mobile allocation in several big countries like USA, China and European countries. Adjacent channel co-existence needs to be investigated, given that there are strongly protected bands on each side of the band. There may be radio astronomy in parts of the band so maybe some areas must be avoided. For all these reasons, this band is thus categorized as a medium to low priority band.

2.4.2.5 Frequency band 55.78 – 57 GHz

Information on current regulation and usage

According to ITU-R FIXED and MOBILE has a primary allocation in all regions. Other primary services in the band are EESS, Space Research and Inter-Satellite communication. Coexistence with these services needs to be investigated. This band is available for high-density applications [33] in the fixed servicebut no actual usage yet.

In Europe and USA the range 55.78-56.9 GHz has no mobile allocation. Additional allocation for the band 55.78-58.2 GHz is given to Japan, which is also allocated to the radiolocation service on a primary basis

Opportunities for METIS

This band has no mobile allocation in Europe and USA. In order for METIS systems to get into this band it has to first evaluate coexistence with the other primary systems. This band is hence considered to be medium relevant candidate band for further investigation.

2.4.2.6 Frequency band 57 – 66 GHz

Information on current regulation and utilization

The band 57 - 64 GHz is allocated to the fixed service (FS) on a worldwide primary basis. In particular, this band, in conjunction to the adjacent 64 - 66 GHz band, seems very suitable for short distances (approximately 1 km), high capacity links deployed in dense scenarios.

It is considered that the physical propagation features in this band enable a license exempt, “light licensing” or similar mechanism still ensuring highly efficient re-use of the frequency band, which may include access to spectrum through the use of flexible frequency arrangements.

The channel plan for part of this band (57-59 GHz) used to follow ERC/REC 12-09. This was superseded by the new Recommendation ECC/REC/(09)01 which combines the whole 57-64 GHz range specifically for P-P application with Multi Gigabit Wireless Systems (MGWS) following ERC Recommendation 70-03 and EN 302 567.

According an ECC questionnaire in 2010 (ECC Report 173 [10]), around 700 links are in use in this band in few countries according to the old Recommendation. Almost all capacities have been reported, most being licensed on a link by link basis (7 answers), but some administrations foresee also block license (4 answers). In Lithuania, Sweden, Slovenia, UK and Germany the band is unlicensed. The great majority of links is allocated to fixed and mobile infrastructure. Concerning the usage, new equipment following the new Recommendation is becoming available.

It shall be noticed that band 59 - 61 GHz can be used for NATO / military applications also, as well as for SRD (ISM possible in 61-61.5 GHz).

The band 64 - 66 GHz is allocated to the Fixed Service on a Primary Basis in the European Common Allocation table and the ITU Radio Regulations (RR) and has been opened for use by Fixed Service (FS) systems in some European countries. In particular, this band seems very suitable for very short distance links deployed in dense scenarios. ECC Recommendation (05)02 provides an approach for deployment of such FS links in this band.

It is considered that the physical propagation features in this band make possible a lighter licensing regime than usually used for FS systems, which may include access to spectrum through the use of flexible frequency arrangements.

According a ECC questionnaire in 2010 (ECC Report 173 [10]), only one link in the UK was reported the band 64 – 66 GHz. Apart from Lithuania, indicating unlicensed regime, a trend for a link by link authorization regime can be referred. Foreseen application for high capacity P-P links is reported. The frequency band is used according to the ECC/REC/(05)02. SRD use has also been indicated, with potential openings and lack of equipment.

Opportunities for METIS

Although parts of this band have recently been opened for license exempt utilizations in the fixed/wireless domain, it offers a potential for additional spectrum for METIS scenarios, if required, also on a license exempt basis, with the advantage of having a common radio interface / radio resource management with the other METIS bands.

There are indications [34] that the co-existence between a METIS system and the other primary services allocated to this band, both for indoor and outdoor deployments of low transmit power METIS devices, seems feasible. Hence this band is a considered highly relevant candidate band for further investigations. Coexistence with unlicensed devices, in particular IEEE 802.11ad systems, requires further investigation.

2.4.2.7 Frequency band 66 - 71 GHz

Information on current regulation and utilization

The band 66-71 GHz is allocated in all three ITU Regions equally to the following services on a co-primary basis:

- INTER-SATELLITE
- MOBILE with footnotes 5.553 and 5.558
- MOBILE-SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION-SATELLITE with footnote 5.554

The relevant footnote **5.553** in the ITU-R RR states:

"In the bands 43.5-47 GHz and 66-71 GHz, stations in the land mobile service may be operated subject to not causing harmful interference to the space radio communication services to which these bands are allocated (see No. 5.43)."

No regulation is in place in CEPT, as well as no indication of utilizations within this band. However, there is a note in the ECA indicating this band for usage of "future civil systems". There is no apparent terrestrial usage of the band in Europe, neither elsewhere in the world.

Opportunities for METIS

Due to the global allocation status and the very limited usage, there is a high possible potential for global harmonization of this band. Coexistence studies in other bands have typically shown that sharing between terrestrial services and Inter Satellite Service (ISS) is feasible without significant limitations. Therefore, this band is considered to be a highly relevant candidate band for further investigation.

2.4.2.8 Frequency band 71-76 and 81-86 GHz

Propagation characteristics [3]

Both bands fall into an atmospheric window where atmospheric absorption is less than 0.5 dB/km, meaning that links can be operated across many kilometres, provided that a high antenna gain is used. However, in practice links are much shorter due to rain attenuation. Similar to all high-frequency radio propagation, rain attenuation has to be considered when planning a link. Propagation at 70/80 GHz can experience large attenuations in the presence of heavy rain.

Nevertheless, ITU and other bodies have collected rain data from around the world for decades, and so rainfall characteristics are well understood. With such information, radio links can be engineered to overcome even the worst weather conditions or be designed so that predictable levels of weather outage can be achieved. Currently available 70/80 GHz equipment can achieve higher than 1 Gb/s connectivity with 99.999% weather availability (equivalent to only 5 min of outage per year due to weather conditions; often referred to as carrier class performance) over distances of 2–3 km throughout most of Europe and US. For a lower 99.9% availability (8h of weather-caused outage per year), distances of 5 km can be achieved. Examples of existing solutions offering high data rate 70/80 GHz point-to-point backhaul solutions are given in references [4], [5], [6], [7], [8] and [9].

One strong benefit of 70/80 GHz wireless is that, with the exception of rain, it is unaffected by most other transmission deteriorations. Because the transmission wavelength is about 1 mm, and relatively large compared to most small particle airborne effects, 70/80 GHz wireless is unaffected by water particles (fog and mist), sand, dust, or other small-particle transmission path impairments. Thick fog, for example, at a density of 0.1 gr/m^3 (about 50 m visibility) has just 0.4 dB/km attenuation at 70/80 GHz, yielding negligible effects on typical link distances.

Information on current regulation and utilization

The bands 71 - 76 GHz and 81 - 86 GHz are both allocated to the FIXED and the MOBILE service, with the exception of 75.5 - 76 GHz only having a FIXED allocation. Both ranges are co-primary allocated to the FIXED-SATELLITE service (71 - 76 is S/E, downlink and 81 - 86 GHz is E/S, uplink). In addition, 71 - 74 GHz is allocated to MOBILE-SATELLITE (S/E) and 81 - 84 GHz is MOBILE-SATELLITE (E/S). The range 74 - 76 GHz is additionally allocated to the BROADCASTING and BROADCASTING-SATELLITE service. The range 75.5 - 76 GHz is additionally allocated to the Amateur and Amateur-satellite service on a secondary basis. The range 81 - 86 GHz has an additional allocation to the RADIO ASTRONOMY service on a primary basis. The band 81 - 84 GHz has a secondary allocation to the space research service.

The bands 71 - 74 GHz and 81 - 84 GHz have been identified as NATO Type 3 bands, i.e., for possible military use in NATO Europe; nevertheless the European Table of Frequency Allocations and Utilisations (ERC Report 25 [30], footnote EU27) mentions that "*The band can be shared between civil and military users according to national requirements and legislation*" [11]. This should be taken into account by administrations wishing to use whole or parts of the frequency bands 71 - 76 GHz and/or 81 - 86 GHz for civil Fixed Service (FS) links [10], [11]. There is no indication of current or planned military usage of this band, however, some countries reserve the band for military purposes [10].

Coexistence and compatibility studies have been performed by ECC between fixed service (FS) in 70/80 GHz bands and other passive services [12].

ITU RR No. 5.340 prohibits all emissions, *inter alia*, in the band 86 - 92 GHz due to its usage for radio astronomy, which implies that out-of-band emissions above 86 GHz have to be strictly limited.
The band is a rising band for fixed service equipment, which is within CEPT regulated according to ECC/REC/(05)07 [11].

Opportunities for METIS

The band is expected to have rapidly increasing use for fixed links in the coming years but there may be scope for sharing with access systems provided that the band does not go into congestion too quickly. Hence, the overall conclusion is that this band is highly relevant for further investigation within METIS.

2.4.3 Conclusions on the assessment of frequency bands in the range 40.5 - 95 GHz

The table below summarizes the assessment results of spectrum bands in the frequency range 40.5 - 275 GHz.

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

Summary of assessment results for the bands above 40.5 GHz

2.5 Frequency range 95 – 275 GHz

Information on current regulation and utilization

A number of radio services – including the fixed and the mobile service – have allocations in bands within the frequency range 95-275 GHz. However, the actual utilisation is limited to some bands and merely to science services: Radio astronomy, Passive sensors (satellite), Non-Specific SRDs, Amateur, Amateur Satellite, Earth exploration-satellite. Within CEPT, harmonisation measures exist only for Non-Specific SRDs (ERC/REC 70-03).

Opportunities for METIS

This frequency range is not in the primary focus of METIS, but might be considered in more detail at a later state of the project if considered appropriate.

3 Spectrum Access Schemes and Authorization Regimes

This section gives an overview of the spectrum access schemes and authorization regimes that are currently in place and expected to be practiced in the future. Thus, this section includes the foreseen development in authorizations level in the regulatory landscape. A classification of spectrum access and authorization concepts is given in Figure 5.

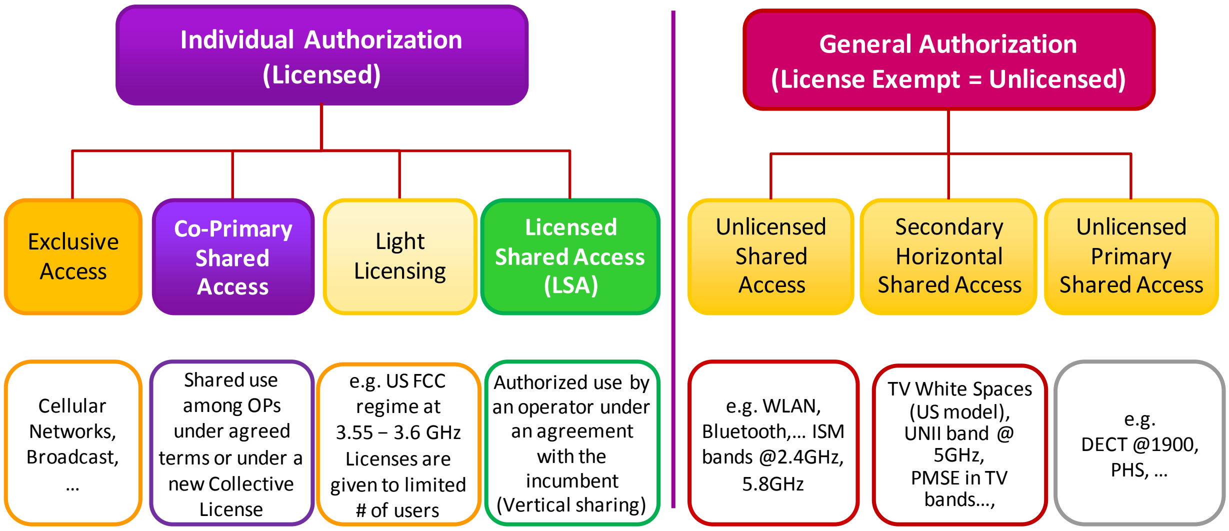


Figure 5 – Spectrum access schemes and authorization regimes

In general, the use of and the access to radio spectrum can be divided into two categories:

- Individual Authorization (Licensed)
- General Authorization (Licence Exempt / Unlicensed)

For some of these authorization regimes [14], we can distinguish between "primary" and "secondary" usage and/or allocation. Hereafter, the different spectrum access/sharing models with corresponding use cases in the different authorizations regimes are described.

3.1 Individual Authorization (Licensed)

In this authorization regime the usage rights of spectrum are exclusive in time, frequency and geographic region. The license for using spectrum is granted by the National Regulatory Authority (NRA), e.g., to mobile network operators (MNOs). It is valid for a certain frequency block over a fixed time and applies either nationwide or to a limited geographic region.

Under this individual authorization regime, there are different levels of spectrum access and potential sharing models that are discussed in the following subsections.

3.1.1 Exclusive Access (Dedicated licensed)

Licenses are granted by the NRA in accordance with national law and rules either directly following an operator's application, or through a beauty contest procedure, or through an auction which has been the most common way during the last decade. The licensee has the sole right to use this spectrum according to the assignment rules either nation-wide or just within a certain region or locally.

Dedicated licensed operation of a system implies that the system does not have to share the communication resources with any other system or service of equal or higher priority. Adjacent channel/band interference is either handled via presumption of conformity with existing (radio) specifications or through the definition of regulatory requirements (such as e.g. the principle of Least Restrictive Technical Conditions (LRTC) applied within CEPT).

In some cases – subject to the particular licensing conditions used by the issuing NRA - this implies that there may be systems or services present with lower priority, e.g., secondary users that are required to protect the service offered by the licensed (primary) user. In these cases the primary or licensed user typically has to be protected from interference and can claim protection from e.g. secondary systems or services and/or systems with lower regulatory priority/status.

In relation to [14] this type of authorization scheme is classified as individual authorization with individual licenses.

3.1.2 Co-Primary shared access

This refers to a spectrum access model where primary license holders agree on a joint use of (parts of) their licensed spectrum.

Sharing between systems of the same regulatory status may be realized through mutual agreements between spectrum users or enforced via requirements set up by a regulator. The exact usage conditions (policies) would have to be laid down in a mutual agreement, and the entire model would be subject to permission by the NRA. Note that in this model the users would have equal access rights without priorities being set by regulation.

Among the envisioned future spectrum sharing schemes the ones that are most suitable for Co-Primary sharing and also valid for light-licensing sharing scenarios are (noting that those schemes may also combined with other licensing schemes):

Spectrum pooling or *limited spectrum pool scenario*: In spectrum pooling, the NRA refrains from partitioning the band into blocks/sub-bands and instead issues authorizations, usually licences, to several operators that allow them to access the band. An issued license is equivalent to an entrance ticket to a shared spectrum pool. This allows an operator to obtain an authorization to use up to the whole band on a shared basis with a limited number of other known authorized users. This setup does not provide guarantee for instantaneous access to a minimum amount of spectrum, but it is envisioned that mutual agreements between licensees are such that the long term share of an individual operator has a predictable minimum value. The band is thus shared among a limited number of operators in some way, e.g. in time, in space, and/or in frequency. The pooling rules (i.e. the rules according to which resources are distributed among licensees inside the spectrum pool) and the number of licenses is a priori known. This ensures that some level of predictability for the achievable capacity and return of investment is provided to sharing parties. It is envisioned that each operator owns exclusively some piece of spectrum (primary component carriers) while there is also another piece of spectrum to be shared among operators (secondary component carriers). Mutual agreements allow operators with low traffic load using few secondary component carriers for satisfying their QoS while remaining carriers can be utilized by operators with a high traffic load. In the long run all operators can benefit and satisfy their QoS with a higher probability in comparison to conventional orthogonal spectrum sharing.

Mutual renting: A band is subdivided into a number of licensed blocks which are “owned” by one operator, but unused resources from own licensed blocks can be “rented” to other block owners. This situation enables operators to mutually allow other operators to “rent” parts of their licensed spectrum or resource block. An operator may rent spectrum from multiple operators simultaneously. A block owner has pre-emptive priority to access the own block (this can be subject to agreements between parties). This implies that the owner of the block is assumed to always have strict priority in accessing its licensed spectrum, including the possibility of pre-emption at any time. This approach facilitates a more dynamic use of radio spectrum and gives an operator an additional source of income from its temporarily unused spectrum. The approach could also be applied to bands that have initially been used in a dedicated licensed way and there is e.g. a need to increase peak data rate beyond what is possible within one licensed block.

3.1.3 Light-licensing

Another spectrum access scheme without the need of exclusive license is the so called light-licensing scheme. It refers to a simplified procedure of issuing spectrum usage authorizations (compared to full-blown licenses). Light-licensing is typically applied in situations where there is no or little immediate concern about interference, but where it is desirable to perform a check if the planned usage is likely to cause problems to other already existing usages (cf. the light licensing scheme used in e.g. the UK for Broadband Wireless Access in the 5.8 GHz band), or where there may be a need to make changes to the use of the spectrum in the future so that there is a need to maintain a record of spectrum users.

The relevant sharing scenarios for light-licensing are spectrum pooling and mutual renting, which are already explained in section 3.1.2.

3.1.4 Licensed Shared Access (LSA)

This is a new access model in which a primary license holder (incumbent) would grant spectrum access rights to one or more other users which can use the band under specific service conditions. The details of the spectrum usage would be subject to an individual agreement and permission by the NRA.

The LSA concept was originally proposed by an industry consortium under the name "Authorized Shared Access" (ASA) [15]. The Radio Spectrum Policy Group (RSPG) and the European Commission largely adopted the concept but renamed it to LSA. The two abbreviations are thus synonyms for the same concept. This concept is defined in [1] as "An individual licensed regime of a limited number of licensees in a frequency band, already allocated to one or more incumbent users, for which the additional users are allowed to use the spectrum (or part of the spectrum) in accordance with sharing rules included in the rights of use of spectrum granted to the licensees, thereby allowing all the licensees to provide a certain level of QoS." The concept and the definition are at the time of writing evolving.

The main stakeholders for the LSA framework are:

- *Incumbent*: the incumbent could offer the unused spectrum to one or several LSA licensees. The Incumbent would negotiate the LSA spectrum usage with the LSA licensee(s) according to the LSA spectrum award rules defined by the regulator.
- *LSA Licensee*: the LSA licensee would share the spectrum with the Incumbent. As a prerequisite the LSA licensee needs to obtain an LSA spectrum usage license, granted by the Administration/Regulator, and a sharing agreement, i.e. a contract negotiated between the Incumbent and the LSA licensee that specifies the LSA spectrum sharing conditions need to be established.
- *Regulator*: would guarantee and award LSA use rights to the LSA licensee and would in addition define the framework for the LSA spectrum award rules for the incumbent.

Figure 6 depicts the stakeholders of the LSA framework.

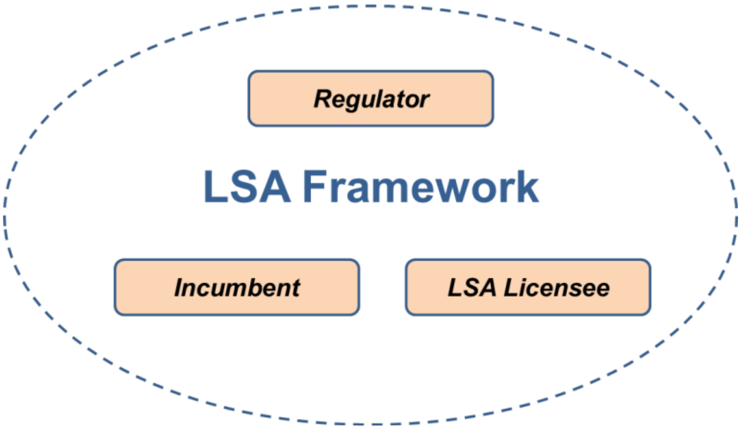


Figure 6 – Stakeholders in the LSA framework

In this authorization scheme the NRA is assumed to issue licenses to mobile operators that allow them to use a band as a LSA licensee. The NRA only issues a limited number of licenses for access to the band, and as such a certain level of performance predictability can be realized.

The rationale of this access model is to make underutilized spectrum available to a limited number of additional users while still maintaining quality of service. Interference issues could be resolved and avoided either statically by corresponding planning or dynamically through the use of data base access and cognitive radio technologies.

The set of conditions under which the sharing is performed between LSA licensees is believed to most commonly specify that the service provided by the LSA incumbent must be protected by the LSA licensees. It is, however, envisaged that the LSA licensee "inherits" the regulatory status of the incumbent, e.g. for cross-border coordination purposes. A communication resource that may be accessible by LSA may be varying over spectral, spatial, and/or temporal dimensions.

The main envisioned benefit of LSA is that the number of LSA licensees is limited and that these LSA licensees are known to each other. This setting will provide a higher level of guarantee for return of investment – and thus a higher motivation for investment in infrastructure - compared to the case if the LSA opportunities were made available under a license exempt scheme.

By issuing LSA licenses the NRA also enables the incumbent to know who would be responsible for causing interference to its service, if this should ever happen.

A NRA may issue a single or multiple LSA licenses. In the first case, the LSA system is the only system that has the right to access the spectrum opportunities left idle by the incumbent system; as such it needs only to share with the incumbent. In the second case, several systems having the LSA licenses need to share with the incumbent system (by appropriately protecting their services mutually) as well as to share the spectrum opportunities among each other, much alike as in the abovementioned licensed authorization sharing options.

In brief it can be stated that LSA adds additional complexity to sharing, since the systems also need to protect the incumbent service. In return already licensed bands are opened up for secondary access with maintaining a high level of performance predictability.

3.1.5 LSA evolution over time

Initial LSA implementations as envisaged in the near future are expected to be very similar to dedicated licensed schemes as of today. An LSA band will likely be partitioned into several blocks which are then licensed to individual operators. Each operator will have to protect incumbent usage within his own licensed block.

At a later stage the LSA concept may also be combined with spectrum sharing schemes described above for the dedicated licensed case, i.e. spectrum pooling or mutual renting between LSA licensees. Due to the higher likelihood for having a central entity for coordination of incumbent protection (in most cases a geo-location database), sharing between LSA licensees has a higher likelihood for being implemented via the same database, which in this case would functionally be extended to a "spectrum coordinator" role. Those more advanced LSA schemes are of particular interest for research in METIS, since the simple LSA schemes are expected to be state of the art by the time METIS results materialize in the market.

3.2 General Authorization (Unlicensed)

In this option the usage and access rights are generally granted without an individual license but subject to certain technical restrictions or conditions (e.g. limited transmit power, functional features like duty cycle or listen before talk, …). Beside the term "License exempt", also the terms "unlicensed" and "license free" are used. It is important to note that in license exempt bands there is no protection guaranty among the users, any user may be interfered by others.

A system operating under a general authorization regime in an unlicensed band needs to share the spectrum with any other system claiming access to the band. Thus, the spectrum might need to be shared between lots of users with very diverse requirements while supporting different use cases.

This type of regulatory regime (unlicensed) provides the least predictable system performance (QoS) but also the lowest spectrum cost, as the cost for unlicensed spectrum is typically zero.

In the language used by the European Commission, unlicensed spectrum is referred to as "Collective Use of Spectrum" (CUS - [16]). The different spectrum access schemes and potential sharing models falling under this authorization regime are described in the subsections below.

3.2.1 Unlicensed Shared Access

This access scheme refers to frequency bands that are generally allowed to be used by several users and in which primary service is not allocated. Users share the band horizontally without protection rights against each other. The most common example is the 2.4 GHz ISM band.

3.2.2 Secondary Horizontal Shared Access

This access scheme is like the previous one but with an obligation to protect spectrum users of higher priority, typically primary users. In this case the secondary opportunities provided need to be shared among the possibly numerous unlicensed systems. This type of secondary usage provides very little guarantee of realizable performance for any involved system and as such most likely no large infrastructure investments will be possible.

In relation to [14], unlicensed secondary use is classified as general authorization with either light-licensing or license-exempt. Light-licensing is included in this option since there may be a regulatory requirement to register secondary users in a database, e.g. a geo-location database, before they get access to the spectrum.

3.2.3 Unlicensed Primary Shared Access

This access scheme applies to the cases where in a frequency band there is a primary service allocation and, in parallel, it is generally authorized that everybody can use it by the one allowed technology. Mutual protection is not required by regulation, but taken care to the level needed by the technology used. An example of such a current situation is DECT operating in the band 1880-1900 MHz. Here DECT is primary via mobile service allocation from ITU-R. DECT devices should implement spectrum sharing etiquette to prevent harmful interference.

4 Technical requirements arising from new spectrum authorization regimes

The new spectrum authorization regimes motivate to enhance performance and capacity of mobile broad band (MBB) systems via spectrum sharing, which involves different sharing players and sharing models. Generally, the players in spectrum sharing can be categorized into mobile network operators (MNO), other communication systems (than MBB, like Wi-Fi) and non-communication systems (e.g. radar system). The authorization regimes, introduced in Section 3, describe in what kind of regulatory environment a METIS system is expected to operate. To support operation under the listed regulatory regimes we find that a METIS system is required to be designed to operate in the following spectrum sharing modes: primary user mode, unlicensed mode and licensed shared access mode. This section outlines the technical solutions that are needed to support the various modes of operation.

Based on the spectrum sharing players and spectrum sharing modes, the spectrum sharing scenarios for METIS can be identified and suitable technical solutions can be mapped to those scenarios. Note that the sharing modes described in the following do not include all possible cases but rather reflect the interest of METIS on further investigation and development of technologies. More sharing modes could be included in the future, if identified as relevant and promising.

4.1 Potential spectrum sharing technologies

Since radio spectrum is an open medium, there is a large potential that different systems sharing radio spectrum generate interference to each other. Thus, the main technological challenge for spectrum sharing is to manage the interference and maximize the usage efficiency of the shared spectrum. In general, the mutual interference due to spectrum sharing can be managed in the following dimensions:

- **Frequency dimension:** Different systems use orthogonal frequency resource blocks to avoid interference;
- **Time dimension:** Different systems use different time intervals (like TDMA), for the usage of the same spectrum at the same time, to avoid interference;
- **Location dimension:** Different systems different locations with sufficient separation, for the usage of the same spectrum at the same time, to avoid interference;
- **Spatial dimension:** Different systems manage the interference via orthogonal spatial resources, for the usage of the same spectrum at the same time. Such interference management is enabled by multi-antenna techniques. One example is the cooperative beamforming between base stations of different operators;
- **Code dimension:** Different systems manage the interference via orthogonal code resources, for the usage of the same spectrum at the same time. This can be realized by CDMA-like techniques or wireless network coding;

For MBB systems to share spectrum with other potential systems, coordination/coexistence capabilities are required to manage the interference via the dimensions described above, probably in a dynamic and/or adaptive manner. Such coordination/coexistence capabilities can be broadly categorized in distributed solutions and centralized solutions. The coordination/coexistence can be between multiple MBB systems or between MBB systems and other systems. In a distributed solution the systems coordinate among each other. In a centralized solution each system coordinates separately with a central entity and the systems do not directly interact with each other. Both solution types may be combined.

4.1.1 Distributed techniques

Distributed solutions have the advantage that coordination can be more efficient since it can take place in a local context. In principle it is possible to coordinate only those transmissions that actually create interference between systems. Solutions for distributed coordination can be fully integrated into standards and can thus be defined so that they operate without the need for commercial agreements between operators or equipment owners, like the situation for Wi-Fi systems.

In a *peer-to-peer coexistence protocol* the coordination of spectrum sharing happens through explicit exchange of messages directly between the sharing systems via some well-defined interface. The protocol defines the behaviour of the nodes when receiving certain messages or when certain events take place. An example of such a protocol is given in [18]. According to that, spectrum sharing coordination is realized by means of spectrum usage favours given and received by the operators. It is assumed there is some sort of connection between the radio access networks of the operators.

In *coexistence beacon* based solutions the systems regularly transmit commonly understood signals that indicate presence and potentially additional information, e.g., activity factor and when they intent to transmit. Other systems can use this information in order to adapt their spectrum access behaviour to provide fair spectrum sharing. An example of a coexistence beacon implementation is the 802.22.1 standard [19].

In *MAC behaviour* based schemes the MAC protocol is designed to enable spectrum sharing. Examples are the request to send / clear to send (RTS/CTS) functionality employed in IEEE 802.11 WLAN systems and the frequency hopping used in Bluetooth. A *Wi-Fi coexistence mode* is another example of how a MAC behaviour may be adapted to allow for smooth coexistence with Wi-Fi systems. The MAC protocol may leave coexistence gaps in the occupied spectrum, i.e. silent periods during which Wi-Fi systems are able to operate. In this mode the MAC behaviour may alternatively use a listen-before-talk approach that allows Wi-Fi systems to gain channel access.

Spectrum sensing and dynamic frequency/channel selection (DFS/DCS) are solutions in which systems dynamically select their operating frequency range based on measurement results. The measurements can e.g. be energy detection, or feature detection. Feature detection can be used to detect the abovementioned coexistence beacons. Due to the so-called "hidden node problem" DFS/DCS is typically not considered as a very reliable method which may make it unattractive as sole means for protecting a primary user.

As seen above, the distributed techniques can be with or without cooperation between the sharing systems: The *peer-to-peer coexistence protocol* and *the coexistence beacon* based solutions are examples with cooperation, while the *MAC behaviour based schemes* and *the spectrum sensing and dynamic frequency/channel selection solutions* are examples without cooperation.

4.1.2 Centralized coordination/coexistence techniques for spectrum sharing

Centralized solutions are expected to be useful for sharing on somewhat longer time scales, i.e. the granularity of spectrum sharing would be on a higher level than the actual radio resource allocation granularity within each system. The limitation that coordination is done on a comparably slow time scale implies that a typical solution is conservative and likely to separate users on orthogonal resources without complete information on whether they would actually interfere or not. The benefits are in terms of reliability, predictability and control. If monetary transactions are involved in spectrum sharing, centralized approaches are likely preferable.

An example of a centralized sharing technique is the *geo-location database (GLDB)* approach in which a system queries a database to acquire information on which resources are available at a specific location [20]. This is typically the required solution for access to locally unused TV bands [21].

Another example is the *spectrum coordinator* approach where sharing systems negotiate with a central resource management entity to obtain short term grants to use spectrum resources on an exclusive basis [22]. This grant sets the frame for the system internal radio resource management. The spectrum coordinator can in some cases be seen as an extension of the geo-location database.

4.2 Spectrum Sharing Modes

Components in a future multi-RAT multi-carrier MBB system can be envisaged at a given time in a given frequency band to operate in one of the three different modes of spectrum sharing: Primary user mode, unlicensed mode, and licensed shared mode. These modes relate to the regulatory framework of the band as well as the spectrum sharing models (mentioned in 4.1) and consequently impact the number of technologies present and hence which sharing solutions are suitable.

The relation between these modes and the spectrum access schemes described in Section 3 is illustrated in the below table. To make clear the hierarchical structure of the sharing players in the different spectrum sharing modes, we further define the different spectrum sharing models: Co-primary, primary-secondary, equally secondary and unlicensed. The relation between these sharing models and the spectrum sharing modes is also listed in the following table. In particular, equally secondary refers to the case where several secondary users have the same right to access spectrum opportunities in a band allocated to a primary user, whereas equally unlicensed refers to the case where there is no primary user for the secondary users to protect.

Table 1: Mapping of the spectrum sharing modes onto the spectrum access schemes and the spectrum sharing models

Spectrum sharing mode	Spectrum access scheme	Spectrum sharing model
Primary user mode	Exclusive Co-primary Shared Light Licensing	Co-primary Primary-secondary
Unlicensed mode	Unlicensed Shared Secondary Horizontal Shared Unlicensed Primary Shared	Primary-secondary Equally secondary Unlicensed
Licensed shared access mode	Licensed Shared Access (LSA)	Primary-secondary Equally secondary

4.2.1 Primary user mode

It is well recognized that exclusive use of dedicated spectrum is the preferred way of spectrum usage for MBB cellular operators. This type of spectrum access allows long term investments in large scale networks. In a primary user mode a MBB system will normally have dedicated spectrum access without sharing. The only relevant spectrum sharing scenario that can occur is horizontal sharing with other primary systems, under the co-primary or light licensing regimes, cf. Sections 3.1.2 and 3.1.3. The most relevant such sharing scenarios are the mutual renting and limited spectrum pool scenarios.

Concerning technical solutions for the primary user mode a spectrum coordinator or a peer-to-peer messaging protocol over the backhaul seem to give the largest flexibility, since it could address both the mutual renting and the limited spectrum pool scenario. The spectrum coordinator approach is likely limited in the supported granularity of the sharing, i.e. the solution might be less than optimally efficient. The different solutions may also be combined to give additional benefits that may be exploited by a system in a particular sharing scenario. For example, coexistence beacons can be part of a coordination protocol, e.g. when they serve the purpose of claiming resources or estimating path loss between coordinating nodes.

If coexistence is limited to systems of the same kind, or optimal performance is only required for those situations, an alternative to the previous solutions is the use of over-the-air peer-to-peer coexistence messaging protocols. The advantage of over-the-air coordination compared to a backhaul-based solution could be a faster coordination leading to overall higher efficiency. This solution could be combined with a DCS/DFS or beacon approach for coexistence with known or unknown other systems in bands where the allowed technologies are not known.

Based on the spectrum sharing players and spectrum sharing models for the primary user mode, the spectrum sharing opportunities for METIS in the primary user mode can be identified, which are shown in Figure 7.

Figure 7 - Spectrum sharing actors in primary user mode.

4.2.2 Unlicensed mode

In an unlicensed mode an MBB system has to share spectrum with other unlicensed systems (cf. Section 3.2.1) while, in special cases, ensuring the protection of primary users of the band (cf. Sections 3.2.2 and 3.2.3). Depending on the nature of the primary system and the regulatory environment, different technical solutions might be required for these scenarios.

For horizontal sharing in an unlicensed band, a system must be prepared for coexistence with any other technology that may be present in the band. Non-system specific sharing methods will thus be needed for robustness. For this case de-centralized solutions for coexistence are preferred. Over-the-air signalling may work for sharing within the same technology, but the limitation to a single coexistence situation may make it less preferred. The most realistic solutions are probably coexistence beacons, MAC behaviour for coexistence (e.g. for Wi-Fi coexistence), and spectrum sensing with DFS/DCS.

Vertical sharing functionality may also be required for a system operating in unlicensed mode if a primary user exists in the band, e.g. TV white spaces in the US. Typically, there will be strict requirements in order not to cause harmful interference to the primary user. The regulator will likely mandate their protection by a particular sharing technique, e.g. a centralized geo-location database solution or a DFS/DCS scheme.

Based on the spectrum sharing players and spectrum sharing models for the unlicensed mode, the spectrum sharing opportunities for METIS in the unlicensed mode can be identified, which are shown in Figure 8.

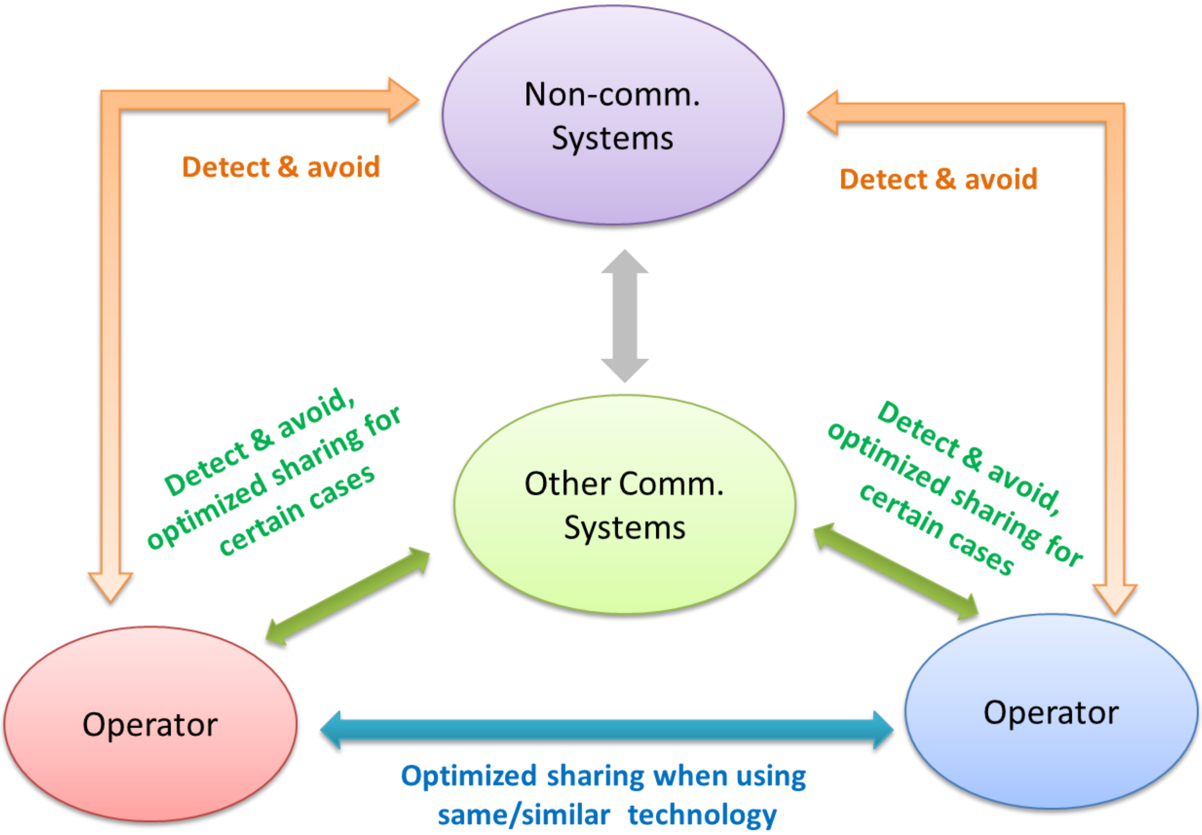


Figure 8 - Spectrum sharing in unlicensed mode.

4.2.3 Licensed shared access mode

In a licensed shared access mode a licensee has the right to access spectrum that is unused by the incumbent user at certain locations and/or times. This vertical sharing is based on well-defined conditions which are part of a LSA sharing license.

In initial applications of licensed shared regulations, e.g., the LSA concept currently being developed (cf. Section 3.1.4), the licenses are expected to be long term and exclusive with respect to other licensees, such that no horizontal sharing would be required. In more evolved licensed shared access frameworks, horizontal sharing between licensees may be applied in addition, cf. Section 3.1.5.

The appropriate spectrum sharing solutions are similar to those applicable in the primary user mode. Centralized solutions will likely be preferred to coordinate the coexistence with the incumbent in licensed shared spectrum. They will be subject to regulatory requirements. Reusing this centralized framework for enabling horizontal coexistence is a straight forward approach to enable horizontal sharing between licensees when applicable. Hence GLDB and spectrum coordinator approaches are possible. Peer-to-peer sharing and coexistence beacon solutions are also envisioned to be applicable to the horizontal sharing, but they would then be separated from the vertical sharing mechanism.

Based on the spectrum sharing players and spectrum sharing models for the LSA mode, the spectrum sharing opportunities for METIS in the LSA mode can be identified, which are shown in Figure 9.

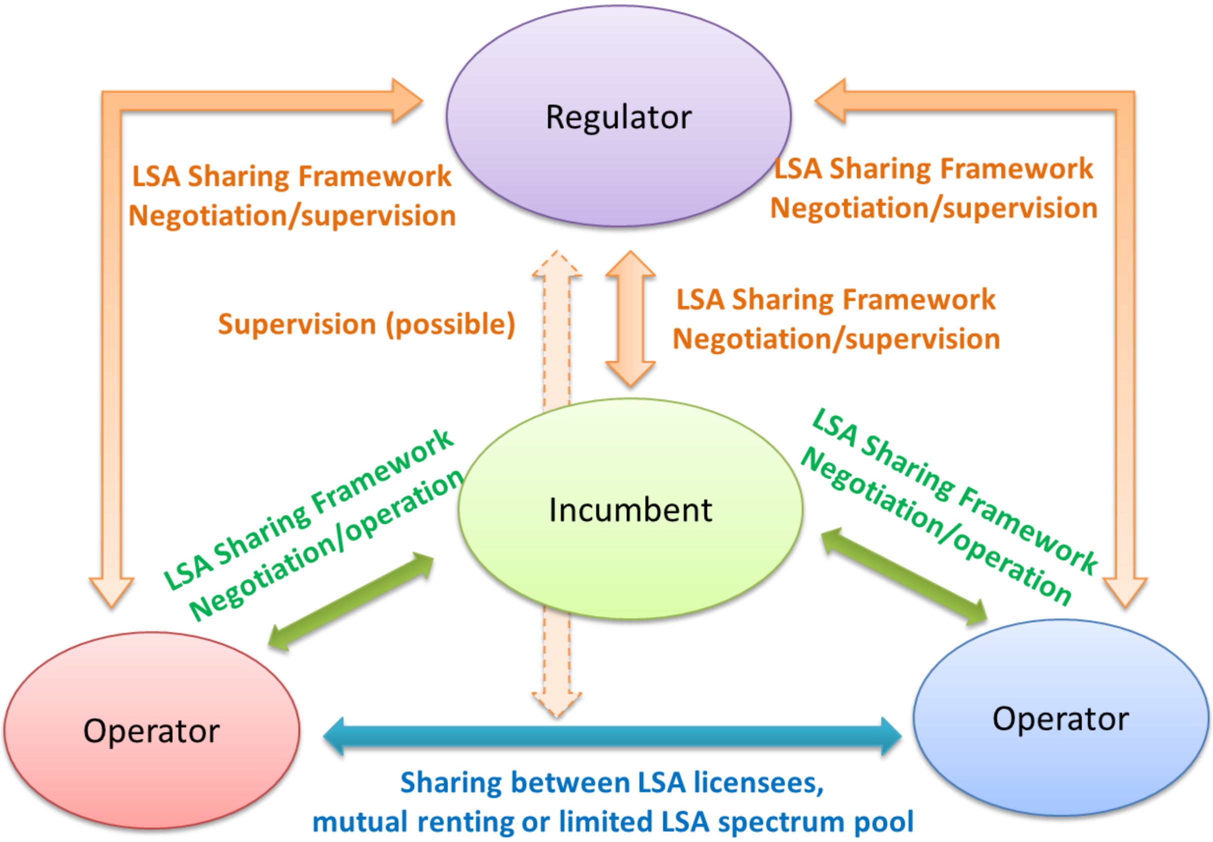


Figure 9 - Spectrum sharing in LSA mode.

4.3 METIS Spectrum Sharing Tool Box

Based on the considerations in the previous sections a number of spectrum sharing “tools” have been identified that will enable an MBB system to operate in potentially relevant spectrum sharing scenarios. In some scenarios one particular tool can enable a certain scenario alone; in other cases a combination of tools may be required. For the latter there may be multiple options that can enable a given scenario.

It needs to be emphasized that in particular situations only a sub-set of these tools may have to be implemented in a given product or product variant, since it may be designed to address only a subset of the spectrum scenarios. But from a conceptual point of view, an MBB system needs to support them all in order to achieve the objective of being able to operate under all different future spectrum authorization models.

The sharing “tools” are collected in a toolbox and may be turned on to enable an encountered sharing situation. The proposed toolbox is illustrated in

Figure 10 and comprises:

- *Coordination protocol* – for efficient spectrum sharing between independent MBB deployments of the same type/technology,
- *Spectrum coordinator support* – a more technology-neutral centralized alternative for tightly coordinated sharing,
- Detect-and-avoid mechanisms such as *Dynamic Frequency Selection* or *Dynamic Channel Selection* – used either as a simple mechanism for low-granularity spectrum sharing or as an initial step of selecting the most favourable channel before other sharing techniques are applied within that channel,

- *Geo-location database support* – to enable scenarios where this is mandated by the regulator for primary user protection, and
- *Wi-Fi coexistence mode* – to enable co-channel operation with Wi-Fi in unlicensed bands.

The tools above are the most typical examples. Further spectrum sharing tools, e.g. cooperated resource allocation, will be developed within METIS.

Furthermore, regarding the dimensions of interference management described in 4.1, the current tools mainly use the frequency, time and location dimensions. In practice, the implementation of techniques using these three dimensions is more straightforward than that with the spatial and code dimensions. However, the spatial and code dimensions may also be taken into account in future developed tools, if they are found effective and promising for certain scenarios or test cases.

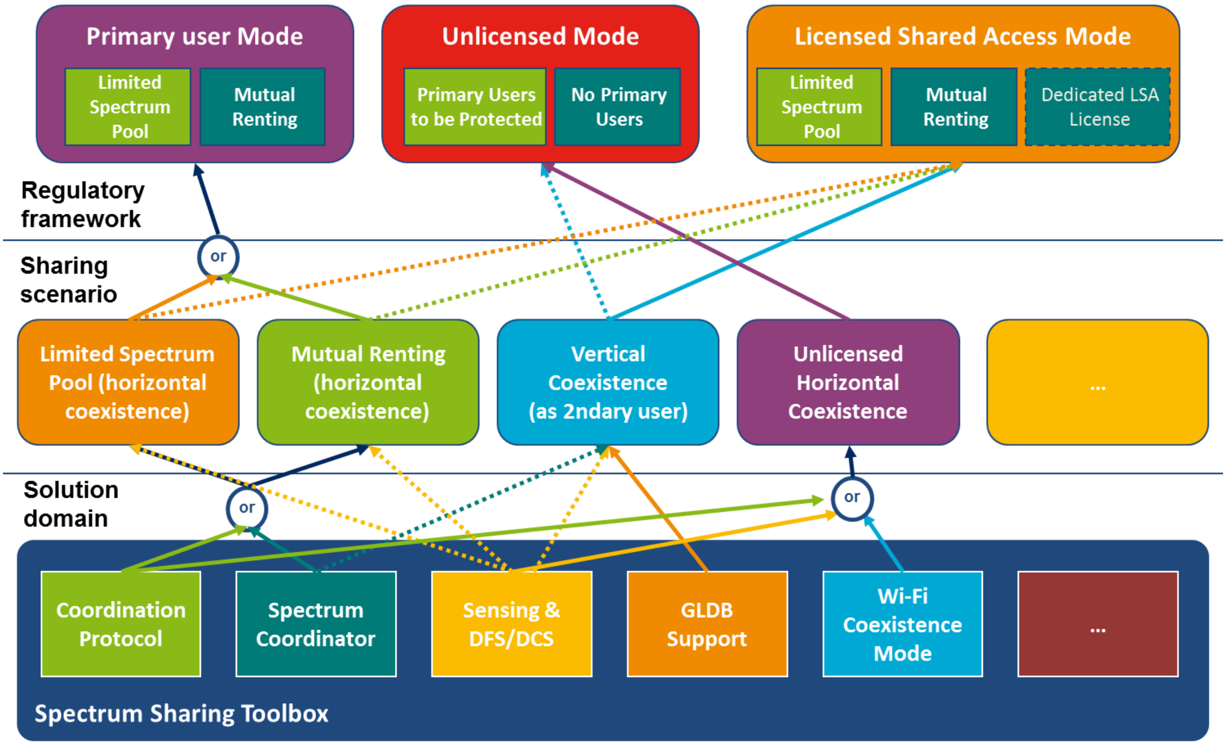


Figure 10 – The spectrum sharing toolbox. Solid arrows illustrate "required" relations (e.g., needed tools or scenarios which are necessary parts of a regulatory framework) whereas dotted arrows illustrate "optional" or "possible" relations

4.3.1 Tools to Enable Sharing in Primary User Mode

To address the primary user mode the coordination protocol and the spectrum coordinator are seen as the most promising tools. The former should enable the highest sharing efficiency and can benefit from the possibility to specify the behaviour of the involved systems and a (default) sharing policy in detail. The latter will likely provide a lower supported sharing granularity and efficiency, due to the need to include some safety margins. On the other hand it would enable better control of the shared resource. Depending on the systems involved, their requirements and their deployment one tool would likely be preferable over the other.

In order to minimize the need for coordination, an automatic channel selection (sensing and DFS/DCS) mechanism would likely be involved as a first step in such scenarios, if applicable, in order to identify and select the best channel that causes the lowest sharing overhead.

4.3.2 Tools to Enable Sharing in Unlicensed Mode

For the unlicensed mode differentiation between techniques for horizontal and vertical sharing is needed.

For vertical sharing, there are scenarios where detection and DCS/DFS as well as geo-location database (GLDB)-based approaches are suitable. The support of either of those will typically be a regulatory requirement. Extending a GLDB to a function as a spectrum coordinator for horizontal sharing is also an option.

For horizontal sharing in unlicensed bands a case-by-case combination of coordination protocol (for optimized coexistence with other MBB systems of the same type), Wi-Fi coexistence mode for sharing with Wi-Fi systems, and detection and DCS/DFS for avoidance of interference by unknown other systems is envisaged.

4.3.3 Tools to Enable Licensed Shared Access Mode

The licensed shared mode inherently calls for vertical sharing mechanism. GLDB support is the more likely option but a sensing and DCS/DFS based solution might be applicable in certain scenarios. Also in this mode the choice of the vertical sharing mechanism will likely be an external requirement.

For the horizontal sharing the range of envisaged solutions includes basically all options which have been discussed before for the primary user mode: coordination protocol possibly combined with detection and DCS/DFS, or alternatively spectrum coordinator. The latter would likely be combined with the GLDB for primary user protection.

Spectrum sensing and DCS/DFS approaches as a sole measure for horizontal sharing seem to be in conflict with the expectation that licensed shared mode supports predictable quality-of-service. A Wi-Fi coexistence mode seems unlikely since one would probably not mix such techniques in an individual authorization context like a licensed shared framework.

4.4 Key Enablers to Enhance Spectrum Sharing Efficiency

Among the dimensions for interference management in 4.1, the frequency dimension is one of the most important dimensions to allow flexible sharing, as well as to fulfil requirements like availability. When using the frequency dimension to manage interference, certain guard-band between the signal spectra of different sharing systems has to be reserved to either achieve protection of primary systems or restrict mutual interference between equally sharing systems (when the different sharing systems are not perfectly synchronized). In this case, the smaller the guard-band required, the higher the spectrum sharing efficiency, i.e. the usage efficiency of the shared spectrum. Actually, the size of the guard-band mainly depends on the out-of-band radiation characteristic of the transmit signals. Therefore, new waveforms with ultra-low out-of-band emissions (e.g., Filter Bank Multicarrier (FBMC) waveforms) will be key enablers to enhance the spectrum sharing efficiency. Furthermore, for a given emission mask, such waveforms allow higher transmit power without generating harmful interference to neighbouring channels. Thus, the use of such waveforms and the exploitation of the ultra-low out-of-band radiation characteristic should be investigated. A further advantage of such waveforms is that they can efficiently make use of non-contiguous spectrum with small spectrum fragments, which is a typical case in some spectrum sharing scenarios.

4.5 Discussion

A spectrum sharing scenario is primarily characterized by the regulatory regime that is in place and the corresponding requirements. In some cases there may be freedom to implement different technical solutions in order to cope with the regulatory requirements, whereas in other cases a specific regulatory scenario may uniquely call for a certain technical solution. For example, for vertical sharing the need to effectively protect primary users typically leads to very specific regulatory requirements that normally allow only one specific technical solution. Horizontal sharing regulatory requirements tend to allow more freedom so that more than one option may be possible. Sometimes the solution for horizontal sharing will be subject to industry agreement or standardization; sometimes no agreement may be necessary at all.

For technical realization of spectrum sharing, interference management is the main challenge. For managing the interference in different dimensions (e.g. frequency, time and location), different technical solutions can be envisaged to enable a spectrum sharing scenario. Sometimes also a combination of different technical solutions can be required to enable a MBB system to operate in a given spectrum sharing scenario.

To allow a MBB system to be designed to operate in a large number of sharing scenarios the spectrum sharing toolbox is introduced. It enables the choice of sharing techniques on demand when a specific sharing situation is encountered. When required the relevant sharing solutions will be turned on and smooth coexistence with other systems will be ensured.

The inclusion of all proposed sharing tools in the toolbox is required in order to allow for operation and sharing spectrum in a wide range of regulatory frameworks.

Finally, the ultra-low out-of-band radiation characteristic of the new waveforms should be exploited to further enhance the spectrum sharing efficiency.

5 Spectrum Demand Analysis

In contrast to past migration steps in mobile communications, METIS will not only address the fast growing mobile data volume of classical consumer-driven services but also support of new classes of mobile services and applications with requirements not yet addressed. These requirements will affect the spectrum selection significantly.

In order to cover this broader migration strategy, a specific spectrum demand methodology taking into account these new service and application classes with their specific demand, the resulting new requirements on spectrum, as well as the impact of the new radio access concepts introduced by METIS will be needed.

5.1 Review of spectrum demand methodology

Classical spectrum demand approaches are following a two-step approach. In a first step the service and application growth is evaluated based on market analysis. Typical metrics used are service and application adoption, data volume per service, geographical usage patterns, predicted terminal penetration, etc. In an independent study, the capacity and peak data rates per area, per cell or at the cell edge (worst case) is estimated for the expected radio access technologies. Comparing the two results, spectrum demand is determined. This is typically done for three scenarios defined by growth rates "faster than expected", "average", and “lower than expected".

Figure 11 shows a simplified sketch of the classical evaluation methodology.

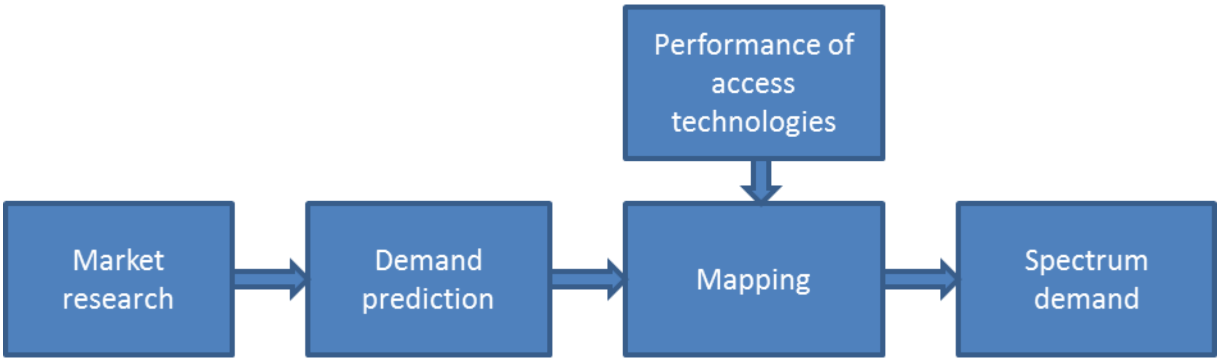


Figure 11 – Classical spectrum demand evaluation methodology

5.2 Spectrum demand analysis for METIS use cases

In contrast to the classical approaches described above, the use case specific spectrum demand evaluation has to take into account scenarios and technologies not yet covered. Some examples are:

- Evaluation of spectrum resources above 10 GHz that require new access technologies which cannot be addressed with the existing approaches.
- Safety critical applications and disaster relief scenarios where not the data volume but the availability is the key requirement.
- Huge amounts of only locally appearing traffic will be addressed by new radio access technologies in order to reduce the resulting spectrum demand to an acceptable level.

Due to the unforeseeable adoption of the scenarios and test cases as well as radio access concepts developed in METIS, an overall spectrum demand cannot be estimated. The following section will however provide initial findings on the spectrum demand taking the new radio concepts and HTs into account. Since the definition of the HTs including their performance and spectrum implementation is ongoing, final conclusion will only be provided in future deliverables.

New radio concepts and HTs

Hereafter, the radio concepts and HTs under development in METIS in order to support the use cases are characterized from their spectrum implementation point of view.

HT Device-to-Device (D2D)

Various concepts for integrating direct device-to-device links in wide-area communications are currently discussed. Some of them, e.g., establishing D2D links by IEEE WLAN standards in ISM bands in order to offload the cellular networks, are already implemented.

METIS will integrate existing solutions in its overall concept but it will focus on developing new D2D options that help to meet the requirements of the test cases.

- METIS is in particular evaluating the possibility to use D2D links in currently not heavily used TDD guard bands but also as underlay to the cellular network uplink and downlink FDD bands. In these cases, the main motivation is to find attractive options for using rarely used spectrum (some TDD bands) or to increase the spectrum usage efficiency in case of FDD systems. Both options will offload the cellular networks.
- Another option addressed by METIS is to provide interference management for D2D links that do not yet have efficient means for interference management and QoS control. Here, D2D links using ISM spectrum (see above), IEEE 802.11p car-to-car links, and SRD links might benefit since they are currently not having any centralized interference management. Here, the HT D2D is linked to the HT URC for safety-critical car-to-car communications and to the HT MTC for the management of SRD links.
- A third option is the infrastructure-less operation of D2D links as a fall-back solution in cases of disasters. In contrast to the two cases described above, here D2D links are not managed and controlled by a centralized network management.
- As a combination of the above cases, the use of D2D links for coverage extension of wide-area networks is also addressed in METIS.

HT Ultra-Dense Networks (UDN)

Densification of base station or access points is seen as a major means to increase network efficiency and, with this, spectral efficiency. METIS builds on this trend and evolves – from a spectrum engineering point of view - densification concepts

- by evaluating the use of higher frequency bands for ultra-dense networks,
- by providing solutions for the coexistence problems resulting from the use of UDN in many already used bands, and
- by efficiently integrating UDN solutions in different deployment-specific spectrum bands (partly with high available bandwidth) in an overall wide-area concept.

HT Moving Networks (MN)

The HT Moving Networks intends to integrate a broad range of concepts that are based on mobile or moving access points, repeaters, and even base stations. Besides the already known mobile relays and repeaters serving users in trains or cars with their respective access and backhaul links, the HT MN will address clusters of mobile access points and base station building moving networks and the use of vehicle-mounted base stations providing network capacity at places where typically the traffic demand is low and building peak capacity networks is therefore economically infeasible (“traffic demand follows cars”).

The introduction of many of the above listed concepts results in significant coexistence problems and spectrum engineering challenges that are addressed in METIS. Spectrum allocations for the access links (terminal to moving access point) and the backhaul links (moving access point to wide-area network base station) are discussed.

HT Ultra-Reliable Communications (URC)

The METIS HT URC addresses the growing need of safety-critical applications for reliable wireless communication links. Typical examples are railway networks supporting the European Train Control System (ETCS) or car-to-car communications. Today, railway GSM-R networks suffer for example from adjacent-channel interference and car-to-car communications from the lack of interference and capacity management in cases of high traffic demand. Providing, for these scenarios, reliability in terms of guaranteed QoS with strict requirements on the maximum allowed delay for successful transmission of packets will result in additional requirements on spectrum engineering. New waveforms that are more robust with respect to adjacent channel interference dynamically allocated guard bands in the spectral domain or optimized deployment concepts reducing the adjacent interference problem for URC links are spectrum engineering approaches addressed in METIS.

HT Massive Machine Type Communication (MTC)

The growing adoption of wireless connectivity for machine-to-machine communications with their application-specific, broad range of new requirements in terms of overhead efficiency, supported stand-by time, coverage and latency requires revising the access concepts in wireless wide-area networks. Concepts supporting massive machine type communications (MTC) scenarios are addressed in METIS.

Typically, three classes of links are to be considered. The access links connecting the base stations with “aggregators” or selected major sensors / actuators, the local links or submetering links connecting the aggregators with local sensors / actuators, and finally device-to-device links only locally connecting devices as sensors and actuators that do not necessarily need to be connected to wide area networks. For the latter class, often SRD technology deployed in SRD / ISM bands is used. Although these links might use existing technology, METIS can provide interference and other management functionalities for these links as well. Note that there are currently growing concerns about the interference problems in SRD bands that could be addressed by this approach.

For the access links, deep indoor coverage is required in some cases resulting that can most efficiently be supported in lower frequencies, e.g., spectrum below 1 GHz. In contrast to this, for the local links mainly the implementation costs are relevant so that a broader range of spectrum bands can be used.

5.3 Spectrum access and usage for METIS test cases

This section contains a detailed spectrum access and usage analysis for the twelve test cases (TCs) described in deliverable D1.1 [13].

5.3.1 TC 1: Virtual reality office

Test case summary. In this TC, a 3D telepresence and virtual reality company, with intensive and highly demanding multimedia devices, installs itself in a new premises sited in an old building. Multimedia devices data-rates needed are around 1 Gbps each. This scenario is placed in an industrial environment, with team members spread in different rooms and even on different floors.

Spectrum Access. From spectrum usage point of view, the requirements of this TC could likely be fulfilled by means of using different Spectrum Authorization Options (SAO), but then different QoS levels will be obtained:

- *Unlicensed bands:* Predictable QoS is likely mission critical in this test case since the company relies on having sufficient network performance in its daily operation. Since in unlicensed bands QoS is difficult to predict and cannot be guaranteed (which is not to be confused with QoS being low), unlicensed bands will most likely not be suitable for providing the main connectivity in this TC. How big this risk is will depend on the size of the premises controlled by the computer animation company, and the possibility of uncontrolled equipment radiating in its neighbourhood in an uncoordinated way. Unlicensed bands might however play a complementary role for offloading purposes or for opportunistically enhancing QoS beyond the average requirement.
- *Exclusive spectrum access rights:* Being able to provide certain QoS with a very high probability is likely mission critical in this TC. Since this SA will lead to good QoS, it is from that point of view very suitable.
- *Licensed and co-primary shared access:* Due to the high cost of exclusive licensing and since in this TC the demand will be confined to a certain controlled area of limited size (the company premises) a dynamic (lower than daily based) Frequency / Space / Power assignments might be beneficial in order to lower the cost without significant risk of lowering the expected QoS. These SAOs are based on dynamic assignments combined with mechanism for ensuring the targeted QoS under appropriate agreement with the incumbent, therefore they are suitable schemes for this test case.
- *Light licensing:* This SAO's fitness for this TC will depend on the used access technology space domain granularity actually implemented. Since the spectrum usage is very local, in order to make the spectrum usage cost appropriate, a very high granularity of access rights is needed.

Bandwidth and frequency range aspects. Even taking into account the usage of highly spectrum efficient technologies, as e.g. multiple MIMO antennas, which are facilitated by test case's low mobility description, large chunks of spectrum will be needed in order to provide the required peak data rate and capacity per area. In order to provide 2 GHz or more as the targeted bandwidth, the availability analysis in section 2 shows that this will most likely moving to frequencies above 27.5 GHz. On the other hand frequency range selection will be impacted by the possibility to maintain indoor NLOS communications. In this sense, it should be taken into account that losses due to diffraction, reflection, and material penetration for NLOS conditions increase with carrier frequency. Therefore the maximum frequency band usable will depend on the economic feasibility of the required deployment density for a given frequency, the presence of walls and their material, if communicating devices are in different floors, etc. Different scenarios will impose different higher frequency limits. Frequencies over 90 GHz may not seem as practical in NLOS scenarios although this has not yet been investigated quantitatively.

If achievable spectral efficiency and spatial diversity enable the fulfilment of this test case's throughput requirements with only a 0.7 GHz frequency bandwidth, the 9.9 to 10.6 frequency band may also be used, providing lower losses in indoor NLOS scenarios.

5.3.2 TC 2 : Dense urban information society

Test case summary. Future users in urban areas will require high communication data rates wherever they may be located. At the same time, people in urban environments tend to follow *unpredictable moving patterns*. They thus create (possibly unpredictable) local concentrations of very high data traffic demand. The TC assumes that there are certain legacy RANs present with deployment parameters typical as of today and assumed functionality corresponding to e.g. 3GPP Rel-11. 500 Gbyte traffic per month and user is assumed (1000x traffic increase compared to today). 95% area coverage with 100 Mbit/s is assumed to be required.

Spectrum access. A mix of traditional dedicated licensed (highly reliable) and complementary shared licensed and unlicensed shared spectrum appears most suitable for this TC. The dedicated licensed spectrum provides reliable coverage and mobility support and enables controlling QoS for those traffic types that require it, but possibly has limited capacity and may not support the maximum QoS (i.e. users may experience limited QoS while being connected only via dedicated licensed spectrum) for elastic services. In cases where the locations of such peak demands are indeed unpredictable, it is likely that the network is not dimensioned to cope with the local traffic demand. In cases where demand is predictable the network is likely dimensioned appropriately, but it may still be economically preferable to partly rely on shared (licensed or unlicensed) spectrum also in this situation.

Bandwidth and frequency range aspects. To meet these user demands the future METIS system will require a very large bandwidth within limited areas. E.g., the users will request an experience of having immediate access to large Cloud based files (10MB) and as such the peak rates required for handling this will be very high, in the order of several Gbps. Even when assuming that the spectral efficiency of the METIS system will be better than today's systems, the required bandwidth for meeting the requirement of a single user may be several hundreds of MHz. Serving multiple simultaneous users, including users streaming uncompressed interactive high quality 3D visual content, will likely require much more spectrum. As such, meeting the expectations of the users will require much larger bandwidths in the order of 2GHz, which as shown in section 2 will likely be available only at frequencies above 27 GHz (e.g. 27.5 – 29.5 GHz; 40.5 – 42.5 GHz; 47.2 – 50.2 GHz; etc.)

It should be noted that user equipment devices are expected to be connected, in some occasions simultaneously, to IMT frequency bands below 6 GHz (providing the basic coverage), as well as to ISM bands and to the above mentioned high frequencies bands, for traffic offloading.

5.3.3 TC 3: Shopping mall

Test case summary. Future extended rich communication in indoor environment, with involvement of MNOs (both wide and small/local area), as well as of manifold wireless sensor networks is a large shopping mall with high density of customers together with staff of shops and real estate owner.

Augmented reality services will be deployed, provisioning of personalized information (e.g. detailed product information, real-time price comparisons) dependent on their location before or inside the shops. Dependent on finally offered services data rates will cover a large range from few packets up to real-time video for product presentations.

Dependent on radio link availability a connection between the parties can be realized via the local or mobile radio network infrastructure or via direct D2D communication. D2D may be also a communication feasibility for service assistants e.g. inside the catering areas (human-to-human as well as human-to-machine).

Spectrum access. Within a shopping mall a number of different services requirements exist, ranging from low to high data rates as well as from spectrum access with high reliability (e.g. emergency applications) to lower reliability.

Therefore, a mixture of traditional regulatory regime (mobile coverage) and spectrum sharing (e.g. LSA/ASA to keep OPEX/CAPEX for operators low) and license-exempt approach is considered appropriate for this TC.

Bandwidth and frequency range aspects. To meet the high-end throughput requirements within the range of requirements represented by this TC, very high frequency bands are expected to be suitable. Large spectrum bandwidth is required within a limited area in which high reliability is required.

Under the assumption that application layer failsafe mechanisms helping to cope with smaller network outages are implemented, also less reliable spectrum could be used to some extent, for traffic offloading. As reliability over time is more important than reliability over space it is however clear that a sufficient amount of reliable (dedicated) spectrum is needed.

The larger bandwidths available would also ease to cope with the high capacity demand. In order to assure the mobility required, also lower frequency bands have to be used in addition. The different QoS requirements offer the possibility to use LSA or even unlicensed spectrum in addition to licensed spectrum.

Setting 2 GHz needed bandwidth as a working assumption, and accordingly with the availability analysis in section 2, frequencies ranges above 27.5 GHz will be required. Depending on propagation scenarios, if NLOS radio paths are foreseen as required an upper limit of 90GHz may be considered.

5.3.4 TC 4: Stadium

Test case summary. The situation assumed in this TC is an event in a stadium with a lot of people interested to high quality video contents vision and exchange (think about, i.e., a football match or other sports events like Olympic games or Formula 1 races or more generally events that gather a lot of people in a confined area). In such cases the coverage of the stadium is obtained thanks to a low power node network that can be deployed in an easy and fast way. All the nodes are connected via fibre or wireless high bandwidth links. Thanks to advanced baseband algorithms the network is able to control the interference (also with the existing and already deployed macro layer) and optimize the system capacity.

Reliability is of value here, but main objective is to get high capacity per area. Therefore, if reliable spectrum would not be available, less reliability could be tolerated in order to get more capacity.

Spectrum access: Depending on the specific test case realization, both licensed and unlicensed bands need to be considered. Any additional spectrum that could be made available would help.

Exclusive access and co-primary sharing are interesting, but might not be enough. Due to the nature of the events, the availability of the spectrum can be of fixed-time period. And hence ASA/LSA based spectrum usage can be quite promising. However here it would be problematic, if one would need to evacuate the spectrum during an event.

Bandwidth and frequency range aspects. Capacity is an essential requirement and therefore wide spectrum availability is needed. Continuous bandwidth would be valuable, but in order to get more capacity that could be compromised within the limits of what the technology can support. Due to the importance of capacity, high frequencies are likely going to be needed, allowing also better options for continuous high bandwidths.

For this scenario the preferred frequency bands are:

- IMT and/or IMT-A frequencies (700 MHz – 5 GHz) for guaranteed coverage with 20 - 100 MHz tentative bandwidth
- 9.9-10.6 GHz (belonging to band X) and/or 27.5 - 29.5 (belonging to band K_a) may also be feasible in small cells
- The use of millimetre waves, which present a number of relevant possible bands as 40.5 – 42.5 GHz; 47.2 – 50.2 GHz; etc. as analysed in section 2) will enable highly resolved spatial multiplexing and large bandwidth for high capacity
- Also unlicensed bands could be used for traffic offloading, since it is foreseen that corresponding RATs will be supported by most of the user equipment.

5.3.5 TC 5: Tele-protection in smart grid network

Test case summary. A smart energy distribution grid system aims at improving the efficiency of energy distribution but also enabling prompt reactions to unforeseen events as for example blackout.

Therefore, real-time information is critical. Maximum latency shall be in the order of a few milliseconds.

Spectrum access. Suitable spectrum authorization options need to have a permanent availability in order to match real-time requirements. Options are thus:

- Individual authorization (Licensed spectrum),
  - Exclusive access,
  - Co-primary Shared Access,
- Licensed Shared Access.

Bandwidth and frequency range aspects. Expectations for traffic volume is low, therefore,

- the assigned bandwidth could be narrow (few MHz),
- multiband access could be justified, but not so central.

Preferred frequencies are:

- IMT (450 MHz-6 GHz).

5.3.6 TC 6: Traffic jam

Test case summary. This test case is focused on the communication needs of humans and vehicles when they are unexpectedly stuck in a traffic jam. Such incidents could increase the traffic volume required in an area where this (i.e. the traffic volume) would typically be much lower.

The popularity of communication devices such as smart phones and tablet PCs is expected to increase the demands for video services. In order to provide an adequate QoS, it is important that the video quality is maintained without any interruptions or important quality degradation regardless of the number of users. The main challenge in this scenario is to deliver such services efficiently at affordable costs for the network operators. Traffic jams are prone to occur in rural areas or in the access roads to major urban centres. In the former, the provision of high data rate services is quite challenging due to the sparse network infrastructure deployed by mobile network operators, whereas in the latter, the sudden increase in the demand for radio resources can saturate the existent network infrastructure and compromise the provision of services to the users in the surrounding area.

Spectrum access. Users should enjoy seamless consumption of video services regardless the number of users. This requirement implies that reliability is of interest in this test case. However, the very high demands for capacity (i.e. 20 Gbps per km^2/4Mbps per vehicle in a 10-

lane highroad) indicate that even cases with unreliable spectrum access (i.e. unlicensed) should not be excluded if this is the only way to meet the capacity requirements.

On the other hand crowd communication scenario TCs have stringent requirements for either delay or link throughput, or both. Such requirements dictate the development of flexible spectrum access methods in order to meet the tight performance requirements. So, mixture of individual authorization and general authorization options could be applied in this test case. Though, based on the fact that traffic jams tend to occur at specific places (e.g. motorway construction sites, highway roads that join cities etc.) and on specific time periods (e.g. rush hour) LSA could be very promising scheme for this test case compared to other authorization schemes (i.e. unlicensed spectrum access) which might not be adequate.

Bandwidth and frequency range aspects. The following considerations should be taken into account:

- Preferred bands are:
  - Lower IMT bands (450 MHz – 2 GHz), in urban areas also 2- 6 GHz
  - ISM frequency bands (2.4 GHz, 5 GHz) in urban areas
  - Additional high frequency bands are needed for traffic offloading but, depending on the area to be covered, a large number of access points could be needed. The 9.9 – 10.6 GHz band or the 27.5 – 29.5 GHz band are the high frequency bands studied in Section 2 offering considerable bandwidth in the lower frequencies. Additional spectrum is available at higher frequencies, but its usage could lead to very small coverage areas and therefore deployment CAPEX and OPEX increase.
- Assigned bandwidth needs to be wide. Accordingly with the previous frequency bands discussion 700 MHz could be identified in the 10 GHz frequency band and 2 GHz can be identified in the 28 GHz band.

Capacity is the fundamental requirement of this test case. In addition, coverage is not an issue. Thus, getting more capacity could be achieved in low frequencies (the ones listed above) with exploiting radio resource management techniques to obtain non-contiguous bandwidth, or by obtaining (larger) resource blocks that could possibly be available at higher frequencies.

5.3.7 TC 7: Blind spots

Test case summary. Provision of universal high speed wireless access, will require the enhancement of coverage in currently blind or almost blind spots, as may be in some distant rural areas and deeply shadowed urban areas. These scenarios are characterized by a high probability of vehicles presence in the neighbouring of “blind areas” requiring better coverage.

Spectrum access considerations. Since the target is to increase the coverage in “blind spots”, the coverage will be provided by short range access points in the neighbour of the UE (nearby vehicles on-boarded relays would be a typical solution) and therefore no specific restriction for spectrum access is foreseen, it could be the MNO assigned spectrum (FDD/TDD) or more easily unlicensed spectrum commonly usable by regular UEs (as Wi-Fi). If backhaul from the short range access point to the network is also provided by radio an individual authorization scheme will be needed, it could be using the MNO spectrum (classical relay approach), but also a LSA mechanism could be used with QoS guarantee, unloading the valuable MNO assigned spectrum.

Bandwidth and frequency range aspects. Depending on the number of UEs simultaneously served by the short range access point (and the availability of high spectrum efficiency technologies), the absolute value of the required bandwidth will reach from 50 up to 100 MHz, which initially could be found below 6 GHz in MNO assigned bandwidth or unlicensed spectrum.

If the short radio access point, used for coverage increase in the blind spot, uses also a radio link for backhaul, the same amount of 50 – 100 MHz will be needed, and in order to use them as part of MNO assigned band, highly space efficient advance antenna (as beam-forming) technology is required, or alternatively LSA bands above 6GHz could also be used.

5.3.8 TC 8: Real-time remote computing for mobile terminals

Test case summary. Cloud computing technology enables the terminals to shift complex processing tasks to remote servers, behaving the terminal itself only as user interface. Beyond 2020 the usage of this technology will be expand to many high mobility environment, as public transport, cars, etc., requiring reliable robust and extremely low latency mobile communications for devices at up to 350km/h. In order to meet the QoS demand for these scenarios a direct UE radio link with MNO access point is not seen appropriate, since technologies as advanced antenna systems need to be used to provide appropriate coverage inside the vehicle. Therefore, a two radio hops approach is foreseen: one hop from MNO to vehicle roof mounted communication system and another on from it to the final UE.

Spectrum access. The UE devices in this scenarios are served by on-board vehicle communication equipment, thus in a controlled environment in which the unlicensed spectrum could be used, avoiding usage of MNO assigned bandwidth and therefore the interference that signal spill over form the vehicle could produce. The vehicle to MNO radio link will need to be based on an individual authorization scheme, as using MNO spectrum or LSA with QoS guarantee. Anyhow since around 60 Gbps/km^2 are foreseen to be needed [13], the MNO assigned spectrum is not foreseen to meet this requirement even if high spectrum and special efficiency systems are provided by means of innovative antenna systems.

Bandwidth and frequency range aspects. The bandwidth requirement for this test case is extremely high. Even If an inter-site distance of 200 m and with an average spectral efficiency of 2bits/s/Hz is considered, in order to obtain the targeted 60 Gbps/km^2 more than 200 MHz will be required, and if a more realistic 400 m inter-site distance is used a 1GHz bandwidth will be required. These requirement could be lowered if advance beam forming technology is available for high speed vehicles.

If an average value of 500 MHz is targeted, frequencies for the backhaul link could be found below or around 10 GHz. This spectrum is suitable for mobile services with real-time constraints. For example, 5925 – 6425 MHz could be an option. Higher frequencies could be used for in vehicle communication unlicensed spectrum.

5.3.9 TC 9: Open air festivals

Test case summary. The situation is an outdoor music festival where an average of 100.000 users generates a traffic volume of 900 Gbps/km^2. In the same area, several other devices co-exist, e.g., sensors, cameras etc., which offer specific services that require good coverage and reliable communication.

Spectrum access. Reliability, both in space and time, is a prerequisite for the communication between headquarters, guards, medics, surveillance cameras, and a wide range of sensors. The best authorization option for this type of communication is dedicated licensing or alternatively the LSA approach.

The data services that concern visitors have lower reliability requirements and thus a combination of a licensed, an LSA and an unlicensed approach can be used. Unlicensed access to spectrum could prove useful to boost user's bitrates and to serve cell edge users.

Bandwidth and frequency range aspects. The main challenge for the open air festival test case is the traffic volume requirement of 900 Gbps/km^2 due to the high user density. Moreover, this test case can mainly be realized with the use of wireless backhaul links. To achieve such an extreme capacity requirement it is needed to move to millimetre-wave frequency bands which offer wide portions of bandwidth.

Moreover, it is anticipated that a significant part of the crowd generated traffic will be consumed within the same crowd. For that reason, device-to-device (D2D) communication, underlying the cellular network, could be used to reduce the traffic load on the fixed infrastructure and increase the total throughput in the festival area. To further increase the spectral efficiency, a non-orthogonal sharing between D2D and cellular users might be preferable.

Security communication within the festival area needs extended range guaranties and thus lower frequency ranges should be used. Higher data traffic (multimedia content) can be transmitted by the channels established by small cell access points (SAPs). In this case millimetre-wave frequencies are expected to be needed for the communication between SAPs and UEs as well as between SAPs and the central macro-BS.

The assigned bandwidth needs to be wide to support the high area capacity requirement of 900 Gbps/km^2.

Similarly to TC4 the most appropriate test bands for this test case are:

- IMT and/or IMT-A frequencies (700 MHz – 5 GHz) for guarantee coverage with 20 - 100 MHz tentative bandwidth
- 9.9-10.6 GHz (belonging to band X) and/or 27.5 - 29.5 (belonging to band K_a) may also be feasible in small cells
- The use of millimetre waves, which present a number of relevant possible bands as 40.5 – 42.5 GHz ; 47.2 – 50.2 GHz; etc as analysed in section 2) will enable highly resolved spatial multiplexing and large bandwidth for high capacity
- Also ISM band could be used for traffic offloading, since it is foreseen that this RAT will be present in most of the user equipment.

5.3.10 TC 10: Emergency communications

Test case summary. In cases of large disasters, it can be assumed that public networks and many other communication systems are not available anymore. A fast reestablishment of mobile communication based on a prioritization and need-to-have basis will be based on car-mounted multi-hop or even mesh networking, use of high altitude platforms or satellites.

Spectrum access. High priority users will be those needing help and having only access to their cell phones with limited remaining battery capacity. Therefore, a prioritised spectrum access for these users is needed.

Bandwidth and frequency range aspects. Spectrum with good propagation conditions (lower frequency bands) providing larger coverage will be beneficial. The spectrum used by mobile phones of missed people must be supported as well.

The required data rates will be small (voice) to medium (video), i.e., less than 10 Mbps. The number of users will be restricted and can be controlled based on national disaster prioritization plans.

Overall spectrum demand is not expected to be a problem since the operating infrastructure density will be low.

Therefore, the spectrum requirements are:

- UHF spectrum provides a good compromise between availability of technology, phones, and spectrum (given the tendency that UHF might – at least to some extend - become available for IMT services) and good propagation conditions.

- Legacy public mobile network spectrum must be monitored in order to serve those needing help.
- Broadcast spectrum will be used to serve the public with information, i.e., the terrestrial broadcast networks will be re-established if affected at all.
- PPDR systems will be prepared to cover these cases.
- METIS might integrate options to use sub 1 GHz spectrum allocated to public mobile networks for setting up a multi-hop or mesh infrastructure. Licences will not be required if national disaster legislation covers this case.

5.3.11 TC 11: Massive deployment of sensors and actuators

Test case summary. Towards 2020, many objects will be able to communicate and interact wirelessly. Some of these devices will provide information about the surrounding of the users. They could be sensors measuring a certain phenomenon, or tags providing information about the presence of certain objects of interest. Based on information harvested from surrounding sensors, tags, and other sources, the UE could provide the users with contextual information so as to help the users to better understand and enjoy their environment. The real world and the virtual world will become increasingly connected, as the human users will be provided with augmented reality services.

Possible applications are monitoring of materials, structures and critical components, such as buildings, wind mills, high-speed trains and applications connected to agriculture. Further, portable objects may be equipped with tiny tags for the purpose of tracking the location of the objects or monitoring the usage or environment of these objects. Reliability is not so critical for the communication related to the sensors.

Spectrum access. To allow for low cost operation, the use of unlicensed bands, e.g. ISM bands, TVWS bands etc. is more likely than the use of exclusively licensed bands. Bands with licensed shared access and co-primary access are also options.

Only in cases where the tags need to be able to issue an alert which has to be received at reasonably low latency (e.g. within a few seconds), reliable licensed spectrum would be the preferred option. In general, spectrum sharing is very beneficial. On the one hand, the spectrum cost can be reduced. On the other hand, since the data traffic is relatively low per node, mutual protection can be achieved more easily. Furthermore, a certain collision rate is tolerable, since the sensor information contains certain redundancy and thus, it may be sufficient if only a certain percentage of the sensor data reaches the gateway/base station correctly.

Bandwidth and frequency range aspects. This test case requires low power and low cost transmission. To allow low transmission power and low cost of electronics, use of medium frequency ranges are favourable, as: IMT (450 MHz - 6 GHz) and ISM (2.45, 5.25 GHz), depending on propagation scenario (rural, urban, indoor). Frequency ranges might need to include higher frequencies for urban areas and dense usage. Also due to low transmission rate needs, and low impact of latency only small bandwidth access is required. The needed bandwidth is eventually influenced by the high number of devices involved.

5.3.12 TC 12: Traffic efficiency and safety

Test case summary. This test case addresses the requirements for road safety and traffic efficiency. Two types of information exchange are considered: vehicle to vehicle (V2V), and vehicle to vulnerable road user (V2VRU).

V2V communication for traffic safety mainly consists of periodic and event driven broadcasting of warning message at a rate of 5-10 Hz. These messages contain information about the vehicle’s position and velocity. The payload of each message is around 500 bytes but may increase in the future. The communication range varies from 300m in urban areas to 1km in highway scenarios, while the node density is up to 1000 per km^2 in urban areas and 100 per km^2 in rural/highway scenarios.

V2VRU communication is required for early detection of vulnerable road users by their consumer equipment (CE). Up to 5000 devices per km^2 in urban scenarios with a periodic multicast of 300 bytes with 5-10 Hz plus an event-triggered traffic of up to 500 devices per km^2 and the same update frequency have to be carried. Rural scenarios show significantly lower activity.

Spectrum access. The major challenges of this test case are the high mobility of vehicles and the strict latency/reliability requirement. The high relative velocity between vehicles results in complex propagation environments. The requirement of less than 10ms latency with an Availability Indicator (basically indicating coverage) of 99.999%, which is extremely challenging and can only be satisfied by a system with high availability and sufficient spectrum. The state-of-art technology for V2V and V2VRU communications is based on the IEEE802.11p standard. Roadside base stations (as already foreseen in 802.11p) will be required to guarantee the high levels of availability and low latency. However, 802.11p is missing reliable congestion avoidance capabilities. It can also not be expected that all vulnerable UEs can be localized with .11p radio modems (that their CE might not be equipped with).

Given that a wide variety of devices need to communicate, probably Bluetooth, WLAN, 802.11p and cellular will be integrated and coordinated on a METIS level. This will distribute the mobile data volume on various systems and reduce the traffic volume challenge. The latency requirements will however become significant and the main bottleneck.

As a life-critical service, V2V and V2VRU communication requires reliable spectrum access; therefore exclusive licensing in Europe would be preferred. Furthermore, the high mobility of vehicles and the requirement of ubiquitous spatial availability also make the reuse of other licensed spectrum on an LSA basis difficult. If non-exclusive spectrum access is to be considered in this test case, contiguous spatial availability must be guaranteed in the whole of Europe.

Bandwidth and frequency range aspects. Currently, spectrum for intelligent transport system (ITS) is allocated between 5850-5925 MHz in the US. In Europe, there is currently 30 MHz of spectrum allocated between 5875-5905 MHz, and it will be potentially expanded to 70 MHz. However, in both of the standards for traffic safety and efficiency (DSRC in the US and ITS-G5 in Europe), only 10 MHz bandwidth is dedicated to the road safety application as described above. In scenarios with high density of VRU and vehicle, 10 MHz may not be sufficient to meet the reliability requirement in all location and time. Additional spectrum in lower frequency ranges (<6 GHz, or even <1 GHz) would be needed, as the NLOS link coverage is of crucial importance in scenarios like intersections.

6 Summary

In general, the availability and usage options for spectrum are fundamental for the implementation of any radio technology. This document explains and analyses the expected spectrum scenarios addressed in METIS.

In order to make explore the potential of additional spectrum the following challenges are addressed in METIS:

- Analysis of new bands, in particular by extending the spectrum range for mobile communications to yet rarely used higher frequency bands,
- Development of new spectrum sharing concepts that help to improve spectrum usage efficiency,
- Provision of enablers for the efficient use of the new METIS radio concepts that guarantee coexistence and interference management, and
- Design of an overall spectrum management concept.

The first two of these topics are addressed in this deliverable. The remaining topics and refined results on the first topics will be described in upcoming deliverables.

Following the approach outlined above, this deliverable combines a requirement based top-down design with a technology driven bottom-up approach.

In a bottom-up process, spectrum bands are explored and potential bands for future mobile communications use are analyzed. An analysis of spectrum access schemes and authorization regimes is provided, allowing to open up new spectrum usage options and to increase the overall spectrum efficiency. Implementation aspects resulting from these new spectrum authorization regimes are discussed in detail. A "Spectrum Sharing Tool Box" is introduced that provides a framework for the efficient implementation of the defined sharing concepts.

In a top-down process, the scenarios and test cases defined in METIS deliverable D1.1 are reviewed from a spectrum need and usage point of view. Linking the test cases to the METIS radio access concepts and horizontal topics that are most promising for their implementation allows a first mapping of the test case specific spectrum needs onto new and existing spectrum options, in particular those that might become available under new spectrum sharing regimes.

The analysis clearly highlights the importance of making new spectrum usage options available. Without these new options many of the upcoming applications depending on wireless connectivity cannot be implemented. Using higher frequencies more extensively is an attractive option but will not solve all problems. Efficient spectrum sharing concepts, e.g., implemented using a Spectrum Sharing Tool Box as presented here, might help to activate additional spectrum resources in many bands.

The analysis also indicates that not only more spectrum and more efficient spectrum usage concepts are required but that the broader range of application requirements will also result in new challenges on spectrum engineering with respect to guaranteeing co-existence, compatibility, and coverage. The implementation of the new METIS radio concepts, in particular, the METIS Horizontal Topics, that are mandatory for supporting the envisaged new application domains and for providing the required efficiency gains will critically depend on how these spectrum engineering challenges are addressed.

All results presented in this deliverable are initial and preliminary. Future deliverables will provide more detailed results and a quantitative analysis of the mapping between the top-down requirements and the bottom-up technical options developed in METIS.

7 References

[1] Marcus, M., Pattan, B., "Millimeterwave propagation; spectrum management implications," *Microwave Magazine, IEEE* , vol.6, no.2, pp.54,62, June 2005

[2] Wells, J., "Multigigabit wireless technology at 70 GHz, 80 GHz and 90 GHz", http://blog.quintarelli.it/files/multigigabit-wireless-technology-at-70-ghz-80-ghz-and-90-ghz.pdf

[3] Wells, J., "Faster than fiber: The future of multi-G/s wireless," *Microwave Magazine, IEEE* , vol.10, no.3, pp.104,112, May 2009

[4] http://www.aviatnetworks.com/products/all-packet-microwave/e-link-1000q/

[5] http://www.bridgewave.com/products/80Ghz.cfm

[6] http://www.airepointe.com/607080ghzwirelessbridge.html

[7] http://www.lightpointe.com/607080ghzradio.html

[8] http://www.ceragon.com/newproduct.asp?ID=50

[9] http://www.fwasolutions.com/products_gigabeam.html

[10] ECC Report 173: Fixed Service in Europe - Current use and future trends post 2011

[11] ECC Recommendation (05)07: Radio Frequency Channel Arrangements for Fixed Service Systems Operating in the Bands 71-76 GHz and 81-86 GHz

[12] ECC Report 124: Coexistence Between Fixed Service Operating in 71-76 / 81-86 GHz and the Passive Services

[13] "Scenarios, requirements and KPIs for 5G mobile and wireless system" Document Number: ICT-317669-METIS/D1.1

[14] ECC Report 132: LIGHT LICENSING, LICENCE-EXEMPT AND COMMONS, June 2009

[15] "Authorised Shared Access – an evolutionary spectrum authorization scheme for sustainable economic growth and consumer benefit", Qualcomm presentation at WG FM 17th May 2011, Miesbach, Germany, http://www.archive .ero.dk.

[16] Europe's Information Society - Thematic Portal on Shared Spectrum Access: http://ec.europa.eu/information_society/policy/ecomm/radio_spectrum/sectorial/shared_use/index_en.htmhttp://ec.europa.eu/information_society/policy/ecomm/radio_spectrum/sectorial/shared_use/index_en.htm

[17] Mikael Fallgren and Bogdan Timus (editors), "Future radio access scenarios, requirements and KPIs," METIS deliverable D1.1, March 2013.

[18] Marianna Goldhammer, "802.16h Main Concepts," presentation, doc.: IEEE 802.19-05/0051r0. 2005-11-15.

[19] Buchwald, G. J., et al, "The Design and Operation of the IEEE 802.22.1 Disabling Beacon for the Protection of TV Whitespace Incumbents," in Proc. IEEE DySPAN 2008, Chicago, IL, Oct 14-17 2008.

[20] CEPT Electronic Communications Committee, "Technical and operational requirements for the possible operation of Cognitive Radio Systems in the 'White Space' of the frequency band 470-790 MHz," ECC Report 159, Cardiff, January 2011.

[21] US Federal Communications Commission, "Third report and order and memorandum opinion and order, in the matter of unlicensed operation in the TV broadcast bands," Technical report, 12-36, April 2012.

[22] J. Huang, R. Berry, and M. Honig, "Auction-based Spectrum Sharing," ACM/Springer Journal of Mobile Networks and Applications (MONET) special issue on WiOpt'04, vol. 11, no. 3, pp. 405-418, June 2006.

[23] http://www.efis.dk/views2/search-general.jsp

[24] ERC/REC 12-11. Radio frequency channel arrangement for fixed service systems operating in the band 51.4-52.6 GHz. Luxembourg, 1999.

[25] http://en.wikipedia.org/wiki/Advanced_Extremely_High_Frequency

[26] http://www.infineon.com/cms/en/corporate/press/news/releases/2012/INFPMM201210-001.html

[27] "Modeling of Indoor Wave Propagation Models from 1 G Hz to 10 G Hz" Othman , A. R, and Hamidon, A. H and Wasli , C and Mustaffa , M. F and Ting, J. T. H (2010): 4th International Symposium On Broadband Communication. ISBC 2010, 11 July 2010, Melaka.

[28] http://en.wikipedia.org/wiki/Radar_gun

[29] ITU Radio Regulations: Article 5, Frequency allocations

[30] ERC Report 25: The European Table of Frequency Allocations and Applications in the frequency range 8.3 kHz to 3000 GHz (ECA Table)

[31] CEPT, "Reviesed ECR Recommendation 25-10. FREQUENCY RANGES FOR THE USE OF TEMPORARY TERRESTRIAL AUDIO AND VIDEO SAP/SAB LINKS (INCL. ENG/OB)." Available online: http://www.arcep.fr/fileadmin/reprise/dossiers/frequences/ERC-REC-25-10E.pdf

[32] CEPT, "CEPT/ERC/RECOMMENDATION 12-10. "HARMONISED RADIO FREQUENCY ARRANGEMENTS FOR DIGITAL SYSTEMS OPERATING IN THE BAND 48.5 GHz - 50.2 GHz." Available online: http://www.erodocdb.dk/docs/doc98/official/Pdf/Rec1210e.PDF

[33] CEPT, "ERC RECOMMENDATION 12-12 (Luxembourg 1999, revised 2001). RADIO FREQUENCY CHANNEL ARRANGEMENT FOR FIXED SERVICE SYSTEMS OPERATING IN THE BAND 55.78 – 57.0 GHz." Available online: http://www.erodocdb.dk/docs/doc98/official/Pdf/Rec1212e.pdf

[34] CEPT ECC, "ECC REPORT 114. COMPATIBILITY STUDIES BETWEEN MULTIPLE GIGABIT WIRELESS SYSTEMS IN FREQUENCY RANGE 57-66 GHz AND OTHER SERVICES AND SYSTEMS (EXCEPT ITS IN 63-64 GHz)." Available online: http://www.erodocdb.dk/docs/doc98/official/pdf/ECCRep114.pdf

ANNEX I **Propagation characteristics for millimetre waves**

Millimetre waves (MMW) or millimetre band is the portion of radio spectrum between 30 GHz-300 GHz (10mm-1mm). Apart from the free space loss, MMW are susceptible to additional loss factors such as:

a) **Atmospheric Gaseous Losses**: The H_2O and O_2 resonances have been studied extensively for purposes of predicting millimetre propagation characteristics. In ANNEX II an expanded plot of the atmospheric absorption versus frequency at altitudes of 4 km and sea level, for water content of 1 gr/m^3 and 7.5 gr/m^3, respectively, is shown.

b) **Rain Losses**: MMW propagation is also affected by rain. Raindrops are roughly the same size as the radio wavelengths and, therefore, cause scattering of the radio signal. The attenuation per kilometre as a function of rain rate is shown in ANNEX II. An increase in the rain factor reduces the communications signal availability. For example, for an availability of 99.99%, the outage is 8.8 hr/year or 1.44min on a 24-hr basis.

c) **Foliage losses**: Foliage losses at millimetre-wave frequencies are significant. In fact, foliage loss may be limiting propagation impairment in some cases. An empirical relationship has been developed (CCIR Rpt 236-2), which can predict the loss. For the case where the foliage depth is less than 400m, the loss is given in dB by the following formula:

$$L = 0.2 f^{0.3} R^{0.6}$$

where f is the frequency in MHz, and R is the depth of foliage transversed in meters. The relationship applies for R<400mand 200MHz< f <95GHz.

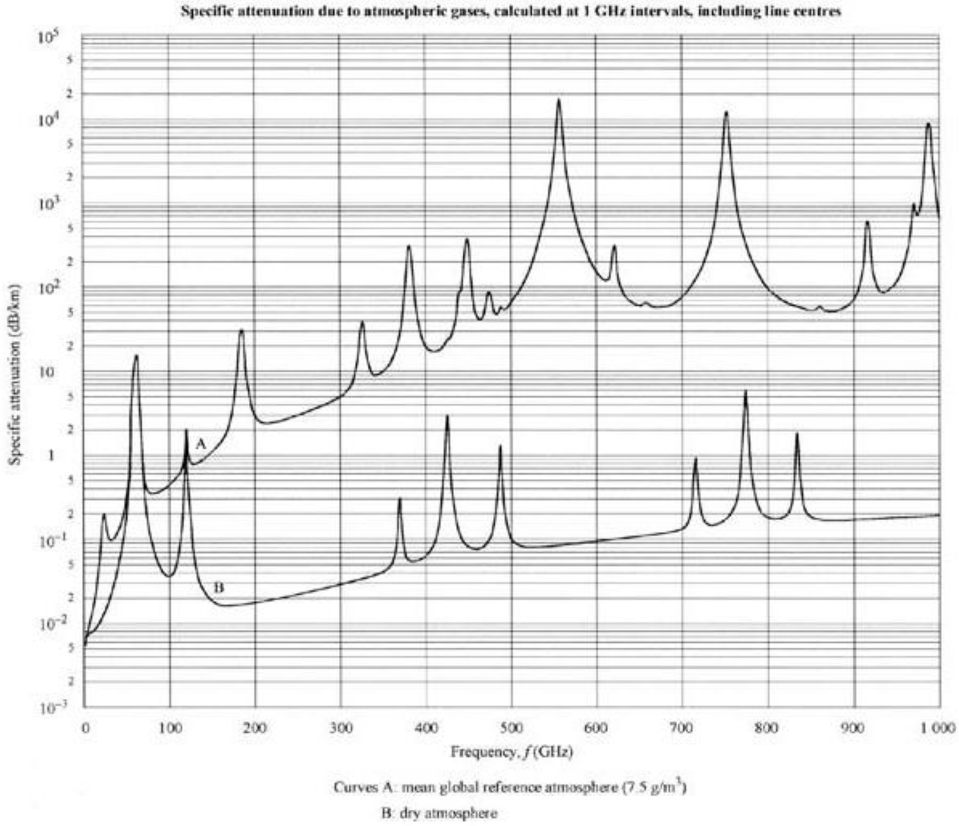
d) **Scattering/Diffraction**: If there is no LOS path between the transmitter and the receiver, the signal may still reach the receiver via reflections from objects in proximity to the receiver or via diffraction or bending. The short wavelengths of millimetre-wave signals result in low diffraction. Like light waves, the signals are subject more to shadowing and reflection. (Shadowing makes it easier to shield against unwanted signals in communications systems).

Normally, for non-LOS paths, the greatest contribution at the receiver is reflected power. Reflections and the associated amount of signal diffusion are strongly dependent on the reflectivity of the reflecting material. Shorter wavelengths (higher frequencies) cause the reflecting material to appear relatively “rougher,” which results in greater diffusion of the signal and less specular (i.e., direct) reflection. Diffusion provides less power at the receiver than specular reflected power.

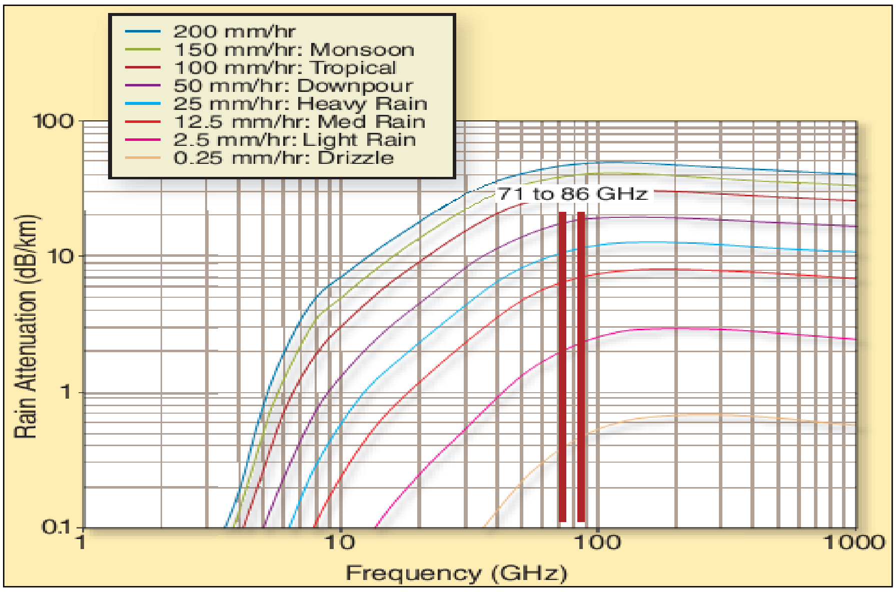
ANNEX II **Examples of propagation characteristics**

Propagation characteristics play key parameter in the spectrum selection process. Some basic propagation characteristics for the spectrum range considered in this report are collected in this section.

Propagation characteristics (ITU-R P.675-5)



Rain attenuation at microwave and millimetre-wave frequencies according to [2]



ANNEX III **Additional information on the band 71-275 GHz**

As discussed in Section 2, the frequency range above 95 GHz does currently not have the highest priority for METIS. Nevertheless, some demonstration and even commercial applications of relevance for METIS are already using this frequency range. The following tables collect some information on characteristics of these bands. In order to provide a comprehensive overview, the considered frequency range is extended and covers selected frequency bands above 70 GHz.

Comparison of high data rate transmission technologies according to [3]

	70/80 GHz	**Fiber Optics**	**Microwave Radio (6-40 GHz)**	**60 GHz**	**Free Space Optics**
Typical Data Rates	1Gbps (up to 10Gbps)	Virtually Unlimited	400Mbps	1Gbps	1Gbps (up to 10 and 40 Gbps)
Typical link distances (99.999% availability)	3km	Virtually Unlimited	5 km	400m	200m
Relative system complexity	Low	Low	High	Low	Medium
Relative cost of ownership	Medium	High	Medium	Low or Medium	Low or Medium
License, install and commission time	Hours or Days	Years	Weeks or months	Hours or days	Hours or Days
Guaranteed interference and regulatory protection	Yes	Yes	Yes	No	No
Spectrum availability and licensing	Available worldwide, usually as a low-cost, rapidly available light license(see also [10], [11], [12])	n/a	Usually available for the area licensing from country regulator	Available for unlicensed use in Europe and USA	Spectrum freely available as technology not regulated

Results of coexistence studies in ECC report 124 [12].

Active Service	Passive service	Conclusion
FS in the band 81-86 GHz	EESS in the band 86-92 GHz	For the FS operating in the band 81-86 GHz, an unwanted emission mask in the band 86 – 89 GHz is proposed starting with -41 dBW/100MHz at 86 GHz and decaying to -55 dBW/100MHz at 87 GHz (see [12], section 3.4).
FS in the band 81-86 GHz	RAS in the band 81-86 GHz	Any FS station should not be in LoS from the RA station.
FS in the band 71-76 GHz	RAS in the band 76-77.5 GHz	A separation distance between the RAS station and the FS station should be considered depending on the FS station orientation. This separation distance should be determined on a case-by-case basis by national Administrations.
FS in the band 81-86 GHz	RAS in the bands 79-81 and 86-92 GHz	
FS: Fixed Service, EESS: Earth Exploration Satellite Service, RAS: Radio Astronomy Service, LoS: Line of Sight		

Astronomical usage in the band 71-238 GHz

Table 1.8-1: Important Astronomical Uses of the 71 – 238 GHz Bands[11, 12]		
Scientific Topic	*Common Molecular Probes*	*Frequencies (GHz)*
Star formation, mass loss from young proto-stars, protostellar disks	CO, HCN, HCO^+, N_2H^+, CS, H_2CO, HC_3N, CH_3OH, CH_3CN, SO_2	115, 230, 88,[13] 89,[14] 93, 96, 144, 234, 72, 142, 218, 72, 91,100, 109, 136, 145, 154 , multiple lines for CH_3OH, CH_3CN, SO_2
Galactic structure, molecular clouds	CO, H_2CO, HCO^+, HCN	115, 230, 72, 141, 89, 88[15]
External galaxies, molecules at high red shift	CO, HCN, HCO^+, CH_3OH	115, 230, 88[16], 89,[17] multiple lines for CH_3OH
Evolved stars, planetary nebulae	CO, HCN, HCO^+, SiS, SiO, SiC_2, CCH, C_4H, HC_5N, SO_2, HC_3N	115, 230, 88,[18] 89, 73, 91, 109, 142, 87, 174, multiple for C_4H through HC_3N
Diffuse clouds	CO, HCN, HCO^+, SO, CN, CCH, C_3H_2	115, 88, 89, 100, 113, 87, 88
Comets, planetary atmospheres	HCN, HCO^+, CS, H_2CO	88,[19] 89,[20] 96, 144, 234, 144, 218
Astrochemistry	Numerous molecules	
Interstellar masers	SiO, H_2O, CH_3OH, HCN	86, 130, 217, 107, etc
Isotope ratios	CO, HCN, CN, H_2CO, MgNC, NaCl	113/115, 88/86, 110/113, multiple for CH_3OH, MgNC, NaCl
Astrobiology	PO, CP, PN, H_2CO, all organics	109, 152, 174, 95, 97, 143, 238, 97, 140, 234, 71, 142, 218, various