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Deliverable D2.1

Requirement analysis and design approaches for 5G air interface

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Editor(s):	Eeva Lähetkangas (Nokia Siemens Networks), Hao Lin (France Telecom – Orange)
Author(s):	Petar Popovski, Cedomir Stefanovic, Hiroyuki Yomo, Nuno Pratas (Aalborg University), Frank Schaich, André Santos, Volker Braun (Alcatel-Lucent Bell Labs), David Gozalvez-Serrano (BMW Forschung und Technik GmbH), Erik Ström, Tommy Svensson, Wanlu Sun (Chalmers University of Technology), Petra Weitkemper, Anass Benjebbour, Yuuya Saito, Yoshihisa Kishiyama (DOCOMO), Ning He (Ericsson AB), Hao Lin, Isabelle Siaud, Pierre Siohan (France Telecom – Orange), Malte Schellmann, Zhao Zhao, Martin Schubert (Huawei ERC), Eeva Lähetkangas, Jaakko Vihriälä, Kari Pajukoski (Nokia Siemens Networks), Gerd Ascheid, Stefan Heinen, Arun Ashok, Aamir Ishaque, Volker Luecken (RWTH Aachen University), Armin Dekorsy, Carsten Bockelmann (University of Bremen), Fabian Quint (University of Kaiserslautern), Nandana Rajatheva, Pekka Pirinen (University of Oulu), Amer Baghdadi, Frederic Guilloud (Institut Mines-Télécom - Télécom Bretagne)
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Abstract:

This document describes the problem space for the METIS research conducted in the radio link context. Firstly, a requirement analysis for the air interface design is conducted based on the test case descriptions presented in METIS deliverable D1.1. It follows an introduction of the research topics being pursued in the radio link research together with an illustration of how these topics are addressing the derived requirements. Moreover, it is shown which of those requirements address the needs of the METIS horizontal topics. To facilitate the achievement of these three objectives, a framework of General Requirements is introduced, which will be used throughout the project to assess and evaluate developed radio link solutions and to allow for measuring against the overall system performance goals.

Keywords:

air interface, availability, coding, cost, coverage, dense deployment, energy efficiency, fading, faster than Nyquist, filter-bank multicarrier, flexibility, full-duplex, general requirement metric, latency, link adaptation, machine-to-machine, medium access control, mobility, modulation, multiple access, non-orthogonal multiple access, orthogonal frequency division multiple access, overhead, power-domain multiplexing, radio resource management, reliability, research topic, signalling, spectrum efficiency, time division duplexing, waveform

Executive summary

In this document, the problem space for the METIS research conducted in the radio link context is described. Within this scope, the document addresses three main objectives:

1. Translation of challenges and requirements from the test case descriptions presented in METIS deliverable D1.1 to the radio link context.
2. Description of the research topics being pursued towards 5G air interface, together with an illustration which of the above requirements are addressed therein.
3. Description on how the research topics further connect to the METIS horizontal topics.

As a means to facilitate achieving these objectives in a consistent and self-contained way, a mapping approach is developed, which uses the instruments of so called *General Requirement Metrics* (GRMs) and *General Requirement Tags* (GRTs): While GRMs represent quantifiable measures that will be used to evaluate and compare different radio link solutions addressing similar targets, GRTs represent non-quantifiable aspects that are of high relevance to be considered in the radio link research. As the names imply, all the translated GRMs/GRTs are presented in a symbolic way without involving any numerical values.

Concerning the first objective, the higher layer requirements relevant for the radio link context are extracted from the test case descriptions in D1.1 and are broken down to seven GRMs and five GRTs. These GRMs/GRTs are then categorized according to the seven KPIs introduced in deliverable D1.1, while giving appropriate explanations for each of the assignments.

Concerning the second objective, an introduction into the fourteen research topics defined for the radio link research is presented, which are used to refine the three main research directions identified by the three tasks of this WP:

1. Flexible air interface design
2. Waveforms, coding & modulation and transceiver design;
3. Multiple-access, MAC & RRM.

The research topics have been defined such that they cover at least two contributing partners, ensuring to obtain and later compare different solutions to similar problems. The large variety of topics cover a broad range of approaches towards new solutions, spanning conventional (OFDM-like) and novel waveforms, PHY, MAC and cross-layer design as well as several aspects of flexibility. For each of those research topics, a general description of the particular research problem is given, restricted research assumptions (if applicable) are stated and the particular issues to be investigated are sketched. Furthermore, the GRMs/GRTs relevant for that research topic are listed and short explanations on their relevance are given.

Concerning the third objective, the GRM/GRT mapping approach is utilized to link the radio link requirements to the METIS horizontal topics, which is based on a brief requirement analysis for each of the horizontal topics. At the end of the document, an overview on the radio link research topics addressing the needs of the horizontal topics is presented.

Contents

List of Tables

List of Abbreviations, Acronyms and Definitions

3GPP	Third Generation Partnership Project
ACK	Acknowledgement
AI	Air Interface
AMC	Adaptive Modulation and Coding
AP	Access Point
ARQ	Automatic Repeat reQuest
AV	Availability
BB	Baseband
BS	Base Station
CAPEX	Capital expenditures
CDF	Cumulative Distribution Function
CFR	Carrier Frequency Range
CONN	Connection
COV	Coverage
CP	Cyclic Prefix
CP-OFDM	Cyclic-Prefix Orthogonal Frequency Division Multiplexing
CS	Compressed Sensing
D2D	Device-to-Device
DD	Dense Deployment
DL	Downlink
E2E	End-to-End
ECON-AU	Energy Consumption per area unit
ECON-B	Energy consumption per bit
ENHET	Enabler for network heterogeneity
FAIR	Fairness
FBMC	Filter-Bank Multi-Carrier
FDD	Frequency Division Duplex
FMT	Filtered Multi-Tone
FTN	Faster Than Nyquist
GGMA	GRM/GRT Mapping Approach
GRM	General Requirement Metric
GRT	General Requirement Tag
HARQ	Hybrid ARQ
HT	Horizontal Topic
HW	Hardware
IF	Intermediate Frequency
IIP3	3rd Order Intercept Point
IM	Interface Management
INTG	Integrity
KPI	Key Performance Indicator
LA	Local Area
LAT	Latency
LTE	Long Term Evolution
LTE-A	LTE Advanced
MA	Multiple Access
MAC	Medium Access Control
MAX	Maximum
MC-CDMA	Multi-Carrier CDMA
MIMO	Multiple Input Multiple Output
MIN	Minimum
ML	Maximum Likelihood
MMC	Massive Machine Communication

mmW	millimetre Wave
MN	Moving Networks
MODCOD	Modulation & coding
MTC	Machine Type Communication
MU	Multi User
MUD	Multi-User Detection
NACK	Negative ACK
NDSU	New Dynamic Spectrum Usage
NOMA	Non-Orthogonal Multiple Access
NSN	Number of Supported Nodes
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational expenditure
OQAM	Offset QAM
PA	Power Amplifier
PAPR	Peak-to-Average Power Ratio
P/E-CON	Power/Energy Consumption
PER	Packet Error Rate
PHY	Physical
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RASSR	Random Access Schemes Success Rate
RASE	Random Access Schemes Efficiency
REL	Reliability
RF	Radio Frequency
RL	Radio Link
RRM	Radio Resource Management
RT	Research Topic
RTT	Round Trip Time
SBW	Supported bandwidth
SCMA	Sparse Code Multiple Access
SE	Spectral Efficiency
SIC	Successive Interference Cancellation
SIG	Signaling
SoTA	State of The Art
TC	Test Case
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TP	Throughput
TRX	Transceiver
TTI	Transmission Time Interval
TX	Transmitter
UDN	Ultra Dense Network
UE	User Equipment
UL	Uplink
URC	Ultra-Reliable Communication
V2V	Vehicle-to-Vehicle
WF	Waveform
WP	Work Package

1 Introduction

This deliverable provides an overview on the requirements for 5G air interface (AI), where the air interface is defined to contain both Layer 1 (L1), i.e. physical (PHY), and some parts of the Layer 2 (L2), i.e. Medium Access Control (MAC) and Radio Resource Management (RRM). Moreover, the document defines the research topics pursued towards 5G air interface solutions and illustrates how the aforementioned requirements are addressed by these. Thus, a basic framework is established which serves as a guideline for the detailed research activities conducted within the three tasks of the radio link (RL) research:

- T2.1: Flexible Air Interface Design
- T2.2: Waveforms, Coding & Modulation and Transceiver Design
- T2.3: Multiple Access, MAC and RRM

1.1 Objective and scope of the document

Scope of D2.1:

D2.1 focuses on the radio link problem space: It describes the problems to be solved from the radio link perspective while establishing a direct relation to the test cases (TCs) defined by the leading work package (WP) of METIS project, i.e. WP1: Scenarios, Requirements and Key Performance Indicators, as well as to the METIS horizontal topics (HTs) [OBT+13]. The main purpose of D2.1 is therefore the translation of the problem formulation and requirement definition from D1.1 [MET13-D11] to the radio link context and connecting it to the envisaged radio link research, according to the high level research activity description.

Objectives of D2.1:

D2.1 aims to achieve the following three main objectives related to the METIS air interface:

Objective 1: Translate requirements from the end user and operator level to the radio link context.

Objective 2: Describe research topics and provide a clear mapping how they will address the above requirements.

Objective 3: Illustrate how research topics may further be connected to METIS horizontal topics.

1.2 Achieving D2.1 objectives via a mapping approach

In D1.1, twelve test cases have been defined to cover and illustrate the main challenges to be addressed in the METIS project. They are defined from an end user and operator perspective without restricting the solution space. From the radio link perspective it is not straightforward to derive corresponding link layer challenges as many other external aspects may impact the possible solution: The requirements concerning air interface may highly depend on several aspects investigated in other WPs during the METIS project, such as scenario and test case specific propagation models, antenna configurations, etc. Thus, defining the exact requirements for future air interface, especially paired with numerical values, becomes evidently difficult in the early phase of METIS project.

To solve this issue, a GRM/GRT mapping approach (GGMA) is developed. In this approach, General Requirement Metrics (GRMs) and General Requirement Tags (GRTs) are defined for the radio link research.

- A GRM is a quantitatively measureable metric that could be used to measure and compare different AI specific solutions developed within the radio link research.
- A GRT, on the other hand, is a non-measurable design feature that supplements the GRMs.

With this approach, a mapping between the end user and operator requirements and the corresponding requirements from radio link perspective can be established. Furthermore, this approach facilitates linking the Research Topics (RTs) pursued on radio link level to those requirements as well as to the METIS horizontal topics. GRMs/GRTs are identified to be MAC related requirements, so that their relationship to higher layer requirements, Key Performance Indicators (KPIs) and the METIS HTs can be easily described.

The implementation of GGMA contains three mapping steps for addressing D2.1 objectives:

- **KPI and GRM/GRT mapping to achieve objective 1**: map the end user and operator requirements to GRMs/GRTs.
    - Preliminary descriptions of the relationships between the requirements coming from the METIS test cases and GRMs/GRTs defined for the radio link research are provided. The mapping of requirements with quantitative values is excluded at this early stage of the project, to avoid limiting the flexibility in the research on new solution approaches.
- **RT and GRM/GRT mapping to achieve objective 2**: map the research topics to their corresponding GRMs/GRTs.
    - A short introductory description is given for each of the research topics pursued on radio link level, covering the main opportunities, challenges and targets. This mapping indicates that a certain research topic aims to improve the mapped GRMs/GRTs, together with a reasoning why it will address these specific GRMs/GRTs.
- **HT and GRM/GRT mapping to achieve objective 3**: map the GRMs/GRTs to METIS horizontal topics.
    - For each of the five METIS horizontal topics the main requirements have been identified, which are translated to the radio link related aspects by using the defined GRMs/GRTs. Together with the mapping achieved under objective 2, this allows for obtaining first hints on the potential radio link enablers for each of the horizontal topics.

Figure 1.1 gives a clear view of the GGMA framework ,addressing the three above introduced D2.1 objectives. Furthermore, the section number indicates where in this document the mapping steps are implemented.

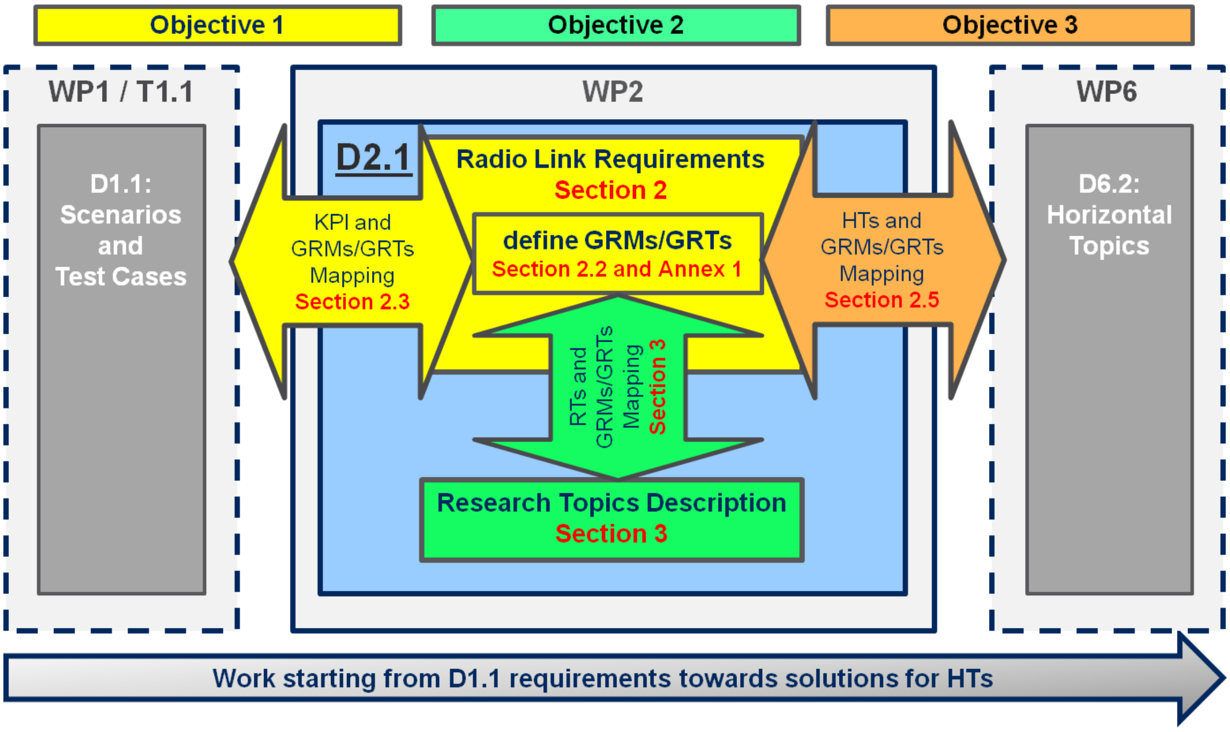

Figure 1.1: GGMA implementation addressing D2.1 objectives.

1.3 Structure of the document

The rest of the document is organised as follows:

- Section 2 shows how the first and third D2.1 objectives are addressed.
- Section 3 addresses the second D2.1 objective: Introducing research topics and providing a clear mapping how they will address the defined GRMs/GRTs.
- Section 4 gives a summary of the work done in D2.1.

In addition, this document has Annexes. Annex 1 contains the exhaustive version of the table presented in section 2.1, summarizing the detailed requirements from the test cases. Annex 2, provides more detailed descriptions of the GRMs/GRTs presented in section 2.2.

2 5G air interface requirements

In this section the requirements for METIS air interface envisioned in 5G mobile and wireless systems are described. In Section 2.1, the most relevant and challenging air interface related KPIs extracted from the test case descriptions in D1.1 are listed. Afterwards, in Section 2.2, the specific requirements for the radio link perspective in terms of General Requirement Metrics and Tags (GRMs and GRTs) are defined, which are then connected to above KPIs paired with appropriate reasoning in Section 2.3. A mapping between the defined GRMs/GRTs and METIS horizontal topics is provided in Section 2.4. Finally, the defined 5G air interface requirements are summarized in form of a KPI and GRM/GRT mapping table in Section 2.5.

2.1 Test cases and KPIs

There are twelve test cases identified in D1.1 [MET13-D11], which are all considered in the scope of the radio link research. According to the description in [MET13-D11], the requirements of each test case are described from an end user and operator perspective. In order to quantify these higher layer requirements, a list of KPIs defined in D1.1 is summarized in the following:

- **KPI1: Traffic volume density**
- **KPI2: Experienced user throughput**
- **KPI3: Latency**
- **KPI4: Reliability**
- **KPI5: Availability and retainability**
- **KPI6: Energy consumption**
- **KPI7: Cost**.

For the radio link perspective, each of these KPIs can be understood as a main category of requirements where a particular radio link specific requirement could be assigned to. The KPIs thus span the global space of performance metrics relevant for the radio link research. However, the above list of KPIs lacks an important aspect particularly relevant for future air interface design, which should be capable of supporting diverse future radio services while ensuring an efficient use of the available system resources. This is the requirement of flexibility and scalability, which is supposed to cover the following aspects:

1) An efficient and scalable system design supporting different cell types from macro to small cells;
2) A much wider frequency support, which covers both carrier frequency and bandwidth;
3) High spectral efficiency supporting more advanced dynamic spectrum usage schemes;
4) Cost-efficient and scalable solution supporting different communication types, e.g. human-type and machine-type.

To conveniently cover these considerations, flexibility and scalability is added as an additional KPI to the above list:

- **KPI8: Flexibility and scalability.**

For each of the twelve test cases defined in D1.1 [MET13-D11], the requirements with respect to the above KPIs that are most relevant for the radio link perspective and the air interface design have been collected in Table 2.1. While this table represents a compact version focusing on the most relevant requirements only, an exhaustive list covering all test case specific requirements can be found in Annex 1.

Table 2.1: Main KPIs / requirements in the test cases extracted from [MET13-D11]

Test case	KPI	Requirement
TC1: Virtual reality office	I. Traffic volume density	average 100 [Mbps/m^2], peak 500 [Mbps/m^2], downlink (DL) and uplink (UL), Corresponds to 100 [Tbps/km^2]/500 [Tbps/km^2] average user density = 0.1 [UEs/m^2]
	II. Experienced user throughput	1 [Gbps], UL and DL (with 95% availability) average throughput = 0.5 [Gbps], DL and UL
	III. Latency	10 [ms] (MAC) round trip time (RTT) at maximum (required by TCP/IP).
TC2: Dense urban information society	I. Traffic volume density	700 [Gbps/km^2] DL and UL; Max 0.2 [UEs/m^2]
	II. Experienced user throughput	300 [Mbps] for DL and 60 [Mbps] for UL (with 95% availability)
TC3: Shopping mall	I. Traffic volume density	170 [Gbps/km^2] in DL and 67 [Gbps/km^2] in UL; Users: 0.1 per [m^2]; Sensors: 0.7 per [m^2]
	II. Experienced user throughput	300 [Mbps] in DL and 60 [Mbps] in UL
	IV. Reliability	95% of time 99.9% of time for safety related sensors
	V. Availability and retainability	95% in space 99% in space for safety related sensors
TC4: Stadium	I. Traffic volume density Traffic volume per area User/device density	 0.1-10 [Mbps/m^2] = 0.1-10 [Tbps/km^2] 0.4-1 per [m^2]
	II. Experienced user throughput	0.3-20 [Mbps] DL and UL
TC5: Teleprotection in smart grid network	III. Latency	8 [ms] one trip time for event triggered message
	IV. Reliability	99.999% in time
TC6: Traffic jam	I. Traffic volume density	480 [Gbps/ km^2]; Average 4000 per [km^2]; Max 0.2 per [m^2] on the lane in traffic jam
	II. Experienced user throughput	100 [Mbps] in DL and 20 [Mbps] in UL
TC7: Blind spots	II. Experienced user throughput	100 [Mbps] in DL and 20 [Mbps] in UL
	VI. Energy consumption	30% reduction (infrastructure); 50% reduction for UE.
TC8: Real-time remote computing for mobile terminals	II. Experienced user throughput	100 [Mbps] in DL and 20 [Mbps] in UL
	III. Latency	< 10 [ms] End-to-End (E2E)
	IV. Reliability (Channel & mobility)	In car/bus/train; Up to 350 [km/h]
TC9: Open air festival	I. Traffic volume density	900 [Gbps/km^2] DL and UL; user/device density (Av. 0.1 per [m^2], Max 4 per [m^2])
	II. Experienced user throughput	30 [Mbps] UL and DL

Test case	KPI	Requirement
TC10: Emergency communications	IV. Reliability	Infrastructure setup < 10 [s]; Call setup < 1 [s]
	V. Availability and retainability	99,9% discovery rate
TC11: Massive deployment of sensors and actuators	V. Availability and retainability	99,9%
	VI. Energy consumption	0.015 [µJ/bit] for a data rate in the order of 1 [kbps] UEs / devices: Low-energy operation required, battery power supply (with long battery life)
	VII. Cost	Sensors should be very low cost
TC12: Traffic efficiency and safety	III. Latency	5 [ms]
	IV. Reliability (Channel & mobility)	99,999% (Outdoor; Up to 500 [km/h])

2.2 5G air interface general requirement definitions

The requirements concerning future air interface are highly dependent on several aspects investigated in other work packages (WPs) in the METIS project, such as scenario and test case specific propagation models, antenna configurations, spectrum, deployment solutions, etc. This is illustrated in Figure 2.1, where we point out the decisive input needed from other WPs to identify the exact quantitative requirements for the future air interface. Thus, in the early phase of METIS project, the requirements are defined in a general manner, i.e. in the form of general metrics by implementing the GRM/GRT mapping approach and neglecting any quantitative specifications for the moment.

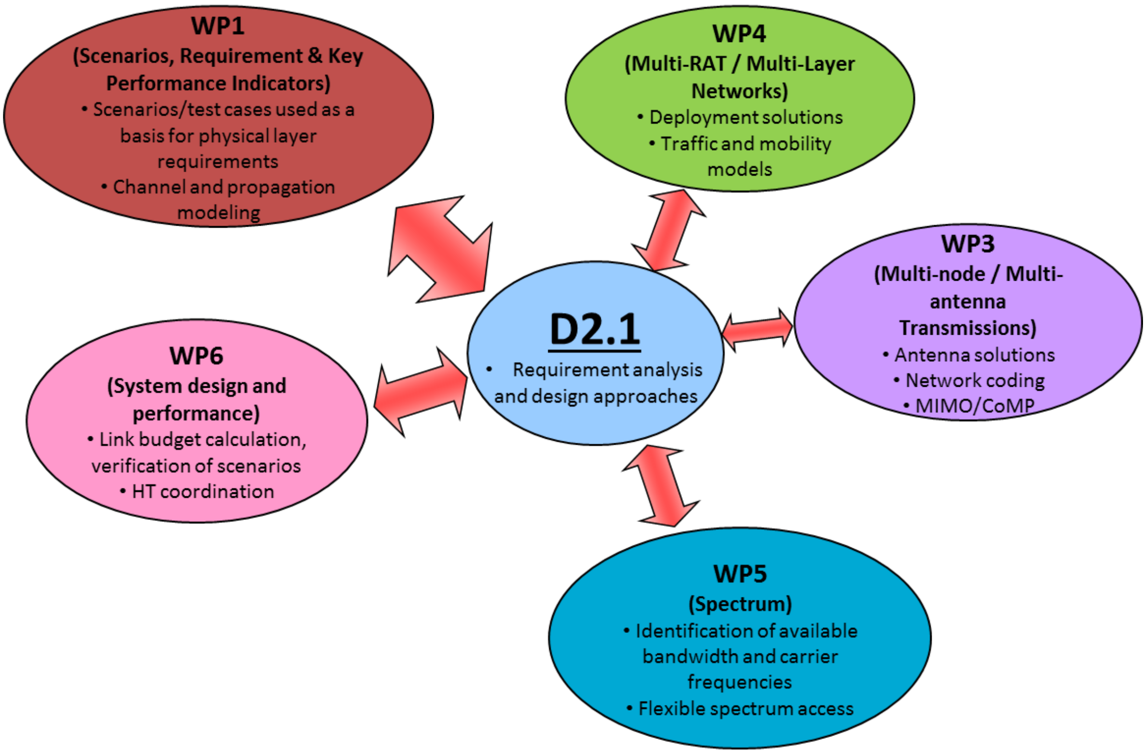

Figure 2.1: Relationship between D2.1 and METIS WPs.

The GRM/GRT mapping approach, which is used to translate requirements from end user and operator perspective to the technical requirements relevant for the radio link research, was described in Section 1.2. In the following, we define

- Generic Requirement Metrics (GRMs), used to measure and compare different air interface specific solutions developed towards future air interface;
- General Requirement Tags (GRTs), other non-measurable design features that need to be considered in the radio link design process in addition to GRMs.

In this section short descriptions of the GRMs/GRTs defined for the radio link research are provided. The defined GRMs/GRTs are further grouped into categories matching the higher layer KPIs introduced in Section 2.2, which is done in Section 2.3. More detailed descriptions for each GRM/GRT can be found in Annex 2.

2.2.1 GRM definitions

In the following, seven GRMs defined from the MAC layer point of view are presented. Note that since GRMs represent quantifiable metrics, they are scalable by their definition.

GRM1: Multi-user/cell throughput (MU/C-TP) and MAC spectral efficiency (MAC-SE)

The MU/C-TP is measured in bits/s/(user group or cell) and it is defined as the time-averaged aggregate throughput of a set of users or users in a given area, such as under a certain cell[1], respectively.

The MAC-SE describes the relation of MU/C-TP to the bandwidth in a given area, such as under a certain cell.

GRM2: Max supported number of connections (MAX#-CONN), Random access schemes success rate (RASSR) and Random access schemes efficiency (RASE)

The MAX#-CONN covers two definitions:

- It measures the maximum supported number of connected user equipments (UEs)/devices, where a connection can be defined by accounting for a certain minimal quality parameters (e. g. if the connection is active then what is the minimal throughput). Here the connection means either device to access point/cell or Device-To-Device (D2D). but the control link for all such connections are centralized by network.
- It measures the maximum number of D2D connections per device, which are independent of network.

The RASSR and RASE are used to measure the success rate and the efficiency of the random access schemes.

GRM3: Fairness (MAC-FAIR) and Availability (MAC-AV)

The MAC-FAIR is used to describe the distribution of the user throughput, which is different from the sum cell throughput.

The MAC-AV is defined as the percentage of users for which a certain quality of service (QoS) requirement is met.

GRM4: MAC latency (MAC-LAT)

Achieved throughput is meaningful only if packets can be delivered within a certain time frame. The MAC-LAT is defined as the time elapsed between the following two occasions: 1) the transmitter MAC receives a packet from its upper layer; 2) the receiver MAC delivers the packet to its upper layer.

A packet that, for some reason, is never delivered is called a dropped packet. Dropped packets are considered to have infinite delay. Furthermore, note that if the MAC (or layers below it) uses retransmission schemes, the retransmission delays are, by definition, included in MAC-LAT.

[1] Cell throughput is a special case of a throughput defined for users in a given area.

GRM5: MAC-packet error rate, reliability and integrity (MAC-PER/REL/INTG)
The MAC-PER is the probability that a packet that is received by the transmitter MAC from its upper layer, is not delivered to the receiver MAC upper layer.

The MAC-REL is defined as the probability that a packet that is received by the transmitter MAC by its upper layer, is delivered by the receiver MAC to its upper layer error-free and with MAC latency, GRM4, below a certain defined deadline.

The MAC-INTG is the probability that a packet that is delivered from the receiver MAC to its upper layer and whose MAC latency, GRM4, is below a certain deadline, is error-free.

Together with GRM4, GRM5 may be understood to cover QoS requirements of METIS air interface. Both these GRMs also capture the effect of mobility scaling, as both GRMs are expected to degrade when mobility increases, given that the same solution is applied without modification.

GRM6: MAC coverage (MAC-COV)
The MAC-COV is the relative volume of a region (one, two, or three-dimensional) in which the MAC reliability, GRM5, exceeds a certain outage threshold.

GRM7: Energy consumption per bit / area unit (ECON-B/AU)
The ECON-B is used to measure the energy consumption efficiency, which is defined as the overall consumed energy over a given time interval, normalized by the total number of info bits that have been correctly delivered over the same time interval. The consumed energy is impacted by signal processing (digital and radio frequency (RF) parts) and protocol design, for instance, power management, etc. Similarly, ECON-AU denotes the overall consumed energy normalized by the MAC-COV area.

2.2.2 GRT definitions

In addition to the GRMs, five GRTs that capture other important aspects to be considered in the radio link research are defined.

GRT1: Modem hardware cost (COST-HW)
The COST-HW concerning device types such as access nodes, terminals, relay nodes, Machine-Type-Communication (MTC) devices etc. can be defined as the cost for the production of a single modem. Mainly depending on the required baseband (BB)[2] and radio frequency hardware cost, the modem cost can increase or decrease based on the communication system design. On top of baseband and radio frequency hardware, also other parts of a modem can be included, like peripherals and cooling devices.

GRT2: Carrier frequency range (CFR)
The spectrum bands to be used for future wireless systems are not fixed yet and are possibly even extended after rollout. The range of possible frequency bands is expected to be very high, from 380 MHz up to 3000 GHz [MET13-D51]. The solutions investigated towards future air interface should take into account this wide range of carrier frequencies. A solution may either be fully flexible (no limitations) or contain some restrictions with certain minimum and maximum supported carrier frequency (f_{c_min}, f_{c_max}). In case air interface solutions are designed especially for a certain frequency range, the coordination with other air interface

[2] According to [3GPP12036888], baseband cost is the most remarkable factor in the modem cost.

solutions targeted for other frequency ranges should be considered (different air interface solutions could eventually be used for different carrier frequencies).

GRT3: Supported bandwidth (SBW)
To enable a truly dynamic spectrum usage and sharing, it is necessary to avoid specifying any fixed allocation of a certain frequency bandwidth. It is expected that the system bandwidth of next generation mobile system will be significantly increased when compared with the current systems, and it may even be extended further after rollout. Similar as the flexibility in terms of carrier frequency, also the supported bandwidth should be kept flexible. Furthermore, the scalability with respect to the bandwidth should be indicated.

GRT4: Number of supported nodes (NSN)
This measure is closely related to GRM2, but here the focus is on the scalability with respect to the number of nodes. Some schemes do not simply scale with the number of users like multiuser diversity schemes and certain multiple access schemes, which may lead to inefficient use of resources if a massive amount of devices needs to be simultaneously served. Thus, the scalability should always be taken into consideration for future solution design.

GRT5: Enabler for network heterogeneity (ENHET)
This GRT includes two-fold requirement: on one hand, future air interface solutions are expected to be cost and performance efficient, supporting a wide range of cell sizes, going from macro size to small size. On the other hand, it is envisioned for future air interface to provide solutions for enabling diverse network links, like in-band wireless backhauling, radio access and D2D, covering both coordinated or non-coordinated network nodes.

2.3 KPIs translated to radio link context

As briefly explained above, GRMs and GRTs, which represent the requirements specific for the radio link research, can be categorized according to the seven plus one higher layer KPIs introduced in D1.1 and detailed in section 2.1. This way, a direct translation of the KPIs used globally in the METIS project to the particular measures used in the radio link context can be obtained. The categorization of GRMs and GRTs will be carried out in the following subsections for each of the eight KPIs. It should be noted that this categorization does not represent a one-by-one mapping between the two measures, since a single KPIs may cover several GRMs/GRTs, and a single GRM/GRT may even be assigned to several KPIs. Since the relationship between GRMs/GRTs and KPIs is not always evident, appropriate reasoning and interrelations are indicated.

2.3.1 KPI1: Traffic volume density

The test cases impose different capacity requirements, such as traffic density or volume (bits/s/m^2) including user density (number of users/m^2) requirements related further with certain user data requirements. Physical and MAC layers need to be designed so that they can support different and variable amount of users and devices with different average and peak aggregated throughput requirements for certain area.

Table 2.2: GRMs/GRTs related to KPI1

GRM/GRT	Reasoning
GRM1: MU/C-TP & MAC-SE Multi-user/Cell Throughput and MAC spectral efficiency	For a given network density, the supported traffic volume density directly depends on the MU/C-TP. For a given system bandwidth and network density, the supported traffic volume density directly depends on the MAC-SE.
GRM2: MAX#-CONN Max supported number of connections	Increasing MAX#-CONN directly enables higher user density requirements.
GRT2: CRF Carrier frequency range	Flexibility in terms of carrier frequency allows the system to switch transmission bands according to traffic demand and current load conditions, which may increase the total traffic volume density.
GRT3: SBW Supported bandwidth	Scalability with respect to bandwidth allows the system to provide a service even in crowded or fragmented spectrum, enabling higher throughput and traffic volume density.
GRT4: NSN Number of supported nodes	Flexibility in terms of NSN would enable the usage of the same solution for very different scenarios, like hot spot with few heavy users characterized by high traffic volume density, and also sensor networks with low data rate but high density.
GRT5: ENHET Enabler for network heterogeneity	If a solution is flexible and scalable in terms of ENHET, it can be used to cover scenarios with high traffic volume density occurring in small cells, but also scenarios with low user throughput.

2.3.2 KPI2: Experienced user throughput

The test cases impose different user data rate (bits/s/user) requirements, related also to certain reliability and availability values. Physical and MAC layers need to be designed so that they can support different and variable user throughput requirements with certain average and peak values.

Table 2.3: GRMs/GRTs related to KPI2

GRM/GRT	Reasoning
GRM1: MU/C-TP & MAC-SE Multi-user/Cell Throughput and MAC spectral efficiency	The experienced user throughput depends on the MAC-SE. Depending on the fairness, the experienced user throughput depends also on the MU/C-TP.
GRM2: MAX#-CONN / RASSR / RASE Max supported number of connections, Random access schemes success rate and Random access scheme efficiency	If not all users can be served due to limitations of MAX#-CONN, their experienced user throughput is 0. Also RASSR and RASE are related to experienced user throughput of random access based traffic.
GRM3: MAC-FAIR / MAC-AV MAC fairness and MAC availability	MAC-FAIR describes the distribution of the experienced user throughput, e.g. in a certain area. The MAC-AV is the percentage of users with a certain QoS which typically includes the experienced user throughput.
GRM4: MAC-LAT MAC latency	Latency affects directly the end user throughput. Low latency is required for e.g. gigabit transmission control protocol (TCP) transmissions.
GRM5: MAC-PER/REL/INTG MAC packet error rate, reliability and integrity	User experienced throughput is conditioned by a certain quality of service, further depending on MAC reliability. More reliable and lossless MAC is required e.g. for gigabit TCP transmissions.
GRM6: MAC-COV MAC coverage	MAC-COV relates to the probability for a certain experienced user throughput depending on the location of the user.
GRM7: ECON-B/AU Energy consumption per bit/area unit	If total energy is limited, high ECON-B decreases the experienced user throughput.
GRT2: CRF Carrier frequency range	Flexibility in terms of carrier frequency allows a user terminal to switch transmission bands according to its traffic demand and current load conditions, which may increase the total throughput.
GRT3: SBW Supported bandwidth	Scalability with respect to bandwidth allows the user terminal to establish a service even in crowded or fragmented spectrum, enabling higher user throughput.

2.3.3 KPI3: Latency

Latency requirements of different services vary remarkably according to service and application type. MAC and PHY latencies are just a fraction of the end-to-end latency targets and the related requirements are dependent on higher layer solutions, e.g. deployment solutions, etc.

Table 2.4: GRMs/GRTs related to KPI3

GRM/GRT	Reasoning
GRM2: MAX#-CONN Max supported number of connections	In case a user cannot be served because of exceeding the MAX#CONN, the latency will be infinity for this user.
GRM4: MAC-LAT MAC latency	MAC latency (MAC-LAT) is an integral part of end-user latency

2.3.4 KPI4: Reliability

In the context of air interface, reliability refers to the robustness of the communication link at the physical and MAC layers against the uncertainties of the communication channel, transceiver imperfections, collisions and device discovery errors, etc.

Table 2.5: GRMs/GRTs related to KPI4

GRM/GRT	Reasoning
GRM2: MAX#-CONN / RASSR / RASE Max supported number of connections (MAX#-CONN), Random access schemes success rate and Random access schemes efficiency	If MAX#CONN is exceeded, a new user entering the system cannot be served, driving its delay to infinity. Reliability thus cannot be achieved for this user. The reliability of random access based traffic is affected by RASSR and RASE.
GRM4: MAC-LAT MAC latency	MAC-LAT is an important parameter in the reliability definition, which has a direct influence on this KPI.
GRM5: MAC-PER/REL/INTG MAC packet error rate, reliability and integrity	The three sub-metrics cover different aspects in terms of reliability, i.e. MAC-PER evaluates part of the transmission performance, without latency involvement; MAC-INTG indicates the MAC error detector capability; MAC-REL has a more general definition, which indicates a complete PHY and MAC reliability evaluation.

2.3.5 KPI5: Availability and retainability

The availability reflects two aspects [MET13-D11]: 1) the probability that the measured service reliability for a user is guaranteed at an acceptable level, below which the service is deemed as unavailable; 2) the percentage of the uses or communication links for which the service reliability is guaranteed at an acceptable level within a certain area. The retainability reflects the probability that one service can always have guaranteed reliability within the service session, as long as it is made available.

Table 2.6: GRMs/GRTs related to KPI5

GRM/GRT	Reasoning
GRM2: MAX#-CONN / RASSR / RASE Max supported number of connections, Random access schemes success rate and Random access schemes efficiency	Availability can only be ensured if MAX#-CONN is larger than the users requesting a connection. The availability and retainability of random access based traffic is affected by RASSR and RASE.
GRM3: MAC-FAIR / MAC-AV MAC fairness and MAC availability	Depending on the measure for the fairness (e.g. throughput or weighted throughput), MAC-FAIR is related especially to availability and retainability taking also QoE requirements into account. MAC-AV represents the measure for availability on MAC level.
GRM5: MAC-PER/REL/INTG MAC packet error rate, reliability and integrity	As the definition hints, the availability and retainability are highly decided by the reliability.
GRM6: MAC-COV MAC coverage	Since MAC-COV directly depends on the relative occurrence of outage inside a certain area, it is closely related to availability and retainability.
GRM7: ECON-B/AU Energy consumption per bit/area unit	If total energy is limited, ECON-AU influences the availability and retainability.
GRT2: CFR Carrier frequency range	Flexibility in terms of carrier frequency may help to define a class of highly available/retainable connections, since it increases the number of available options to set up a connection.
GRT3: SBW Supported bandwidth	Flexibility in terms of amount of used bandwidth (e.g. in different carrier frequencies, fragmented spectrum) increases the number of available options and thus may help to define a class of highly available/retainable connections.
GRT4: NSN Number of supported nodes	Solutions that scale with the number of users support high availability and retainability.
GRT5: ENHET Enabler for network heterogeneity	If a solution is flexible and scalable in terms of ENHET, it can be used to cover scenarios with high traffic volume density occurring in small cells, but also scenarios with low user throughput, allowing for large coverage and thus increasing the availability and retainability for a given area. Furthermore, this GRT takes into account specific properties of the different deployment solutions, which are tackled and developed in the METIS project, in order to achieve above KPIs

2.3.6 KPI6: Energy consumption

Power/energy consumption (P/E-CON) is an important factor for battery powered user devices or sensors affecting directly their operation time. Base stations have generally higher transmission powers than user terminals and therefore their improved energy efficiency has global impact in the reduction of greenhouse gasses emissions. Considering scenarios for the dense network and ubiquitous network, where the massive machine communication is a key application, the power consumption becomes an extremely important issue. Moreover, the evaluation of P/E-CON is also fairly important to compare different technologies and protocol design.

Table 2.7: GRMs/GRTs related to KPI6

GRM/GRT	Reasoning
GRM7: ECON-B/AU Energy consumption per bit/area unit	The ECON-B/AU is directly related to energy consumption.
GRT2: CFR Carrier frequency range	The choice of carrier frequency affects the total required energy consumption. Depending on the distance between user terminal and base station, either a higher or lower carrier frequency may be better suited. It may be beneficial from energy consumption point of view to have only one BB processing unit running even though several carrier frequencies are used in a system.
GRT3: SBW Supported bandwidth	Being able to flexibly scale the used bandwidth may allow optimized usage of power amplifiers, which may reduce the amount of total energy needed. It may be beneficial from energy consumption point of view to have only one BB processing unit running even though several bandwidth allocations are used by a system.

2.3.7 KPI7: Cost

The monetary cost of a network directly impacts the acceptance by operators in the market. In order to become a widely accepted solution and generate revenue for the operators, it has to compete with legacy and concurrent solutions. A cost in general covers the terminal cost and the network cost. The latter can further include deployment cost[3] and operational cost[4]. These costs are not totally independent but interconnected with a common factor, the so-called modem cost[5], which is mainly considered in D2.1. Energy consumption is also an aspect of operational cost since devices and access nodes should not consume large amounts of energy when not actively transmitting/receiving or serving a device.

Table 2.8: GRMs/GRTs related to KPI7

GRM/GRT	Reasoning
GRM1: MU/C-TP &MAC-SE Multi-user/Cell Throughput and MAC spectral efficiency	For a certain traffic load, the required spectrum depends on MAC-SE, possibly influencing the spectrum license cost. For a certain traffic volume density and assuming sufficient coverage of the access points (APs), the required number of AP depends on the maximum achievable MU/C-TP, influencing the capital expenditures (CAPEX) part of the cost.
GRM2: MAX#-CONN	With many supported connections less hardware may be required.
GRM6: MAC-COV MAC coverage	With high MAC coverage less hardware may be required.
GRM7: ECON-B/AU Energy consumption per bit/area unit	ECON-B and ECON-AU are directly related to energy consumption and consequently on the operational expenditures (OPEX) cost.
GRT1: COST-HW Modem hardware cost	The cost of components like COST-HW directly influences the CAPEX cost.
GRT2: CFR Carrier frequency range	If a technical solution can work on a large CFR, this enables CAPEX cost savings as the same baseband design can be reused at different carrier frequencies, further decreasing total baseband development costs. A system that is flexible in terms of CFR may also lead to lower spectrum licensing costs.
GRT3: SBW Supported bandwidth	If the supported bandwidth of a technical solution is flexible, this may enable CAPEX cost savings as the same baseband design can be reused for different bandwidths, further decreasing total baseband development costs.
GRT4: NSN Number of supported nodes	If the number of supported nodes increases and the solution is scalable, no additional infrastructure HW may be required.

[3] Deployment cost depends e.g. on number of nodes, cost per node, costs for site rent, costs for backhaul connection, modem cost and installation costs.
[4] Operational cost covers all costs that appear during operation, e.g. energy costs and maintenance costs.
[5] Modem cost has a direct impact on the terminal cost and deployment cost. Meanwhile modem cost is related with the energy consumption (GRM7), which has an impact on the operational cost.

2.3.8 KPI8: Flexibility and scalability

In order to provide feasible support of the diverse future radio services and to ensure an efficient use of the available system resources, METIS air interface needs to be flexible and scalable with respect to certain parameters. Under this KPI, the most important air interface related aspects in form of GRTs are listed for which flexibility and scalability needs to be considered. Note that no GRMs are listed here, since these represent quantifiable metrics and thus are scalable by definition.

The listed GRTs can be used as a tool to evaluate whether novel air interface solutions from the METIS project can address the flexibility and scalability requirement. Alternatively, these GRTs can also be used to set a design principle aiming for integrating diverse solutions into one holistic design, allowing to fully address all twelve TCs.

Table 2.9: GRMs/GRTs related to KPI8

GRT	Relation of this GRT to other KPIs
GRT2: CFR Carrier frequency range	These GRTs represent the most important (non-measurable) air interface related aspects for which flexibility needs to be considered in METIS air interface design.
GRT3: SBW Supported bandwidth	
GRT4: NSN Number of supported nodes	
GRT5: ENHET Enabler for network heterogeneity	

2.4 Summary of 5G air interface requirements

As a means to translate higher layer requirements to radio link context, a mapping approach called GGMA was developed. In this approach, the concept of GRM and GRT was used, representing either particular measures to evaluate and compare different air interface solutions or some important aspects to be considered in the radio link related research work. The GRMs/GRTs were defined at MAC level and their relationships with the higher layer requirements and KPIs were clearly described, which eventually allowed us to identify the radio link related requirements in a more specific and parameterized manner.

As a summary, Table 2.10 reports the most important outcome of the task for translating the higher layer requirements to the radio link context, which confirms the accomplishment of the first objective in this document.

Table 2.10: Mapping of KPIs and GRMs/GRTs

	KPI1: Traffic volume density	KPI2: Experienced user throughput	KPI3: Latency	KPI4: Reliability	KPI5: Availability and retainability	KPi6: Energy consumption	KPI7: Cost	KPI8: Flexibility and scalability
GRM1: MU/C-TP & MAC-SE	x	x					x	
GRM2: MAX#-CONN / RASSR / RASE	x	x	x	x	x		x	
GRM3: MAC-FAIR / MAC-AV		x			x			
GRM4: MAC-LAT		x	x	x				
GRM5: MAC-PER/REL/INGT		x		x	x			
GRM6: MAC-COV		x			x		x	
GRM7: ECON-B/AU		x			x	x	x	
GRT1: COST-HW							x	
GRT2: CFR	x	x			x	x	x	x
GRT3: SBW	x	x			x	x	x	x
GRT4: NSN	x				x		x	x
GRT5: ENHET	x				x			x

2.5 Linking air interface requirements to the METIS horizontal topics

The Horizontal Topics (HTs) play a vital role for the overall system design pursued in the METIS project. A brief introduction to these HTs was presented in [OBT+13]. A detailed analysis of each HT has been conducted by the corresponding Horizontal Topic Driver in the METIS project; the results are expected to be published in the METIS deliverable D6.2 later on in the project.

In the following, a brief summary of the main targets and requirements for the five HTs is presented, as they have been formulated in the Horizontal Topic Drivers' analysis.

Direct device-to-device (D2D)

- Increase coverage (availability and retainability)
- Provide fall-back solution (reliability)
- Offload backhaul, reduce transmit power by reducing link distance (cost efficiency)
- Increase spectrum usage and capacity per area (spectrum efficiency)
- Improve service quality by reducing radio link distance

Massive machine communication (MMC)

- Provide up- and downscaling connectivity (scalability)
- Low power consumption, low hardware and operational cost (cost efficiency)
- High availability and reliability without massive investments in infrastructure
- Low data rate; short packets require low signalling overhead
- Strict latency constraints, in particular for safety-critical applications

Moving networks (MN)

- Improve mobility management and connectivity of mobile terminals
- Increase coverage and capacity (availability and retainability)
- Guaranteed E2E latency and high reliability for safety-critical applications
- Enable flexible, dynamic and adaptive network deployment
- Low power consumption, low operational cost

Ultra-dense networks (UDN)

- Increase spectral efficiency
- Signalling overhead reduction
- Flexible use of spectrum including sharing, also for enabling flexible wireless backhaul
- Support of dense crowds of users whose access requests are dynamically changing in time.

Ultra-reliable communication (URC)

- Extreme requirements on availability and reliability: Low error probability and low outage rate
- Guaranteed E2E latency

In Table 2.11, a mapping between GRMs/GRTs as defined in Section 2.2 and the METIS HTs si provided. This mapping has been derived in a straightforward manner from the requirements defined for each of the HTs. Crosses indicate that a GRM addresses a requirement that has been explicitly mentioned for the corresponding HT (see the summary above), whereas for crosses in brackets, the high relevance of the GRM for the corresponding HT becomes evident from the overall context of the HT analysis. Together with mappings between GRMs/GRTs and the RTs in this WP, which are described in Section 3, this information can be used to obtain some first hints towards the question which RTs could be considered potential enablers for each of the five METIS HTs. Nevertheless, for completeness, at the end of Section 3.3 an additional table is provided which indicates the RTs that are expected to provide solutions that explicitly aim to address the HTs' needs.

It should be noted that none of the RTs is able to address all the requirements of one HT at the same time, and further that a single RT may address requirements of different HTs. This does not need to be seen a drawback though, since a solution for an HT may be composed of multiple RTs coming even from different WPs, where each of these RTs may address a different subset of the complete set of requirements defined for that HT.

Table 2.11: Mapping of GRMs/GRTs and METIS HTs

	GRM1: MU/C-TP & MAC-SE	GRM2: MAX#-CONN / RASSR / RASE	GRM3: MAC-FAIR/AV	GRM4: MAC-LAT	GRM5: MAC-PER/REL/INTG	GRM6: MAC-COV	GRM7: ECON-B/AU	GRT1: COST-HW	GRT2: CFR	GRT3: SBW	GRT4: NSN	GRT5: ENHET
Direct device-to-device	x	(x)		(x)	x	x	x	(x)	(x)			
Massive machine communication		x	x	x	x	x	x	x			x	
Moving Networks	x		x	x	x	x	x	x	(x)	(x)		(x)
Ultra-dense networks	x		(x)	(x)			(x)	(x)	x	x	x	(x)
Ultra-reliable communications			x	x	x	x			(x)			

Some notes on the mapping of GRT2-5 in Table 2.11:

- GRT2 and GRT3 are especially relevant for dynamic spectrum sharing. Hence, switching the carrier frequency (GRT2) is relevant for all HTs except MMC. Bandwidth adaptation (GRT3) depends on the mix of traffic types (i.e. narrow-band and broad-band), which is expected to be of high relevance particularly for MN and UDN.
- GRT4 relates to scenarios where the number of nodes may scale from a few to a very large number, as we encounter in MMC and UDN.
- GRT5 considers scalability aspects in HetNet scenarios. It will thus be important for MN an UDN.

3 Radio link related research topics

In this section, the research topics envisaged in this work package are briefly described without describing specific solutions or concrete algorithms beyond State of The Art (SoTA). Moreover, a mapping step between the research topics and GRM/GRTs is presented to achieve the second objective of D2.1. The details are given in Section 3.1 and the mapping table is reported in Table 3.15.

3.1 Main research topics

As presented in Section1, the research activities conducted within this work package are guided by three research tasks, which further define fourteen research topics. These topics cover PHY/MAC/RRM aspects and are described in Sections 3.2.1-3.2.14. The relationship between the research topics and the three research tasks can be given as follows

- T2.1: Flexible air interface includes first six research topics (Sections 3.1.1-3.1.6).
- T2.2: Waveforms, coding & modulation and transceiver design includes the next four research topics (Sections 3.1.7-3.1.10).
- T2.3: Multiple-access, MAC and RRM include the final four research topics (Sections 3.1.11-3.1.14).

For readers who want to immediately have a bird's view on the GRM/GRT that are addressed by each of these research topics, a mapping table is provided in Section 3.2.

For each research topic, the following aspects are described:

- General description: Short introductive description of the research topic with main opportunities and challenges.
- GRMs/GRTs related to this research topic: A list of GRMs/GRTs, for which the research topic aims for improvements. The mapping between fourteen research topics and the GRMs/GRTs is summarized also in Section 3.2.
- Restricted research assumptions: List of research assumptions taken for the research topic (if any), which may restrict the problem space further by considering a particular context only.
- Issues to be researched: Short explanation of the research items within this topic.

3.1.1 Air interface in dense deployment (AI-DD)

General description

The ambitious METIS goal of supporting more than thousand fold of traffic by 2020 can be met by increasing the number of cells. Densification of base stations (BSs) / access points (APs) is a classical means of providing increased capacity in wireless communication. This leads to a very dense small cell deployment and justifies METIS air interface scope especially on local area (LA) networks as one of the main focus areas. In ultra dense networks (UDNs) a given access node will often serve only a single or very few terminals at a time. The access node should not require much higher output powers than a terminal, i.e. transmit powers of access nodes and terminals become similar. One should therefore try to minimize the differences between UL and DL, in the extreme case one could even consider all nodes in a network as devices, and in this case there would be only links. Dense networks may be integrated under so called umbrella networks or clusters to ensure seamless coverage resulting in multi-layers of networks or clusters thus requiring AI support from PHY and MAC layers. To keep the total cost of deployment low in dense deployment scenarios, it is particularly important to have low modem costs, low installation costs and robust network with low maintenance demand.

A LA system can be deployed either in standalone or coordinated manner with APs capable to operate in both modes. In a coordinated wireless LA network, an access controller (centralized or distributed) communicates with the APs to provide scalable coordinated control across the wireless network.

In order to support increased typical user data rates it is desirable that as many of the dense APs as possible are provided with a high capacity backhaul. We believe that a shared wireless backhaul will have a significant place in supporting dense deployments in certain areas, linking APs wirelessly over other APs to one or several aggregation nodes. Multi-hop relaying between UEs/APs may be required in order to provide improved coverage for the highest bitrates. Furthermore multi-hop in a mesh of access points will provide robustness to failure of individual nodes. A challenge, however, in particular if access links and backhaul links share the same pool of radio resources, is how to share and coordinate the resources optimally when taking interference into account (related to multi-node and multi-antenna transmission research in METIS).

To obtain multi-Gb/s, not only at the MAC layer but even above TCP, latency must be reduced in addition to increasing the data rate. In order to maximize energy efficiency and to minimize latency, control/user data transmission itself should be done quickly in time domain, leading to short transmission time interval (TTI). The historical trends in the relationship between carrier bandwidth and TTI length are illustrated in Figure 3.1. As higher-order modulation is inherently energy inefficient this leads to higher spectrum allocation demands. Consequently, a relatively large amount of spectrum may be required. Lower TTI leads further to decreased buffering times, decreased amount of needed buffers and thus to lower baseband cost for buffering. Since the actual latency is affected by not only TTI but also by processing times, control and reference signalling structures should be designed to support efficient pipeline processing at the receiver. Overall, latency reduction (e.g. with respect to physical hybrid ARQ (HARQ) round trip time (RTT)) can together with increased amount of used spectrum be seen as the main physical layer requirement to reach high bit rates with cost roughly on the same level as in today’s technologies.

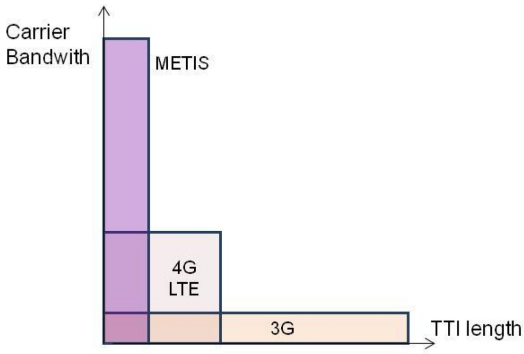

Figure 3.1: Relationship between carrier BW and TTI length according to historical trends.

In order to fulfil the need for increased amount of spectrum, spectrum at frequencies higher than those currently used for mobile broadband may be used alternatively or additionally. These frequencies include, 4 GHz–10GHz (G, H, I bands) and 10GHz-100GHz (J, K, L, M bands) [MET13-D51]. To simplify terminal complexity, the availability of large contiguous spectrum bands is preferable. For some frequency regions where large contiguous spectrum band may not be available, user equipment may be required to aggregate multiple frequency bands having differing characteristics. Thus, the air interface design needs to be harmonized so that same framework can be used for different aggregated frequency bands.

Dense deployments of small cells would have poor energy efficiency if the small cells are always actively transmitting signals as in current radio standards, e.g. Long Term Evolution

(LTE). Better energy efficiency would be gained in case UEs/devices not actively transmitting or receiving data, APs in cells with no active users and APs not participating in backhauling would be able to sleep during the inactive time, further leading to strict latency requirements of wake-up and call setup related control signaling on physical layer.

Complementary to the densification of cells - especially if operating in traditional frequency bands - to fulfil the thousand fold increase in traffic demand requires enhancements in spectral efficiency. Dense deployment environment with smaller cell size requires a new numerology optimized for this environment, and can further be used to achieve enhanced spectral efficiency. In addition, overheads due to control signalling etc. must also be taken into account and minimized as much as possible.

This research topic will provide efficient solutions to the low modem cost requirement, high data-rates, low physical layer latency and physical layer enablers for interference management in dense deployment environment.

GRMs/GRTs related to this RT

Table 3.1: GRMs related to RT AI-DD

Related GRM/GRT	Reasons
GRM1: MU/C-TP & MAC-SE	A good trade-off between link level spectral efficiency / link level throughput and power consumption and HW cost is to be addressed, improving finally the multi-user / cell throughput.
GRM4: MAC-LAT GRM5: MAC-PER/REL/INTG	In this RT, low physical layer latency (up to HARQ RTT ~1ms) is aimed to be reached (see reasoning for GRT1). Physical layer latency and HARQ RTT concerning one data-acknowledgement loop affects the corresponding MAC level latency / reliability. Enabling low physical layer RTTs gives MAC layer more flexibility in terms of scheduling and enables lower MAC latencies or better reliability (more HARQ rounds increasing reliability can be fitted in certain time).
GRM7: ECON-B/AU	Achieving low control plane latency is essential for minimizing power consumption with 'always on' type of connection. Dense network with short link distance and low power enable lower energy consumption.
GRT1: COST-HW	Due to increased number of APs in dense deployment, modem cost (especially BB cost) needs to be minimized. RF cost needs to be addressed especially for the designs with multiple bands aggregation to get enough spectrums. Low physical layer latency (up to HARQ RTT ~1ms) is required in certain dense deployment scenarios with high data rates to enable reasonable implementation cost with reduced need of buffering.
GRT2: CFR GRT3: SBW	Air interface design is targeted to have support for flexibility and scalability of spectrum resources.
GRT5: ENHET	Air interface design to enable seamless networks by supporting mechanism to integrate the local area UDNs with the wide area/umbrella networks.

Restricted research assumptions

This research topic does include the consideration of higher frequencies above 3GHz including millimetre wave (mmW) bands, together with the following assumptions:

- Emphasis is on local area UDN deployments.
- Dynamic time division duplexing (TDD), due to its capability to allocate the available bandwidth dynamically to any direction and low radio component cost, also motivated from wireless backhaul and devise-to-devise communication point of view. In addition, TDD does not require duplex filters and also the amount of available bandwidth is larger for TDD (over frequency division duplexing (FDD)).
- OFDM-based waveform (not excluding pre-coded OFDM), in order to enable low latency due to good time localization and low cost receiver with good multiple input multiple output (MIMO)/beamforming performance. Frame based access with local network synchronization (meaning that frames of different devices and cells in the network have concurrent timings), due to efficient usage of resources.

Issues to be researched

Under this research topic, the following issues are planned to be researched:

- Physical frame numerology (parameters such as TDD guard period, cyclic prefix etc.), frame structure and control signaling optimized for ultra-dense deployment environment with orthogonal frequency division multiple access (OFDMA)/TDD, enabling low physical layer latency and including potential possibility to re-use the similar design principles for OFDMA at wide range of carrier frequencies (in order to apply a same baseband design for a set of carrier frequencies). More specific design and relation to different set of carrier frequencies are also included in the study. Modem (including both access point and terminal) cost requirements and evolvements of (component) technology are taken into account.
- Air interface to support/enable mechanisms for efficient interference coordination/cancelling in case of shared frequency, fast or semi-static, among different network layers and concerning cross-links. Crosslink interference is specific to TDD and it may severely degrade performance. Interference coordination may have impact on the organization of resources, on pilot and control signaling and transmission coordination etc.
- Air interface to support/enable mechanisms for switching on/off UDN nodes on demand in a layered deployment and handing over traffic from/to umbrella cells as well as mechanisms to switch off idle nodes in a very dense deployment. This may have impact on the organization of resources, on pilot and control signaling, on random access schemes etc.
- Air interface design to support MAC layer and wireless backhauling.

3.1.2 Optimized signalling structure for low-cost MMC devices (SIG-MMC)

General description

The expected widespread use of low-cost MMC devices, which some forecasts indicate will reach tens of billions devices and span a wide application range, will not be handled efficiently by the current wireless communication networks. Although in most cases, each of these individual devices will only transmit small data portions very sporadically, it was observed that for some applications the group behaviour follows one of a botnet [SJLPW+12], i.e. a large amount of devices will access the network simultaneously. Current wireless systems were neither designed to handle efficiently small data packets nor the simultaneous access of thousands of devices, even in the case where the aggregated data traffic demand is within the system capacity, mostly due to lack of capacity for the generated signalling overhead. Therefore this leads to the necessity of designing a signalling structure that is optimized to handle such a traffic profile.

The MMC devices are expected to be low-cost, which implies that these will have reduced transceiver complexity such as lower transmission power, single antenna, reduced RF bandwidth, and low baseband computational power. All these factors will introduce a reduction of the coverage; therefore there is the need to investigate low-cost enhancements for improving the coverage, which can range from alternative transmission schemes, in regards to the existing ones, to the use of aggregation devices. This motivates the recourse to alternative approaches that can take advantage of legacy systems (such as the paging network) to achieve large scale downlink MMC coverage and the use of the coordinated relay and device-to-device paradigm to enable reliable uplink MMC coverage and efficient coexistence with non-MMC devices.

GRMs/GRTs related to this RT

Table 3.2: GRMs related to RT SIG-MMC

Related GRM/GRT	Reasons
GRM2: MAX#-CONN / RASSR / RASE	The access point/base station should be able to support a massive number of low-cost MMC devices (MAX#-CONN); The access point/base station should be able to handle a massive number of low-cost MMC devices accessing asynchronously, therefore it is required to have available a high throughput random access protocol (RASSR, RASE).
GRM4: MAC-LAT	Minimal amount of control plane procedures needed to convey low amounts of user data; Trade-Off between latency and battery life; Low signalling overhead related to QoS requirements.
GRM5: MAC-PER/REL/INTG	The network should be able to serve mobile MMC devices up to 350 km/h.
GRM6: MAC-COV	The base station should compensate the loss in coverage due to low-power transmission MMC devices (when compared with “normal” devices).
GRM7: ECON-B/AU	The energy spent per information bit successively received (ECON-B) is important, since it allows to measure how much is the protocol overhead and efficiency. The amount of active time should be minimized for the sake of extending the time between battery charges. Efficient transmission of short packets and sporadic

	transmission; Signalling overhead/power consumption should scale with device capabilities for both AP/BS and devices, particularly for MMC devices; Very low signalling overhead for very low data rates.
GRT1: COST-HW	The complexity is shifted from the devices to the network side, leading to: Low cost devices; Low base band complexity at MMC device side and higher complexity at the network infrastructure side; Low RF complexity at MMC device side and higher complexity at the network infrastructure side.

Restricted Research Assumptions

- Small data packets transmission.
- Signalling structure design for MMC (UL&DL) in cellular system.

Issues to be researched

Under this research topic, the following issues are planned to be researched:

- Investigate what is the best channel access protocol according to the packet size, while assuming perfect channel knowledge and synchronization;
- Investigate the use of coordinated relay schemes and device-to-device communication to enhance MMC uplink coverage and energy efficiency.
- Develop and evaluate a hybrid scheme that exploits traffic characteristics using a priori knowledge for scheduling periodically operating devices on a quasi-statically basis and devices communicating sporadically on a random basis to efficiently reduce signalling overhead.
- Investigate the use of legacy paging systems for downlink MMC coverage by acquiring benchmarks regarding power consumption and how to perform group based RRM signalling, while considering diverse QoS requirements.

3.1.3 Air interface supporting new and dynamic spectrum usage (AI-NDSU)

General description

One design goal for flexible air interface is to enable future radio to operate in new spectrum bands and support for dynamic usage of spectrum. This research topic includes RF architecture and air interface support to dynamic spectrum sharing.

For the dynamic usage of spectrum, frequency agile front end is needed to adapt the transceiver or user equipment for multiband operation. Such an RF front end should be able to be configured to operate at a particular band based on the spectrum availability.

Figure 3.2 below illustrates the requirements set on a METIS air interface if it is to operate in shared spectrum. In the illustrated case the METIS system may use the white parts of the frequency range. Note that the amount and location (in frequency) varies over time. Note also that here no frequency range is available at all times, thus imposing the requirement that the air interface may not be designed to have fixed physical channels for control signalling. Such physical channels need to be dynamically reconfigurable. The time scale could range between a couple of TTI to several minutes, hours or even days, depending on the sharing scenario considered.

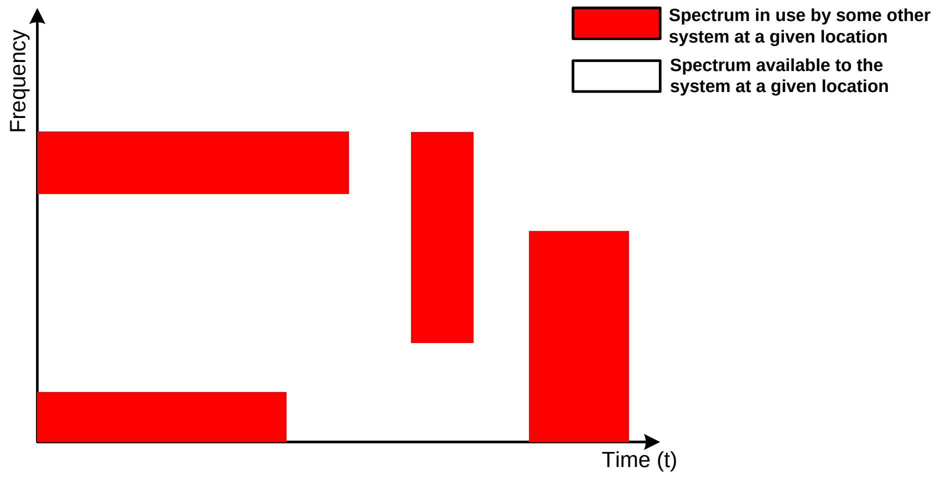

Figure 3.2: Illustration of the spectrum environment a future METIS system is likely to cope with.

GRMs/GRTs related to this RT

Table 3.3: GRMs related to RT AI-NDSU

Related GRM/GRT	Reasons
GRT2**:** CFR	In order to support different spectrum of operation, the RF front end should be tuneable based on the spectrum availability and user requirements. From the RF terminal perspective this implies a frequency agile front end. The RF front end is frequency selective and the frequency of operation distinctly characterizes the performance of the RF terminal.
GRT3:SBW	Support for multiple bandwidth of operation. Air interface design to support new spectrum and dynamic spectrum sharing.

Restricted research assumptions

- A common reconfigurable RF front end for the receive chain.
    - Dynamically configurable spectrum in frequency-time-space domain, e.g. with respect to radio access technologies, operators and primary and secondary spectrum usages, should be a design principle as the amount and location (in frequency) varies over time and no frequency range is assumed to be available at all times.
- The principle described above imposes the requirement that the air interface may not be designed to have fixed physical channels for control signalling. Such physical channels need to be dynamically reconfigurable.

Issues to be researched

- A frequency agile front end is researched, where a single front end can be adapted for multi-band operation. This will lead to optimum usage of frequency resources. In this direction, we will build an experimental cognitive RF platform for the UHF band. The major task at hand is a filterless frequency agile architecture for the wideband operation. Such an implementation is prone to strong in-band and out-of-band blockers, which can desensitize the receiver. The situation is getting worse in an FDD scenario where the transmit energy leaks into the receive band. The challenge for the FDD mode is to sustain the transmitter (TX) leakage without affecting the receiver performance. In order to achieve that, the receiver should have very high linearity of 26dBm (IIP3) [HW11]. The TX leakage problem can be addressed with other duplex modes such as TDD or half FDD. The effect of these modes on the RF performance has to be researched in this regard. Moreover alternative architectures such as high intermediate frequency (IF) have to be investigated where with a high linear front end, limited FDD is also possible.

- Investigate dynamically reconfigurable (in frequency) control channels with respect to e.g. frame structure with control channels and reference signal structures.

Refer also to [MET13-D51] where various sharing scenarios are currently listed, which will call for the development of appropriate PHY layer concepts fully exploiting the capabilities offered by the dynamic spectrum access (e.g. air interface design and RRM supporting different kind of shared accesses).

3.1.4 Interface-management and advanced link-adaptation techniques (IM-LA)

General description

The services to be offered by future mobile radio are expected to become substantially diverse and heterogeneous, e.g. due to the advent of machine-type communication and its integration into mobile radio systems. Therefore, it is reasonable to assume that a single configuration of the air interface setup, as we have it in today's systems, may no longer be sufficient to conveniently serve all the needs of the services to be offered. Instead, it may be necessary to provide a set of different system configurations between which the system is able to switch dynamically. Thus, we will move from a "one-fits-all" solution to a configurable, multi-purpose solution that facilitates a more efficient use of the available system resources, like spectrum, transmit power and processing power. To facilitate this kind of dynamic air interface management, the different types of air interface configurations that should be supported by the system need to be defined together with appropriate selection criteria. The selection will be implemented based on specifically designed metrics that may take not only properties of the devices and the requested service into account, but also conditions in the actual RL. The latter will require some signaling between devices and network infrastructure, which needs to be clearly specified based on appropriate measurements conducted on either side of the RL.

GRMs/GRTs related to this RT

Table 3.4: GRMs related to RT IM-LA

Related GRM/GRT	Reasons
GRM1: MU/C-TP / MAC-SE	Configuring the air interface for the specific needs of particular traffic types (e.g. MTC with short packet transmission) may improve the overall throughput by reducing waste of resources.
GRM2: MAX#-CONN	Adaptive multiple access schemes can support ultra-dense scenarios, e.g. by overloading (more users than dimensions).
GRM4: MAC-LAT	Low latency communication enabled by adaptive frame structure and TTI.

GRM5: MAC-PER/REL/INTG	Depending on the fading situation in the channel, the air interface can be adapted in its subcarrier spacing, transmission bandwidth, coding scheme (e.g. spread spectrum) to improve the signal conditions. This will finally impact the system's reliability.
GRM6: MAC-COV	Link budget analysis is a key component for multiple interface management and advanced link adaptation technique in order to ensure targeted radio coverage with the appropriate QoS.
GRM7: ECON-B/AU	In particular for communication requiring low rates only, selecting an appropriate configuration supporting short packets can significantly improve the energy cost per transmitted bit (ECON-B).

Restricted research assumptions

- The possible configurations supported by the flexible air interface design should be confined to a set with a small number of candidates, to limit the effort for the adaptation. This will call for an appropriate trade-off between achievable performance gains and cost in terms of system complexity.

Issues to be researched

A single monolithic air interface design will not be able to suit the competing needs of different applications. We will study a *Software Configurable Air Interface* that is able to adapt to given traffic type and UE conditions, as illustrated in Figure 3.3.

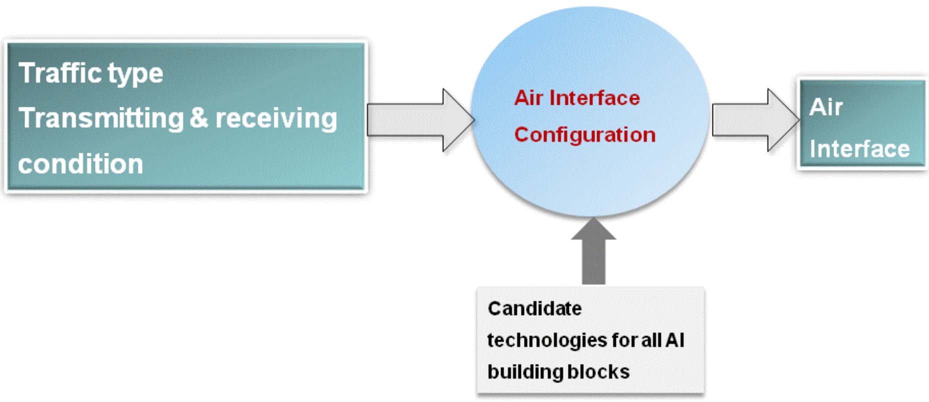

Figure 3.3: Software-configurable air interface.

The following issues will be addressed:

- Adaptive Waveform: Supporting different pulse shapes per subcarrier and a dynamic switching between these according to the requirements of the requested service. Factors that need to be taken into account when selecting a waveform includes the overhead due to cyclic prefix and guard bands, out-of-band leakage, peak-to-average power ratio (PAPR), link adaptation due to colored interference and capabilities of transmitters and receivers.
- Support of variable subcarrier spacings within a multi-carrier broadband signal
- Energy-efficient link adaptation techniques for flexible air interfaces and multiple interface management. To allow for easy selection of the adaptation options, dedicated

channel quality indicator metrics will be derived based on a combination of several of the GRMs listed in Table 3.4.

- Adaptive Multiple Access Scheme: Another software configurable air interface component that adapts to the various QoS of traffic is the selection of multiple access schemes: contention-based and scheduled. To select MAC schemes makes most sense on the uplink since the downlink can always be scheduled with better performance.
- The choice of protocols depends on traffic's delay requirements and the size of packets.
- Dynamic switching between narrow-band and broad-band (spread spectrum) transmission for low-rate communication.
- Adaptive Frame Structure: Some use cases have more stringent latency requirements than current systems can support. However, not all applications require such a low latency communication at the air interface. To have a further reduction of TTI length for the whole system will not be a flexible solution. We will study a set of different TTI lengths to co-exist. Based on UE characteristics, each UE can be configured with one or more TTI lengths in the system.
- Adaptive Data Transmission Scheme: The future air interface can also adapt its transmission and retransmission mechanisms with different kinds of traffic (e.g. video, background) according to their QoS.

  In terms of transmission mechanisms, specific performance optimization strategies can be designed for small packet transmission (e.g. background traffic, real-time gaming etc.) and video traffic which exhibit very different traffic and QoS characteristics.

  Applications that send periodic small packets such as keepalive or status update messages are deterministic. That is, the packet arrival is known a priori and is fairly periodic. These packets are similar to voice packets. Semi-persistent or persistent resource allocation can be applied to this type of traffic.

  Non-deterministic traffic can be further classified into delay tolerant and delay sensitive traffic. Examples of delay sensitive small packets are real-time gaming and sensor reports of emergency information. These packets need to be sent out immediately with minimal delay. On the other hand, traffic such as smart meter reports can allow for larger delay from hundreds of ms to seconds (or more). The mechanism to transmit these two kinds of small packets can be further optimized. Contention-based or scheduled transmission with low signaling overhead can be used for these kinds of traffic.
- Adaptive Coding an Modulation Family: Current systems use a limited set of coding and modulation schemes. Performance gains are expected by adapting the coding and modulation scheme to the different traffics and channel conditions resulting from the new scenarios and test cases introduced by METIS.

3.1.5 Signalling for advanced multiple-access and new waveforms (SIG-MAWF)

General description

Innovative radio access technologies to enhance the spectrum efficiency are very important in the future. The OFDMA access scheme currently used by the Long-term evolution (LTE), has a lot of advantages like simple implementation, simple use of MIMO schemes and so on that allow a high spectral efficiency at moderate costs. However, from information theory it is known that with strictly orthogonal schemes like OFDMA the maximum sum rate of the multiple access channel is not fully achieved. From an information-theoretical point of view, non-orthogonal user multiplexing using superposition coding at the transmitter and successive interference cancellation at the receiver can achieve the capacity region of the downlink broadcast channel. As bandwidth is one of the scarce resources, future systems should make the best out of it leading to the idea of relaxing the orthogonality constraint. Thus, as a new multiple access scheme, non-orthogonal multiple access (NOMA) scheme by power domain multi-user multiplexing at the transmitter side and successive interference cancellation (SIC) at the receiver side is considered in the downlink. NOMA can exploit the power-domain more by utilizing the path-loss difference among users in wide area deployments.

If a new air interface is proposed, not only the transmission scheme itself has to be defined, but also the required signalling has to be taken into account. Especially for the multiple access, the procedures and signals have to be designed carefully with respect to performance, as well as with respect to overhead.

GRMs/GRTs related to this RT

Table 3.5: GRMs related to RT SIG-MAWF

Related GRM/GRT	Reasons
GRM1: MU/C-TP & MAC-SE	This research topic is mainly targeting significant increase of the cell throughput (MU/C-TP).

Issues to be researched

There are many key technologies related to NOMA such as multi-user scheduling, link adaptation, multi-user power allocation, and MIMO extension that require brand new designs. In addition, taking into account practical considerations, it is also important to assess NOMA system-level performance gains compared to existing orthogonal multiple access, and develop NOMA specific technologies that can deal with real-world imperfections, such as error propagation of real SIC receivers, non-ideal channel estimation, etc. In this research topic, specific signalling aspects for NOMA will be addressed with special focus on enabling

- scheduling (user selection) scheme for NOMA,
- multi-user power allocation (MUPA),
- link adaptation scheme for NOMA,
- HARQ scheme for NOMA,
- combination of NOMA and MIMO.

System-level performance gains of NOMA over the orthogonal multiple access adopted by the Long-Term Evolution (LTE) are one focus in section 3.1.11.

3.1.6 Air interface of moving networks (AI-MN)

General description

It is desired that moving networks, including vehicle-to-vehicle (V2V), vehicular-to-infrastructure (V2I) and vehicular-to-device (V2D) communications, are capable to support the provision of traffic safety applications, as well as meeting the wireless broadband access demands of the vehicular users in the form of enabling moving relays/cells/networks.

It might not be possible to support the high level of reliability that is needed by traffic safety applications by wireless communication systems. A failure to comply with the reliability requirements can render the traffic safety service completely useless and even harmful to the users relying on the service. The air interface must therefore be designed in such a manner that it enables the use of wireless links for traffic safety applications despite the fact that a high reliability level cannot always be guaranteed by the wireless communication system.

To efficiently support mobile broadband for moving relays/cells/networks efficient backhauling and handover algorithms are essential, which calls for that the air interface of moving networks must incorporate novel channel estimation and prediction techniques in order to cope with the propagation channel of highly mobile users, as well as the D2D links between vehicles (i.e. V2V and V2D). The direct communication between the cars can be coordinated and its reliability can most likely be improved if a backhaul link is available to the infrastructure nodes. However, it is highly desirable that D2D transceivers can still communicate in ad-hoc mode without network assistance, as this would increase the availability of traffic safety applications beyond the coverage of the network. In this case, multiple access schemes based on time-division might be preferable due to efficiency and reliability reasons.

GRMs/GRTs related to this RT

Table 3.6: GRMs related to RT AI-MN

Related GRM/GRT	Reasons
GRM4: MAC-LAT	The low MAC latency is mandatory for realizing vehicular safety application.
GRM5: MAC-PER/REL/INTG	The MAC reliability and integrity must be very high, at least for safety applications.

Issues to be researched

- Development of a new framework for ultra-reliable communications that enables traffic safety applications to make use of wireless connectivity, despite the fact that the wireless communication system cannot always guarantee the reliability requirements demanded by the applications.
- Development of channel estimation algorithms that exploit the sparseness of the channel in the delay-Doppler domain and are robust against time-variations.
- The network synchronization is a crucial aspect for reliable V2V communications. Idea for network synchronization: by modelling the local clocks as affine functions of the global time, it is possible to formulate distributed algorithms to synchronize the transceiver clocks, no matter whether they are connected to the fixed infrastructure or not. The synchronization process is based on the exchange of time-stamp messages.
- The backhaul link of moving networks is a bottleneck. Transmit channel state information can be used to improve the backhaul link capacity. Antenna aided channel prediction will be investigated (in collaboration with multi-node and multi-antenna transmission research).

3.1.7 Faster than Nyquist (FTN)

General description

FTN originates from 1975 and was introduced by J. E. Mazo [Maz75]. It started as a general concept relying on a theoretical approach. Mazo stated, that, although intersymbol interference (ISI) is introduced, a denser packing of pulses up to a given degree (with keeping the single pulse characteristics fixed) does not reduce the minimum Euklidean distance. So, the transmission of these pulses may be done in a way not obeying to Nyquist's criterion without degrading performance at moderate and high signal to noise ratios while increasing the spectral efficiency. For that means an appropriate receiver has to be applied (e.g. sequence detector).

After years of reduced attention, FTN has been revitalized by various groups in the beginning of the 21st century and has been developed with respect to various aspects, such as receiver design, the extension of the principle to frequency domain (i.e. stacking sub-carriers closer in frequency domain introducing controlled intercarrier interference in addition to stacking pulses closer in time than Nyquist would advise) and the combination of FTN and MIMO.

The detection of FTN signals is rather complex (compared to non-FTN transmissions), as the controlled interference introduced at the transmitter has to be taken into account for reception (e.g. by applying sequence detectors). However, relying on Moore's law by the time 5G is to be implemented, FTN might be feasible for the uplink of a cellular network (as here the complexity resides at the base station) or for serving high-end devices in downlink (smartphones, tablet PCs, vehicles). If designed aggressively, FTN may drive the transmission to its ISI limits, so its usage may be restricted to links with very low delay spreads (e.g. cell center UEs located close to the serving point receiving only few echos) and optimally with zero to low mobility (static and nomadic users). To what extent FTN may tolerate these impairments is one of the questions to be answered. Thus, FTN may not to be seen as a basic signaling method for future cellular systems, as full coverage and high mobility are not supported to the same extent as conventional OFDM does. However, it may be applied as a special transmission mode boosting the overall throughput, if respective users are available.

Target of the studies in METIS with respect to FTN is to answer the following question: "Which are there scenarios in a realistic cellular communication setting for which gains from FTN can be achieved at a given complexity?"

GRMs/GRTs related to this RT

Table 3.7: GRMs related to RT FTN

Related GRM/GRT	Reasons
GRM1: MU/C-TP & MAC-SE	The sole purpose of FTN is to increase the link spectral efficiency by going beyond the Nyquist rate, which is related to the MU/C-TP & MAC-SE Although, the research work conducted in the framework of FTN will stay only on the link level, the use of outcomes could be envisaged in the cell-related multi-user aspects.

Issues to be researched

- Appropriate receiver design: As stated above reception of FTN signals is rather complex compared to the detection of non-FTN signals. So, receive strategies possibly reducing complexity while keeping the gains are of interest.
- Through the partial overlap the PAPR may be affected negatively. So, a PAPR analysis of FTN signals and possibly means to improve on it are required.

- A relevant item to be researched with FTN having in mind as a potential candidate for 5G is to find the boundaries of FTN with respect to its coverage area (e.g. path loss and delay spread considerations) and the tolerable grade of mobility.
- Efficiency evaluation w.r.t. SoTA systems and evolutionary extensions (e.g. move to higher modulation orders). FTN is a possible contender to higher order modulation. To increase the link spectral efficiency, one is able to either introduce FTN or higher order modulations (e.g. 256 quadrature amplitude modulation (QAM)). A direct comparison with respect to efficiency, inherent complexity and sensitivity to distortions when applying the same net bit rate helps deciding for the better approach.
- General design parameters of FTN (such as impact of underlying waveform and the choice of basic signal characteristics, e.g. subcarrier spacing) are of importance.
- FTN together with Filter-Bank Multi-Carrier (FBMC) will be considered and possible extensions to MIMO.

3.1.8 FBMC related solutions (FBMC)

General description

Many state-of-the-art wideband systems (including LTE) use CP-OFDM based transmission schemes. The CP-OFDM based systems (if not pre-coded) usually exhibit rectangular waveform on each of its subcarriers and do not provide efficient methods to filter its waveform due to the design limit of its transceiver structure. The FBMC transmission [KMM10], on the other hand, provides a filter-bank analysis and synthesis filter to enable efficient pulse shaping for the signal conveyed on each individual subcarrier. Such transceiver structure usually requires higher complexity in implementation, both due to the filter processing and the increased complexity in equalization and interference management. However, the usage of digital polyphase filter bank structures, together with the rapid growth of digital processing capabilities in recent years had made FBMC a reasonable approach.

As one type of modulation scheme, FBMC Offset QAM (FBMC/OQAM) [SSL02] can usually achieve higher link spectral efficiency than CP-OFDM due to the abandoning of the cyclic-prefix overhead. Meanwhile, by choosing an appropriate prototype filter, FBMC/OQAM systems usually generate much lower out-of-band leakage. This enables FBMC/OQAM to utilize the spectrum resources more efficiently by deploying narrower guard-band and more dynamically by being more co-existent friendly with other systems. Further advantage foreseeable is the robustness against fading channel conditions and imperfect synchronizations by selecting the appropriate prototype filter.

As another type of modulation scheme, FBMC Filtered Multi-Tone(FBMC/FMT) is usually less spectral efficient than FBMC/OQAM. Nevertheless, due to the non-overlapping of the neighboring subcarriers, FBMC/FMT systems can offer similar orthogonality as CP-OFDM systems, while still providing the advantages of optimized subcarrier shaping.

The target of the studies in METIS with respect to FBMC is to investigate the feasibilities and potential gains for replacing CP-OFDM with FBMC as transmission schemes for METIS system, as well as to analyze the computational effort required for realistic usage.

GRMs/GRTs related to this RT

Table 3.8: GRMs related to RT FBMC

Related GRM/GRT	Reasons
GRM1: MU/C-TP & MAC-SE	The FBMC-based applications may increase the throughput/spectral efficiency at a cell level due to its good frequency localization property.
GRM5: MAC-PER/REL/INTG	The improved robustness of FBMC against inter-band interference or Doppler effects can reduce the MAC-PER/REL.

Restricted research assumptions

Some restricted assumptions are outlined here:

- Lower frequency (e.g. <10 GHz) or spectrum sharing are favored scenarios for FBMC, where either the spectrum usage policy is more stringent in terms of some emission requirements (such as ACLR), or where the requirement is to be more coexistence-friendly to other systems. However, these scenarios should not be deemed as design restrictions, as FBMC is suitable for a more general case.
- Single user SISO and MIMO will be considered.

Issues to be researched

- The FBMC partners will investigate the waveform design to select the suitable prototype filter(s)
- The FBMC partners will investigate FBMC link transmission scheme
    - to design and optimize transceiver structure
    - to design symbol and frame structure
    - to support MIMO (with certain MIMO modes).
- The FBMC partners will also study emission spectrum characteristics of FBMC system, including non-ideal transmitters.

3.1.9 Modulation & coding and new channel coding concept (MODCOD)

General description

A main feature of the emerging wireless communication systems concerns the increasing number of requirements in the overall design of the system. This feature will be developed further with current convergence trends in mobile and wireless communications. Among the most important requirements, we can cite error probability, throughput, latency, complexity, energy consumption, PAPR, and propagation conditions.

The multiplication of these requirements has been leading the parameters of wireless communication systems to increase also drastically. Moreover, each of these parameters has a wide range of mandatory and/or optional values: coding schemes (with various frame sizes and many code rates), modulations (with several types of constellation), multi-antenna configurations, multiple interleaving rules, etc.

Two main consequences related to this RT can be underlined: the first one is that a specific protocol named ACM (Adaptive Coding and Modulation) has to be implemented, to manage all the parameters according to requirements such as the spectral efficiency and the frame error rate (FER). Estimation of the FER at the receiver side is not straightforward. Therefore, a Channel Quality Indicator (CQI) is usually sent from the receiver to the transmitter, but an offset margin is subtracted to the estimated SINR in order to avoid packet losses when the modulation and coding scheme is overestimated.

The second consequence is that a wide of range of algorithms are proposed in the literature to encompass all the variety of parameters and requirements. Besides the optimal algorithms for signal detection, demodulation and decoding, many suboptimal variants are explored to reduce the computational complexity and the memory requirements. In addition, they often target to optimize one specific performance metric, or a very limited set.

Target of the studies in METIS with respect to MODCOD are related to these two consequences. First, new FER estimator will be investigated, and their performance will be analysed. Then, we will study how to increase the size of the parameter set taken into account in the baseband processing algorithms. Finally, new coding schemes enabling to reduce the parameter set size will be studied.

GRMs/GRTs related to this RT

Table 3.9: GRMs related to RT MODCOD

Related GRM/GRT	Reasons
GRM1: MU/C-TP & MAC-SE	The spectral efficiency is a major challenge, since high spectral efficiencies will enable to increase throughput as required by METIS goals.
GRM4: MAC-LAT	Novel iterative processing techniques will improve the error performance in coded transmissions. This will have a positive effect on the number of required retransmissions and thus improve the MAC latency in the system.
GRM5: MAC-PER/REL/INTG	Coding and modulation schemes are to be designed according to mobility conditions (interleaving length, error correcting capabilities, etc.).
GRM7: ECON-B/AU	The optimization techniques of the digital baseband processing will impact the energy consumption (ECON-B). It is considered as an optimization objective for the proposed solutions related to the adaptive flexible baseband processing.
GRT1: COST-HW	The complexity in terms of arithmetic/logic computations and memory of the proposed solutions related to digital baseband processing will be evaluated and related optimization techniques will be investigated to improve this GRT.

Restricted research assumptions

- Spectral efficiency estimation based on single sample per transmitted symbol.
- Fast bit error rate estimation based on the decoded soft values .
- Adaptive-complexity baseband processing and optimization techniques considering a wide range of system parameters and communication techniques with iterative processing techniques.
- Envelope constrained multiple access capable waveforms.

Issues to be researched

- The main focus will be on the digital baseband implementation and more specifically on channel coding, modulation, and MIMO techniques. Considering the selected scenarios and test-cases, we want to explore different system configurations and parameters related to these techniques. We also want to propose an adaptive flexible baseband processing and optimization techniques which enable to satisfy the target KPIs in terms of throughput, latency, energy consumption, and error rate performance. This will be done in conjunction with a careful consideration of the underlined hardware complexity (arithmetic/logic computations and memory accesses). Novel iterative processing techniques at the receiver side will be explored in this context.
- New coding and modulation for ACM schemes will also be investigated based on lattice codes, so as to improve the flexibility and the average spectral efficiency. On the other hand, new link adaptation based on the bit error rate estimation will also be investigated. The bit error rate estimation will be based on the observation of the reliability of the decoded bits.
- End-to-end energy efficient envelope constrained multiple access capable waveforms will be investigated that are compatible with OFDM transceivers.

3.1.10 Advanced transceiver design (TRX)

General description

Transceiver issues are related to baseband as well as RF signal processing and hence digital and analog domain operations are involved. This RT excludes the scope for the transceiver design dedicated to FBMC waveform/FTN signaling as those are treated within the topics FBMC and FTN. However, it does not mean that the outcome of this RT cannot be reused for FBMC/FTN. The analog domain processing needs to take care of power amplifiers, related non-linearities, fitting into spectral mask, I/Q imbalances, phase noise compensation; while the digital domain design should provide appropriate techniques, i.e., interleaving, framing, synchronization, channel estimation, equalization, etc.

The key challenge of the transceiver design is that it is expected to be tailored to the new emerging scenarios or the new enablers. For instance, the higher frequencies envisioned in future 5G, e.g. mm waves, could request for completely novel design methodologies; The new waveforms or improvements to existing OFDM based scheme [MGK+12] that is considered as an important enabler for 5G also calls for a re-design of the transceiver chain; in addition, restricting latency requirement, which is imposed either by dense networks or V2V communications, also requires a careful revision of the transceiver design.

The power consumption is another new dimension with previous projects such as EARTH focusing on maximizing the base station energy efficiency where power consumption by different components in the transceiver section is identified and optimized [DDG+12]. A lot of new scenarios are being considered requiring reliable operation in many different environments from low rate data rate transmission in emergency scenarios to high quality video downloading in fast mobile conditions such as high speed trains.

GRMs/GRTs related to this RT

Table 3.10: GRMs related to RT TRX

Related GRM/GRT	Reasons
GRM4: MAC-LAT	This includes latency from input to encoder at TX to end of decoder at RX which should be within specified limits.
GRM5: MAC-PER/REL/INTG	This RT aims to provide efficient solutions to effectively improve the transmission accuracy, e.g. reduce the error rate.
GRM6: MAC-COV	Considering the power output at transmitter and receiver sensitivity needed, maximum and minimum coverage distances are determined (based on path loss models such as Okamura-Hata etc).
GRM7: ECON-B/AU	Joule/bit (ECON-B), this reflects energy efficiency, which needs to be maximized and compared against existing designs.
GRT1: COST-HW	Cost related GRT is relevant to transceiver design as it should be benchmarked by these factors.
GRT2: CFR	Design is expected to go into higher frequencies.
GRT3: SBW	Associated to GRT2, increased bandwidth affects the transceiver model.

Restricted research assumptions

- Exclusion of FBMC/FTN in the design.

Issues to be researched

- Investigation of the fundamental functional block design and required adaptations of new or existing waveforms to support MIMO transmission. New transceiver design will be driven by new or adaptations of existing waveforms (excluding FBMC/FTN) and scenarios such as higher frequencies, latency requirements, developed in this task both regarding analog and baseband processing.
- New enhanced transceivers to pay attention to the flexibility requirements arising from new usage scenarios and applications. The analysis of algorithmic gain and implementation impact including RF imperfections for new design.
- The transceiver design will based on new scenarios as identified above, and also considering V2V networks, ultra-dense networks with strong line-of-sight etc.
- Besides analysing the similarity between uplink and downlink conditions and its impact on the TRX design, full duplex transmissions for short RLs will be investigated. Facilitation of full duplex single-carrier communication with the aid of receiver-side interference cancellation.
- Transceiver design for energy efficiency.

3.1.11 Multiple Access (MA)

General description

The research topic of Multiple Access (MA) is further classified into sub topics such as non-orthogonal MA, MA for new scenarios like D2D and MMC, the MA with cognitive radio, and finally the advanced coded multi-carrier access.

Non-Orthogonal MA: In the future, it is important to be able to use radio access technologies with enhanced spectrum efficiency. The currently widely used OFDMA access scheme has a lot of advantages like simple implementation, simple use of MIMO schemes and so on that allows a high spectral efficiency at moderate costs. However, as bandwidth is one of the scarce resources, future systems should make the best out of it leading to the idea of relaxing the orthogonality constraint. Furthermore, non-orthogonal multiple access (NOMA) realizes non-orthogonal user multiplexing in the power domain by using superposition coding at the transmitter side and successive interference cancellation at the receiver side. NOMA is independent of the waveform used, thus it can be applied to both OFDM-based waveform and any other future waveforms.

MA using FBMC: The choice of FBMC systems at the PHY layer also impact the MA performance in time and frequency. Typical FBMC has pre/post-transition signal due to the filtering, which might be a problem for some MA scenarios. If FBMC can improve the frequency separation between users or services, it generally also produces a higher spreading in time, which has impact on the framing. Synchronization between users/services needs also to be revisited for FBMC systems.

MA for D2D and MMC scenarios: Ultra-dense networks need to handle large number of simultaneous transmissions in a small geographical area. This poses new challenges to resolve multiple access problems efficiently and flexibly, especially in scenarios where device-to-device (D2D) communications and/or massive sets of machine-to-machine communications (MMC) take place. Multi-mode FBMC design provides opportunities to adaptively trade off link and power efficiency that can be utilized in multiple access and multiplexing optimization. Massive sets of Machine Type Communications (MTC) devices force great demands for current multiple access schemes, which need to be evolved to permit the deployment of MMC. New MA schemes need to allow a high utilization of the medium as well as to be efficient in terms of signalling overhead and complexity to enable low cost MTC devices.

MA with Cognitive Radio: To adapt cognitive radio technologies for future wireless communication systems, devices are expected to support dynamic use of spectrum in the frequency range from 400 MHz up to several GHz. A cognitive radio can support both primary and secondary users. MA is possible under an opportunistic way when a free spectrum hole or white space can be sensed. Cost effective receivers with frequency agile front ends of high dynamic range is required for such a wideband operation. Effect of duplex schemes such as FDD, half-duplex FDD and TDD on the RF performance needs to be investigated therefore.

Advanced coded multi-carrier access: The future wireless network is expected to support very diverse traffic characteristics: from very low latency to very high latency, from very small packets to very large packets. It is also expected that future network will be able to support thousands of devices (e.g. machines and smartphones). A flexible system that can adapt the amount of overhead and signalling is desirable. Many current and future applications generate small packets. It includes real-time gaming, instant message, machine type of traffic, and status update message. The problems of small packet transmission on the uplink are: Support of massive numbers of terminals, signalling overhead, and latency.

CDMA is a well known multiple access technique in which the data symbols are spread out over orthogonal or non-orthogonal code sequences. Multicarrier CDMA (MC-CDMA) takes advantages of both OFDMA and CDMA to enable flexible code domain multiplexing with the simplicity of the OFDMA transceiver techniques especially for wideband communication. Sparse Code Multiple Access (SCMA) is a type of MC-CDMA with a particular choice of a sparse code book facilitating low-complexity maximum likelihood (ML) detection. The possibility of overloading (more users than dimensions) allows a less strict access policy. In particular, the request/grant procedure for uplink scheduling can be relaxed or even omitted. This is beneficial for dense user distributions and scenarios with small latency requirements.

GRMs/GRTs related to this RT

This research topic is mainly targeting improvement of spectrum efficiency, the number of simultaneously supported UEs, the cell throughput and fairness among users' data rates.

Table 3.11: GRMs related to RT MA

Related GRM/GRT	Reasons
GRM1: MU/C-TP & MAC-SE	The new MA should achieve a higher MAC level SE.
GRM2: MAC#-CONN	The new MA should support the expected increasing number of devices (MAX#-CONN).
GRM3: MAC-FAIR / MAC-AV	The new MA should aim for a fair distribution of user throughput.
GRM4: MAC-LAT	The new MA should avoid the latency caused by the signalling overhead (e.g. request/grant procedure for uplink scheduling).
GRM7: ECON-B/AU	Metric ECON-B is needed to evaluate energy efficiency of the multiple access scheme.
GRT2: CFR	The range of frequencies supported by the front end distinctly characterizes the cognitive radio.
GRT4: NSN	This tag takes into account the limitations, e.g., resulting from the number of available waveform modes.

Restricted research assumptions

- Non-Orthogonal MA: Differently from multi-user (MU-MIMO), NOMA does not rely on the spatial domain degrees of freedom for user multiplexing. Thus, it should have benefits in scenarios which have only a limited number of transmit antennas. In addition, NOMA exploits the power domain by using the difference of channel gains among users. Thus, the scenario for dense wide area deployments is the main target.
- MA for D2D and MMC scenarios: Focus is on planning multiple access scheme that fits to ultra-dense D2D and MMC scenarios having strong line-of-sight connection

Issues to be researched

Quasi-or non-Orthogonal MA

- The system-level performance of NOMA taking into account more practical aspects of the cellular system and some of the key functionalities and parameters of the LTE radio interface, such as adaptive modulation and coding (AMC), Hybrid ARQ (HARQ), frequency-domain scheduling, and outer-loop link adaptation is to be evaluated. NOMA specific functionalities such as multi-user power allocation, dynamic user multiplexing order, and successive interference cancellation with error propagation, are also considered to maximize NOMA gains. Using computer simulations, the overall cell throughput, cell-edge user throughput and the degree of proportional fairness achieved by NOMA is to be investigated under various configurations.

- Potential system-level performance gains and practical challenges of NOMA over the orthogonal multiple access adopted by the Long-Term Evolution (LTE).

MA using FBMC

- Counteract the time spreading of FBMC new waveforms. FBMC synchronization cannot take advantage, as OFDM, of the Cyclic Prefix, but FBMC systems have also specific features which can be utilized.
- Research of FBMC waveforms taking into account multiuser framing aspects and research of efficient synchronization methods with low latency.

MA for D2D and MMC scenarios

- FBMC will be investigated as multiple-access scheme in multiuser/multicell scenario, aiming at high spectral and energy efficiency and low latency. Applicability of FBMC-MA is to be studied both in the up- and downlink direction. Flexible and scalable solutions to encapsulate both high speed and low data rate applications are targeted. Robust multiple access schemes are searched against various system imperfections and uncertainties.
- Development of a quasi-orthogonal MA scheme for the DL allowing the addressing of massive sets of MTC devices, where a CDMA structure is used. The objective is to increase the number of available codes by allowing non-orthogonality but also keep orthogonality for channels of higher importance such as broadcast channels that take care of management functionalities. Besides the code design the grouping of devices leading to a more efficient utilization of the code resources is another research aspect, where concepts of legacy paging systems are used as a starting point.

MA with Cognitive Radio:

- To adapt cognitive radio technologies for future wireless communication systems, devices are expected to support the dynamic use of frequency spectrum. A cognitive scenario can support also the users with data rate demand (secondary users) in addition to the licensed primary users. The spectrum has to be sensed for availability with an efficient sensing mechanism depending on which the secondary user can use the spectrum. In this way MA is possible in an opportunistic way. Not only the cognitive radio has to satisfy the specifications of the secondary user in this case but also it shouldn't affect the primary user performance. In addition to the frequency agile front end, wherein the user can scan and use the available spectrum, challenges such as unwanted emissions (which otherwise is taken care by external filters), interference rejection, and interoperability with legacy standards are the concerns which will be researched.

Advanced coded multi-carrier access:

- In MC-CDMA, overlaid non-orthogonal CDMA codes are detected after OFDMA reception processing. The sequence design is an important factor for a CDMA system in terms of the performance and the reception complexity. An MC-CDMA system can be overloaded to provide service for larger amount of connections. Once the system is overloaded, a non-linear receiver is required to achieve a near optimal ML detection quality at the expense of the exponential complexity of the reception. Conceptually, the complexity of reception can be reduced if the spread symbol contains a sparse pattern with a few non-zero elements within the spreading length. Like LDPC coding in the binary field, the sparsity of the overlaid complex codewords allows us to reuse the message passing algorithm (MPA) [HWT08] in complex domain for iteratively joint multi-user detection with near optimal performance in the ML sense. The multi-dimensional constellation design is a challenging problem which has been studied with respect to different aspects of communications [FW89],[BVR+96],[FU98]. We will design SCMA codebooks based on the concept of the multi-dimensional lattice constellation.

3.1.12 Medium Access Control (MAC)

General description

A number of novel topics like massive machine communication (MMC), device to device / vehicle to X (D2D/V2X) and mmW communications provide new challenges and requirements for MAC design, which have to be addressed to adapt current MAC technologies to these new contexts.

Proliferation of machine type communication (MTC) is becoming an important research, design and implementation issue in current and future telecommunication networks, due to the expected number of users and corresponding revenues. Especially, the amount of signalling that is required to access the channel in MMC is of critical importance and limits the number of supportable devices. Thus, various applications with wireless MTC have rekindled the research interest in random access protocols for a large number of accessing devices. Slotted ALOHA and its derivatives represent a simple but popular solution for distributed random access in wireless networks. Recently, the incorporation of the successive interference cancellation in slotted ALOHA provided for substantially higher throughputs.

Furthermore, advanced physical layer processing can be incorporated into MAC design to achieve a lower signalling overhead and higher number of supported users. One of the characteristics of MTC is sporadic channel access of the nodes to transmit only a short message, which can be exploited at the fusion centre. Specifically, the design of joint activity and data detection algorithms offers the advantage, that a random access like channel use can be combined with parallel access by multiple nodes. In this context, novel technologies like compressed sensing provide a powerful tool to provide new solutions to collision problems in random access and allow for estimation of activity to save signalling if a scheduled or hybrid MAC solution is required.

On the other hand, MAC for V2X and direct D2D communication should be designed to keep the latency within the potentially challenging limits imposed by certain applications, such as traffic safety and traffic efficiency. A further challenge is that it might be desirable for the MAC to be able to function even in scenarios with limited or no coverage from the fixed infrastructure. That is, it should be possible for a number of nodes to form an ad-hoc network.

Finally, in the context of ultra-dense network in millimeter-wave bands, to compensate for reduced received energy due to small antenna aperture at higher frequencies, highly directive antennas can be used. This may give impact on MAC layer design. Contention based schemes (802.11 like) might encounter severe “hidden node” problems, with narrow beam transmissions, but with advantage in almost no control channel overhead and quick access in low load. Scheduled MAC schemes often require central node and control, but have less hidden node and collision problems.

GRMs/GRTs related to this RT

Table 3.12: GRMs related to RT MAC

Related GRM/GRT	Reasons
GRM2: MAC#-CONN / RASSR / RASE	Measured the amount of all devices in contrast to only active ones and therefore is an important metric for sporadic communication, where only a few out of many may be active (MAX#-CONN). Random access schemes are an important part of the set of protocol that govern the MAC and main performance metrics are efficiency (RASE) and success rate (RASSR).
GRM4: MAC-LAT	The MAC latency is one of the main performance metrics for the MAC layer.
GRM5: MAC-PER/REL/INTG	MAC packet error rate, reliability and integrity is, of course, greatly impacted by the MAC design and is therefore one of the main performance metrics.
GRM7: ECON-B/AU	Advanced MAC design will help decrease the active phases of devices thereby lowering the energy consumption (ECON-B). Especially, if sporadic activity is exploited to reduce the communication overhead.

Restricted research assumptions

- Random access and contention based MAC schemes for MMC.
- Non-orthogonal MA to exploit physical layer processing in MAC schemes.
- Distributed synchronization and MAC schemes.

Issues to be researched

Under this research topic, the following issues are planned to be researched:

- Use of feedback to adapt the access strategy of the users. In general, wireless systems are capable of sending feedback to the users during the random access scheme. This could be used to modify user access strategy and provide higher throughputs and increased probability of successful access.
- Design of random access schemes taking into account constraints of SIC and the capture effect. The potential of interference cancelation is, in general, limited by the number of colliding signals and their power ratios, which places design constraints that do not exist in erasure coding, but should be taken into account for design.
- Design of SIC based random access schemes boosting the intermediate throughput of the scheme. Typically, intermediate performance of erasure codes is rather limited. In analogously designed random access schemes, this implies that the number of resolved users increases rather slowly during the contention period, followed by a sharp increase at the end of the contention period, when the Successive Interference Cancelation (SIC) manages to "turn on". In terms of throughput, the intermediate throughput is low, followed by a sharp increase at the end of the contention period. On the other hand, intermediate performance of random access schemes, i.e., successful user resolution (successful access) and/or throughput, could be important in actual application scenario, raising need for the design of SIC based random access schemes with favorable intermediate performance.

- Design protocol coding based access reservation schemes that are able to adapt the size of the contention space according with the input load. The contention space size adaptation is accomplished by enabling users to contend using code-words formed by multiple access reservation tokens, instead of contending using the traditional single access reservation token. The main issue to be researched is how these contention code-words should be designed so that the system success rate and efficiency is maximized.
- Network synchronization to support ad-hoc time-division MAC. First approach: consensus algorithms based on time-stamp exchange with a random access MAC.
- Distributed allocation of time slots to support real-time, broadcast traffic. First approach: adaptation of the existing scheme called self-organizing time division multiple access (TDMA).
- MAC design for UDN including understanding of the potential benefits of a hybrid MAC approach, to leverage the advantages and avoid the disadvantages of the contention based and the scheduled based protocols. Depending on the outcome of the wireless self-backhauling study of METIS multi-node and multi-antenna transmission research, interactions between routing and MAC may also be studied.
- Design of advanced multi-user detection (MUD) concepts to exploit sporadic activity for joint activity and data estimation using non-orthogonal medium access based on compressed sensing.
- Integration of the compressed sensing (CS) based MUD concepts into systems context. This includes the consideration of channel coding, e.g., by iterative processing and the consideration of synchronization and channel estimation in a context, where node activity is uncertain.
- The applicability of CS based MUD to novel waveforms has to be reviewed. Novel waveforms change the medium access scheme, possibly allowing an extension of CS based MUD concepts.

3.1.13 Hybrid Automatic Repeat Request (HARQ)

General description

HARQ retransmission schemes are applied on the MAC layer in order to ensure timely and reliable packet delivery to the higher layers and are therefore an important component for Ultra-reliable Communication. Enhancements of HARQ may have the objective to improve reliability or spectrum efficiency, or to reduce latency or signaling overhead. Possible solutions include:

- Coding principles including soft combining and soft decision decoding algorithms,
- Feedback mechanisms including Acknowledgement / Negative acknowledgement (ACK/NACK) and reliability information,
- Protocol issues including synchronous/asynchronous HARQ protocols or maximum delay requirements.

GRMs/GRTs related to this RT

Table 3.13: GRMs related to RT HARQ

Related GRM/GRT	Reasons
GRM1: MU/C-TP & MAC-SE	HARQ solutions may improve MAC spectral efficiency.
GRM2: MAC#-CONN	The signalling overhead for HARQ may constrain the number of active devices per cell / base station (MAX#-CONN).
GRM4: MAC-LAT	The MAC latency is impacted by the physical HARQ RTT and by the retransmission statistics. Low MAC latency shall be achievable, say ~1ms, in particular for emerging industrial applications or traffic safety.
GRM5: MAC-PER/REL/INTG	Very low residual PER after HARQ retransmissions shall be achievable, say below 0.1% or even lower, in particular for Ultra-reliable Communication and depending on the service requirements.
GRM7: ECON-B/AU	HARQ solutions may improve energy efficiency (ECON-B), e.g. by enabling fractional retransmissions.
GRT1: COST-HW	The baseband complexity is primarily impacted by the HARQ RTT, encoding/soft combining and decoding algorithms and soft buffer requirements and algorithms for feedback computation.

Restricted research assumptions

- HARQ relying on ACK/NACK signalling
- HARQ relying on a-priori methods in case of unreliable feedback channel

Issues to be researched

Under this research topic, the following issues are planned to be researched:

- Delay dependent retransmission and link adaptation schemes, taking maximum delay requirements into account.
- A-priori methods to estimate successful delivery (Probabilities of delivery within ‘n’ transmissions) in case of unreliable feedback channel.
- Evaluate solutions to enhance spectrum efficiency such as adaptive or reliability based HARQ involving fractional retransmissions.
- Develop HARQ protocol solutions to reduce signalling overhead.

3.1.14 Radio link enablers for RRM (RRM)

General description

In general, Radio Resource Management (RRM) is in charge of dynamically controlling the utilization of transmit resources, such as channels, power, codes, etc., given load condition and service as well as terminal requirements. Especially the new HTs such as D2D require the integration of new/enhanced RRM solutions within today's network management strategies.

Therefore, new and appropriate enablers on link layer (PHY) are mandatory for improving RRM efficiency. Since the expected large diversity of terminal classes, QoS requirements, and traffic characteristics need to be taken into account for optimizing RRM strategies, this research topic focuses on the development of such enablers.

Considering for example the HT D2D, the reusing of cellular networks' spectrum for D2D communication in uplink or downlink requires taking care of possible negative effects introduced by underlaying D2D operation. Since D2D communication should in the ideal case not disturb the cellular system performance, proper sensing, scheduling, and handling of interference is mandatory. When considering network-assisted D2D including RRM, a certain amount of context information beyond what is common today needs to be frequently exchanged between UEs and network in particular in mobile D2D scenarios. This increased amount of signaling induces overhead which needs to be handled in an efficient manner so that the system performance is not degraded due to the introduction of D2D.

GRMs/GRTs related to this RT

Table 3.14: GRMs related to RT RRM

Related GRM/GRT	Reasons
GRM2: MAC#-CONN	An efficient RR allocation is mandatory to operate a large number of UEs / devices per area (MAX#-CONN).

Issues to be researched

We assume network-assisted D2D in underlay mode where the focus lies on signaling for RRM including mode selection, power control, and resource allocation. The required RRM enablers from link level perspective will be evaluated and a concept for how to derive and exchange link level context information in an efficient manner will be developed. This concept includes a velocity-dependent signaling scheme that uses the available context sources a modern UE possesses, such as motion sensors, accelerometers, gyroscopes, and speedometers (in case of vehicular UEs), to improve/optimize signaling for RRM on terminal side according to the current conditions experienced by the UE.

Besides the research activity listed in the next subsection, this RT will serve as a "pool" to collect aspects from other radio link technology components that have relevance for RRM. It is thus expected that the list of research activities will be filled up with further details during the progress of the project as soon as the impact on RRM becomes more concrete and tangible.

3.2 Summary of mapping between RTs and GRMs/GRTs

To have a global view on the RTs addressing the GRMs/GRTs, a mapping table between the fourteen RTs and GRMs/GRTs defined for the radio link research is summarized below. It turns out that all the defined GRMs and GRTs are addressed by at least one RT. Moreover, it can be observed that certain requirements, e.g. GRM1, GRM4 and GRM5, are addressed by more than half of the RTs. From that, it can be expected to obtain a large set of different solutions addressing similar performance targets from the radio link research in the METIS project.

Table 3.15: Mapping of GRMs/GRTs and RTs

	3.1.1: AI-DD	3.1.2: SIG-MMC	3.1.3: AI-NDSU	3.1.4: IM-LA	3.1.5: SIG-MAWF	3.1.6: AI-MN	3.1.7: FTN	3.1.8: FBMC	3.1.9: MODCOD	3.1.10: TRX	3.1.11: MA	3.1.12: MAC	3.1.13: HARQ	3.1.14: RRM
GRM1: MU/C-TP & MAC-SE	x			x	x		x	x	x		x		x	
GRM2: MAX#-CONN / RASSR / RASE		x		x							x	x	x	
GRM3: MAC-FAIR / MAC-AV											x			
GRM4: MAC-LAT	x	x		x		x			x	x	x	x	x	
GRM5: MAC-PER/REL/INTG	x	x		x		x		x	x	x		x	x	
GRM6: MAC-COV		x		x						x				
GRM7: ECON-B/AU	x	x		x					x	x	x	x	x	x
GRT1: COST-HW	x	x							x	x			x	
GRT2: CFR	x		x							x	x			
GRT3: SBW	x		x							x				
GRT4: NSN											x			
GRT5: ENHET	x													

3.3 Linking radio link research topics to the METIS horizontal topics

After having introduced the research topics investigated on the radio link, a direct link between these and the METIS Horizontal Topics (HTs) can be established. Based on the requirement mapping conducted in section 0, which established a direct relationship between HTs and GRMs/GRTs, one could, together with the above Table 3.15, draw a first conclusion on the RTs addressing the requirements of the METIS HTs. However, for the generation of the Table 3.16 shown below, we did conduct that exercise. Instead, the activities in each RT were analyzed with respect to the question whether the solution approach may be seen a promising technology enabler for one of the HTs. In other words, it has not been sufficient for a RT to simply address a single GRM/GRT from those listed for each HT in Table 2.11. But instead, the combination of GRMs/GRTs addressed by a solution approach within an RT was supposed to clearly indicate a promising track towards a potential solution for realizing the corresponding HT.

Table 3.16: Research topics expected to deliver potential enablers for METIS HTs

	3.1.1: AI-DD	3.1.2: SIG-MMC	3.1.3: AI-NDSU	3.1.4: IM-LA	3.1.5: SIG-MAWF	3.1.6: AI-MN	3.1.7: FTN	3.1.8: FBMC	3.1.9: MODCOD	3.1.10: TRX	3.1.11: MA	3.1.12: MAC	3.1.13: HARQ	3.1.14: RRM
Direct device to device	x						x	x				x		
Massive machine communication		x	x	x				x	x		x	x		
Moving networks				x		x		x	x		x			
Ultra-dense networks	x	x	x	x				x			x	x		
Ultra-reliable communications		x		x				x				x	x	

4 Summary

This deliverable describes the problem space for the research conducted towards 5G air interface. By taking a radio link perspective, the most relevant challenges and requirements were derived from the test case descriptions given in D1.1, and it was briefly illustrated how these are addressed by the envisaged research topics pursued in the radio link research. In particular, the document addressed three main objectives:

1. Translation of requirements from test cases to the radio link context.
2. Description of the research topics with indication of the requirements to be addressed therein.
3. Description how research topics further connect to METIS horizontal topics.

Concerning the first objective, the main requirements relevant for the radio link context for each test case were extracted and these higher layer requirements were broken down to seven General Requirement Metrics (GRMs) and five General Requirement Tags (GRTs). For each of the KPIs defined in D1.1 plus one defined for the scope of the air interface design, the relevant GRMs/GRTs were listed, and their interrelation was explained. Table 2.10 summarizes the outcome of addressing the first objective.

Concerning the second objective, fourteen research topics have been described in detail, and were further categorized according to the three main research directions of the radio link research. For each of the research topics, the relevant GRMs/GRTs were listed, and explanations on how the topics address these GRMs/GRTs were given. As a result, a global mapping table that points out the relationship between all research topics and the GRMs/GRTs was constructed in Table 3.15.

Concerning the third objective, the GRM/GRT mapping approach has been utilized to link the requirements to the METIS horizontal topics, following a requirement analysis conducted for each HT. Results of this linking procedure are found in Table 2.11. Together with Table 3.15, this allows to obtain some first hints towards the question which research topics could provide potential enablers for each of the five METIS horizontal topics. Nevertheless, for completeness, we additionally provide Table 3.16, which indicates the research topics that are suggesting promising tracks towards potential solutions for realizing the corresponding HT, since these explicitly aim to address the HT's needs.

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6 ANNEX 1: KPIs / requirements

Table 6.1 lists the detailed requirements from the TCs concerning the KPIs and affecting air interface from RL perspective.

Table 6.1: Detailed KPIs / requirements in the TCs [MET13-D11]

Test case	KPI	Requirement
TC1 Virtual reality office	I. Traffic volume density Traffic volume per area User/device density	 average 100 [Mbps/m^2], peak 500 [Mbps/m^2], for DL and UL, Corresponds to 100 [Tbps/km^2]/500 [Tbps/km^2] average user density = 0.1 [UEs/m^2] Data rate requirements and traffic direction vary largely depending on the service and time instant.
	II. Experienced user throughput Average user data rate during busy period	1 [Gbps], UL and DL (with 95% availability) (up to 5 [Gbps], UL and DL, with 20% availability) 0.5 [Gbps], DL and UL
	III. Latency	10 [ms] (MAC) RTT at maximum (required by TCP/IP).
	IV. Reliability Channel environment Mobility	99% (in time, for working hours) Indoor (with thick inner walls) Static or nomadic: 0-6 [km/h]
	V. Availability and retainability	95% (in location)
	VI. Energy consumption Infrastructure UEs/devices	No special challenge Preferably low (very low when no data transmission) UEs / devices: Battery for several hours
	VII. Cost	Low cost network deployment Network scalability required with easy and low cost roll-out.
TC2 Dense urban information society	I. Traffic volume density Traffic volume per area User/device density	 700 [Gbps/km^2] DL and UL Max 0.2 [UEs/m^2] Data rate requirements and traffic direction vary largely depending on the used services (mix of different traffic forms, e.g. bursty traffic and video streaming).
	II. Experienced user throughput Average user data rate during busy period	300 [Mbps] for DL and 60 [Mbps] for UL (with 95% availability) (up to 1 [Gbps] for limited areas) 5 [Mbps] DL and 1 [Mbps] for UL

Test case	KPI	Requirement
	III. Latency (E2E)	Latency requirements vary largely depending on the service: • < 0.5 [s] for web page download and video starting • < 2-5 [ms] for augmented reality processing • Video streaming: Required by TCP/IP (minus fixed intra). • D2D: certain D2D discovery and setup time reqs, < 1 [ms] HARQ feedback latency
	IV. Reliability Channel environment Mobility	95% (in time) Indoor (local area) and outdoor. Static/low to medium: 0-3 (or even up to 50) [km/h]
	V. Availability and retainability	95% (in location) D2D: minimum 250 [m] link coverage
	VI. Energy consumption Infrastructure UEs/devices D2D	Preferably low (very low when no data transmission) Similar than today (battery for several hours) Lower than for the cellular radio
	VII. Cost	Today's infrastructure and mobile broadband UE cost. Much lower cost for sensor devices.
TC3 Shopping mall	I. Traffic volume density Traffic volume per area User/device density	170 [Gbps/km^2] in DL and 67 [Gbps/km^2] in UL Users: 0.1 per [m^2] Sensors: 0.7 per [m^2]
	II. Experienced user throughput Average user data rate during busy period	300 [Mbps] in DL and 60 [Mbps] in UL
	III. Latency	User plane RTT < 5 [ms] control plane for sensor network attach < 5 [ms]
	IV. Reliability Channel environment Mobility	95% of time 99.9% of time for safety related sensors Indoor Static (sensors) walking speed (users)
	V. Availability and retainability	95% in space 99% in space for safety related sensors
	VI. Energy consumption Infrastructure UEs/devices	No strict constraint Auto-configuration, on/off important Some constraints for sensors with battery

Test case	KPI	Requirement
	VII. Cost	Sensor network cost scalable with number of sensors Sensor cost should be low
TC4 Stadium	I. Traffic volume density Traffic volume per area User/device density	 0.1-10 [Mbps/m^2] = 0.1-10 [Tbps/km^2] 0.4-1 per [m^2]
	II. Experienced user throughput Average user data rate during busy period	0.3-20 [Mbps] DL and UL 0.3-3 [Mbps] DL and UL
	III. Latency	RTT < 5 [ms]
	IV. Reliability Channel environment Mobility	No special requirement Outdoor Static/walking speed
	V. Availability and retainability	95% in space within stadium
	VI. Energy consumption Infrastructure UEs/devices	 No specific constraint, auto-configuration important No special requirement
	VII. Cost	No special requirements
TC5 Teleprotection in smart grid network	I. Traffic volume density Traffic volume per area User/device density	 No special requirement 1-1000 per [km^2] = 10^{-6} - 10^{-3} per [m^2]
	II. Experienced user throughput Average user data rate during busy period	0.15-1.5 [Mbps] No specific requirement
	III. Latency	8 [ms] one trip time for event triggered message
	IV. Reliability Channel environment Mobility	99,999% in time No specific requirement Static
	V. Availability and retainability	100% network availability at each substation location, possibly with fallback solutions
	VI. Energy consumption Infrastructure UEs/devices	 Battery backup 24 hours No specific requirement
	VII. Cost	Not crucial, reuse of existing infrastructure preferred for cost reasons
TC6 Traffic jam	I. Traffic volume density Traffic volume per area User/device density	 480 [Gbps/ km^2] Average 4000 per [km^2] = 0.004 per [m^2] Max 0.2 per [m^2] on the lane in traffic jam

Test case	KPI	Requirement
	II. Experienced user throughput Average user data rate during busy period	100 [Mbps] in DL and 20 [Mbps] in UL
	III. Latency	E2E < 100 [ms]
	IV. Reliability Channel environment Mobility	> 95% in time Outdoor/incar Static/ walking speed
	V. Availability and retainability	> 95% of users
	VI. Energy consumption Infrastructure UEs/devices	 No specific requirement Energy constraint due to battery
	VII. Cost	Additional network deployment should be avoided
TC7 Blind spots	I. Traffic volume density Traffic volume per area User/device density	 12-120 [Gbps/km^2] DL and UL (rural - urban) 100-1000 per [km^2] = 10^{-4} - 10^{-3} per [m^2] (both user and vehicle serving as hot spot. Distribution of both is correlated.)
	II. Experienced user throughput Average user data rate during busy period	100 [Mbps] in DL and 20 [Mbps] in UL No specific requirement
	III. Latency	< 100 [ms]
	IV. Reliability Channel environment Mobility	> 95% in time Indoor/outdoor/incar Max 30 km/h (user); < 10 km/h (vehicle)
	V. Availability and retainability	> 95% of users inside blind spots
	VI. Energy consumption Infrastructure UEs/devices	 30% saving in efficiency (compared to legacy systems) 50% saving in efficiency
	VII. Cost	50% saving of infrastructure cost
TC8 Real-time remote computing for mobile terminals	I. Traffic volume density Traffic volume per area User/device density	 60 [Gbps/km^2] Up to 5 active devices per car, ~100 cars/km^2 50 per bus 300 per train
	II. Experienced user throughput Average user data rate during busy period	100 [Mbps] in DL and 20 [Mbps] in UL
	III. Latency	< 10 [ms] E2E

Test case	KPI	Requirement
	IV. Reliability Channel environment Mobility	95% In car/bus/train Up to 350 [km/h]
	V. Availability and retainability	99%
	VI. Energy consumption Infrastructure UEs/devices	No strict constraint Auto-configuration, on/off important Significantly reduced battery consumption
	VII. Cost	No specific constraint Infrastructure cost comparable to today
TC9 Open air festival	I. Traffic volume density Traffic volume per area User/device density	900 [Gbps/km^2] Av. 0.1 per [m^2] Max 4 per [m^2]
	II. Experienced user throughput Average user data rate during busy period	30 [Mbps] UL and DL 9 [Mbps] UL and DL
	III. Latency	< 1 [s] for machine traffic 10-50 [ms] user traffic < 10 [min] for delay tolerant traffic
	IV. Reliability Channel environment Mobility	>99% in time of event Outdoor Static to walking speed
	V. Availability and retainability	95% for user traffic 100% for sensors
	VI. Energy consumption Infrastructure UEs/devices	Limited power supply in rural areas Energy constraint for sensors due to battery
	VII. Cost	Limited availability of backhaul link, probably wireless backhaul
TC10 Emergency communications	I. Traffic volume density Traffic volume per area User/device density	10 voice calls and 10 SMS per UE per week per 10 [m^2], e.g. 2.58 Mbps/km^2 for GSM 0.1 per [m^2]
	II. Experienced user throughput Average user data rate during busy period	Voice call throughput, e.g. 13 kbit/s for GSM Not specified, rather low
	III. Latency	Not specified, no specific constraint
	IV. Reliability Channel environement Mobility	Infrastructure setup < 10 [s] Call setup < 1 [s] Outdoor indoor, user covered by rubble Static to walking speed

Test case	KPI	Requirement
	V. Availability and retainability	99,9% discovery rate
	VI. Energy consumption Infrastructure UEs/devices	 80% saving compared to normal operation 10 voice calls and 10 SMS per week per device
	VII. Cost	No constraint
TC11 Massive deployment of sensors and actuators	I. Traffic volume density Traffic volume per area User/device density	 Up to 300 [Mbps] per cell $3*10^5$ per cell
	II. Experienced user throughput Average user data rate during busy period	1 [kbps] 20 [byte] per day
	III. Latency	No specific requirements, rather loose in the order of few minutes
	IV. Reliability Channel environment Mobility	Not specified Indoor/outdoor/invehicle Static up to high speed train
	V. Availability and retainability	99,9%
	VI. Energy consumption Infrastructure UEs/devices	 No specific constraints 0.015 [µJ/bit] for a data rate in the order of 1 [kbps] UEs / devices: Low-energy operation required, battery power supply (with long battery life)
	VII. Cost	Sensors should be very low cost
TC12 Traffic efficiency and safety	I. Traffic volume density Traffic volume per area User/device density	 0.01-0.1 [Gbps/km^2] 100-1000 per [km^2]
	II. Experienced user throughput Average user data rate during busy period	100 [kbps]
	III. Latency	5 [ms]
	IV. Reliability Channel environment Mobility	99,999% Outdoor Up to 500 [km/h]
	V. Availability and retainability	Approx. 100%
	VI. Energy consumption Infrastructure UEs/devices	No strict constraint Auto-configuration, on/off important
	VII. Cost	No strict constraints

7 ANNEX 2: Detailed GRM/GRT descriptions

In this annex, the GRMs/GRTs are defined in more detail.

GRM1: Multi-user/cell throughput (MU/C-TP) and MAC Spectral efficiency (MAC-SE)

MU/C-TP is defined as the time-averaged aggregate throughput of a set of users (multi-user throughput) or users in a given area, such as under a certain cell (cell throughput). In here, since in some cases it is difficult to define what a cell is (e. g multiple cooperative serving Base Stations), cell throughput can be considered a special case of a throughput defined for users in a given area. The multi-user/cell throughput is measured in bits/s/cell. For a system consisting of N_{cell} cells and with $R_{UE_{n,s}}$ denoting the number of correctly received bits by a user n over a time window W in a cell s comprising N_{UE} users, the multi-user/cell throughput, R_{MU}, is defined by the following equation:

$$R_{MU} = \frac{\sum_{n=1}^{N_{UE}} \sum_{s=1}^{N_{cell}} R_{UE_{n,s}}}{W \cdot N_{cell}}$$

The multi-user/cell throughput provides a way to assess the capacity of the system in terms of the supported number of users (N_{UE}) multiplied by the data rate per user (R_{UE}).

MAC-SE describes the relation of MU/C-TP to the bandwidth (BW) used in the given area (such as a cell) and is defined by

$$S_{eff\_MAC} = \frac{R_{MU}}{BW}$$

GRM2: Max number of connections (MAX#-CONN), Random access schemes success rate (RASSR) and Random access schemes efficiency (RASE)

This GRM in sense of maximum number of connections (MAX#-CONN), where a connection can be defined by accounting for a certain minimal quality parameters (e. g. if the connection is active then what is the minimal throughput, or if a connected device is asleep, what is the latency of the first transmission), may cover two cases:

1. Maximum number of UEs or devices that can be connected to a cell (defined by one AP), for UEs/devices either in idle or in active modes. This may refer both to random access schemes or scheduled transmissions and this also includes situations where D2D is activated. Note that in this aspect, it is mainly assumed that all the communication links are network dependent, i.e. either both of the data and control links are coordinated by the network, or only the control link is coordinated by network for D2D cases.

   GRM2 is connected to the user/device density requirements given in D1.1. To connect this GRM to the requirements given in D1.1, this number can be defined as

   $$N_{MAX\#-CONN} = \frac{d_{max} A}{N_{AP}}$$

   where

   - d_{max} Maximum user density [user/m^2]
   - A Size of the area [m^2]
   - N_{AP} Number of APs per area

   The mapping of device density to this GRM depends on the AP density given by the deployment.

2. This GRM measures the maximum number of D2D connections per device. Such D2D connection is totally autonomous without any network involvement.

The concrete calculation or exact definition highly depends on the technical solution under consideration and has to be defined case by case.

This GRM may refer to random access schemes success rate (RASSR) and random access schemes efficiency (RASE). Random access schemes are an integral part of infrastructure based communication systems. A common performance measure is success rate, which is obtained as the total number of users being able to access the system successfully, N_S, normalized by the total number of users contending for access, N_T. This metric is formalized as follows,

$$RASSR = \frac{N_S}{N_T}$$

Another performance measure is the efficiency, which is obtained as the total number of users being able to access the system successfully, N_S, normalized by the total number of resources spent to complete the random access procedure, N_R. This metric is formalized as follows,

$$RASE = \frac{N_S}{N_R}$$

GRM3: MAC Fairness (MAC-FAIR) and MAC Availability (MAC-AV)

In many scenarios not only the sum throughput in a certain area (such as a cell) but also the distribution of the throughput is of importance. One possibility to judge the fairness is the Cumulative Density Function (CDF) of the metric of interest, but for simplification the uniformity of a distribution can be measured by the Jain index defined by

$$J(X) = \frac{(E(X))^2}{E(X^2)}$$

where X is a random variable, e.g. the throughput. A Jain index of 1 refers to a uniform distribution meaning perfect fairness whereas a small Jain index indicates a large variation of the random variable.

If this single parameter is not sufficient to describe or compare the fairness, the whole CDF of the metric of interest can be used instead.

Availability is defined as the percentage of users for which a certain QoS requirement is met. In the context of radio link research in METIS, the QoS requirements are expressed in terms of GRM. For example, applications might have associated a MAC reliability requirement R_{QoS} that must be fulfilled . The non-fulfilment of the MAC reliability requirement might invalidate the usefulness of the application. In this case, the availability at the MAC layer A_{MAC} is defined as the probability that the MAC reliability R_{MAC} for each user is equal or above the requirement R_{QoS} specified by the application:

$$A_{MAC} = \Pr\{R_{MAC} \geq R_{QoS}\} = P_{R_{MAC}}(R_{QoS}).$$

For example, an availability of 95% for a MAC reliability requirement of 99% indicates that for the 95% of the users a MAC reliability of 99% is achieved.

GRM4: MAC latency (MAC-LAT)

MAC latency is defined as the time elapsed from when the transmitter MAC receives a packet from its upper layer until it is delivered from the receiver MAC to its upper layer. Packets that are never delivered are said to have infinite delay. Hence, the MAC latency is defined as

$$\tau_{MM} = t_d - t_0$$

where t_d is the time when RX MAC delivers the packet to its upper layer and t_0 is the time when the TX MAC received the packet. A simple example is depicted in Figure 7.1, where τ_{MM} is the MAC latency, τ_{ca} is the channel access delay, τ_p is the propagation delay (which includes the TX PHY processing baseband and RF delays), and τ_{dec} is the decoding delay (which includes the RX PHY and MAC processing delays). In general, the MAC latency also includes any retransmission delays that are due to all ARQ protocols managed by the MAC or PHY layers.

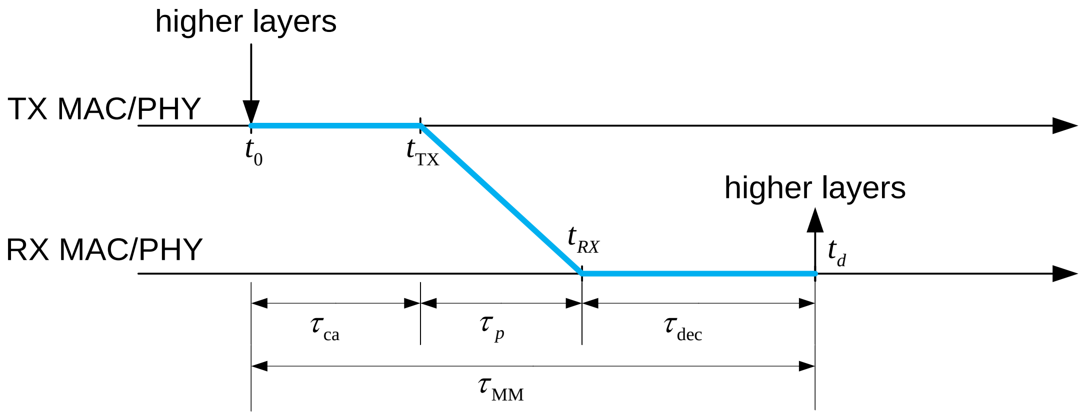


Figure 7.1: Illustration of MAC latency.

The MAC latency is, in general, a random quantity and is fully specified by its CDF

$$P_{\tau_{MM}}(x) = \Pr\{\tau_{MM} \le x\}$$

Since the dropped packets are considered to have infinite delays, we can find the probability of dropped packets from the asymptote of the MAC latency CDF $P_{\tau_{MM}}(x)$ for finite x, formally,

$$\Pr\{\text{packet drop}\} = 1 - \lim_{x\to\infty} P_{\tau_{MM}}(x)$$

see Figure 6.2. The latency properties of the delivered packets are captured by excluding the infinite MAC-to-MAC delays in the CDF. Mathematically, this can be done as

$$P_{\tau_{MM},d}(x) = \Pr\{\tau_{MM} \le x \mid \tau_{MM} < \infty\} = \frac{P_{\tau_{MM}}(x)}{1 - \Pr\{\text{packet drop}\}}$$

Hence, $P_{\tau_{MM},d}(x)$ can be interpreted as the MAC-to-MAC delay CDF of the packets that were *delivered* from the RX MAC and $P_{\tau_{MM}}(x)$ as the CDF of the packets that were *requested to be transmitted* by the upper layer of the TX MAC.

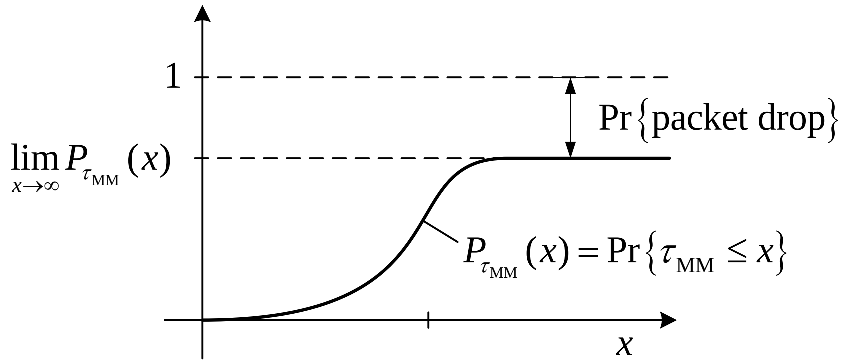


Figure 7.2: CDF of MAC-to-MAC latency.

GRM5: MAC packet error rate, reliability and integrity (MAC-PER/REL/INTG)

The PER includes all errors on the MAC and lower layers that lead to packet loss. Extending the PHY measures BER/FER, which describe errors due to fading/noise, also collisions and device discovery errors are included. In differentiation to the definition of MAC reliability and latency, the PER describes the average packet loss neglecting latency considerations. More specifically packets may be lost due to the following reasons:

- Fading/noise leads to decoding errors;
- Device discovery failure leads to total loss of information;
- Collisions in scheduled or random access lead to loss of a packet.

Thus, the PER is defined as

$$\Pr\{\text{a packet received by the TX MAC from its upper layer is not delivered to RX MAC upper layer}\} = \Pr\{\text{packet drop}\}$$

A packet that is delivered is not necessarily error-free, due to imperfections in the error detection. MAC integrity is the probability that a delivered packet that meets the deadline is also error-free, hence

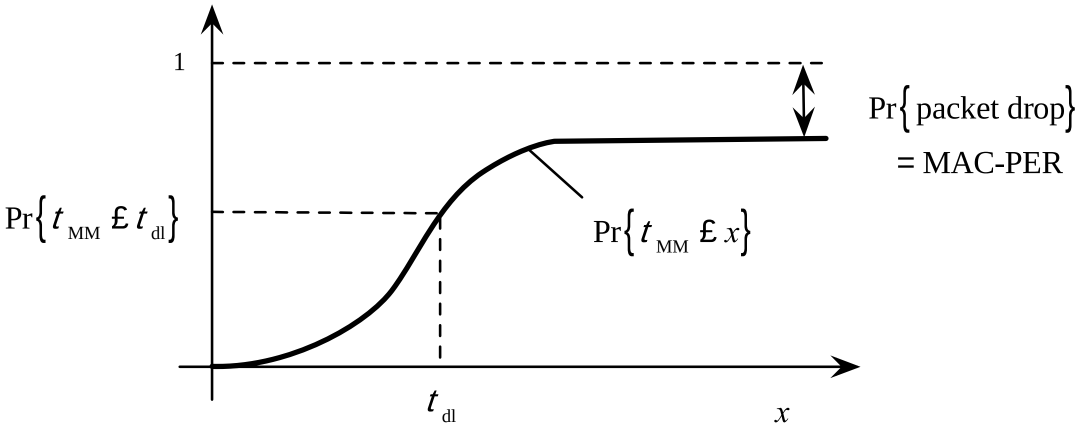
$$\text{MAC integrity} = \Pr\{\text{delivered packet is error free } | \tau_{MM} \le \tau_{dl}\}$$

where τ_{dl} is the deadline.

Now, packets that are useful for the application are those packets that are 1) error-free, and 2) delivered before the deadline. This leads to the natural definition of MAC reliability as

$$\begin{aligned}\text{MAC relibility} &= \Pr\{\text{delivered packet is error-free}, \tau_{MM} \le \tau_{dl}\} \\ &= \Pr\{\text{delivered packet is error free } | \tau_{MM} \le \tau_{dl}\} \Pr\{\tau_{MM} \le \tau_{dl}\}\end{aligned}$$

which establishes the relation between MAC-REL, MAC-INTG and the CDF of MAC-LAT. For example, a MAC reliability of 99% for a deadline of 50 ms indicates that the 99% of the MAC messages can be successfully delivered to their destination within 50 ms. See Figure 7.3 for an illustration.



$$\text{MAC-REL} = \text{MAC-INTG} \times \Pr\{\tau_{\text{MM}} \le \tau_{\text{dl}}\}$$

Figure 7.3: Relation between MAC-REL, MAC-PER, MAC-INTG and MAC-to-MAC delay CDF.

GRM6: MAC Coverage (MAC-COV)

Coverage is related to the relative occurrence of outage inside a certain region. Consider a region R that a transmitter would like to cover. Depending on the transmit power and channel conditions (e.g., path-loss and shadow fading), the not necessarily connected region R_{out} inside R will be in outage. Let the area of the region R be $A(R)$. The (average) coverage is then

$$\text{coverage} = \text{E}\left[\frac{A(R) - A(R_{\text{out}})}{A(R)}\right],$$

where the expectation is over all relevant random channel effects, e.g., shadow fading. The basic concept above is described for 2-dimensional regions, but can easily be extended to 1-dimensional and 3-dimensional regions by interpreting $A(X)$ as the length or volume of the region X. In general, let d denote the dimension of the region.

For MAC coverage, MAC reliability is used to find the outage regions. Recall that the MAC reliability (defined in GRM5) is MAC integrity multiplied with the probability that the MAC-to-MAC delay τ_{MM} is below a specified deadline τ_{dl}, i.e., $R_{\text{MAC}} = \text{MAC-INTG} \times \Pr\{\tau_{\text{MM}} \le \tau_{\text{dl}}\}$,. Given an outage level on the MAC reliability, $R_{\text{MAC,out}}$, we declare outage at the position x when $R_{\text{MAC}}(x) < R_{\text{MAC,out}}$.

To summarize, the MAC coverage, for a given τ_{dl} and $R_{\text{MAC,out}}$, in the region R, is defined as

$$C_{MAC} = \text{E}\left[\frac{A(R) - A(R_{\text{out}})}{A(R)}\right]$$

$$A(X) = \text{area (volume, length) of region } X$$

$$R_{\text{out}} = \text{region where outage occurs}$$

$$R_{\text{out}} = \{x \in \mathbb{R}^d : R_{\text{MAC}}(x) < R_{\text{MAC,out}}\}$$

GRM7: Energy consumption per bit / area unit (ECON-B/AU)

From PHY layer perspective, the factors that determine P/E-CON are:

- Signal processing (P/E-CON-SP): the energy used for digital and analog-front-end processing (without including RF-power amplifier (PA)) in the transceiver chain, which is further closely related to

- Digital signal processing: complexity in terms of the arithmetic operations and the memory access and the data rate.
- Analog front-end processing: DA/AD converting & mixer/oscillator, which are the function of carrier frequency and sampling frequency.

- Radiation power (P/E-CON-Rad): the power used to radiate the signal form the antenna to the medium, which further depends on
  - RF-PA, coverage, waveforms and antenna.

Therefore, the overall P/E-CON-PHY is the sum of P/E-CON-SP and P/E-CON-Rad.

By introducing the following mathematical notations

- E_{PHY} = P/E-CON-PHY
- E_{PHY}^{SP} = P/E-CON-PHY-SP
- E_{PHY}^{Rad} = P/E-CON-PHY-Rad,

physical layer power/energy consumption can be defined as

$$E_{PHY} = E_{PHY}^{SP} + E_{PHY}^{Rad}.$$

From MAC layer perspective, in addition to the above definition, the power/energy consumption must be differentiated with regards to different software protocol design, such as power management, etc.

For example, assume that the power management of certain MAC procedure has two statuses, idle and active. Then, for a given duration, the P/E-CON from MAC layer perspective can be measured by

$$E_{MAC} = E_{PHY}(idle) + E_{PHY}(active),$$

where

- E_{MAC} = P/E-CON-MAC
- $E_{PHY}(idle)$= P/E-CON-PHY at idle status
- $E_{PHY}(active)$= P/E-CON-PHY at active status

Note that the concrete expression depends on the envisaged protocol procedure.

Energy consumption per bit (ECON-B) indicates the overall consumed energy over a given time duration, normalized by the total number of correctly delivered info bits over the same time measure.

$$\xi_{MAC} = \frac{E_{MAC}}{B_{info}}\ (Joule/bit),$$

where B_{info} is the total number of correctly delivered info bits over the same time duration for measuring the consumed energy E_{MAC}.

Alternatively, the P/E-CON efficiency can also be indicated with an energy consumption per area unit (ECON-AU) metric that normalizes the overall consumed energy at a given duration over coverage area, i.e. no

$$\Gamma_{MAC} = \frac{E_{MAC}}{A_{MAC}},$$

where A stands for the coverage area such as GRM6 (MAC-COV).

GRT1: Modem hardware cost (COST-HW)

In the following, all device types relevant to radio link research in METIS (access points, terminals, relay nodes, MTC devices etc.) are considered. The hardware cost can be defined as the cost for the production of a single modem. Mainly depending on the required baseband and RF hardware cost, the modem cost can increase or decrease based on the communication system design. On top of baseband[6] and RF hardware, also other parts of a modem can be included, like peripherals and cooling devices. The modem hardware cost is defined as:

$$COST_{HW} = \mathrm{f}(COST_{DBB}, COST_{AFE}),$$

where

$COST_{DBB}$	Digital baseband cost;
$COST_{AFE}$	Cost of the analog front-end, which contains the analog baseband components and RF front-end.

GRT2: Carrier frequency range (CFR)

The spectrum bands to be used for future wireless systems are not fixed yet and maybe extended even after rollout. The range of possible frequency bands is expected to be very high, from below 380 MHz up to 3000 GHz [MET12-D51]. Solutions proposed by radio link research are expected to work in this wide range of carrier frequencies. A solution may in ideal case be fully flexible (no limitations) or contain some restrictions with certain minimum and maximum supported carrier frequency (f_{c_min}, f_{c_max} respectively).

In case air interface solutions are designed especially for a certain frequency range (e.g. mmW), integration with other air interface solutions targeted for other frequency ranges should be considered (different air interface solutions could eventually be used for different carrier frequencies).

GRT3: Supported bandwidth (SBW)

To be able to have a truly dynamic spectrum allocation/usage, it is necessary not to specify any fixed allocation of a certain frequency bandwidth. For instance in the LTE standard some time-frequency resources are reserved for control signalling which prevents a truly dynamic usage of the spectrum-time space. It is expected that the system bandwidth of next generation system will be increased significantly compared to current systems and may be extended further after rollout. Similar to the flexibility in terms of carrier frequency, also the supported or required bandwidth should be flexible.

GRT4: Number of supported nodes (NSN)

This measure is closely related to GRM2, but here the focus is on the flexibility or scalability with respect to the number of nodes, which are either in active mode or in idle mode. Some schemes do not simply scale with the number of users, like multiuser diversity schemes and certain multiple access schemes.

[6] According to [3GPP12-36888], baseband cost is the most remarkable factor in the modem cost. In [3GPP12-36888], a fractional cost breakdown of LTE baseband, based on input collected from several chip vendors, is presented and shows that the majority of the baseband cost is caused by data processing (especially at the receiver) and buffering (HARQ- and post-fast Fourier Transform buffering).

GRT5: Enabler for Network Heterogeneity (ENHET)

This GRT includes two-fold requirement: on one hand, future air interface solutions are expected to be cost and performance efficient, supporting a wide range of cell sizes, going from macro size to small size. On the other hand, it is envisioned for future air interface to provide solutions for enabling diverse network links, like in-band wireless backhauling, radio access and D2D, covering both coordinated or non-coordinated network nodes.