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Novel radio link concepts and state of the art analysis

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Abstract:

This document provides a detailed overview of the Radio Link concepts being developed in METIS as well as a detailed analysis of the related state of the art. For each of the research topics identified for the radio link research covering flexible air interface, new waveforms, modulation and coding techniques as well as multiple access, medium access control and enablers for radio resource management, a detailed description of the aspects to be investigated will be given, going beyond the limits imposed by the systems operated today and their planned evolutions. The state of the art analysis, which is conducted for each of the research topics separately, covers current standards, their future evolutions as well as latest academic research. Elaborating on how the approaches followed in the radio link research may advance this state of the art carves a promising track towards innovative solutions addressing the challenges of future wireless communication.

Keywords:

air interface, availability, dense deployment, coding, cost, coverage, energy efficiency, fading, faster than Nyquist, filter-bank multicarrier, flexibility, full-duplex, 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, signaling, spectrum efficiency, waveform

Executive summary

This document provides a detailed overview of the Radio Link concepts being developed in METIS together with a detailed analysis of the related state of the art. The research on Radio Link concepts was grouped into fourteen research topics in the first deliverable D2.1, covering a wide range of research on PHY and MAC layer, including flexible air interface design, new waveforms, modulation and coding techniques as well as multiple access, medium access control and enablers for radio resource management. For each of these fourteen research topics this document provides a detailed description of the aspects to be investigated, going beyond the limits imposed by the systems operated today and their planned evolutions. The state of the art analysis, which is conducted for each of the fourteen research topics separately, covers current standards, their future evolutions as well as latest academic research. Elaborating on how the approaches followed in the radio link research may advance this state of the art carves a promising track towards innovative solutions towards a 5G system addressing the challenges of future wireless communication.

In particular, the document addresses three main objectives:

1. Comprehensive state of the art analysis, including current standards and their evolutions as well as academic research. Thus, the report covers available solutions as well as already known but not yet implemented solutions.
2. Description of the limits of the state of the art and analysis in what respect further research is required to meet the goals of METIS.
3. Identification and detailed description of novel radio link concepts and the specific aspects to be investigated advancing current state of the art.

While deliverable D2.1 described the problem space of the radio link research based on a requirement analysis of the test cases identified at the beginning of the METIS project in D1.1, this deliverable D2.2 focuses on the solution space, analysing existing solutions and detailing novel radio link concepts and solutions in METIS addressing those requirements. For the METIS project, different global challenges for a 5G system have been defined and overall goals have been set. Among these are higher throughput per area and per user, lower latency, support of massive number of devices and lower energy consumption compared to systems of today, which are of especially high relevance for the radio link research. Moreover, new enabling approaches for the global system design, the so called horizontal topics, have been introduced. The radio link research will develop PHY and MAC layer solutions addressing the above challenges, provide the appropriate technology enablers for the horizontal topics and thus contribute to fulfil the METIS overall goals. The foundations of this research will be laid in this document.

Contents

List of Abbreviations, Acronyms, and Definitions

2G	2^{nd} Generation
3G	3^{rd} Generation
3GPP	Third Generation Partnership Project
4G	4^{th} Generation
AC	Access Class
ACK	Acknowledgement
AD	Analog to Digital
AMC	Adaptive Modulation and Coding
AP	Access Point
ARQ	Automatic Repeat reQuest
AV	Availability
AWGN	Additive White Gaussian Noise
B4G	Beyond 4G
BB	Baseband
BER	Bit Error Rate
BH	Backhaul
BLER	Block Error Rate
BLT	Balian-Low theorem
BOM	Bill-of-Materials
BPSK	Binary Phase Shift Keying
BR	Bandwidth Request
BS	Base Station
BW	Bandwidth
C2R	Complex to Real
CA	Collision Avoidance
CAPEX	Capital Expenditure
CCRS	Coordinated and Cooperative Relay Systems
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CFO	Carrier Frequency Offset
CFR	Carrier Frequency Range
C-ITS	Cooperative Intelligent Transport Systems
COV	Coverage
C-plane	Control plane
CP	Cyclic Prefix
CP-OFDM	Cyclic-Prefix Orthogonal Frequency Division Multiplexing
CQI	Channel Quality Indicator
CPM	Constant Phase Modulation
CR	Cognitive Radio
CRAD	Cell Radius
CRC	Cyclic Redundancy Check
CRS	Common Reference Signal
CS	Compressive Sensing
CSI	Channel State Information
CSMA	Carrier Sense Multiple

	Access
C-TP	Cell Throughput
C-UE	Cellular UE
CW	Contention Window
D2D	Device-to-Device
DA	Digital to Analog
DCC	De-centralized Control Congestion
DCF	Distributed Coordinated Function
DeNB	Donor eNB
DFT	Discrete Fourier Transform
DIFS	Distributed Coordination Function Inter-Frame Spacing
DL	Downlink
DMRS	Demodulation Reference Signal
DRX	Discontinuous Reception
DS	Distribution System
DTX	Discontinuous Transmission
DVB	Digital Video Broadcast
DwPTS	DL Pilot Time Slot
ECON-AU	Energy consumption per area unit
ECON-B	Energy consumption per bit
EDCA	Enhanced Distributed Channel Access
EDGE	Enhanced Data Rates for GSM Evolution
EE	Energy Efficiency
eIMTA	enhanced Interference Management and Traffic Adaptation
eNB	Enhanced node B
EPDCCH	Enhanced PDCCH
ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
FAI	Flexible Air Interface
FAIR	Fairness
FBMC	Filter-Bank Multi-Carrier
FD	Full Duplex
FDR	Full Duplex Radio
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FeICIC	Further enhancement of inter-cell interference coordination
FER	Frame Error Rate
FFT	Fast Fourier Transform

FIR	Finite Impulse Response
FMT	Filtered Multi-Tone
FSPA	Full Search Power Allocation
FTN	Faster Than Nyquist
FTPA	Fractional TPA
GBR	Guaranteed Bit Rate
GFDM	Generalized Frequency Division Multiple Access
GGMA	GR/GRM Mapping Approach
GI	Guard Interval
GLB	Green Link Budget
GOMP	Group Orthogonal Matching Pursuit
GP	Guard Period
GPRS	General Packet Radio Service
GPS	Global Positioning Service
GR	General Requirement
GRM	General Requirement Metric
GRT	General Requirement Tag
GSM	Global System for Mobile Communications
HARQ	Hybrid ARQ
HETNET	Heterogeneous Networks
HPA	High Power Amplifier
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HT	Horizontal Topic
HW	Hardware
ICI	Inter Carrier Interference
ID	Identifier
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IFDMA	Interleaved FDMA
IFFT	Inverse Fast Fourier Transform
IM	Intermodulation
INTG	Integrity
IOTA	Isotropic Orthogonal Transform Algorithm
IP	Internet Protocol
IR	Incremental Redundancy
IRC	Interference Rejection Combining
IS	Interference Suppression
ISI	Inter Symbol Interference
ITS	Intelligent Transport Systems
KPI	Key Performance Indicator
L1	Layer 1
LA	Local Area
LAN	Local Area Network
LAT	Latency
LDPC	Low Density Parity Check
LDS	Low Density Signature
LFDMA	Localized FDMA
LLC	Logical Link Control
LNA	Low Noise Amplifier
LOLA	Low-Latency
LOS	Line of Sight
LSE	Link Spectral Efficiency
LTE	Long Term Evolution
LTE-A	LTE Advanced
M2M	Machine to Machine
MA	Multiple Access
MAC	Medium Access Control
MAI	Multiple Access Interference
MAP	Maximum A-Posteriori
MAX	Maximum
MBSFN	Multicast Broadcast Single Frequency Network
MC	Multi Carrier
MCS	Modulation Coding Scheme
MDFT	Modified Discrete Fourier Transform
MIM	Multiple Interface Management
MIMO	Multiple Input Multiple Output
MLD	Maximum Likelihood Detection
MMC	Massive Machine Communication
MMSE	Minimum Mean Square Error
mmW	Millimeter Wave
MN	Moving Networks
MPA	Message Passing Algorithm
MRE	Multi-rate equalizer
MTC	Machine Type Communication
MTD	Machine Type Device
MTU	Maximum Transmission Unit
MU	Multi User
MUD	Multi User Detection
MU-MIMO	Multi User MIMO
MUPA	Multi User Power Allocation
NACK	Negative ACK
NLOS	Non Line of Sight
NOMA	Non-Orthogonal Multiple Access
NW	Network
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OFDP	Optimal Finite Duration Pulse
OMA	Orthogonal Multiple Access

OPEX	Operational expenditure
OQAM	Offset QAM
PAL	Protocol Adaptation Layers
PAM	Pulse Amplitude Modulation
PAPR	Peak-to-Average Power Ratio
PAR	Project Authorization Request
PBCH	Physical Broadcast CHannel
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PER	Packet Error Rate
PHY	Physical
PMI	Precoder Matrix Indicator
PMP	Point to Multipoint
PRB	Physical Resource Block
ProSe	Proximity Service
PSS	Primary Synchronization Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RA	Random Access
RAN	Radio Access Network
RAST	Random Access Schemes Throughput
RAT	Radio Access Technology
REL	Reliability
RF	Radio Frequency
RLC	Radio Link Control
RMS	Root Mean Square
RN	Relay Node
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio Resource Management
RS	Reference Signal
RT	Research Topic
RTG	RX/TX Transition Gap
RTT	Round Trip Time
Rx	Receiver
SA2	System Aspect, Work Group 2: 3GPP Architecture
SAW	Surface Acoustic Wave
SBW	Supported Bandwidth
SC	Subcarrier
SCMA	Sparse Code Multiple

	Access
SDM	Spatial Division Multiplex
SE	Spectral Efficiency
SFO	Sampling Frequency Offset
SG	Scheduling Grant
SI	Study Item
SIC	Successive Interference Cancellation
SIFS	Short Interframe Spacing
SINR	Signal to Interference plus Noise Ratio
SISO	Single-Input Single Output
SLNR	Signal-to-Leakage and Noise Ratio
SMT	Staggered Multi-Tone
SotA	State of the Art
SR	Scheduling Request
SRS	Sounding Reference Signal
SSID	Service Set Identifier
SSS	Secondary Synchronization Signal
STA	Station
STBC	Space Time Block Code
STDMA	Self-organizing Time Division Multiple Access
SU	Single User
TA	Timing Advance
TC	Test Case
TCCA	TETRA + Critical Communications Association
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TETRA	Terrestrial Trunked Radio
TFL	Time Frequency Localization
TGad	Task Group ad (IEEE802.11ad)
TM	Transmission Mode
TP	Throughput
TPA	Transmit Power Allocation
TPC	Transmission Power Control
TTG	Tx/Rx Transition Gap
TTI	Transmission Time Interval
Tx	Transmitter
UDN	Ultra Dense Network
UE	User Equipment
UHF	Ultra High Frequency
UL	Uplink
UMTS	Universal Mobile Telecommunications System
U-plane	User plane
V2D	Vehicle-to-Device
V2I	Vehicle-to-Infrastructure

V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-X
VANET	Vehicular Ad Hoc Network
VHT	Very High Throughput
VoIP	Voice over IP
WA	Wide Area
WAVE	Wireless Access in Vehicular Environments
W-CDMA	Wideband CDMA
WI	Work Item
WiGig	Wireless Gigabit Alliance
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WP	Work Package
WPAN	Wireless Personal Area Network
WSS-US	Wide-Sense Stationary Uncorrelated Scattering
XOR	Exclusive OR
ZF	Zero Forcing

1 Introduction

This deliverable provides an overview of the Radio Link concepts being developed in METIS as well as a detailed analysis of the related state of the art. The aim of the report is to give a complete though preliminary view on all radio link aspects investigated in METIS, coupled with an elaboration on how these will advance the current state of the art towards a 5G system. The content of this document will serve as a guideline and starting point for upcoming deliverables D2.3 and D2.4, where detailed research results will be presented.

In the following, we will give a detailed description of the objective of this document, explain its structure and briefly summarize the radio link requirements presented in the previous deliverable D2.1, which represent the means for the overall connection of the radio link research to the METIS test cases, overall goals and METIS Horizontal topics.

1.1 Objective of document

While D2.1 [MET13-D21] described the problem space of the radio link research in METIS, where the requirements for the research have been deduced from the end-user requirements defined in D1.1 [MET13-D11], this document D2.2 focuses on the solution space aiming to fulfil those requirements. For each of the research topics, which have been briefly introduced in D2.1, D2.2 provides a comprehensive state of the art analysis and details the new design approaches followed to address the requirements and targets identified in D2.1.

This deliverable covers all tasks of the radio link research and will provide an outlook on the planned research, thus defining the entire radio link solution space, which can be mapped to the problem space defined in D2.1. The generic requirement metrics (GRMs) defined in D2.1 will be used for the evaluation and comparison of different radio link solutions introduced in this deliverable, the results being subject of the succeeding deliverables D2.3 and D2.4.

Currently standardization bodies such as 3GPP or IEEE are planning to address some of the new challenging requirements described in D1.1 in their future releases or amendments, and hence these should be considered as a kind of baseline. In the past, however, these standards mainly focussed on user-centric traffic; other use cases, like MMC or ultra-reliable communication, were not in the main focus or were considered of secondary importance. In contrast to this, METIS aims for a flexible air interface design providing an integrated solution for all the use cases to be covered by future mobile and wireless communication, where many different kinds of services with very diverse demands can be successfully delivered with the desired quality at minimum system cost. In this respect we plan to go far beyond currently planned amendments of 3GPP and IEEE standards, where the goal of integrating different services to this extent is beyond their current scope.

Academia provides a huge amount of new ideas to solve certain problems, but often the target use case is rather specific and practical application may be limited. Within METIS and especially in radio link research, we aim to go beyond the state of the art and combine the most promising solutions for facilitating a flexible air interface design. Solutions proposed in the past serve as inspiration and starting point, but to achieve our challenging goals, we also need to give room for completely new ideas and solutions. Research should thus cover the entire space of ideas that may fuel the development of novel design approaches.

The objectives can be summarized as follows

- Comprehensive state of the art analysis with respect to the identified radio link research topics including
    - current or planned standards reflecting the available solutions
    - academic state of the art describing known but not yet implemented solutions.

- Description of the limits of the state of the art and analysis in what respect further research is required to meet the goals of METIS.
- Detailed description of the planned research starting from a general description of the research area and followed by an identification of the specific aspects to be investigated and advancing current state of the art.

These objectives will be addressed for each of the 14 radio link research topic in chapter 2.

1.2 Structure of the document

The elaborations can be found as follows:

- **Chapter 1: Introduction**

  This chapter aims to clarify the scope of D2.2 and set certain objectives of D2.2

- **Chapter 2: Radio Link Research Topics**

  In this chapter all radio link research topics will be described in more detail with comprehensive state of the art analysis. This analysis will include current or planned standards reflecting the available solutions as well as academic state of the art describing known but not yet implemented solutions. For each research topic (RT) there will be the following subchapters

  1. General description
  2. Related State of the art and limits
  3. Detailed description of planned research

- **Chapter 3: Summary**

  The last chapter summarizes the main findings presented in the document.

1.3 The overall connection: Radio link requirements

While this document focuses on the solution space by describing in detail the radio link research topics, keeping the problem space in mind is essential to steer the research directions and ensure a harmonized work towards the overall goals of METIS. The problem space for the radio link research has been subject of deliverable D2.1.

In order to connect the outcome of radio link research to the METIS overall goals and test cases, a requirement and KPI mapping framework has been established and explained in D2.1. By taking a radio link specific perspective, the most relevant challenges and requirements were derived from the test case descriptions given in D1.1, and it was illustrated how these will be addressed by the radio link research topics.

In D1.1, a set of test cases (TCs) has been defined to illustrate the main challenges to be addressed in the METIS project. These TCs were defined in D1.1 from an end user perspective, without restricting the solution space. From a radio link perspective, it is not straightforward to derive corresponding link layer challenges, as many other aspects impact the possible solution, such as scenario/TC specific propagation models, antenna solutions, deployment proposals, bandwidth and carrier frequency proposals and architecture aspects.

To solve this issue we developed in D2.1 a mapping approach based on so-called general requirement metrics (GRMs) and general requirement tags (GRTs), capturing the requirements most relevant for the radio link research. With this approach, we can establish a mapping between the end user requirements and the radio link requirements. Furthermore, this approach can help us to link the radio link research topics to the radio link requirements as well as to METIS Horizontal Topics (HTs) as illustrated in Figure 1.1. The GRMs defined in D2.1 will be used in the succeeding deliverables for the evaluation and comparison of the different radio link solutions introduced and detailed in this deliverable.

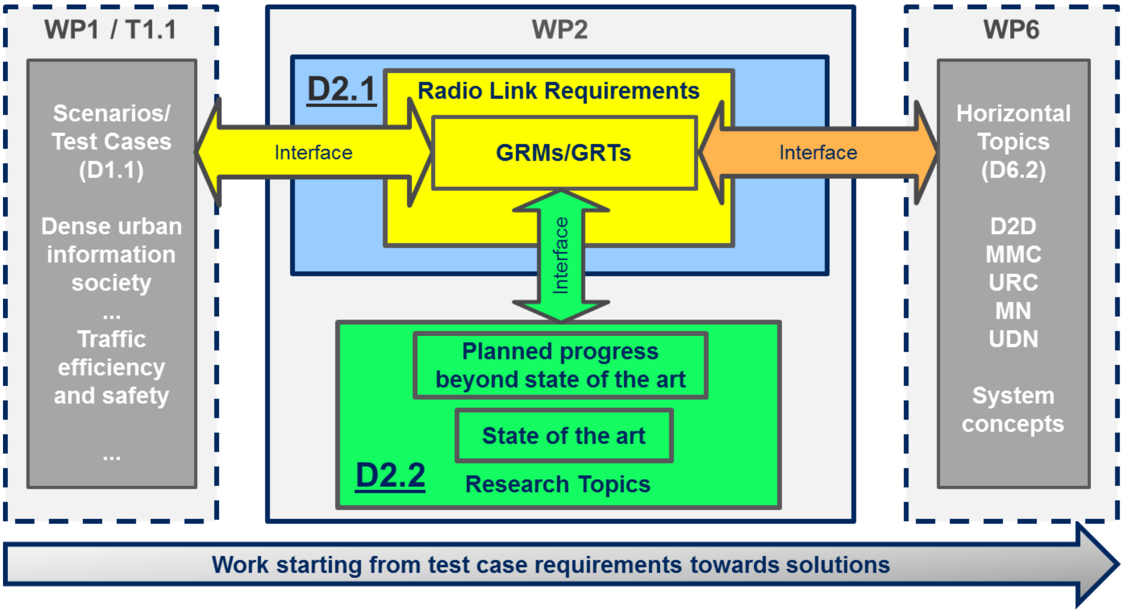


Figure 1.1 Illustration of requirement mapping framework in D2.1

2 Radio Link Research Topics

In order to achieve the general goal of METIS of 1000 times data volume per area and 10 to 100 times user throughput, a threefold approach is chosen leading to a combination of

- increased spectrum, e.g. by using higher frequency bands up to and including mmW bands,
- network densification by introducing a large amount of access points, possibly as an underlay system,
- and, last but not least, significant improvements of spectral efficiency.

In addition also new approaches and technology enabler for fulfilling the end user requirements are considered in METIS, like moving networks enabling moving relays, and direct device-to-device (D2D) for further offloading. Furthermore, also new challenges are addressed like support of massive machine communication (MMC) and ultra-reliable communication (URC). All these challenges are reflected in the radio link research in METIS, focusing on the PHY and MAC enablers to achieve the goals of METIS.

The METIS radio link research is structured into three tasks 2.1 – 2.3. The first 6 RT cover task 2.1 "Flexible Air Interface Design", followed by the 4 topics in task 2.2 "Waveforms, Coding & Modulation and Transceiver Design" and finally 4 topics covering task 2.3 "Multiple Access, MAC and RRM".

The radio link research topics are related to the following topics in METIS

- METIS horizontal topics (HTs)
    - Ultra dense networks
    - Direct D2D
    - Massive machine communication
    - Moving networks
    - Ultra reliable communication
- Enablers for usage of new spectrum and cognitive radio
- Improving spectral efficiency
- Flexibility and scalability, which was identified in D2.1 to be a major goal for the air interface design

In order to provide mature integrated radio link solutions to the entire system concept, close collaboration and coordination between the individual proposals is necessary. This coordination will be done along different paths. Each radio link concept to be proposed, e.g., for a certain horizontal topic like MMC, consists of PHY and MAC layer solutions. Therefore, already in WP2 the PHY and MAC solutions targeting a certain problem or network aspect should be aligned and combined. Furthermore, concurrent solutions addressing the same solutions have to be compared in a realistic environment. In this document the basis is laid by showing relevant relations between different proposals. This is a continuous process during the entire project and will therefore be updated and elaborated further in future deliverables.

The relation of all radio link research activities to the overall METIS HTs defined in [MET13-D62], METIS overall goals and other radio link challenges will be briefly explained in the following, allowing to structure the diversity of approaches which are explained in more detail in the following subchapters and indicate planned collaboration and coordination.

Network densification is covered by the HT ultra-dense networks (UDN) and is assumed to be one important enabler to achieve the goal of increased throughput per area. Several radio link research topics investigate air interface aspects relevant for UDN, like transceiver design for full duplex (2.10), and medium access control for UDN (2.12). By investigating and improving general aspects such as latency and throughput, by providing solutions enabling wireless backhauling for an OFDM system and together with the usage of higher and dynamic frequency bands, the research in section 2.1 aims to provide air interface solutions optimized especially for dense deployment.

Another focus of METIS is the future spectrum usage, like the use of higher frequency bands and cognitive radio (CR) approaches. Radio link research provides possible solutions for the air interface for dynamic spectrum usage (2.3), constrained envelope modulation schemes suited also for high frequencies including mmW (2.9), multiple access schemes for cognitive radio (2.11) and application of Filter Bank Multicarrier (FBMC) for CR (2.8) to exploit these new opportunities.

The challenge of providing much higher throughput per area and per user may not solely be reached by network densification or new spectrum, but also increasing spectral efficiency should contribute to achieve the goal. This is targeted by research activities on Faster than Nyquist (FTN) (2.7), application of FBMC (2.8) and related multiple access techniques (2.11), non-orthogonal multiple access (2.11), new modulation and coding techniques (2.9) and advanced equalizers for single-carrier transmission (2.10).

The idea of direct D2D communication is to offload traffic and to enhance the frequency reuse factor. Radio link research plans to provide specific Radio Resource Management (RRM) enablers (2.14) and multiple access techniques for D2D (2.11).

A new application becoming relevant for future wireless networks is MMC. This is specifically challenging for the radio link layer. To enable an efficient support of MMC, new multiple access (2.11) and medium access control schemes (2.12), HARQ enhancements (2.13), synchronization issues (2.12) and general signalling aspects for MMC (2.2) are to be investigated in the radio link research. In these research topics, also URC is considered.

Last but not least, moving networks (MN) are an important enabler to extend coverage and reliability of the network and impose a challenge for the radio link as well. Robust solutions designed based on FBMC systems (2.8) are investigated as well as an air interface designed for moving networks (2.6).

With all these requirements and the diversity of solutions, flexible design and interface management are of increasing importance, as most likely a one-fits-all solution will not be able to efficiently address all the demand of the diverse services of future wireless networks. These aspects are also investigated in this WP by advanced link adaptation (2.4), flexible modulation and coding (2.9) and HARQ design (2.13) as well as flexible signalling structures (2.5).

2.1 Air interface in dense deployment

2.1.1 General description

In the METIS deliverable D2.1, the air interface design in dense deployment is described targeting METIS goals of the future demands in terms of perceived traffic growth in dense environment at the same time the demands of low cost and low energy consumption. The ultra-dense networks are assumed for local area deployment with access nodes and user terminals in the same order in density and in transmit power. Dense networks may be integrated under so called umbrella networks or clusters to ensure seamless coverage resulting in multi-layers of networks or clusters.

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

2.1.2 Related state of the art and limits

TDD LTE-A [3GPP-TS36211] and WLAN 802.11ac/ad [IEEE-802.11][PG11][IEEE-802.11ad] physical frames are both based on OFDM. TDD LTE-A frame, presented in Figure 2.1 a) follows the LTE frame structure type 2. One radio frame consists of 10 subframes, having 1 ms duration each. DL/UL direction switching is included in the form of the special subframe providing support for two switching point periodicities[1] (5ms and 10ms) and containing three fields: DL pilot time slot (DwPTS), guard period (GP) and UL pilot time slot (UpPTS), for which the lengths can be configured between 3-12, 1-10 and 1-2 OFDM symbols respectively. GP time includes sum of the switching times of both switching directions (DL-UL and UL-DL). The UL/DL switching ratio can be adjusted only with limited flexibility; 7 UL/DL configurations have been defined in 3GPP with DL:UL ratio varying from 2:3 to 9:1.

The WLAN systems are typically based on carrier sense multiple access with collision avoidance (CSMA/CA). Basically, each station senses the medium for a period of time defined as distributed coordinated function (DCF) inter-frame space (DIFS); in case the medium is idle the station can take the ownership and begin a frame exchanging sequence. The short inter-frame space (SIFS) is inserted between successive frames. The SIFS, mainly dominated by the processing delays over propagation delays, is designed to accommodate for the following actions: PHY Rx latency, MAC processing and PHY Tx latency. As the duration of DIFS has been defined to be SIFS + 2×SlotTime, it allows the station owning the medium to finish the transmission sequence without interruptions from the other stations. The principle of DIFS and SIFS timings is shown in Figure 2.1 b).

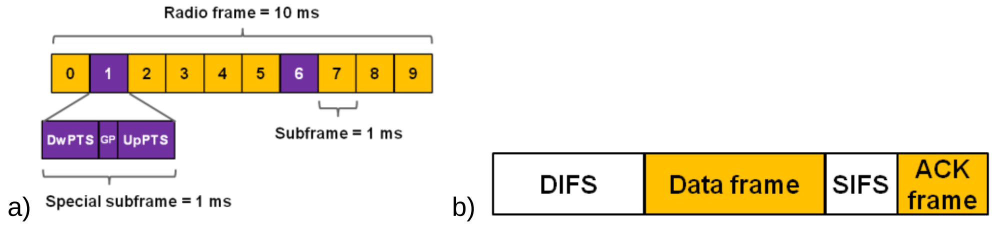


Figure 2.1 Frame structure of a) TDD LTE-A, b) WLAN 802.11ac guard times

The main physical layer limits of TDD-LTE and WLAN 802.11ac/ad technologies are summarized in Table 2.1.

Table 2.1 Main physical layer parameters and limits of TDD LTE-A and 802.11ac/802.11ad

	TDD LTE-A Release 11	802.11ac/802.11ad	METIS UDN target
SC spacing	15 kHz	802.11ac: 312.5 kHz 802.11ad: 5.15625 MHz	Under study (same BB design applicable for different SC spacing)
Carrier frequencies	Varying from 699-716MHz to 3600-3800MHz	802.11ac: 5 GHz 802.11ad: 60 GHz	>~3 GHz ...100 GHz
Channel bandwidth	1.4MHz, 3MHz, 5MHz, 10MHz, 15MHz, 20MHz	802.11ac: 20MHz, 40 MHz, 80 MHz, 160 MHz, 80 MHz + 80 MHz 802.11ad: 2.16 GHz	Estimated maximum available BWs varies according to carrier frequency (100 MHz ... 1-2 GHz)
UL/DL switching period	5ms (and 10ms) = hard limit for the physical layer latency	Not restricted by frame structure.	Flexible
UL/DL ratio	Varying from 2:3 to 9:1 in a subframe	Not restricted by frame structure.	Flexible

[1] In 3GPP Rel'12, there is a study on enhanced interference management and traffic adaptation (eIMTA), which may allow for more flexible switching points between radio frames.

Minimum TDD switching time	Minimum allowed TA adjustment = 20.3 µs	SIFS = 16 µs	Lower (should not cause too much overhead)
CP/GI overhead	CP overhead: 6.6% (with normal CP length of 4.7µs in front of every 66.7 µs symbol)	GI overhead: 802.11ac: 11.1% at minimum (0.4 µs GI in every 3.6 µs symbol) 802.11ad: 25 % (48.5 ns GI in 0.194 µs symbol)	Lower (should not cause too much overhead)
Frequency guard overheads	10% at minimum (with channel bandwidths of 3, 5, 10, 15, 20 MHz)	802.11ac: From 5.5% at minimum (with 160 MHz BW), up to 12.5% (with smaller bandwidths). 802.11ad: approximately 19 % for SC and OFDM PHY (approximately 1760 MHz BW in 2.16 GHz wide channel)	Lower (should not cause too much overhead)
RS (Reference Signal) & Ctrl overheads	For DL with normal CP length: CRS (Common Reference Signal): 3.6-14.3% (depends on the # of antenna ports) UE specific DM-RS: 7.1-14.3% (depends on the # of layers) PDCCH: 7.1-21.4% (+ possible EPDCCH overhead in Rel11)	Overheads hard to define since data length can be variable.	Lower
Physical HARQ RTT	Variant from 8ms up to 16ms (depends on the link direction, UL/DL configuration and subframe number)	No support for PHY layer HARQ	Lower (around e.g. ~1 ms)
# of HARQ processes	DL: varies between 4 and 15 UL: varies between 1 and 7	No support for PHY layer HARQ	Under study
Physical 2-way control signaling latency	≥13.5 ms in total (depends on the used UL/DL configuration)		Lower (around e.g. ~1 ms)
Multi-antenna support	8x8 MIMO (DL) 4xN (N≥4) MIMO (UL)	802.11ac: up to 8 layers in DL (MU-MIMO), a station can receive up to 4 layers. 802.11ad: beamforming, no spatial multiplexing (1 layer transmission only)	Massive MIMO should be enabled by PHY layer solutions.
Link independent design	Separate designs for DL, UL, D2D	Not restricted.	UL and DL links with symmetric elements
Cross-link interference mitigation	Not possible to orthogonalize RSs over cross-links		Under study
Standalone / centrally coordinated deployment and	Supports in-band relaying. If a UE is connected to a relay, the eNB cannot control the scheduling, HARQ and	WLAN can be deployed by both standalone and centrally coordinated manner.	PHY layer should support (self-)coordinated operation among multiple cells and standalone

wireless backhauling	SR/CQI/ACK for the UE. There is no inherent support for control signaling supporting both coordinated and standalone modes.		operation, multi-hop in a mesh of access nodes to one or several aggregation nodes in any spectral bands and mechanisms for switching on/off UDN (e.g. idle) nodes on demand and handing over traffic from/to umbrella cells -> need of flexible resource management and robust control plane.

The impact of 5G dense deployment environment and how the evolvements in component technology may affect to the physical TDD frame numerology have been studied in [LPB+13]. Adaptive CP length is studied in [ZL04]. The paper proposes a method for estimation of RMS delay spread, and based on the estimate, selects the CP length. The CP length and power allocation are jointly optimized in [DTL10]. The approach is iterative and suboptimal, but significant improvements can be achieved. Joint bit loading and adaptive cyclic prefix is studied in [DTL09]. A dynamic UL-DL configuration and interference management for TDD systems are motivated and evaluated in the context of LTE layered network with macro cells and small cells in [SKE+12]. The effect of CP length for OFDM systems is reported in [BBK04].

2.1.3 Detailed description of planned research

To meet the METIS requirements on ultra-dense deployment, the METIS UDN system is targeting much higher data rates, spanning to much larger frequency regions with wider bandwidths and at the same time targeting much lower energy consumption and cost compared to the existing technologies. Also new connection types (wireless backhauling, D2D etc.) need to be supported. As a result, an air interface to support flexibility and better (self-) coordination among access nodes in a UDN context is needed. Moreover, a METIS UDN is much denser than the LTE-A system resulting in more symmetric uplink and downlink in power (compared to macro or micro cell deployments) which gives additional opportunities to explore. The main physical layer parameters to be researched and aimed to be improved by this RT were listed in Table 2.1 together with initial target and comparison to existing LTE-A and WLAN 802.11ac/ad technologies.

In this RT, the air interface concept for dense deployment consists of the following building blocks:

- OFDM-based waveform, due to good time localization enabling low latency and low cost receiver with good MIMO/beamforming performance.
- Dynamic TDD, due to its capability to flexibly and dynamically allocate the available bandwidth to any link direction, motivated by bursty traffic demand in small cells and need to support new connection types. In addition, TDD has lower radio component cost, it does not require duplex filters, the amount of available bandwidth is larger for TDD (over FDD) and it enables utilization of channel reciprocity.
- Synchronization: All nodes in a UDN should be assumed to be (locally) synchronized (e.g. by using a distributed synchronization algorithm), which simplifies coordination among devices, RRM, and increases energy efficiency since a device can perform multiple measurements simultaneously.
- Frame based access (meaning that frames of different devices and cells in the network have concurrent timings), due to efficient usage of resources.

- Physical layer frequency numerology optimized for UDN: the air interface needs to support usage of different carrier frequencies, from low (~3 GHz) to very high (mmW, up to 100 GHz) frequencies with increasing amount of available BW. LTE-A technology may be estimated to reserve the frequencies at least around 3GHz, so they (and lower frequencies) may not be that prominent for METIS UDN. Ideally, to reduce cost and complexity of the baseband (BB), same BB design should be reused for multiple carrier frequencies and bandwidths. When increasing carrier frequency (towards mmW), the available BW and SC spacing may be simultaneously increased (in step-wise manner in order to minimize complexity), to keep the FFT size manageable and by using clock rate of integer multiples of e.g. the LTE-A base clock. Furthermore, numerology optimized for mmW is under study to ensure the move towards the new higher frequency region.
- Physical frame TDD numerology optimized for UDN: TDD parameters such as guard period (GP), cyclic prefix (CP) etc. are investigated and optimized for UDN environment together with certain expected evolvements in component technology. These aspects enable usage of shorter GP and CP times compared to existing technologies even with low carrier frequencies. The delay spread and therefore related frame numerology may further be variable according to the carrier frequency (in step-wise manner in order to minimize complexity).
- Frame structure (and control signaling) optimized for UDN environment: The UDN optimized TDD numerology enables the usage of shorter subframe length and a physical subframe structure design fully optimized for TDD (with potentially more frequent TDD switching inside e.g. one scheduling interval). These aspects will provide more flexibility and further improve e.g. total link spectral efficiency and PHY layer latency (related to e.g. HARQ RTT and control signaling). Moreover, related HARQ scheme and timings together with considerations about the needed amount of soft buffering are to be investigated. More specific design and relation to different set of carrier frequencies are also included in the study. Flexible control signaling mechanism supporting both coordinated and standalone modes is to be further investigated. A flexible or variable TTI length to contain a whole IP datagram thus avoid segmentation is also under investigation.
- Modulation and coding: Given the large considered bandwidths, it is important to enable fractional allocations of the total bandwidth to individual users (e.g. with either multi-carrier transmission scheme). A desirable feature is to maintain the possibility of simple frequency-domain equalization. An adaptive coding scheme which enables switching among different code classes may be beneficial.
- Multi-antenna and high-gain beamforming: In some of the high frequency bands, radio wavelengths are substantially smaller than those in conventional cellular networks, further enabling a considerable number of antenna elements to be equipped inside an access node without compromising its physical dimensions. Even though the expected transmission distances in UDN are short, the required levels of received energy are challenging given the envisioned high data rates. Beamforming at the access node, for both transmitter and receiver, is one possibility to increase received energy. In general, the amount of antenna elements can be increased as increase of carrier frequency which is part of the study.

2.2 Optimized signaling structure for low-cost MMC devices

2.2.1 General description

The expected widespread use of low-cost MMC devices, which some forecasts [Eri10] indicate will reach tens of billions devices world wide 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 behavior follows one of a botnet [SJL+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 signaling overhead. Therefore this leads to the necessity of designing a signaling 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 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 coverage for MMC and the use of the coordinated relay and device-to-device paradigm to enable reliable uplink coverage for MMC and efficient coexistence with non-MMC devices.

2.2.2 Related state of the art and limits

From the industry side, currently MMC traffic is mostly handled through solutions based on the GSM family (GSM/GPRS/EDGE). As consequence, in 3GPP [3GPP-TR37868] there has been an effort to not only enhance further the GSM related standards as to facilitate the serving of this kind of traffic; as well as to set the path so that LTE related standards can take over the MMC. This latter effort has been mostly on the reduction of complexity at the terminal side.

In 3GPP there is an on-going effort on enabling low cost LTE devices [LKH+13], [3GPP-TR36888] for MMC, where the reduction in cost comes mainly from lowering the device bandwidth, baseband processing complexity, and using half-duplex transceivers. From the many challenges to enable these devices to coexist with normal LTE devices [Bea12], the main one is the reduced coverage, which is commonly addressed by reducing the cell sizes, introducing relays, or increasing the transmission time. The latter option is the one gaining traction [Bea12].

The efforts related to enable cost effective MMC in LTE, have been championed by two FP7 projects the EXpAnding LTE for Devices (EXALTED) and Achieving LOw-LAtency in Wireless Communications (LOLA).

EXALTED aimed at the specification of a communication system for MMC – denoted as LTE-M - coexisting with LTE in the same frequency band. EXALTED was dedicated to optimize the LTE system for a set of MMC requirements, taking backward compatibility issues into account. The MMC requirements include improved energy efficiency and reduced cost for the MMC devices, and efficient support of small payloads, extended coverage and support of 100-1000 active MMC devices per cell for the system. The assumed latency requirements were rather relaxed (>100ms message delay). Optimization for stationary devices was also considered.

LOLA's main target was the optimization of latency in LTE systems for specific MMC use cases. LOLA provided input to 3GPP standardization directly and targeted the improvement of LTE MAC and PHY-layers in terms of framing, scheduler design, and adaptive coding and modulation and ACK/NACK feedback.

From the academia side, in the literature there can be found several efforts to enable efficient MMC within GSM and LTE cellular networks [CL+13]. The current focus is mostly on the characterization of the effect of a massive amount of Machine Type Devices requesting access in a cell [SJL+12], [PVS11], [MSP+13], on adaptive contention and load control schemes to handle massive contention access [PTS+12, SPV12, LLK+12, CLW+12] and on traffic aggregation in cellular devices from non-cellular networks [LKH+13].

Most MMC application scenarios are expected to dominate the traffic load in uplink direction, therefore there is a concern in regards to the uplink scheduling [GLA12] and coverage degradation due to low complexity MMC devices [Bea12].

In cellular communication systems, such as LTE, uplink scheduling takes place at the eNB and the allocation decisions are communicated to the users (UEs) through appropriate control channels. As the number of devices grows, so does the associated signaling load. Based on the scheduling requests, the eNB decides the RB allocation at each TTI, and sends this to the MMC devices through the corresponding DL control channel. Hence LTE is unable to support hundreds of MMC devices demanding simultaneous access to the shared channel in future MMC scenarios. Since MMC-enabled LTE is a rather recent research area, the bibliography on MMC Scheduling is still scarce. In [LC11], [LCL11] a group based scheduling approach reducing complexity for radio resources management and scheduling is proposed. It is based on the formation of groups of MMC devices or "clusters", where each cluster is associated with a prescribed QoS profile. Then MMC devices are transparently connected to and managed by LTE, since the eNB controls the cluster entities. Scheduling prioritization is imposed on a cluster basis, a policy that significantly reduces complexity and overhead. Cluster formation is dictated by the packet arrival rate and maximum tolerable jitter. In [JWM+07], [PKH+08], [FLK+08], and [MLM+10], semi-persistent scheduling schemes have been proposed for effectively dealing with periodic data traffic characteristics. Semi-persistent scheduling takes an allocation decision for a longer time period, thus reducing physical layer control signaling overhead.

The coverage of MMC devices can be enhanced through the use of the D2D communication paradigm. Within the literature dedicated to D2D, the synergies to be gained by combining MMC and D2D have not until now been identified, although the authors of [LK06] have motivated that the use of relaying in the uplink direction in cellular network is one of the key aspects to enable MMC within a cellular network. Within the D2D context, the work can be classified in regards to how the spectrum is shared with the cellular network, i.e. either in underlaying [DRW+09, DRJ+09, JYD+09] or in overlaying [KA08] D2D. In 3GPP it was started a study item on proximity services based on D2D [3GPP-TR36843]. Further, it should be noted that the approaches currently applied to D2D are also applicable to Vehicular-to-Vehicular (V2V), as shown in [ZCY+13]. There are two main design directions currently found in the literature:

- Network-assisted D2D. The network performs all the decisions in regards to resource sharing mode selection (D2D or via the cellular infrastructure), power control, scheduling, selection of transmission format (such as modulation, coding rates, multi-antenna transmission mode, etc.);
- D2D with minimal network assistance. The network provides at most only synchronization signals to the devices.

In [MSL+11] the authors introduce three receiving modes for reliable D2D communication when the D2D UEs share the cellular radio resources. The first mode treats the interference as noise, the second mode decodes the interference and then cancels it. For the transient region between low and very strong interference, instead of the conventional approach where resources are orthogonal, the authors propose a mode in which the interference is retransmitted to the receiver which then cancels it from the original transmission.

2.2.3 Detailed description of planned research

The research topics considered here are in line with the ones proposed in RT 12 dealing with random access. Under this research topic, it is planned to pursue the following research topics:

- Current LTE specifications were designed to cover broadband applications and a relatively small number of served UEs per cell. To achieve a high peak data rate and enable high mobility a certain amount of control signaling is necessary. But most M2M applications transmit or receive only a small amount of data, which leads to high amount of control information compared to the actual payload. In typical MMC scenarios with a huge number of MTC devices, the overall amount of control information would easily impose a burden on the access network that finally results in congestion situations. Hence, decreasing signaling overhead is crucial for a METIS MMC solution. A sophisticated, traffic-aware access management scheme can directly reduce signaling overhead, assuming that collisions can be resolved. Therefore, we will 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. Once, the device is scheduled no additional signaling information is required. This can lead to a reduced signaling overhead, where long-term traffic characteristics are exploited. Using a clever random access scheme has the main advantage that exchange of scheduling information on a TTI basis is not required for minimizing signaling overhead.
- For sporadic traffic with random arrivals a scheme based on an approach that combines random access transmission and advanced PHY multi-devices detection transmission is considered. Here, traditional S-ALOHA throughput is enhanced by a narrowband spreading of the uplink signal. The spreading is performed by quasi-orthogonal codes that are not pre-assigned, i.e. the machine randomly chooses a code in order to perform its transmission. Therefore, when receiver complexity in the base station is allowed to increase, a SIC-like receiver is employed and is able to simultaneously detect many machines transmissions. This approach also supports the issue of the low power transmission by the spreading gain imposed by the code.
- Another of the challenges that MMC poses to the cellular network, is the one of low transmission power that can lead to outage problems for devices at the cell-edge. In this research track it will be explored the opportunity opened by D2D links for supporting MMC devices, since it can be desirable to carry the MMC traffic not through direct links to a base station (BS), but through a nearby relay. The planned research includes the proposal and analysis of schemes that allow the underlaying of low rate and low power MMC links; while alleviating the problem of massive access through the use of local relay links facilitated by D2D.

2.3 Air interface supporting new and dynamic spectrum usage

2.3.1 General description

In order to improve the spectrum utilization, it is important that the air interface should be able to operate in new spectrum bands and support dynamic usage of spectrum. This research topic focuses on the RF architecture and air interface support to dynamic spectrum sharing. Research of air interface support to operate in new spectrum and dynamic spectrum sharing in dense deployment is included in the research topic 2.1 “Air interface in dense deployment”. The LTE specification has fixed allocation for control channels and true dynamic spectrum usage or reconfigurability is not considered. LTE and LTE-A RF blocking requirements cannot be matched for FDD operation without front end duplexers. Thus the fundamental wideband requirement essential for dynamic spectrum usage are not met.

The spectrum availability varies with time. No frequency range is available at all times which leads to the requirement that the physical channel for control should be dynamically reconfigurable. Efficient spectrum usage is possible with a reconfigurable radio necessitating a frequency-agile front end in the hardware, wherein the front end can tune in to any frequency band based on the spectrum considerations. Such wideband RF architecture needs a filterless design which creates problems with the linearity and frequency selectivity of the system; thereby challenging the SNR of the system.

2.3.2 Related state of the art and limits

For a true dynamic spectrum access the receiver should be filterless meaning without any surface acoustic wave (SAW) based filters or duplexers and hence should be frequency agile. Regardless of an integrated circuit being wideband, the stringent filtering requirements for LTE limits the front end to be narrow band. Challenges such as the frequency selectivity and Tx leakage and hence the support for legacy systems are still bottlenecks. The requirements of such a multiband receiver are dealt in detail in the [HW11][AI13]. The system parameters of a receiver namely the linearity (usually expressed as second and third order intercept points) and noise figure are evaluated under the presence of in-band, out-of-band blockers and Tx leakage. The requirements pointed out are not met in the state of art. [TSN+08] shows a state of the art transceiver for WCDMA/HSDPA. The concerned receiver is a SAW-less tri-band receiver. Although it is multiband, it can be seen that separate receiver chains are incorporated to accommodate different bands rather than a single wideband front end. The paper addresses the Tx leakage problem arising out of an FDD scenario as well as the interference scenario in the absence of the SAW filters. As individual Rx chains are not wideband, specifications in the presence of the interferers are met by selective Tx filtering and high linear stages. The system mentioned above is tested with a WCDMA Tx leakage at -180 MHz and -90 MHz offset or duplex distance. But as the duplex distance becomes smaller to 30 MHz as in the case of LTE bands 12, 13, 14 and 17, filtering of Tx leakage is a big challenge. [BTT+11] shows another state of the art SAW-less receiver supporting multiband operation. The receiver here is designed to support WCDMA as well GSM bands. The referred architecture uses separate eight receiver chains in order to achieve the multiband operation.

Another significant multiband architecture is published in [IGB+10]. The multiband transceiver acts as a frontend for software defined radio and can support DVB-H, GSM/EDGE, WCDMA, GPS, MIMO WiMAX and MIMO WLAN. The architecture is SAW-less and covering wideband frequencies from 100 MHz to 6 GHz. As a single wideband RF front end being not optimal, four different low noise amplifiers (LNA) covers the above said frequency range. For the FDD scenario, the authors have used the duplexer to attenuate the TX leakage but have avoided inter-stage SAW filters to reduce the BOM (bill of materials) and to improve the flexibility. Hence from the state of the art RF architectures described above, dynamic spectrum access can be provided only with multiple receiver chains occupying a large silicon area wherein separate receiver chains support the existing bands. Besides, for an FDD scenario, an efficient method of TX leakage cancellation under wideband operation is yet to be devised. Hence the cost and complexity is increasing with generation and intelligent wideband architecture such as the cognitive radio is needed to handle the ever crunching spectrum scenario.

2.3.3 Detailed description of planned research

As explained in the state of the art chapter, present multiband architectures have separate RX/TX chains to cover multiple frequency bands. Hence the future wireless communication systems are expected to have numerous RX/TX chains in order to handle 2G, 3G, 4G and above. The result is a large bill-of-materials (BOM) due to large number of SAW filters, duplexers, switches, power amplifiers, larger than desired form factor and as well as power consumption. The solution to such a scenario is a frequency agile front end. Such a wideband front end can be dynamically configured and tuned into any desired frequency band. The aim of such architecture is not only wideband operation, but to reduce BOM by a filterless design. A wideband architecture also has to support the legacy systems such as GSM and 3G along with the LTE. This necessitates different duplex modes such as FDD and TDD. Under this scenario, the receiver has to maintain the required frequency selectivity and linearity to sustain the in-band and out-of-band blockers. Besides, the TX leakage coming from the transmitter in an FDD is a big challenge. Design of a high linear RF front end and an investigation of duplex modes to support legacy systems are the main challenges in the design of the frequency agile architecture.

As a first step, a highly linear prototype is designed using of-the-shelf components and a detailed system design is then pursued. The frequency of operation is the UHF, where in addition to four LTE bands (bands 12, 13, 14 and 17), DVB-T2 bands are also present. The system performance of the architecture is weighed against the LTE RF specifications. Instead of any simulation tools, the system level plan can be done using spreadsheet tools. Such a system design will give first hand insights to the various challenges encountered. The frequency selectivity, interference effects and the noise performance can be qualitatively calculated. This approach can be performed across other possible architectures. The most suitable architecture can be then prototyped. The wideband capability, specific requirements for frequency selectivity, linearity requirements and impact on RF performance under different duplex methods can be identified to devise a frequency agile architecture for multiband operation. This new architecture will be able to demonstrate wideband operation with a simplified filter less front end. A convergence of the new approach with legacy standards might also be possible by introducing a half duplex FDD operation.

2.4 Interface-management and advanced link-adaptation techniques

2.4.1 General description

The future wireless network needs to meet a number of new challenges. The QoS/QoE requirements, data rate requirement, packet sizes and traffic pattern will become even more diverse. As we evolve into a more connected lifestyle, the adoption of systems such as smart appliances and smart vehicles mean that there will be massive number of devices connected to the Internet wirelessly. These different terminal types will have different signal processing capability.

Current wireless standards (e.g. LTE), while providing significant enhancements over previous generations, will not be able to fully meet these challenges. The existing design is geared towards a one-size-fit-all solution which is not flexible and efficient enough for the variety of applications and services envisioned for the future. A single monolithic air interface design will not be able to suit the competing needs of different applications. When designing the future air interface, considerations are taken to address several key challenges, in particular:

- Latency
- Overhead
- Capacity (spectral efficiency, number of users etc.)

However, these challenges are not always equally relevant. Depending on the traffic type and UE conditions, one challenge can be more important than another. Some applications will have more stringent latency requirements, while other applications can tolerate more delay. It is inefficient to transmit small packets with a high signaling overhead compared to large packets. With large packets, one can tolerate more dynamic signaling while still keeping high spectral efficiency, but for small packets, the overhead has to be reduced in order to obtain a similar spectral efficiency.

This motivates a software configurable air interface to provide the flexibility in adapting the diverse characteristics of future applications.

Software configurable air interface mechanisms combined with link adaptation techniques is one of key technical challenge of Multiple Interface Management (MIM) to be addressed in the METIS project in order to ensure seamless connectivity with desired QoS and QoE and desired radio coverage. Flexible Air Interface (FAI) and multi-RAT CQI metrics dedicated to FAI and multi-RAT deployments have to be designed and implemented over cross layer mechanisms related to LA metric implementation through PHY/MAC/RRM and IP layer mechanisms and therefore considering radio link as well as network level. In the multi-RAT link adaptation technique current RAT and other emerging RAT from METIS including new waveforms will be encountered.

2.4.2 Related state of the art and limits

In current air interface standards, the configurability of individual components (e.g. waveform, TTI, retransmission mechanisms) is limited. Take an example of the LTE standard [3GPP-TS36300], [DPS11], [Ayv13] the waveform selection is based on physical layer parameters such as Peak-to-Average Power Ratio (PAPR) requirement. It is defined for the downlink with OFDMA and uplink with SC-FDMA. In terms of frame structure, the TTI duration is fixed to 1 ms regardless of the latency requirement of the traffic and channel conditions of the users. Retransmission mechanism using HARQ in LTE is the same for all traffic types. The choice is limited to stop-and-wait protocol with multiple HARQ processes [DPS11].

METIS aims at a variety of applications, with different traffic and channel types, including ultra dense networks, ultra-reliable communication, D2D, M2M, and moving networks. This places extremely high demands on the flexibility of the air interface. It is expected that a single air interface is not enough to cater for the needs of such diverse scenarios. Also, there is a trend towards multi-standard capable base-stations using software defined digital radio technology to reduce the deployment and operational cost. This motivates a software-defined approach.

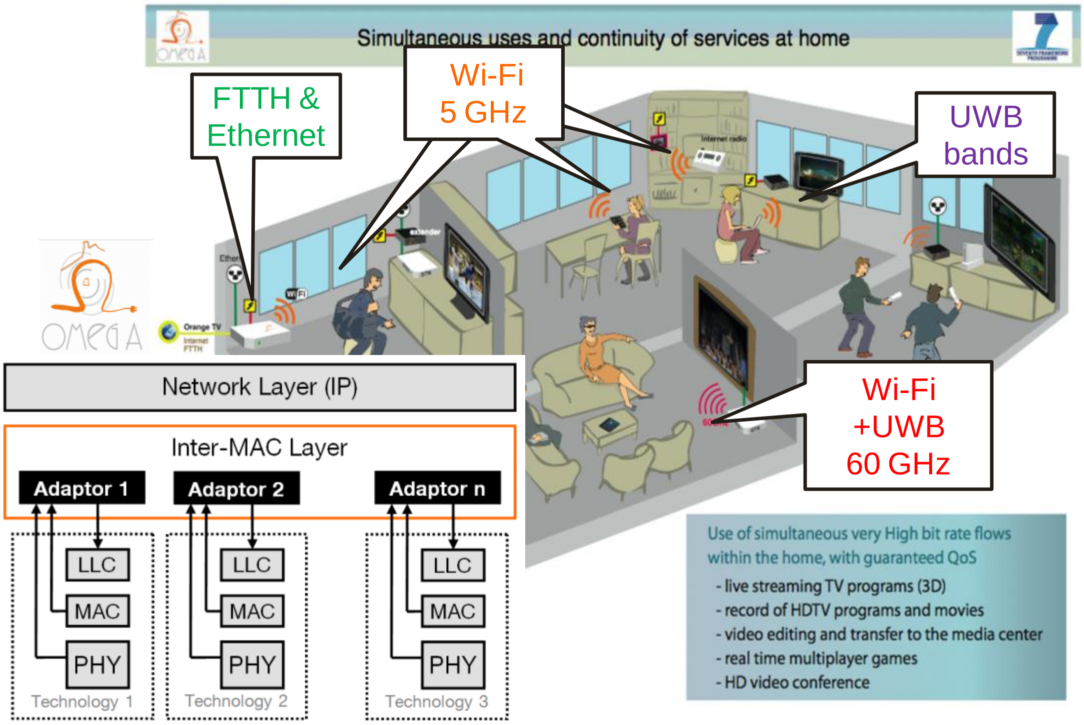


Figure 2.2 : Home network seamless connectivity in the ICT-FP7 OMEGA project.

Link adaptation techniques in the 3GPP standard [Pel13] [3GPP-TS36211],[3GPP-TS36213], [3GPP-TS36214] utilize a feedback CQI information converted into a 4-bit CQI parameter from a RSSI estimation [3GPP-TS36213]. The selection is done following a spectrum efficiency optimization. These algorithms do not encounter Energy Efficiency criteria.

In the ICT-FP7 OMEGA project, Multiple Interface Management (MIM) has been investigated leading to a H/W platform [OMEG2+11] for the Home Network Wi-Fi technologies, UWB and Wireless Optic transmissions have been combined with wireline transmissions to fulfill high QoS and multi-service deployment [OMEG1+11] into a seamless connectivity as shown in **Error! Reference source not found.**. A L2.5 layer has been introduced to manage several nterfaces considering the best path selection between devices assimilated to nodes and other PHY/MAC link efficiency criteria. In the METIS project, complementary mechanisms will be studied to set up low complexity MIM.

2.4.3 Detailed description of planned research

A software configurable air interface is proposed to provide the flexibility in adapting the diverse characteristics of future applications. It is customized to best serve different applications under different transmission and reception conditions at the same time. In general, an air interface consists of several fundamental building blocks: waveform, frame structure, multiple access scheme, transmission/re-transmission mechanism and coding/modulation, as illustrated in Figure 2.3.

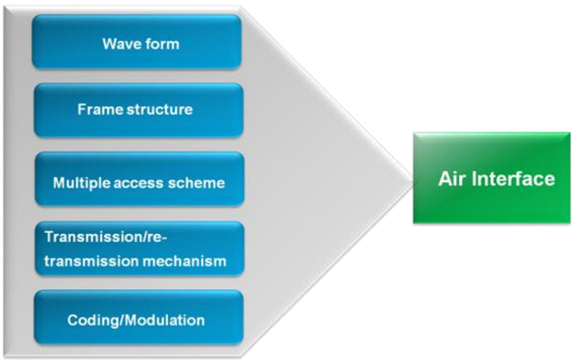


Figure 2.3: Building blocks of an air interface.

The software configurable air interface consists of adaptation mechanisms for the different building blocks as shown in Figure 2.4:

- Adaptive waveform
- Adaptive data transmission scheme
- Adaptive frame structure
- Adaptive multiple access scheme
- Adaptive coding and modulation

The steps to realize air interface adaptation are shown in Figure 2.5. The different candidate schemes for each building block are predefined. Based on a set of input parameters such as the traffic types (e.g. QoS) and transmit/receive conditions (e.g. channel variation, the capabilities of transmitter and receiver), decisions are made to select the best scheme from each building block.

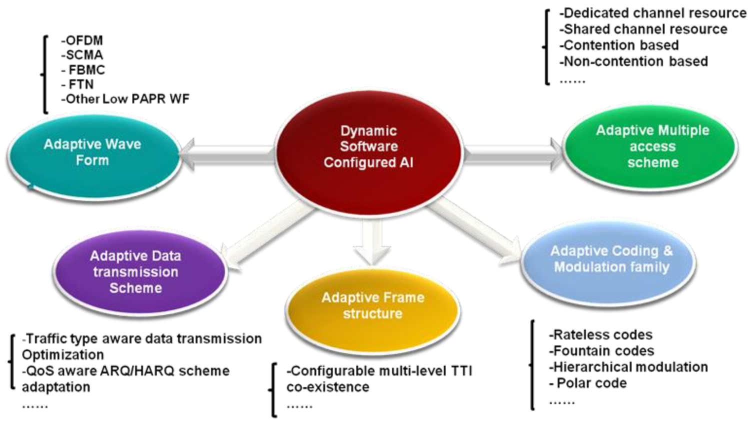


Figure 2.4: Software configurable air interface.

The signaling mechanism required to enable adaptive air interface includes information exchange with the network on UE capability during initial access as well as informing the UEs on the building block selection by the network. Signaling can be explicit (e.g. waveform selection and cyclic prefix selection). Implicit signaling can also be used under some scenarios, e.g. for a fixed mapping between a scheme of each building block and the associated input parameters of traffic type and transmit/receive conditions. From time to time, explicit signaling can be used to override the implicit mapping.

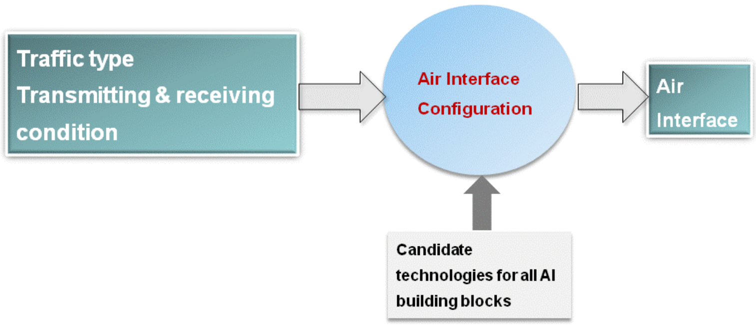


Figure 2.5: Air interface adaptation mechanism.

EE metrics dedicated to multi-RAT link adaptation techniques with low complexity implementation schemes will be investigated in METIS upon FAI and Multi-RAT architectures. The objective in METIS is to design EE CQI metric to perform FAI LA and propose practical set-up architectures regarding PHY and MAC signaling frames. Dedicated FAI use cases related to advanced HET NET architectures composed of Wi-Fi components for small cell deployments integrated into LTE-A macro cells as shown in Figure 2.6 have been designed in Green Touch [GreenT] and will be optimized in the METIS project.

A novel CQI metric based on link budget assessments in order to ensure QoS and radio coverage targets is being designed. This metric, denoted Green Link Budget (GLB) metric performs multi-RAT and FAI link adaptation techniques ensuring QoS, radio coverage and transmit power minimization [US12]. First results exhibit gain up to 16 dB in UDN and short range scenarios.

The next step is to evaluate the GLB metric upon METIS multi-RAT use cases. Close collaboration with the research on network level is planned to sketch the GLB metric relevance in further multi-RAT optimizations.

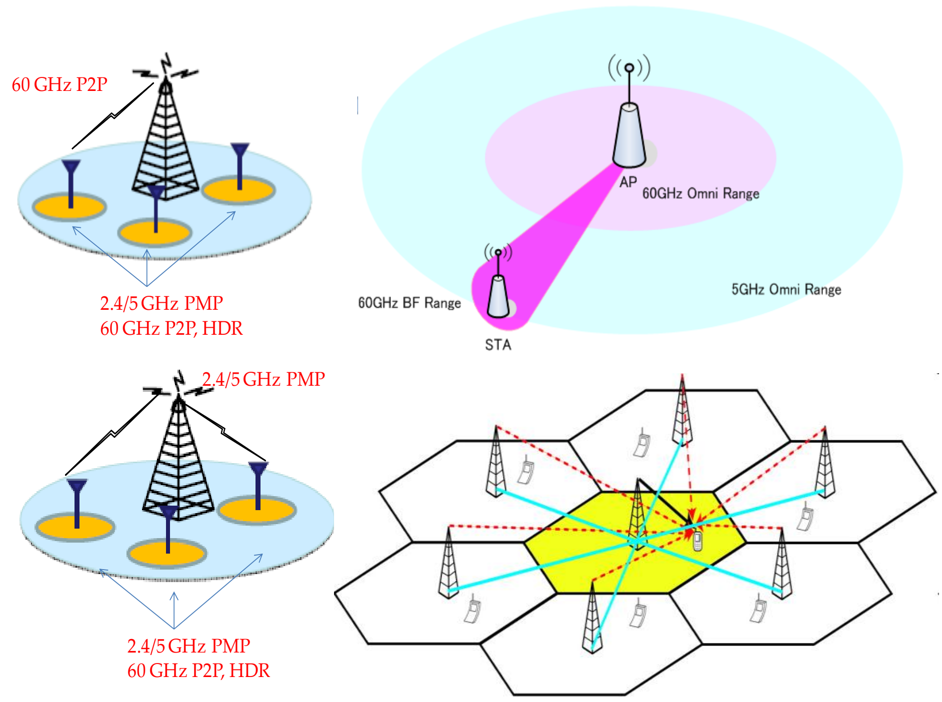


Figure 2.6 : HET NET Flexible air interface use cases

2.5 Signaling for advanced multiple-access and new waveforms

2.5.1 General description

The design of the radio air interface and multiple access for future wireless communication systems should improve the system capacity and spectrum efficiency significantly and also take into account the diversity of environments and requirements that need to be supported. In addition, it is important to vastly reduce overhead while still improving the spectrum efficiency sufficiently. To this end, new signaling concepts/schemes are of interest in order to provide:

- Further improvement of spectrum efficiency by using more advanced multiple access that exploits new dimensions (e.g., power-domain) and utilizes additional signaling information on desired and/or interference signals.
- More dynamic adaptation of the system configuration and interface (e.g., waveform, numerology, reference signal density) according to the environments (e.g., low and high mobility, local area and wide area) and requirements of diverse types of devices (e.g., M2M) and services, as discussed in section 2.4.

2.5.2 Related state of the art and limits

In the future, more advanced transmitter (Tx) and receiver (Rx) cooperation techniques are required in order to further improve system capacity and spectrum efficiency. In particular, co-channel interference, either from inter-cell or co-scheduled intra-cell users, is one dominant limiting factor for achieving higher capacity in current networks. In 3GPP LTE Release 11, the performance requirements were defined for practical linear interference suppression (IS) receivers as they showed promising performance gains [3GPP-TR36829]. In another 3GPP LTE Release 11 work item (FeICIC: Further enhancement of inter-cell interference coordination), non-linear interference cancellation receivers that mitigate strong interference among reference, synchronization signals and control channels (e.g., CRS/PSS/SSS/PBCH) have been shown to provide gains over linear receivers.

Further enhancements to intra-cell and inter-cell interference mitigation at the receiver side for data channels could be achieved by further Tx/Rx cooperation via increasing the degree of knowledge about interfering transmissions with possible tighter coordination in the network. Compared to transmission-side coordination techniques whose performance degrades under imperfect channel knowledge at the transmitter side due to limited feedback, receiver side interference mitigation can to some extent alleviate the burden of channel feedback. The baseline receivers for either intra-cell or inter-cell interference mitigation are linear interference suppression (IS), and non-linear processing interference cancellation (IC), such as successive interference cancellation (SIC) and maximum likelihood detection (MLD). However, in general for inter-cell, the performance of SIC receivers would degrade at cell edge when interfering signals use higher-order MCS while MLD complexity will increase exponentially with the number of interfering signals and MCS level. In LTE Release 12, discussions are ongoing about linear IS receivers and iterative/non-iterative explicit IC receivers with participating transmitters coordinating and providing side knowledge of the interference.

The followings are the two main target scenarios in LTE Release 12:

1. Inter-cell interference for homogeneous and heterogeneous deployment scenarios
2. Intra-cell interference resulting from current SU-/MU-MIMO operation

<u>Inter-cell interference for homogeneous and heterogeneous deployment scenarios</u>

Examples of the information exchanged between cells for inter-cell interference mitigation and studied in LTE Release 12 are:

- The presence and characteristics of interference
- The transmission schemes of interfering signals including:
    - Resource allocation
    - Reference symbols for possibly enabling channel estimation
    - Number of RS ports
    - Physical cell ID / Virtual cell ID
    - Modulation format and/or coding rate.
    - Slot number
    - Cyclic prefix length information
    - System bandwidth for CRS/CSI-RS
    - PDSCH bandwidth for DM-RS
    - MBSFN configuration for CRS
    - PDSCH start symbol

These kind of network-assisted IS/IC requires standardization efforts on the signaling aspects that can enable more effective and robust UE-side interference cancellation and/or suppression with possible network coordination, as well as on the physical layer changes that can translate link-level improvements of these advanced receivers to system-level capacity gains [3GPP13-RP130404]. It is also important to study the trade-off, in terms of performance, complexity, and signaling overhead, when enabling feasible and robust interference cancellation/suppression at the UE side with and without network assistance.

2.5.3 Detailed description of planned research

A new non-orthogonal multiple access (NOMA) scheme is studied where intentional non-orthogonality is introduced in the downlink. For downlink NOMA, power domain is exploited for multi-user multiplexing at the transmitter side and successive interference cancellation (SIC) is used at the receiver side to mitigate intra-user interference. NOMA efficiently exploits the power-domain by translating the channel gain/path-loss difference among users to user multiplexing gains. In addition, differently from the ongoing discussions on network-assisted interference cancellation and suppression (NAICS) in LTE Release 12 where the main focus is on intercell interference, NOMA assumes SIC at the receiver side in order to mitigate intra-cell interference that is intentionally introduced at the transmitter side. There are many key technologies related to NOMA such as multi-user scheduling, multi-user power allocation, MIMO extension that require new designs. These design aspects are discussed in Chapter 2.11. Signaling aspects specific to NOMA (e.g., other users MCS, etc.) are also important in order to balance performance enhancement with signaling overhead. In particular, it is important to clarify how much gain can be expected by additional signaling and to what level of granularity (time/frequency/space) the signaling should be carried out to inform the receiver about the interference from other NOMA multiplexed users.

In the following a brief description of some ideas we plan to pursue in order to reduce the signaling overhead associated with multi-user transmit power allocation of NOMA is presented. Because of the power-domain user multiplexing of NOMA, the transmit power allocation (TPA) to one user affects the achievable throughput of not only that user but also the throughput of other users. Therefore, it is important to clarify the degree of impact of user pairing and TPA on the performance of NOMA while taking into account the issue of signaling overhead. To this end, both exhaustive and simplified user pairing and power allocation schemes will be explored:

- Full search power allocation (FSPA)

The best performance of NOMA can be achieved by exhaustive full search of user pairs and transmit power allocations. In case of full search power allocation (FSPA), all possible combinations of power allocations are considered for each candidate user set. FSPA remains, however, computationally complex. Also, with dynamic TPA, the signaling overhead associated with SIC decoding order and power assignment ratios increases. In order to clarify the impact of user pairing and TPA, examples of simplified schemes to be considered are as follows.

- Fractional transmit power allocation (FTPA)

In order to reduce further the computational complexity of FSPA, a suboptimal fractional transmit power allocation (FTPA) [OKH12], that is similar to the transmission power control used in the LTE uplink is adopted. FTPA decides the power allocation based on the channel gain information of the candidate users and the weighting α_{FTPA} parameter. Note that α_{FTPA} is fixed for all candidate user sets. It is an optimization parameter that needs to be determined *a priori* via computer simulations such that the target performance evaluation metric is maximized.

- Pre-defined user grouping and per-group fixed power allocation (FPA)

In NOMA, users with large channel gain difference (e.g., large path-loss difference) are paired with high probability. Thus, considering practical implementations, simplification of user pairing and TPA could be possible with limited impact on performance. To this end, a simplified scheme where users are divided into different user groups according to their channel gains and the pre-defined thresholds, denoted as Ψ in Figure 2.7, will be explored. In this pre-defined user grouping, the users can be paired together only if they belong to different user groups. In general, dynamic TPA according to instantaneous channel conditions of multiplexed users achieves the best performance because of its efficient utilization of the power resources. With the pre-defined user grouping, however, TPA could also be simplified by applying fixed power assignments to users belonging to the same group. For example, for the user group with good channel gain, small power (e.g. 0.2P) is allocated and for the user group with bad channel gain, large power (e.g. 0.8P) is allocated, where the total power assigned to different user groups is kept equal to P. Pre-defined user grouping and fixed TPA can effectively decrease the amount of downlink signaling related to NOMA. For example, the order of successive interference cancellation (SIC) and information on power assignment do not need to be transmitted in every subframe but rather on a longer time scale. The impact of such reduction of signaling on the performance of NOMA will be investigated.

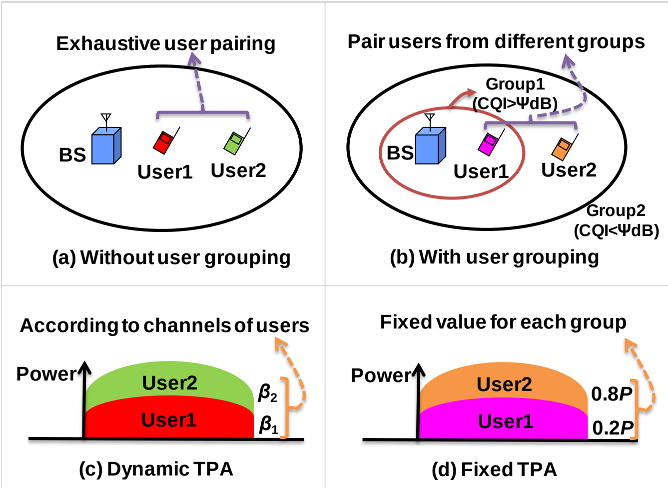


Figure 2.7 User grouping and TPA for NOMA.

In addition, we will study NOMA performance gains with frequency-domain (sub-band) scheduling and sub-band MCS (modulation coding set) selection and compare it to NOMA with wideband scheduling and wideband MCS selection. In LTE, the same channel coding rate (including rate matching) and data modulation scheme are assumed over all the sub-bands allocated to each single user, as the average SINR over all the sub-bands is used for MCS selection. However, for NOMA, such a mismatch between MCS adaptation sub-band unit (e.g., wideband) and power allocation sub-band unit (e.g., sub-band) may not allow to fully exploit NOMA gains.

2.6 Air interface of moving networks

2.6.1 General description

The design of the radio air interface of future wireless communication systems should account for V2V, V2D (vehicular-to-device), and V2I (vehicular-to-infrastructure) communications, so that it is 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.

Nevertheless, the radio interface of future wireless communications networks cannot be designed to support the high level of reliability required by traffic safety applications during the 100% of the time and in every reception scenario, as this would result in an overdesigned and very inefficient system in terms of data rate and power consumption. This limitation complicates the use of wireless communications for traffic safety applications, due to the fact that a failure to comply with the reliability requirements at any moment can render the traffic safety service completely useless or even harmful to the users relying on the service. This calls for the introduction of a new framework to detect and signal the presence of an ultra-reliable link to dependable applications, and to ensure the use of wireless links by these applications only in those instances in which the reliability requirements can be fulfilled.

To efficiently support mobile broadband for moving relays/cells/networks efficient backhauling and handover algorithms are essential, which calls for the incorporation of novel channel estimation and prediction techniques into the air interface in order to cope with the propagation channel of highly mobile users, as well as moving D2D links (i.e. V2V and V2D).

The direct communication between mobile users 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.

2.6.2 Related state of the art and limits

Framework for ultra-reliable communications

LTE incorporates retransmissions schemes based on Hybrid Automatic Repeat Request (HARQ) as well as Adaptive Modulation and Coding (AMC) in order to counteract the impairments of the propagation channel and ensure the correct delivery of information [3GPP-TS36]. In the case of ultra-reliable communications, and more particularly in the case of traffic safety applications, messages have to be delivered under very stringent delay constraints and with very high probability. The failure to comply with the delay constraints of this kind of applications might have serious implications for the safety of users. In this context, the use of HARQ and AMC cannot ensure the timely delivery of information to the upper layers during 100% of the time and in every reception scenario. Moreover, the broadcasting nature of traffic safety messages is generally not well suited to the application of HARQ and AMC mechanisms due to the lack of feedback information.

A very interesting technique that combines error correcting codes and ARQ techniques in the context of reliable communications is deadline dependent coding [UWA+00] [UR05]. The main idea behind deadline dependent coding is to make each component in the communication protocol deadline dependent. Following the main philosophy of reliable communications, the objective is to deliver the information correctly before a certain deadline. By means of retransmissions, the deadline dependent coding protocol increases the probability of receiving the information the closer we come to the deadline.

In [JK09], the authors proposed a generic framework that combines both retransmissions and a timing analysis in order to provide some degree of reliability and hard real-time support. This means that transmissions after a certain deadline are acceptable neither for the first transmission of a packet nor for any retransmission. To this purpose, the framework supports the retransmissions of erroneous packets only as long as their deadline has not been reached, and as long they do not jeopardized the real-time guarantees of other traffic flows. However, the framework is not aimed at safety critical applications, and therefore, does not consider very high reliability levels.

In the context of cellular systems, the work in [NK11] performs an end-to-end analysis of LTE from the point of view of M2M systems, and more particularly, from the point of view of automotive applications, among others. However, no solution for ensuring reliability in this kind of networks is investigated.

Channel estimation

A sufficiently accurate channel model is a pre-requisite for any study or design of a communication system; channel modeling is especially important for channel estimation. The V2I channel is, in many cases, adequately modeled using traditional micro-cell cellular models, since the road infrastructure often is placed at similar positions as micro-cell base stations. However, the V2V channel is different and relatively poorly understood. The main differences between cellular and V2V channels are that in the V2V case, both the transmitter and receiver are mobile and their antennas are placed at approximately the same height [MMK+11] [MTK+09a] [MTK+09b]. Cellular base station antennas are, of course, not moving and are normally placed higher than the typical terminal. This implies that both the small-scale fading (which is due to multipath propagation and Doppler effects) and the large-scale fading (which is due to shadowing effects from large objects, including buses, trucks, and other large vehicles, in the propagation environment) differ. In fact, the established paradigm of separating propagation effects into path loss, small-scale, and large-scale effects has been challenged by some authors [MTK+09b]. Measurement campaigns also indicate that the statistical properties of the channel are time-varying on a time scale that makes the established wide-sense stationary, uncorrelated scattering (WSS-US) model questionable [MMK+11]. Of course, a real-world channel can only be modeled as WSS-US over a certain time interval, the so-called stationarity time. For regular cellular channels, the stationarity time is long enough such that the MAC and physical (PHY) layers can be designed for a WSS-US channel. This, however, will not be true for all vehicular channels, which calls for new CSI estimation algorithms and for new MAC and PHY schemes.

Channel prediction for the backhaul link

Advanced wireless systems need accurate channel state information at the transmitters (CSIT) to facilitate link adaptation, beamforming, multi-user scheduling and in the future also coordinated multipoint transmission. However, channel measurements are outdated at the time of data transmission, due to various delays in the transmission control loop. E.g. in the 3GPP Long Term Evolution (LTE) standard, there are transmission control delays of multiple milliseconds. This is a major problem for terminals at vehicular velocities.

The use of channel predictions can improve the situation. The short-term fading can be predicted from past and present noisy channel measurements using the fading statistics over time and frequency. This provides adequate accuracy for a prediction range in space corresponding to 0.1-0.3 carrier wavelengths, but can rarely offer useful predictions for longer distances. See e.g [EAS02], [Ekm02] for early results on narrowband channels and [Due07] for a survey of results. The recent study [Aro11] uses the best linear (Kalman) predictors on wideband OFDM systems and has confirmed these conclusions.

Prediction 0.1-0.3 wavelengths ahead would be adequate at vehicular velocities if transmission control loops had very low latency (1-2 ms) [SFS+05], [SSO+07], such as in the 4G system proposals investigated by the EU WINNER projects [DOM+09]. Present LTE systems have higher delays of at least 5 ms. Prediction horizons of 0.1-0.3 wavelengths are here adequate at pedestrian velocities, but inadequate for vehicular velocities at carrier frequencies above one GHz. But the vehicular scenario provides an opportunity as well as a challenge: The vehicle velocity and direction is relatively constant over the required 5 ms prediction horizon. Predictions could then be obtained by an antenna located some distance directly in front of the antennas used for transmission. This “predictor antenna” might be the first antenna of a linear antenna array or a separate antenna. This concept has been investigated and the results based on field trials show that the prediction horizon can be at least ten-fold compared to traditional Kalman filter based prediction [SGA+12].

MAC for ad-hoc networks

Cooperative communication (distributed MIMO as well as relaying) requires that the nodes can exchange information to set up the cooperation. Hence, a distributed medium access method is required to allow for an efficient sharing of the wireless channel. The standard MAC for ad-hoc networks is carrier sense multiple access with collision avoidance (CSMA/CA), used, e.g., in the IEEE 802.11 family of wireless local area network standards. In fact, the current standardization for V2X communications is based on 802.11p whose MAC layer is based on CSMA [IEEE-802.11p, IEEE-802.11]. The 802.11p physical layer is based on OFDM. 802.11-style CSMA is known to scale badly, that is, as the number of nodes per unit area increases, the network performance degrades quite drastically [Sjo13]. Better performance can be achieved by other schemes, e.g., self-organizing time-division multiple access (STDMA), which is used by boats for collision avoidance (of ships, not packets) and traffic control purposes [Sjo13]. Better performance compared to CSMA is achieved by scheduling transmissions in time slots and, in case of data traffic congestion, by scheduling simultaneous transmissions from nodes that are located as far away from each other as possible. The required network synchronization (for setting up the time slots) and the node positions (for scheduling simultaneous transmissions) are derived from a mandatory GPS receiver. Hence, STDMA is an excellent example of how positioning and communications can be combined in a synergetic manner. STDMA has been proposed for use in VANETs [Sjo13] and is currently considered by ETSI for possible standardization. However, challenges that remain are to devise schemes for maintaining position and network synchronization in GPS-challenged environments. We believe that we can meet this challenge by using cooperative positioning techniques. Moreover, it is not obvious which transmitters to schedule in the same time slot, since the resulting interference depends only partly on geographical distance for the V2V channel (as opposed to the relatively simple ship-to-ship channel). A first approach to solve this problem would be to schedule the transmission based on the local estimated CSI and current position estimates.

2.6.3 Detailed description of planned research

Framework for ultra-reliable communications

The investigation is focused on developing a novel framework for ultra-reliable communications in the context of traffic safety applications. The concept is based on the idea that despite the fact that it is impossible to always ensure error-free wireless communication during 100% of the time and in every reception scenario, it is pretty much feasible to derive boundary conditions for the transmission success. In particular, the expected presence or absence of reliable connectivity at the time of transmission can be estimated with very high probability by means of estimation and prediction techniques. Current LTE systems do not possess the capability to detect and signal the presence of an ultra-reliable link on a very short time span, which limits its usability for applications based on ultra-reliable communications such as traffic safety. As a result, a novel framework to enable ultra-reliable communications in wireless communications systems will be developed based on three main design principles:

- A transport-agnostic definition from the applications point of view is required in order to allow dependable services to be deployed in a wide range of scenarios. From this perspective, the implementation details related to the wireless communication system should not be included in the general definition of the framework, even if they must be considered for a particular realization of the framework in a given wireless communication system. In this context, the use of advanced Medium Access Control (RT12) and Hybrid Automatic Repeat Request Techniques (RT13) can be integrated into the framework in order to improve the availability of URC in a METIS system
- Wireless communication technologies are typically not designed to provide very high reliability in every scenario, as this would result in an overdesigned system with a very inefficient air interface in terms of data rate and power consumption. Such an approach would harm the acceptance of traffic safety applications in wireless communication systems and restrict their usage. Therefore, wireless communication system should not be designed to provide high levels of reliability everywhere and everytime.
- Dependable services such as traffic safety applications require very high and predictable success rates (e.g., 99.999%) within low deadlines (e.g., 10 ms). Due to the sensitive nature of these applications, it is of paramount importance to warn the service or application about the unavailability of reliability according to the service-specific requirements.

Channel estimation

Channel estimation for V2X channels is challenging for the reasons described above. To increase the quality and efficiency of channel estimation, we plan to use the sparsity of the channel in the delay-Doppler domain and extend the approach in [MMM+12a, MMM+12b] to the time-varying case. The sparsity in delay-Doppler is motivated by the physical considerations (i.e., by modeling the received signal as a sum of a relatively small number of high-power multipath components). However, we will also allow for a diffuse component of the received signal, which has been found in numerous channel measurement campaigns, see [MMM+12a] and the references therein. Once the single-user channel estimation algorithm has been designed, we will extend the framework to also support multiuser detections. That is, if more than one packet is colliding at the receiver, the channel estimation algorithm should detect how many packets are colliding and estimate their channels.

Channel prediction

We plan to continue our research on the predictor antenna system and improve it in the following ways:

- Combine with Kalman tracking, and
- Compensate for antenna coupling.

We are also collaborating with WP3-T3.1 on Massive MIMO, in which we are developing a robust and energy efficient wireless backhaul for very fast moving relays, as described in METIS deliverable D3.1 [MET13-D31] section 2.3.1.

MAC for ad-hoc networks

We will investigate if variations of time-division scheme, similar to STDMA, are suitable for moving networks, especially in situations with limited network support. Key problems to investigate include how to maintain network synchronization and positioning (which will be needed in some MAC approaches).

2.7 Faster than Nyquist (FTN)

2.7.1 General description

With Faster-than-Nyquist signaling modulation symbols are transmitted either more dense in time direction or in frequency direction or a combination of both. By doing so adjacent symbols are not orthogonal to each other anymore, controlled (i.e. perfectly known by the receiver) intersymbol interference is introduced at the transmitter. Detectors are to be designed taking this into account. So, FTN is a means to better make use of the available spectrum at the cost of a more complex detection. FTN is purely a physical layer procedure.

2.7.2 Related state of the art and limits

LTE has been designed with a focus on simple receivers and therefore an orthogonal waveform was selected fulfilling the Nyquist criterion for ISI free transmission. METIS targets a heavy increase in throughput compared to LTE. So, dismissing the design criteria mentioned above, e.g. by applying Faster-than-Nyquist signaling, is one possible step towards this target at the cost of increased receiver complexity, which may be less a bottleneck in future.

In 1975 J. E. Mazo laid the foundation for FTN signaling [Maz75]. He stated that it is possible to exceed Nyquist's border [Pro01] while not increasing the bit error rate. Sounding disputable at first sight, the key aspect making this possible is the minimum Euclidean distance between all available signal sequences not shrinking for signaling rates (BPSK using sinc pulses) up to 25% higher than when obeying Nyquist's rule. So, with implementing a more complex reception scheme relying on sequence detection one is able to exploit this up to a given extent – the Mazo limit. Numerous groups have taken up on this topic:

In [RA05] Rusek and Anderson introduced the two dimensional Mazo limit by extending the FTN principle to the frequency domain, paving the way for multicarrier-FTN (MC-FTN). Here, single symbol transmissions are stacked closer in frequency domain additionally to going beyond the Nyquist rate. In [AR06] the same group stated a doubling of the spectral efficiency of OFDM by applying MC-FTN to be possible in theory. It was shown that Mazo's limit for two dimensional FTN using smaller number of subcarriers is less than Mazo's limit in the time domain which is equal to 0.802T, thus achieving higher data rate.

Lower and upper bounds for information rates were derived by Rusek and Anderson [RA06] for binary, quaternary and octal FTN schemes using root raised cosine pulses. They proved that for some cases, FTN signaling gives higher information rates compared to Nyquist signaling, especially when the modulation order increases [RA06], because of the excess pulse bandwidth effect obtained by the roll-off factor α. A method for computing the minimum distance of non-binary FTN signaling was proposed in [RA08] and tested by M-algorithm receivers which are using a reduced states version of BCJR decoding algorithm [BCJ+74] called M-BCJR. A theoretical assessment of the achievable capacities can be found in [RA09]. FTN with non-sinc pulses is compared with linear transmission systems applying orthogonal pulses. It is shown that by applying FTN the ultimate capacity can be achieved under the constraint of an independent and identically distributed (i.i.d.) Gaussian alphabet for bandlimited pulses over AWGN channels. This achievable capacity is due to the excess pulse bandwidth of the non-sinc pulses. In [KB11], Kim and Bajcsy investigated the cyclostationary FTN systems over AWGN and continuous ISI channels deriving information rates and their upper bounds. They proved that FTN achieves higher capacities using waterfilling compared to i.i.d. transmitted symbols over ISI channels.

Another generalization with respect to the pulse design is presented in [LG03] and [ZLW12]. Originally FTN has been investigated for sinc-pulses. In [LG03] the family of raised-cosine pulses is treated within the framework of binary FTN. They have investigated the structure of error events that reduce the minimum distance in order to extend the theoretical gains to practical ones and they have applied constrained coding as a potential tool for improving FTN. In [ZLW12], a generalized FTN signaling was introduced. The design of the pulses that decrease detection complexity and achieve the required channel capacity was investigated.

MC-FTN applying FBMC using IOTA (Isotropic Orthogonal Transform Algorithm) [FAB95] filters as pulse shapers and a look-up table with pre-calculated coefficients as a FTN mapper was introduced in [DRO11].The receiver architecture was based on iterative decoding with successive interference cancellation. Due to the high complexity of the BCJR decoder only results for FTN-FBMC with a 4-state OQPSK constellation were provided.

Various publications dealing with signal reception based on sequence detection are available (e.g. [PAR08, DRO10, DRO11, KB12, MS10]). Here, the inter-symbol interference introduced by FTN is mapped to a trellis structure and incorporated into various variants of the well-known BCJR algorithm. For FTN systems, three reduced states BCJR algorithms were investigated in [AP10], backup M-BCJR, simple M-BCJR and truncated BCJR algorithms, over additive white Gaussian noise (AWGN) channels. Further lower complex receivers for FTN signaling were investigated in [GFP11]. An implementation of a discrete FTN system model was proposed by McGuire and Sima [MS10] that would reduce the receiver complexity for certain modulation schemes as it is based on matrix multiplication. Though means to reduce complexity are investigated heavily, FTN detection is still rather extensive. So, looking for further detector variants focusing on complexity reduction is still of relevance.

A first connection between FTN and MIMO has been made in [Rus07] and extended in [Rus09]. The research outcomes so far regarding FTN attached to a system applying multiple antennas are rather basic and general so far typically dealing with the existence of the Mazo limit.

2.7.3 Detailed description of planned research

One target of this research topic is to combine FTN signaling with FBMC/OQAM modulation. For doing so, we aim at investigating the following aspects:

1. The capacity analysis when combining FTN and offset signaling.
2. The efficient modem design for FTN-FBMC/OQAM.
3. The efficient receiver design and performance evaluation.

The first aspect is rather a theoretical analysis which is expected to point out the ultimate limit of this idea. The second aspect focuses on the practical implementation viewpoint. The last aspect, which also requires the most of the resources, aims to find an efficient receiver algorithm that, differently from the SotA, largely reduces the computational complexity; moreover, the investigations for the channel estimation and synchronization techniques are also planned in this aspect. FTN generates inter-symbol interference (ISI) at the receiver which should be handled through proper equalization and coding techniques. As FBMC systems also produce interference in wireless channels the interaction between these two is expected to be investigated and optimized.

More generally the items to be researched are:

- Analysis of FTN signaling capacity and spectral efficiency is extended beyond the SotA, to obtain a deeper understanding of the FTN motivation and expected gain.
- Investigate adaptive modulation and coding scheme in combination with FTN.
- Compare FTN to higher order modulation schemes with respect to, e.g., throughput, complexity, etc.
- Investigate the receiver design and evaluate different blocks (e.g. equalizer) performance.
- Alternative receive scheme based upon maximum likelihood detection (MLD) and interference cancellation (multicarrier one-dimensional Mazo limit).
- Boundaries of FTN w.r.t. mobility and delay spread.
- PAPR and non-linearity effect analysis.

2.8 FBMC related solutions

2.8.1 General description

FBMC is a multicarrier transmission scheme that 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. However, the usage of digital polyphase filter bank structures [CEO+00], [SSL02], 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), also known as OFDM/OQAM or Staggered Multi-Tone (SMT) [Far11], can usually achieve higher link spectral efficiency than CP-OFDM due to the abandoning of the cyclic-prefix overhead. Further advantage foreseeable is the robustness against fading channel conditions and imperfect synchronizations by selecting the appropriate prototype filter.

Another type of modulation scheme, FBMC-Filtered Multi-Tone (FBMC/FMT) [CEO+00], also known as fraction-spaced multi-carrier, oversampled OFDM or oversampled DFT modulation, is usually less spectrally 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, at the cost of increased complexity as outlined above.

2.8.2 Related state of the art and limits

General comparison with CP-OFDM

3GPP LTE/-A is based on CP-OFDM multicarrier modulation. According to Balian-Low theorem (BLT) [FS98], CP-OFDM

1) respects the complex orthogonality;
2) but is poorly localized in frequency domain by adopting rectangular waveform;
3) does not achieve maximum spectral efficiency due to the addition of CP.

The property of 2) will usually attribute to a CP-OFDM system (including LTE/-A) with high out-of-band leakage (large guard-bands thus have to be inserted) and poor robustness against Doppler spread. Further possible disadvantages are found in some flexible spectrum usage scenarios, where spectrum sharing and fragmented usage are not efficiently supported [PWK+13].

To overcome the shortcoming 2) and 3) of CP-OFDM, FBMC/OQAM

a1) relaxes to real field orthogonality;

a2) is better localized in time and frequency (depending on the waveform f);

a3) achieves maximum spectral efficiency.

And another FBMC variant, FBMC/FMT

b1) respects the complex orthogonality;

b2) is better localized in time and frequency (depending on the waveform f);

b3) does not achieve maximum spectral efficiency due to the addition of a roll-off factor

Due to the above mentioned theoretic advantages of FBMC/OQAM and FMT, these two FBMC variants are thus the major research focus in the METIS project.

Out-of-band leakage and prototype filter design

By choosing a better frequency localized prototype filter, FBMC systems usually generate much lower out-of-band leakage in digital baseband; however, due to non-linearities present in radio chains, severe spectrum regrowth could happen in RF. If spectrum regrowth can be controlled, FBMC/OQAM enables more efficient spectrum resources utilization by deploying narrower guard-band and improved co-existence with other systems.

Moreover, the selection of prototype filter for FBMC is also closely related to the scenarios defined in METIS, detailed transceiver designs (including synchronization, channel estimation, equalization and MIMO) and other aspects and requirements (i.e. system coexistence requirement, and signal transition time)

Currently, there are two major design criteria for the FBMC/OQAM system:

- Time Frequency Localization (TFL) criterion: For a better localized waveform in time and frequency domain, it is foreseeable that FBMC systems exhibit better robustness than CP-OFDM in doubly-dispersive channel [FAB95], synchronization/estimation in some circumstances and some RF impairments, typically phase noises and Carrier

Frequency Offset (CFO). Some filter designs with the optimized TFL criterion have been proposed, such as IOTA [FAB95], TFL [PSS04].

- Lower sideband criterion: For a more condensed waveform in frequency domain to have extremely low out-of-band leakage and improved spectrum coexistence, the filters with this regard are proposed such as PHYDYAS [PHYD], Rossi [RZS96], Frequency Selective [PSS04].

Nevertheless, it is so far not clear, which prototype filter design is best fitting the METIS project requirement and if advanced waveform adaptation should be taken into consideration. This topic is thus planned for further research.

<u>FBMC link design SotA and limits</u>

An efficient implementation of FBMC transceiver can be derived taking the fast Fourier transform and polyphase components of the FIR filter as in [CEO+00].

For FBMC/OQAM, which relaxes itself to real field orthogonality, the FBMC transceiver design algorithms are usually different from CP-OFDM.

Many contributions have been achieved in the past years. Among them, EU-FP7 project PHYDYAS has dealt with numerous signaling aspects related to FBMC/OQAM, including

- Fast scalable synchronization and initialization (single antenna)
- Transmit and receive processing (single and multiple antennas)
- Optimization of the filter bank design
- Dynamic access and cross-layer aspects
- Backward compatibility with OFDM (use case: WiMAX)
- Radio spectrum analysis and cognitive radio

One can refer for detail to its deliverables and publications [PHYD] produced therein.

In the environment of METIS with challenging new use cases, the SotA FBMC link transceiver could see its limits in the aspects of channel estimation, synchronization, sensitivity against imperfection, and precoding and equalization (including MIMO) etc.

For channel estimation, an auxiliary aided method was originally presented in [JLR03] based on an approximated simple transmission model. The auxiliary pilot can effectively cancel the intrinsic interference on the reference pilot position. This idea was later extended in a general framework [Lel08]. However, the performance is only conditioned when the channel does not present severe frequency and time selectivity. For METIS scenarios, research is planned to look for better channel estimation methods.

To maintain synchronization and reduce impairment distortion, reliable and efficient schemes must be designed for FBMC systems. Many blind and data-aided synchronization algorithms have been proposed in literature. [Bol01] exploits second-order cyclo-stationarity property of FBMC signals. However, its slow convergence limits its applicability. An approximate maximum-likelihood estimator was proposed in [FT07, FIP+09] and later extended to joint CFO and SFO estimator in [MT13]. Finally, a repetitive training sequence based method was proposed in [FPT09]. It was shown that FMT systems require more redundancy or training overhead to create periodic repetitions than necessary for SMT.

With the introduction of novel pulse designs in FBMC systems, the effect of imperfect transceivers needs re-evaluation. Although a generally higher sensitivity to synchronization loss is inherited due to multi-carrier approach, a comparative robustness and an increase in operation region is anticipated from FBMC solutions against traditional OFDM systems. The effects of CFO was studied in [RHV98] for flat-fading channels and later extended to multi-path channels in [SWB+10], both concluding that FBMC systems allow higher CFO range, especially for large number of subcarriers. A detailed treatment of FBMC performance evaluation in the presence of phase noise, I/Q mismatch and non-linearity can be found in [PHYD51].

For precoding and equalization, major challenges for FBMC/OQAM are due to the intrinsic imaginary interference. Precoding scheme based on signal-to-leakage-plus-noise ratio (SLNR) is implemented in [JXZ09] and [STS07] which suppresses the ISI/ICI in MIMO-OFDM. In [BKC+11] and [WC94] authors have investigated how the precoding matrix can be generated based on zero forcing (ZF) and minimum mean square error (MMSE) equalization respectively.

An interference mitigating technique based on the Alamouti coding scheme and maximum likelihood detection (MLD) is presented in [ZR12]. There, they have taken the advantage of combining FBMC with MIMO technique and its diversity gain to improve the performance of the system. On the other hand, [ZB10] has introduced an efficient scheme based on spatial diversity to cancel the ISI and ICI in OFDM/OQAM. Nevertheless, either performance loss or additional overhead cost is observed by the prior arts. Further study on this topic is thus necessary.

Packet transmission issues

A further issue in this field is the transition time of FBMC signal at the beginning and the end and the offset symbol of OQAM, which will lead to time-inefficiency for bursty small package and TDD transmissions [DS10]. Currently SotA includes: PHYDYAS' approach [BRI+10] to simply cut off the transition signal, which leads to a distortion to the original signal or the perfect reconstruction method given in [DS10] which, unfortunately, is only valid for prototype filters with length equal to the IFFT size.

2.8.3 Detailed description of planned research

As introduced in the current limits analysis, we will mainly focus on the investigation of the solutions to the open issues in FBMC/OQAM research work, which are

- Synchronization technique (preamble-based and scattered pilot based)
- Channel estimation method (especially for the case of high velocity)
- Equalization concept (either lower-complexity with improved performance, or relatively high complexity in some extreme cases, e.g. high velocity/MIMO)
- MIMO transmission (especially look for a solution for Alamouti-based mode)
- Precoder and decoder design for FBMC/OQAM systems
- Prototype filter and transceiver parameter selections to METIS scenario requirements (mobility, frequency, cost, etc.)

In addition, we will also study the implementation issues of FBMC system,

- To analyze the PAPR
- To mitigate the tailing effect and enable efficient small package transmission
- To consider transceiver design implementation in regards of extended and modified algorithms for low-complexity operation, and flexible and scalable SDR transceivers in terms of multi-standard (OFDM / FBMC schemes) performance. This will be investigated on existing and proposed architectures focusing on low-power operation.

Despite of the FBMC/OQAM and FMT variants, this research topic will also investigate some alternative approach for filtered multicarrier. While FBMC (filtering per subcarrier) and filtered OFDM (filtering of the complete band) are two extreme cases of applying filtering to multi-carrier systems in general, one alternative solution we will aim on is to perform the filtering function to subsections of the complete band (e.g. a group of subcarriers alike used within a single LTE PRB).

2.9 Modulation & coding and new channel coding concept

2.9.1 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. These requirements are well reflected by the GRMs in D2.1.

The multiplication of these requirements has been leading the number of parameters in 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.

In the following sub-section, starting from the analysis of the state of the art, four sub-topic and their limits are described.

2.9.2 Related state of the art and limits

The physical layer of the LTE standard supports several advanced multi-antenna schemes (such as transmit diversity, spatial multiplexing, and beam-forming), various modulation orders ranging from QPSK to 64 QAM (and even 256 QAM in LTE Release 12), and a wide range of turbo coding rates (from 0.12 to 0.948) with 188 information block sizes (from 40 to 6144 bits). Together with all these multiple possible values, specific possible combinations are specified and referred to as Modulation and Coding Schemes (MCS). MCS usually include a given coding and modulation scheme but the concept can be extended further by including additional parameters, such as the number of antennas for transmission and the MIMO encoding scheme, or the error correcting code type (convolutional, recursive systematic convolutional concatenation, turbo codes, LDPC codes, etc.), or other parameters concerning the transmission format. As an example, 32 MCS per PRB are defined in LTE Release 11, 24 MCS in DVB-T2, and 32 MCS in 802.11n (when including the number of transmit antennas). Table 2.2 illustrates the diversity of the parameters related to constellation sizes and code rates specified in LTE, 802.11n, and 802.16e.

Table 2.2: constellation size and code rate ranges for some wireless standards

	LTE	802.11n	802.16e
Constellation	BPSK – 64 QAM	BPSK – 64 QAM	BPSK – 64 QAM
Code rates	0.12 – 0.948	0.5 – 0.83	0.083 – 0.83
UL waveform **DL waveform**	SC-OFDM OFDM	SC or OFDM	SC or OFDM

From this context, we notice the emergence of the following consequences related to this topic on modulation & coding and new channel coding concept:

1) 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). ACM is related to the mechanisms implied when changing the spectral efficiency of the transmission whenever the FER is changing (for example in the case of channel fading [GS98]). Estimating the FER at the receiver side is not straightforward. Therefore, a Channel Quality Indicator (CQI) is usually sent from the receiver to the transmitter to guarantee a block error rate below 10%. Even though there is no specification on the way CQI should be estimated, it is often based on some form of SNR or SINR estimations, after equalization, thanks to some pilot symbol sequences, before being quantized. However, FER/BER could also be estimated directly from the received soft values at the decoder or demodulator output. There are several techniques for estimating the error rate of a transmission [HLS00]. They are all based on density estimation. However, they also require the knowledge of the channel variance.
2) The second one is that a wide 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 [CHP06][CHE09]. The objective is to improve the final implementation performance in terms of throughput, latency, energy consumption, area, and error rate performance. However, the published results often evaluate these algorithm variants on a limited set of parameters related to the considered technique and to its system integration environment. In addition, they often target to optimize one specific performance metric, or a very limited set. Thus, additional research efforts are required in order to propose optimization techniques considering the increasing set of defined parameters in emerging applications and communication scenarios.
3) The third one is linked to the constellation symbols, varying from BPSK to 64QAM. They are all taken from a 2-dimensional integer lattice, which does not have any coding gain [TVZ99].
4) The last consequence is related to the uplink of LTE, which is based on SC-FDMA, but could be extended to other standards, since energy consumption will certainly become a major issue in the next decade. SC-FDMA generally exhibits a relatively low PAPR because of its inherent single carrier nature [MLG06a] and is therefore seen as an attractive alternative to OFDMA. Two original variants of SC-FDMA have emerged, which differ in the way the subcarriers are mapped to a particular user. These are: (1) interleaved-FDMA (I-FDMA) [SBS97], which assigns equidistant subcarriers to each user, and (2) localized-FDMA (L-FDMA) [MLG06b], whereby groups of contiguous subcarriers are assigned to a particular user. Recently, a generalized version of these two schemes has been proposed, called block-interleaved-FDMA (B-IFDMA) [SFF+07, SFE+09]. The LFDMA variant has been adopted for the uplink multiple access scheme of LTE.

In [WPS11], the performance of precoded SC-FDMA employing a sub-sampled Constant Phase Modulation (CPM) encoder as precoder of SC-FDMA with I-FDMA subcarrier mapping was investigated. This so-called CPM-SC-FDMA scheme can outperform convolutionally encoded Quadrature Phase Shift Keying (QPSK) by up to 4 dB in end-to-end power efficiency, taking High Power Amplifier (HPA) power backoff into account. An important property of CPM-SC-FDMA is that it yields very good envelope properties, down to a fraction of a dB, while at the same time maintaining the OFDMA structure. This allows for a simple multiple access scheme through frequency division and permits coexistence with adaptive OFDMA and reuse of the OFDMA transceiver structure currently in use in OFDMA-based systems.

2.9.3 Detailed description of planned research

The planned researches related to this research topic are directly linked to the four consequences identified in the state-of-the-art:

1) A new error rate estimation scheme will be investigated based on the observation of the reliability of the decoded bits, without any knowledge of the channel variance.
2) A research effort will be planned on the digital baseband (BB) 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 the above techniques and propose an adaptive flexible BB 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.
3) An alternative to 2-dimensional integer lattices would be to increase the dimensionality and the density of the underlying lattice to improve the error rate / spectral efficiency of the transmission scheme. Practical modulation and demodulation schemes for lattice-codes based modulations will be investigated and their performance will be compared to the state-of-art, in terms of error rate performance, spectral efficiency, physical layer latency and complexity. A focus will be especially performed on lattice codes based on LDPC codes [SBP04, SFS08], and on lattice codes from the so-called "construction D" [CS88], with a special emphasis on the encoding and the decoding process, including their complexity and their flexibility.
4) Finally, research on energy-efficient constrained-envelope coded-modulation multiple-access schemes will be investigated, based on CPM-SC-FDMA with a focus on end-to-end energy efficiency (coding and modulation). However, we will also investigate the impact of other key constraints besides end-to-end energy efficiency identified from the relevant horizontal topics for which this technique might be useful. Initially the MMC horizontal topic seems most relevant, e.g. to investigate the potential of flexible spectrum shaping within the CPM-SC-FDMA framework. On the other hand, these kinds of schemes might be useful also for high bandwidth and coverage limited mmW scenarios (UDN, V2V) with high requirements on transceiver energy efficiency and robustness to non-linear HPAs, but with modest requirements on spectral efficiency due to large available bandwidth and dense reuse enabled by short transmission distances.

2.10 Advanced transceiver design

2.10.1 General description

Transceiver design needs to look into signal processing in base band as well as in RF. Coupled with these, both analog and digital techniques are to be investigated addressing new scenarios as conceptualized in proposed 5G systems. While higher frequencies may bring new design paradigms with more analog processing needed, e.g., in beamforming, there may be changes expected in the waveform. Improvements to existing OFDM may be considered which cater to higher data rates, reduced latencies and as much as possible savings in spectrum and energy.

On the topic of efficient spectrum usage, recent developments in self-interference mitigation techniques show that full duplex (FD) communication (i.e., simultaneous transmission and reception in the same frequency band) is feasible. Moreover, there is a growing interest within industry and academia for the design and implementation of FD point-to-point single-antenna and multi-antenna FD relay and FD multiuser systems. In FD systems, the self-interference generated by own transmissions, is progressively canceled in multiple stages so that simultaneous reception is feasible. After performing the best possible cancellation, the residual of the self-interference limits the expected benefits of FD. Transceiver design for these systems therefore needs careful attention as opposed to traditional ones.

On the topic of baseband signal processing, single-carrier communications can be reconsidered for the proposed scenarios with advanced equalization algorithms, multi-rate equalizers in particular. Although single-carrier communications suffers from inter-symbol interference (ISI), it has various advantages over multi-carrier communications. These advantages include lower peak-to-average power ratio (PAPR), simpler synchronization, and improved robustness against Doppler spread. These advantages have vital importance when MMC, D2D, and V2X communications are considered. Hence, single-carrier communications might be a viable alternative to OFDM and FBMC for these applications in particular. With advanced equalization algorithms, single-carrier transmission might even be considered for other applications as well.

2.10.2 Related state of the art and limits

Full duplex (FD)

The current standards including LTE, LTE-A consider only half duplex schemes either TDD or FDD. Bidirectional or two-way communication between two nodes, i.e., simultaneous transmission and reception between two or more nodes *at the same frequency*, was first studied by Shannon himself in [Sha61]. The question is why this should be of greater interest today? The answer lies in the fact that as the cell size is ever shrinking enabling significant increase of carrier center frequencies, the power difference between TX and RX is getting reasonable due to short link range (from kilometers to meters). This can double the capacity in theory. So far mobile cellular access has been optimized for macrocellular use and having small cell link geometry will lead to very different system optimization and access solutions.

To give an idea of drastically new approaches of full duplex radio (FDR) in mobile cellular context, at least the following research directions are of interest:

- Full duplex radios for short range links: Having transmitter and receiver operating at the same frequency at the same time would theoretically double the spectral efficiency of the link. This causes self interference, calling for TX interference cancellation at RX.
- Modulation for full duplex short range links: OFDM modulation has dominated as the major modulation scheme the last few years. It is worth studying in more detail how different non-orthogonal multicarrier based transmission schemes perform in full duplex short range links.
- Interference cancellation in RF and digital domains: It has been shown that utilizing antenna polarization, TX can be reduced from RX quite efficiently. Also, the well known interference cancellation techniques can be used after AD conversion to cancel interference.

Full-duplex experimental demonstrations for narrowband wireless communication systems were first reported in 1998 [CBM98]. During the past few years FDR has gained increasing interest, e.g., due to introduction of full duplex relaying. The feasibility of full duplex communication has been illustrated in [DDS12, JCK+12, AKS+12]. Several implementations of single antenna [DDS12, JCK+12] and multi antenna [ADS+12, DMB+12] have been presented. In addition relaying systems [NLS12, RWW11] and multiuser scenarios [NTP+12] have been investigated.

The main challenge is to cancel the self interference generated by the transmission of high power signal compared to the low power received signal. The benefits are therefore limited by the amount of residual interference left over after employing various reduction techniques. This is in general in the region of 40-60 dB for experimental links. In [SGP+11] full duplex links were used to combat hidden and exposed terminals but also to increase the efficiency of the network. Also, use of interference cancellation to improve efficiency in a WiFi setting has been recently evaluated in [HAW08] and a general multi antenna cases shown in [Kha12, SFC11].

Single-Carrier Communications

LTE and LTE-A employ single-carrier frequency division multiple access (SC-FDMA) as the air-interface solution for the uplink. SC-FDMA employed in these standards can be more precisely described as DFT precoded OFDMA. Although DFT precoding alleviates PAPR problems, SC-FDMA as employed in LTE(-A) still suffers from poor time-frequency localization, throughput loss due to CP, and powerful side-lobes. Furthermore, the ISI observed in SC-FDMA is dealt with linear equalizers in practice whose performance is far from the optimal equalizer. Sub-optimal equalization causes a further loss in throughput.

A multi-rate equalization algorithm is proposed in [BJ13]. The proposed multi-rate equalizer (MRE) decomposes the ISI channel into parallel sub-channels each of which has a fraction of the rate of the original channel. It is demonstrated that as number of sub-channels increases these parallel sub-channels tend to become memoryless which accomplishes the goal of equalization. The multi-rate decomposition proposed in that work is achieved via successive interference cancellation (SIC). It is claimed in [BJ13] that single-carrier communications with MRE can approach independent identically distributed (i.i.d.) capacity of the ISI channel. Furthermore, MRE has a complexity in the order of linear equalizers. Therefore, it is feasible in a computational complexity point of view. MRE has some limitations though. Firstly, it is applicable to single-antenna communications in its current form. Secondly, implementation of MRE still relies on CP which leads to a loss in throughput. Thirdly, MRE has been considered only for rectangular pulse shapes so far which leads to powerful side-lobes. Finally, MRE might increase latency which makes it unsuitable for some METIS applications such as V2V applications.

2.10.3 Detailed description of planned research

Going beyond the available studies on FD radio with an investigation into the limits in the current techniques and possible isolation amounts (in dB, e.g.) quantified, it is proposed to consider a small cell scenario with multiple users. All the studies up to now are mostly experimental; there are no applications in cellular systems. Analysis of capacities and bit error rates are considered for single as well as multiple links. Investigation of the fundamental functional block design and required adaptations of new or existing waveforms to support MIMO transmission is to be carried out. New transceiver design will be driven by new or adaptations of existing waveforms (excluding FBMC/FTN) considering scenarios such as higher frequencies, latency requirements, developed in this task both regarding analog and baseband processing.

Besides analyzing the similarity between uplink and downlink conditions and its impact on the TRX design, full duplex transmissions for short radio links will be investigated. Facilitation of full duplex single-carrier communication with the aid of receiver-side interference cancellation is to be considered. Mixing different physical access schemes for full duplex is to be evaluated, e.g., how SC-OFDM works when combined with regular OFDM. An analysis will be carried out on the additional requirements for dynamic range in the analog to digital conversion to facilitate full duplex (for sufficient own Tx interference suppression).

The MRE can be extended and enhanced in many aspects so that single-carrier transmission might be a serious contender for 5G systems. First of all MRE needs to be extended so that it becomes applicable to multi-user and multi-antenna communication systems. Secondly, implementing MRE without cyclic-prefix will be considered to improve throughput. A solution will be sought which does not require sacrificing from frequency domain implementation. Keeping frequency domain implementation is necessary to keep computational complexity in feasible levels. It is expected that the stable nature of MRE would allow employing overlap-add and overlap-save methods. Thirdly, the MRE will be adapted for non-rectangular pulse shapes which will allow using pulse-shaping filters with better spectral properties. To reduce latency of the MRE alternative single-carrier waveforms will be investigated. In particular, periodically-time-varying-modulations will be considered.

2.11 Multiple Access

2.11.1 General description

In cellular mobile communications, the design of radio access technology (RAT) is one important aspect in improving system capacity in a cost-effective manner. Radio access technologies are typically characterized by multiple access schemes, e.g., frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and OFDMA, which provide the means for multiple users to access and share the system resources simultaneously. In the 3.9 and 4th generation (4G) mobile communication systems such as Long-Term Evolution (LTE) and LTE-Advanced, standardized by 3GPP, orthogonal multiple access (OMA) based on OFDMA or single carrier (SC)-FDMA is adopted to achieve higher throughput performance in packet radio services. Its signal waveform such as orthogonal frequency division multiplexing (OFDM), including discrete Fourier transformation (DFT)-spread OFDM [3GPP-TS36300], provides important benefits, i.e., robustness against multipath interference and good affinity to MIMO technologies, that dramatically increase the achievable data rate. In the future, however, innovative radio access technologies are very important to further enhance the spectrum efficiency. The currently widely used multiple access scheme, OFDMA, 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. The scenarios in METIS envision ultra-dense networks handling large number of simultaneous transmissions in a small geographical area thereby posing new challenges for the multiple access (MA) where large number of users connect to the cloud, D2D and massive set of machine to machine (M2M) communication takes place. Massive sets of MTC devices force great demands for current multiple access schemes, which need to be evolved to permit the deployment of MMC. The future wireless network is also expected to support very diverse traffic characteristics with varying latencies and packet sizes supporting thousands of devices. Non-orthogonal design of multiple access is important in order to increase system capacity and spectrum efficiency while exploiting the expected future evolution in the receiver processing capability (e.g., NOMA). Also, multi-mode design is important in order to provide opportunities to adaptively trade off link and power efficiency that can be utilized in multiple access and multiplexing optimization. Relaxed synchronization between users/services is also important (e.g., FBMC). A flexible system design is also desirable in order to adapt the amount of overheads and signaling (e.g., Advanced coded multi-carrier access). Finally an opportunistic MA is possible with a cognitive architecture. Considering the already congested frequency spectrum, a reliable communication is possible by using the under utilized white spaces. This needs a frequency agile front end and MA using such an architecture is researched giving a perspective of RF front ends.

2.11.2 Related state of the art and limits

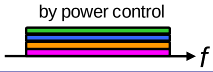
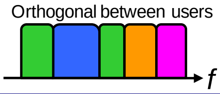
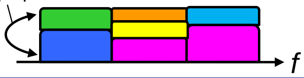
The research topic of Multiple Access (MA) is further classified into sub-topics such as

- Non-orthogonal MA
- MA using FBMC
- MA for D2D and MMC scenarios
- Advanced coded multi-carrier access
- MA with Cognitive Radio

<u>Non-orthogonal MA</u>

In order to obtain more significant gains in terms of system capacity and spectrum efficiency, the exploitation of additional domains/dimensions, that are not yet fully used, is essential. In this regard, we envisage non-orthogonal multiple access (NOMA) which enables the exploitation of the power domain for user multiplexing (superposition) and the evolution of processing capability of the receiver (UE) for interference cancellation, as a candidate future multiple access scheme. Table 2.3 shows the multiple access schemes for 3G (W-CDMA/HSPA), 3.9/4G (LTE/LTE-Advanced), and the future radio access toward the 2020s. Note the evolution of multiple access from non-orthogonal (W-CDMA) to orthogonal (OFDMA), then to non-orthogonal again in future radio access. Also note that although W-CDMA utilizes orthogonal codes in downlink, it can be seen as non-orthogonal access owing to the frequency selectivity of the channel which results into destroying code orthogonality.

Table 2.3 Evolution of multiple access

	W-CDMA	LTE/LTE-Advanced	Future radio access
Radio resource allocation	Non-orthogonal (CDMA)	Orthogonal (OFDMA)	Orthogonal (OFDMA) + Superposition/Cancellation (NOMA)
Link adaptation	Fast TPC (TPC: Transmission power control)	AMC (AMC: Adaptive modulation & coding)	MUPA/AMC (MUPA: Multi-user power allocation)
Multiple access scheme	Non-orthogonal assisted by power control 	Orthogonal between users 	Superposition & interference cancellation 

NOMA can be a promising multiple access for the future radio access according to the following motivations:

- NOMA superposes multiple users in the power domain (forming a superposition coding) so that its user separation is achieved via successive interference cancellation (SIC) [TV05, HK12a]. Thus, NOMA is a scheme that utilizes an additional new domain, i.e., the power domain, which is not sufficiently utilized in 3.9/4G systems. From an information-theoretical point of view, it is well-known that non-orthogonal user multiplexing using superposition coding at the transmitter and SIC at the receiver not only outperforms orthogonal multiplexing, but also it is optimal in the sense of achieving the capacity region of the downlink broadcast channel [TV05].
- NOMA exploits the difference in channel gains between users. When the difference in channel gains is large the performance gain of NOMA compared to OFDMA increases. Also, differently from OFDMA which translates channel gain difference among users into multi-user diversity by appropriate multi-user scheduling metric, NOMA translates channel gain difference into user multiplexing gains by user superposition in power-domain.
- Although NOMA needs channel state information (CSI), e.g., in terms of SINR at the transmitter for power allocation and user pairing, it mainly makes use of the CSI available at the receiver side for improving spectrum efficiency; thus, unlike schemes that rely on

more accurate CSI at the transmitter side (e.g., MIMO, CoMP, etc.), we expect that NOMA could provide performance gains that are robust to mobility.

In [HK12a, EKH12, UKH12, OKH12], NOMA was investigated based on the Shannon formula in both the downlink and uplink. However, more detailed interface design and performance evaluations of NOMA will be addressed in this work in order to clarify its potential gains under practical system assumptions. On the other hand, SIC-based advanced receiver for inter-cell interference mitigation is under study in LTE Release 12 [3GPP13-RP130404]. Differently from the ongoing work in LTE Release 12 on NAICS, NOMA is a power-domain multiple access with SIC-based advanced receiver for intra-cell interference mitigation. Thus, it can be a good candidate scheme to further extend in the future the ongoing work of LTE Release 12 on NAICS from inter-cell to intra-cell with power-domain user multiplexing.

<u>Multiple access with FBMC</u>

In the LTE standard users share the resource in time and frequency with RB allocation. But, as explained in subsection 2.8, the frequency spreading of the OFDM waveform then constitutes a serious drawback. Indeed, firstly to satisfy the frequency transmission mask several subcarriers at the border of the frequency channel must be non-active, which limits the useful throughput and/or the maximum transmission power cannot be attained, which limits the coverage. Furthermore, the poor frequency selectivity of OFDM makes the resulting system sensitive to frequency impairments such as Doppler and Carrier Frequency Offset (CFO). From a MA point of view towards some new scenarios envisioned in future mobile systems, e.g. ultra crowd network, the strong overlapping resulting from the sinc frequency shaping of OFDMA may introduce severe Multiple Access Interference (MAI), which may require guard bands between users, i.e. loss in bandwidth efficiency. Consequently, in the frequency domain, one can directly take advantage of the better frequency selectivity provided by FBMC. In [RRS+10], for a WiMAX-type system, in the single user case, the gain due to the guard band interval is estimated to 8%. This means also that, in order to avoid MAI, with FBMC, compared to OFDMA, less guard band can be left between users.

As explained in [SYB+11], and based on [MKP07], in the UL of an OFDMA system the interference cancellation (IC) cannot perfectly cancel the MAI and IC also adds a significant complexity cost at the base station. At the contrary for FBMC, [SYB+11] also points the fact that for FBMC the interference is intrinsically limited when using frequency selective prototype filters and then IC can be carried out at low cost. In the same line of idea, reference [FPT08] analyses a DL and UL multi-user context in the presence of CFO. The authors compare OFDMA with FBMC (FMT and OQAM). It is shown that in the UL both FBMC solutions can provide a significant advantage over OFDMA. Furthermore, in [FPT09b], the same group introduces a joint symbol timing and CFO estimation for a multiuser FBMC/OQAM system. Nevertheless, this solution seems to be sensitive to the resource allocation pattern. Moreover, since the efficiency of the solution only has been evaluated in AWGN case, it still is an open question whether the degradation due to the fading is significant.

If we now consider TDMA, OFDM has the advantage with its rectangular pulse shape to create adjacent resource blocks being non-overlapping in time. This is no longer true with FBMC systems. Indeed, at the exception of FBMC/FMT of minimum length [RS13], all FBMC signals naturally introduce a time overlapping, if this may be insignificant for long packets, this may become a serious problem if the MAC layer requires the transmission of very short data packets. The proposal in [BRI+10] which consists of a multiplication by a weighting function at the packet's borders cannot completely avoid interference or a loss of spectral efficiency while the solution given in [DS10] is only valid for short length prototype filters, i.e. having a length equal to the FFT size.

<u>MA for D2D and MMC</u>

Modern mobile communication devices have highly sophisticated features and consist of higher processing capabilities compared to early generation mobile devices. Therefore, the

signal processing capability of mobile devices is not expected to be a huge bottleneck in wireless communication system design. With the higher number of mobile devices that we expect in the future, the probability that those communicate within nearby distances will also go higher. These can be inside the same cell. The devices can have a direct link instead of transmitting data through the base station. This is known as device-to-device (D2D) communication. This is a more spectrally and an energy efficient method for communication. It reduces the number of channels used, transmit power at devices, and also saves power at the BS. Also it requires only half of the resources as compared to the cellular communication mode, thus offering better spectral efficiency with respect to that.
D2D communication is expected to enhance spectral and energy efficiency as well as cell-edge coverage of cellular systems. However, many resource management and interference coordination problems need to be taken into consideration to accommodate D2D. Majority of recently published D2D studies assumes that direct D2D communication is an underlaying amendment to legacy cellular network operation [DRW+09, YDR+11, FDM+12] in particular. They use the same BS-mobile station (MS) communication frequency spectrum. This increases the chances of frequency reuse within the same cell in a more effective manner. A consequence, though, is that the underlay D2D transmit powers need to be constrained to have reliable cellular communication. Therefore, the D2D communication is only possible, when the devices are located near each other. A relay placed in between D2D pair can extend the coverage area with less transmit power. This allows devices separated by longer distances to communicate through D2D mode. A relay based D2D communication may encounter the halfduplex issue in relaying. An underlay D2D system with network coding is proposed in [ODR+09], and the authors employ network coding to achieve high diversity order. However, devices use orthogonal channels for transmission in their scheme. As LTE-A standard work in D2D is mainly focused on public safety applications there is need to address other D2D use cases and impact of novel PHY techniques, e.g., FBMC in D2D MA context.

The main challenge for MMC MA is how to support potentially very large number of devices with infrequent small data bursts (for which LTE is not optimized). Random access and overload control techniques have been studied to solve the problem [CLW+12]. However, as [ALG+13] shows there is much room to optimize access performance in various MMC scenarios.

The Third Generation Partnership Project (3GPP) has already started working on evolving LTE-Advanced to accommodate the characteristics of M2M communications. By now, it has specified a reference architectural model [3GPP-TR23888] and addressed several open issues [3GPP-TR23887] for M2M communications over LTE-Advanced.

But there are still issues why the existing specification of LTE cannot meet the technical requirements and allow a proper accommodation of M2M communications.

The devices costs of current M2M networks mainly utilize (E)-GPRS because cost is low and the achieved coverage is good. The cost of LTE devices is much higher than for GSM/GPRS devices, which create a natural benchmark. There are several reasons why LTE devices cause higher manufacturing costs: scalable bandwidth, overdesigned peak data rates and high transmit powers.

The above named limits of LTE and LTE-Advanced should be considered by a Multiple Access scheme for M2M that allows an efficient access to a large number of devices while compensating the resulting restrictions (scalability, transmit power, etc.) given by the device characteristics.

Advanced coded multi-carrier access

As discussed at the beginning of this subsection, LTE-Advanced is based on OFDMA (downlink) and (SC)-FDMA (uplink), which is mainly motivated by the goal of achieving higher throughput performance. This MA scheme has advantages for certain communication scenarios that are typical for classical cellular deployments. However, it is not necessarily the best choice for the scenarios considered in METIS. For example, METIS assumes 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 smart-phones). 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 the small packet transmission on the uplink are:

- Support of massive number of terminals
- Signaling overhead
- Latency

The dynamic signaling overhead for the request/grant procedure increases specially for smaller payload sizes. The cost of the dynamic signaling is higher for small packets since the ratio of overhead to useful payload is high. As an example, the signaling overhead can be around 30% for a packet size of 20 bytes (using QPSK ½). Such signaling overhead comes mainly from UL grants that occupy the downlink control channel resource. Semi-persistent scheduling (SPS), while good for periodic traffic such as VoIP, cannot efficiently support bursty small packets. It is difficult to configure SPS intervals to match the bursty arrival of traffic and therefore it may not meet the QoE requirement of such transmission.

Another problem with the uplink LTE request/grant procedure is that the initial delay of the packet transmission can be quite high. This is disadvantageous for delay sensitive small packets (e.g. real-time gaming) where data should be sent most likely in one transmission attempt.

On the other hand, in order to enable an efficient transmission of uplink small packets, the granularity of channelization in current SC-FDMA system should be further reduced. However, a smaller resource channelization means higher signaling overhead and potentially more interference variation.

To combat the problems described above, a new waveform and access technology is desired with the following features:

- removal or reduction of the overhead of small packet transmission,
- reduction of the latency of small packet transmission,
- supporting of large amount of users to enable massive connectivity,
- better spectral efficiency and link quality

Advanced coded multi-carrier access refers to a multiple access scheme based on the overlaid multi-dimensional codewords carried over OFDM tones or any other multi-carrier modulations. Multi-dimensional shaping gain for better link quality and overloading capability for massive connectivity are the key features of this multiple access scheme. A more detailed description follows in the next subsection.

Multiple Access with Cognitive Radio

In future, congestion to pre-allocated spectrum is going to rise, owing to increase in number of user and demands for higher data rates. In such a scenario, cognitive radio with dynamic spectrum access can be a solution. A CR can essentially sense the unused portion of the spectrum and utilize it for congestion free, high data rate applications. In this way, multiple access can be provided in an opportunistic way by utilizing spectrum sharing architecture. Present efforts in the CR are focused for frequencies less than 1 GHz utilizing the white spaces in the TV bands. A CR is essentially a software defined radio as envisaged by Mitola [Mit95]. For a flexible CR front end it is desirable to eliminate all the external duplexers and SAW filters and hence provides a wideband suited for a CR. Unfortunately such a wideband architecture poses lot of problems for the linearity of a cellular communication receiver. A METIS wireless receiver having 5G also needs to support the existing generations. Hence the existing stringent blocking requirements are integral part of a cognitive radio. [HW11] clearly describes several aspects and challenges of a CR for wireless communication. The requirements derived in the paper is well above what is achieved in the state of art multiband receivers [TSN+08][IGB+10]. [RAE+05] describes a fully integrated 90nm CMOS software defined radio which operates in 800MHz to 5GHz band. Such a wideband architectures needs a power hungry ADC to satisfy the dynamic range requirement and is therefore not usable in a battery powered user equipment. In the above work, the authors designed a wideband receiver with a low power ADC utilizing innovative window functions for filtering. The architecture devised covers all major standards in the above mentioned frequency range but it does not meet the required dynamic range requirements. More over support legacy systems is also not addressed. A wideband receiver working in FDD always faces the problem of Tx leakage. In order to sustain the Tx leakage, the front end demands very high linearity of 26dBm which is above what is been achieved in state of art.

2.11.3 Detailed description of planned research

Non-orthogonal MA

The goal of this study is to clarify the system-level gains of NOMA over OMA assuming LTE compliant radio interface and also establish technology enablers necessary for the support of NOMA. Specifically, NOMA system-level gains (and link-level performance if necessary) will be investigated and compared to existing orthogonal multiple access (OMA), with special focus on

- Efficient transmit power allocation and user scheduling to achieve good tradeoff between complexity and performance.
    - Due to power-domain multi-user multiplexing, the transmit power allocation (TPA) to one user affects the achievable throughput of not only that user but also the throughput of other users. Thus, multi-user power allocation, user pairing as well as adaptive modulation and coding (AMC) are key aspects that have impact on performance gains of NOMA. In order to clarify this degree of impact, both exhaustive and suboptimal schemes will be explored. Note that this topic has some overlap with the study of section 2.5.3 but with more focus on scheduling complexity/performance tradeoff and less focus on the signaling aspect.
- Study of the impact of scheduling granularity (wideband vs. sub-band)
    - In LTE, the same channel coding rate (including rate matching) and data modulation scheme are assumed over all the sub-bands allocated to each single user, as the average SINR over all the sub-bands is used for MCS selection. However, for NOMA, such a mismatch between MCS adaptation sub-band unit (e.g., wideband) and power allocation sub-band unit (e.g., sub-band) might not allow full exploitation of NOMA gains. Thus, we explore NOMA performance gains with sub-band scheduling and sub-band MCS (independent MCS for each sub-band allocated to it) and compare it to NOMA with wideband scheduling and wideband MCS selection (the whole system bandwidth allocated to one UE using the same MCS).
- Study of the impact of error propagation in the SIC receiver
    - SIC receiver is used in NOMA receiver for cell-center users (users with high channel gains). In order to assess the impact of error propagation on system-level performance, it is important to be able to emulate error propagation of SIC in system-level simulations via appropriate link-to-system level mapping (i.e., mapping of link-level performance to system-level simulations). Link-to-system mapping for different patterns of interference (according to NOMA pairing of users with different channel gains and power allocation ratios) is accurate but difficult to implement as extensive link-level simulations are required. To simplify, the introduction of a worst-case error

propagation model will be investigated. This modeling provides an emulation of error propagation via simple link-to-system mapping. However, such a worst-case model is only appropriate in case the impact of error propagation on performance is sufficiently small.

- Impact of channel state information (CSI) feedback quantization and channel estimation error
  - For NOMA, channel state information is used at the transmitter side to allocate power to multiple users and to choose modulation coding set (MCS) of each user and at the receiver side in order to perform signal detection and SIC. Thus, its impact should be clarified. The performance of NOMA will also be investigated in high mobility scenarios where CSI becomes easily outdated.

MA with FBMC

The objective is to study FBMC/OQAM based multiple access, i.e. FBMC/OQAMA. The main focus will be put on the synchronization issue.

- Theoretical interference analysis in multi-user context.
- Synchronization technique for different resource allocation patterns under AWGN and fading channels.

MA for D2D and MMC

Similar to OFDMA based systems, FBMC-MA systems are investigated focusing on D2D and MMC. Optimization problems are to be formulated quantifying the interference due to FBMC in non-ideal environments which may produce unwanted interference components.
Besides FBMC-MA focusing D2D and MMC a quasi-orthogonal MA scheme using CDMA for the DL that is able to address a massive set of MTC devices will be developed. To accommodate a large number of sensors and actuators with very different activity characteristics and low data rates, a MA concept with easy addressing, low energy consumption and low receiver complexity (such as legacy paging systems as a benchmark) while ensuring high reliability needs to be established.
For this task CDMA in the DL with channel dependent spreading modulation is assumed, which allows the support of heterogeneous cellular layouts and the systematic addressing of many devices. The design target is to increase the number of available codes beyond what is possible given by orthogonal codes. Therefore it is necessary to allow non-orthogonality between some of the codes. The concept consists of a broadcast channel that is easy to demodulate by all devices and orthogonal to all other codes. This broadcast channel is used for management functionalities such as the allocation of device or group specific codes assigned to single devices, device groups with common characteristics or groups formed by geographical coherence.

The concept includes the code construction, where the orthogonal code space will be enhanced by quasi-orthogonal functions which lead to acceptable correlation between the non-orthogonal codes. This is done by using bent-sequences to expand the orthogonal code space given gold sequences. Besides the code design the clever grouping of devices using one code for multiple devices increasing the efficiency is another research aspect.

Advanced coded multi-carrier access

The planned research focuses on Sparse Code Multiple Access (SCMA) over OFDM or any other multi-carrier modulations. SCMA is a promising modulation and multiple-access technique to deal with the challenges mentioned above. MC-CDMA [HP97] is a multiple access technique in which QAM symbols are spread out over orthogonal or non-orthogonal code sequences and carried over OFDM tones. The sequence design is an important factor for a MC-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, simultaneously, at the expense of the exponential complexity of the ML reception. Low density signature (LDS) [HRI10] is a special design of CDMA in which the complexity of reception is reduced due to the sparsity of spreading sequences containing a few non-zero elements within the spreading length. Like LDPC coding in the binary field, the sparsity of the overlaid complex codewords let us to reuse the relatively low-cost message passing algorithm (MPA) [HWT08] in complex domain for multi-user detection with a near optimal performance in the MAP sense. As a generalization, the QAM mapper block and the CDMA spreader can be merged together to directly map a set of bits to a complex vector so called a codeword. The whole process is a coding procedure from the binary domain to a multi-dimensional complex domain. Compared to the traditional MC-CDMA, the constellation shaping gain [FW89, BVR96, FU98, BD12] is the advantage of the multi-dimensional codeword modulation technique. The SCMA multiple-access takes advantages of low density codewords as well as multi-dimensional constellation. A systematic approach is desired to design multiple sets of codebooks for multiple user access.

The proposed SCMA technique has the following properties:

- binary domain data are directly encoded to multidimensional complex domain codewords selected from a predefined codebook set,
- multiple access is achievable by generating multiple codebooks one for each layer or user,
- codewords of the codebooks are sparse such that the MPA multi-user detection technique is applicable to detect the multiplexed codewords with a moderate complexity. This facilitates near optimal ML detection with a moderate complexity.
- like LDS, the system can be overloaded such that the number of multiplex layer can be more than the spreading factor. It enables the non-orthogonal superposition technique for better cell throughput and/or supporting of more simultaneous connections
- better link quality and extra spectral efficiency gain due to the shaping gain of the multi-dimensional codewords
- simplicity of OFDMA transmission specially in terms of equalization and channel estimation.

<u>MA using Cognitive Radio</u>

In order to adapt cognitive radio technologies for future wireless communication systems, devices are expected to support the dynamic use of frequency spectrum. A cognitive radio can support both primary (licensed users) and secondary users (unlicensed). Multiple access is possible under an opportunistic way when a free spectrum hole or white space can be sensed. In order to achieve the cognitive functionality, a wideband RF front end receiver will be designed. The limits can be tested by designing a prototype using commercial components. The linearity requirements and frequency selectivity for the frequency agile front end can be thus assessed and then an integrated version can be designed upon. Various duplex modes such as FDD, TDD and half duplex FDD has to be investigated for the architecture and the effects of the duplex modes on the RF performance has to be researched for a cognitive scenario. State of art transceiver for LTE only considers full FDD and TDD and for a wideband cognitive radio for multiple access half duplex FDD is most potential solution. Moreover with the cognitive architecture dynamic carrier aggregation along with legacy control channels becomes a possibility which is beyond the state of art.

2.12 Medium Access Control

2.12.1 General description

The design of Medium Access Control (MAC) protocols that consider the novel requirements and constraint of future applications is an important part of the overall system design of a communication system for beyond 2020. Of the many use cases imaginable for future systems only a subset will be addressed here explicitly. On the one hand, Massive Machine Communication (MMC) provides a lot of challenges in MAC design to allow the access of huge numbers of devices, which show different traffic behavior than the usually assumed human users. On the other hand, UDN also challenge classical MAC paradigms and require careful design especially when mmW applications are targeted. Furthermore, a more general topic is also covered: time synchronization in networks. As synchronized time bases are at the heart of most time division MAC procedures, this topic is of high importance especially in the envisioned highly connected networks of the future.

2.12.2 Related state of the art and limits

The state of the art is structured by subtopics beginning with MMC, followed by UDN and finally network synchronization. A general overview of the state of the art per topic is given including a limit analysis that prepares the research topic detailed in the following section.

<u>MAC for Massive Machine Communication</u>

Current systems like LTE have been designed for large data rates and a limited number of connected devices, which is contrary to the envisioned requirements of Massive Machine-Type communication (MMC). To keep the massive number of nodes with small payloads manageable, the signaling overhead required to communicate with those nodes has to be kept as low as possible. Current activities in LTE-A are focusing on cost reduction and coverage enhancement. Regarding signaling the focus is on a “light mode” without paging and mobility measurements for static devices and only light radio link monitoring, which does not address the design of an efficient MAC for MMC. Besides LTE-A, IEEE 802.11ah standardization is also targeting to include “sensors and meters” in terms of a MAC managing at least 6000 connected devices, which is still far too low considering the massive access envisioned for the future. For further details, please refer to the state of the art of Section 2.2, optimized signaling structure for low-cost MMC devices, which is tightly connected to this research topic.

Overall current standardization activities do not fully address the challenges of MMC due to compatibility issues, e.g. the signaling overhead or advanced random access methods. Therefore, in the following three potential solutions will be discussed in terms of the state of the art: Coded random access addresses efficiency enhancements in random access exploiting successive interference cancellation, coded access reservations is concerned with the improvement of contention based schemes and finally advanced physical layer processing for MAC deals with novel algorithms on the PHY layer to facilitate enhanced MAC schemes.

<u>Coded random access and successive interference cancellation</u>

A toy example that illustrates the concepts of coded random access is presented in Figure 2.8a), showing a graph representation of slotted ALOHA; the left-side nodes represent contending users, the right-side nodes represent the slots and the edges connect the users with the slots in which their transmissions take place. All transmissions performed by a user carry the same message and a pointer to the other replicas. In standard ALOHA framework, only the slot s4 would be considered usable, as it is the only singleton slot.

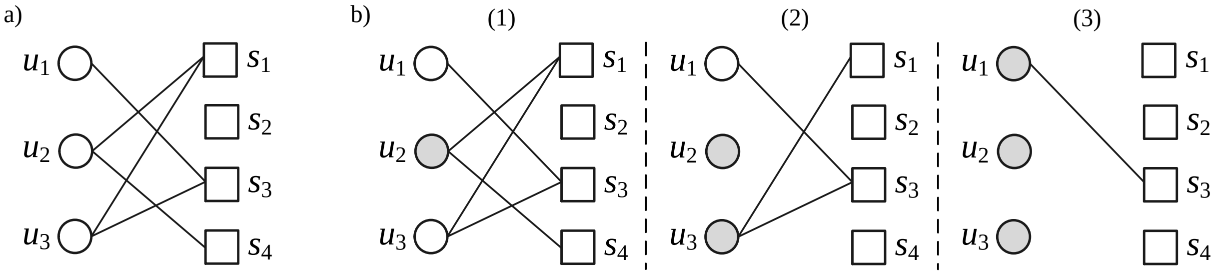


Figure 2.8 Coded random access example

The execution of successive interference cancellation (SIC) for the same example is depicted in Figure 2.8. In the first step singleton slots are identified, i.e., slot s4, and the corresponding transmissions, i.e., the transmission of u2, resolved. Using pointers contained in the resolved transmissions, the replicas are removed, potentially resulting in new singleton slots. In the example, the replica transmitted by u2 is removed from s1, which becomes singleton. SIC iterates in the same way, until there are no new singletons slots or all transmissions have been resolved. The result of the SIC application is that the throughput can be substantially increased.

The above operation is analogous to the iterative belief-propagation erasure-decoding, which motivated the application of the theory and tools from codes-on-graphs to improve the throughput of framed ALOHA [Liv11]. In [Liv11] it was shown using numerical optimization that the strategy that maximizes the throughput is analogous to the encoding of left-irregular LDPC codes. This initial work was followed by papers that applied doubly generalized LDPC codes [PLC11a, PFC10], derived the capacity bounds [PLC11b], and applied spatially coupled codes [LPL+12]. Rateless codes [BLM+98] inspired so-called frameless ALOHA [SPV12, STP+13], where frame length is not fixed, but its termination is adaptive and performed when a criterion related to throughput maximization is satisfied.

Coded access reservation

Access reservation protocols, [BG97], enable users to connect and transmit asynchronously to a multiuser communication system, e.g. a cellular system such as GSM, UMTS and LTE-A [3GPP-TS36201, TPS+13]. The first phase of the access reservation protocol, the contention phase, is susceptible to overload whenever the amount of contending users far surpasses the amount of contention resources. The traditional complementary approaches to avoid overload is to either restrict access or to increase the amount of contention resources. The former leads to the delay of the users access, while the later transfers the resources that could be used elsewhere in cellular system to the contention phase, leading to reduced resources available for actual communication.

Recently a new class of access reservation protocols, denoted as coded reservation [PTS+12, TPSP2-13], has been proposed in the literature, where the contention phase is redefined through the introduction of coded reservation tokens, which allows the expansion of the contention space to the code domain. These coded reservation tokens are obtained by combining multiple contention frames in a virtual contention frame, and then allowing these users to select up to one orthogonal resource per contention frame, as depicted in Figure 2.9. Through this procedure the users create a coded reservation token, which the length corresponds to the number of frames within the contention frame and the set of possible codewords is denoted as codebook.

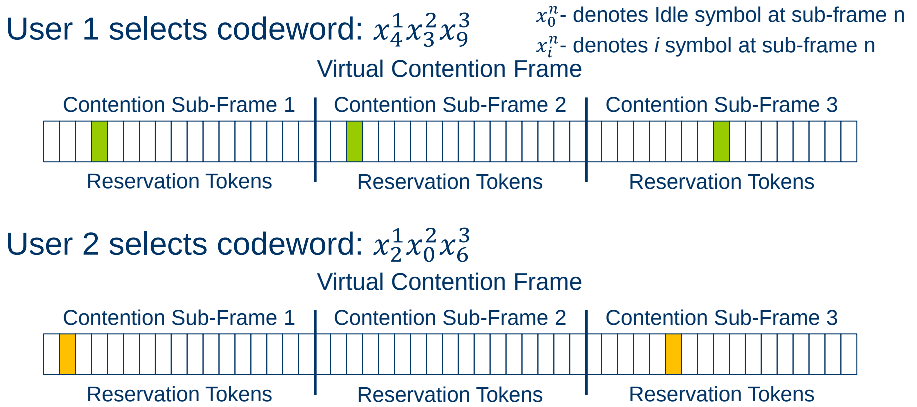


Figure 2.9 - Coded reservation tokens example.

One of the drawbacks of this approach is the introduction of phantom codewords, which is the result of the non-orthogonally of the generated codewords. In [PTS+12, TPS+13b] was reported that by doing blind restriction of the amount of codewords according with the amount of users contending it is possible to minimize the generation of phantom codewords. The efficiency of this sub-optimal scheme has been reported to reach 38% in the high load range, although it might be possible to achieve higher efficiency through the proper coding of the coded reservation tokens and phantom cancellation techniques, which so far have not been reported in the literature.

<u>Advanced physical layer processing for enhanced MAC: joint detection of node activity and data</u>

In order to achieve a minimal signaling overhead for communication setup random access (RA) is often employed, e.g. coded random access. Combining RA with non-orthogonal schemes like CDMA or SCMA described in Section 2.11 allows for collision handling by multi-user detection (MUD), which can be exploited to enhance the throughput of such systems as detailed before. However, from a PHY perspective the set of active users is usually unknown which is contrary to classical MUD setups employing explicitly allocating resources, e.g. LTE. This severely limits the performance of standard multi-user detectors. To determine the active terminals various schemes have been suggested to approach the ideal performance of known active users, e.g. sub-space based activity detection [WC98, LL04] and code based approaches [BDL03]. However, these schemes are mostly limited to systems with a relatively low number of nodes compared to the available resources. For the massive amount of associated users to be expected for future MMC applications, novel approaches like Compressive Sensing (CS) [Don06] are required to provide the means to jointly detect active devices and their data. In order to allow the application of CS it is required that the overall system can be formulated as a linear equation system with sparse coefficients, which has been shown in a CDMA context [HG11, SD11].

<u>MAC for UDN and mmW</u>

A MAC solution is considered in the METIS UDN research for frequency bands in mmW and self-backhauling which are not parts of the LTE-A standard. WiGig (Wireless Gigabit Alliance) [Han11] has developed a medium access control (MAC) layer, a physical (PHY) layer, and several protocol adaptation layers (PALs) for wireless communications in 60GHz band. Typically, WiGig systems will operate at 10 dB higher received power than IEEE 802.11n systems because the total noise power from the wider bandwidth is much higher. 60 GHz stations need to find each other, coordinate operation, and optimize antenna settings. WiGig addresses these challenges in its MAC/PHY specification with a scheduled MAC protocol different to other WLAN standards with contention based MAC protocol, integrated with a specific beamforming protocol.

Network synchronization

TDMA requires, by definition, network synchronization with sub-frame accuracy. For networks without a central controller or with only limited contact with a central controller, the nodes need to agree on a common clock in a distributed fashion. This is a more challenging problem and could be needed in METIS to manage D2D links when the D2D nodes have limited or no contact with the fixed infrastructure.

Existing protocols on network synchronization can be mainly classified into two categories: reference-based clock synchronization and distributed clock synchronization. In the reference-based clock synchronization [GKS03], [MKS+04], all the nodes are required to synchronize to a reference node by building a spanning tree through the network. If the network is static, the spanning tree can be maintained and the synchronization can be achieved easily. However, this mechanism is sensitive to the changing topology and node failure.

On the other hand, in distributed clock synchronization, all nodes implement the same algorithm individually without relying on a network hierarchy. The distributed nature can often result in improved robustness to node failures and mobility in dynamic networks. There are two basic design approaches.

- Converge-to-max [IEEE-802.11], where a node only synchronizes to the transmitter which has greater clock value than the node's own clock. The scalability is a main issue of converge-to-max schemes, since the faster clock might do not have the opportunities to broadcast when there are a large number of nodes.
- Arbitrary-consensus [SA05][SF11], where the goal is to synchronize all the clocks in the network to a common value. Note that it does not matter what this common value is. There are mainly two limitations in the existing arbitrary-consensus synchronization algorithms. Firstly, some schemes, e.g., [SA05], require a scheduled medium access protocol for the broadcast of timing messages, which is hard to implement in distributed networks. Secondly, the delays during the timing message transmission are not considered in some synchronization algorithms, e.g., [SF11].

2.12.3 Detailed description of planned research

In the following the planned research for all MAC topics is outlined following the same order of the topics as in section 2.12.2.

MAC for Massive Machine Communication

Due to the tight connection of the MAC MMC research in this research topic Section 2.2, optimized signaling structure for low-cost MMC devices, the following approaches can be seen as components of an overall MMC PHY/MAC design. Coded random access and coded access reservation are alternative approaches, while the joint device activity and data detection can principally be combined with both. In terms of Section 2.2, these solutions will be designed for compatibility with the chosen signaling approaches and higher level design choices.

Coded Random Access

The coded random access approach can, in the asymptotic case, nearly reach the performance of a scheduled scheme, without the associated scheduling overhead. In non-asymptotic conditions this approach performance still needs further optimization. Therefore, under the coded random access research topic, the following research tracks will be pursued:

1. Design of adaptive mechanisms to terminate the random access with an aim of throughput maximization.
2. Design of coded random access mechanisms when the users are divided into classes with different access strategies.
3. Design of coded random access schemes taking into account constraints of the successive interference cancellation.

4. Design of random access schemes taking into account and the existence of the capture effect.

Coded Access Reservation

Through the application of the coded reservation approach, it is possible to enable a multiuser communication system to receive successfully the reservation requests generated simultaneously from a massive amount of users. One of the main issues in coded reservation is the phantom codewords (false positives), which if not properly dealt with, can affect significantly the efficiency on how the system resources are used. We plan to tackle the adverse effects of the phantom codewords, as follows:

1. The study and formalization of the generalized coded reservation principles:
2. Study and definition of ordered sequences of codewords from a given codebook which when truncated lead to a minimal generation of phantom codewords:
3. Comparative study on the performance of coded reservation in real time access reservation systems and with backlogging.
4. Phantom minimization and collision resolution procedures based on SIC at the data phase.

Joint device activity and data detection for MMC

In contrast to human communication most MMC devices are expected to be only sporadically active, which leads to a large number of devices that are associated with a base station, but only a fraction is actually transmitting data. In LTE-A this requires management of a large number of connections and possibly a large signaling overhead for mobility management, paging, etc. In order to identify the active nodes without further signaling, and to jointly estimate the transmitted payload, novel detection schemes at the base station are required. To this end, the recently emerging compressive sensing theory provides theoretical bounds and algorithms applicable to the joint activity and data detection problem arising in MMC scenarios.

To benefit from compressive sensing from a system view, many open questions like (1) measures of system impact, (2) channel estimation, (3) channel coding aspects, and (4) effects of imperfections still have to be addressed. Regarding the first point different activity error classes have been identified which will be employed as a basis to control the system impact of CS-MUD systems on higher layers. Moreover, channel estimation either pilot based or blind for unknown activity will be addressed. To this end, ideas and concepts from blind channel estimation will be considered to decrease the required amount of signaling as much as possible. Furthermore, first results for the application of channel coding to CS-MUD have shown considerable gains [BSD13], which will be extended to state of the art channel coding.

MAC for UDN and mmW

The goal is a MAC design including understanding of the potential benefits of a hybrid MAC approach (a hybrid of contention based and scheduled based protocols), to leverage the advantages and avoid the disadvantages of the contention based and the scheduled based protocols for UDN and mmW, with larger antenna arrays and beamforming. Depending on the outcome of the wireless self-backhauling study in WP3, we may also study interactions between routing and MAC.

Distributed network synchronization

The following two directions will be considered for network synchronization:

1. When there is no reference clock in the network, the objective is to let all the clocks in the whole network converge to a common value. Under this scenario, by using a practical random broadcast mechanism for message transmission, we will propose distributed

consensus clock synchronization algorithms, which jointly adjust clock frequencies and offsets, for dynamic networks.

2. When there are reference clocks in the network, the objective is to let all the ordinary clocks synchronize to the reference clocks. Under this scenario, we will analyze the theoretical relationship between the convergence speed and the number of the reference clocks. Moreover, we will propose robust distributed clock synchronization algorithms when there are delays and distortions during the message transmission.

2.13 Hybrid Automatic Repeat Request (HARQ)

2.13.1 General description

HARQ retransmission schemes are applied on the MAC layer in order to compensate for incorrect link adaptation so as to ensure timely and reliable packet delivery to the higher layers. With HARQ, incorrectly received packets are stored in the receiver as soft information. This soft information is combined with retransmitted information prior to the decoding in order to improve error rate performance. HARQ schemes can be characterized along the following research aspects:

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

Within the METIS project, HARQ is particularly relevant in the context of ultra-reliable networks and to achieve the overall technical goal of reduced End-to-End latency, where it is particularly related with the design of an air interface for dense deployment. In the context of moving networks, HARQ can help to improve the robustness of the link due to the inherent time diversity.

2.13.2 Related state of the art and limits

There exists a wide variety of HARQ solutions, and a brief overview is given in the sequel.

<u>HARQ coding techniques</u>

HARQ schemes often use puncturing of a mother codeword to derive multiple redundancy versions, e.g. in LTE [3GPP-TS36]. With Incremental Redundancy (IR) HARQ, e.g. [Che03], the redundancy versions are altered for the packet retransmissions. This reduces the effective code rate after soft combining in the receiver and leads to a coding gain in addition to the combining gain [Che03]. Chase Combining HARQ [Cha85] denotes a subset of IR HARQ, where the redundancy versions are not altered for the retransmissions. Puncturing is applicable with FEC schemes such as Convolutional Codes or Convolutional Turbo Codes, e.g. [RM00]. Also the suitability of punctured Low Density Parity Check Codes (LDPC) for IR HARQ is reported, e.g. [VSW05].

A HARQ technique using the Turbo principle was introduced by Narayan and Stüber in 1997 [NS97]. Basic idea is to introduce an interleaver prior to the retransmission. In this way a Turbo Code is constructed by means of the first transmission and the interleaved retransmission.

Multi-user (H)ARQ is a technique based on the Network Coding principle, where a user decodes its own packets as well as packets of another user [LJ06], [LSK+10]. The basic idea introduced in 2006 [LJ06] is to create a single retransmission packet by Exclusive OR (XOR) combining of multiple packets previously transmitted to multiple users, the retransmission packet being broadcast to the multiple users involved.

A single user HARQ technique using the Network Coding principle was introduced by Lang et al. in 2012 [LWD+12, LWD+13]. Basic idea is to create a single retransmission packet by XOR combining of multiple incorrectly transmitted packets. This results in a concatenated code construction with compressed size of the retransmission. A performance comparison of HARQ schemes using the Network Coding principle versus puncturing based HARQ schemes can be found in [WWD+13]. A similar single user HARQ technique, using a network coded superposition of a retransmitted packet with a new packet was presented in [MOS12].

Also a variety of HARQ transmission schemes using Rateless Codes have been presented. Some schemes use a Rateless Code as a physical layer channel code, typically in conjunction with reliability feedback [SVW06][SPP+08]. Other HARQ approaches use Network/Rateless Coding like an outer block code for burst error correction, similar as applied for 3GPP MBMS, for both unicast and multicast, on the MAC layer or on higher layers, e.g. [JMM93], [LHW09], [LLF10].

HARQ feedback mechanisms

A baseline feedback mechanism for HARQ is to transmit a single bit ACK/NACK feedback per transmitted packet. In LTE [3GPP-TS36], this baseline scheme is applicable. Further options include ACK/NACK bundling in case of LTE/TDD, where multiple ACK/NACKs of multiple packets can be combined by means of an AND operation. LTE further allows the mapping of multiple ACK/NACK messages to a single modulation symbol, e.g. to support spatial multiplex transmission of packets.

ACK/NACK is often derived from a check sum involving a Cyclic Redundancy Check (CRC) code. Alternatively, a CRC can be omitted and ACK/NACK be derived from reliability information in the decoder, e.g. [FH09].

With Segment HARQ [SC04], a packet is partitioned into multiple segments, similar to code block segmentation in LTE [3GPP-TS36], and an ACK/NACK feedback message can be transmitted per segment. Apparently this leads to increased overhead for ACK/NACK signaling or to reduced reliability of the ACK/NACK messages.

Reliability-based HARQ allows the receiver to transmit soft reliability information quantifying the quality of an incorrectly received packet, and depending on the reliability information the transmitter can adapt the format of the retransmission, such as size (in terms of physical resources), modulation or coding of the retransmission. An overview of reliability-based HARQ schemes can be found in [TVP+03] and the references therein.

HARQ protocols

A variety of HARQ protocols exist and the design of the HARQ protocol has impact on the control signaling requirements, e.g. [DKN01]. Often a set of concurrent stop-and-wait protocols, also called HARQ processes, are implemented to enable packet exchange with a user in consecutive subframes without interrupts.

Adaptive HARQ allows to adapt the format of the retransmitted packets, i.e. parameters such as modulation and coding scheme, redundancy version or packet size may be adapted for a retransmission. This gives some flexibility for the formatting of the retransmissions so as to improve, for example, reliability or spectrum efficiency. A performance assessment of adaptive HARQ for a WCDMA/HSDPA system can be found in [CWP03]. In the LTE system, adaptive HARQ can be applied in uplink and downlink, but the sequence of redundancy versions is predefined in uplink [3GPP-TS36]. In LTE uplink also non-adaptive HARQ is applicable, where a retransmission can be triggered by sending NACK only, without sending a scheduling grant for the retransmission [3GPP-TS36].

Asynchronous HARQ allows the packet be retransmitted with a variable delay relative to the first transmission, while with synchronous HARQ this delay is fixed. Synchronous and asynchronous HARQ protocols are applied in LTE uplink and downlink, respectively [3GPP-TS36]. Asynchronous HARQ typically offers more scheduling flexibility at the expense of signaling overhead as compared to synchronous HARQ.

Commonly used HARQ protocols further allow to constrain the maximum retransmission delay, e.g. by defining a maximum number of retransmissions or by discarding a pending retransmission after expiry of a timer [3GPP-TS36].

Limits

The LTE/LTE-A system is supporting HARQ in UL and DL, each using a fixed number of eight HARQ processes, which leads to a minimum HARQ RTT (i.e. the period from a first transmission of a packet until the first retransmission for that packet) of 8ms. HARQ RTT needs to be reduced in a METIS system, e.g. by reducing TTI, by reducing the number of HARQ processes or by enabling un-interrupted ACK/NACK transmission with TDD.

LTE is further not supporting advanced HARQ schemes such as multi-user HARQ, Network Coding principles, segment HARQ or reliability-based HARQ, thus valuable spectral efficiency enhancements versus LTE on the order of, say, 30%, may be achievable.

2.13.3 Detailed description of planned research

HARQ is an essential functionality of a link adaptation scheme.
In particular for ultra-reliable links where the successful delivery of packets has to be guaranteed within a predefined deadline, new deadline-driven HARQ concepts are required. In order to increase the efficiency of HARQ implementations, fractional retransmission implementations where data of several independent links are combined - in particular in case of different BLER targets - will also be investigated.

Also HARQ protocol aspects taking into account protocols such as adaptive HARQ, reliability-based HARQ and possibly Network Coded HARQ may be studied. Such protocols may improve spectrum efficiency, in particular for delay-insensitive services such as video downloads.

A particular aspect to be investigated is the feedback transmission with reliability-based HARQ. A link-level performance assessment of reliability-based HARQ schemes when used in the LTE system was presented in [WWD+14]. It was shown that reliability-based HARQ can lead to throughput improvements over conventional HARQ on the order of 35%. It was further shown in [WWD+14] that throughput gains of such order can be achieved also when constraining the possible size of a retransmitted packet to within a small set, e.g. 1.0x, 0.5x and 0.25x the size of the initially transmitted packet. This motivates the usage of multi-level ACK/NACK for reliability feedback, e.g. a 2bit ACK/NACK would allow for the above set of retransmission packet sizes with one ACK level and three NACK levels ($\mathrm{NACK_i}, \mathrm{i} \in \{1, 2, 3\}$) indicating different reliabilities of the received packet. In [WWD+14] also the impact of ACK/NACK transmission errors on throughput was studied with reliability-based HARQ, where it was found that with increasing $\mathrm{NACK_i} \rightarrow \mathrm{NACK_j}$ error rate the resulting throughput degradation is more graceful than with increasing $\mathrm{ACK} \rightarrow \mathrm{NACK}$ or $\mathrm{NACK} \rightarrow \mathrm{ACK}$ error rates. This motivates the usage of asymmetric modulation schemes for conveying the multi-level ACK/NACK feedback with unequal error protection for the ACK and NACK levels, respectively. The potential of such modulation schemes will be investigated by means of link level simulations.

Furthermore, enhanced protocol concepts may be designed, for example, to reduce latency, signaling overhead, or buffering requirements, or to allow for more flexibility, etc.

2.14 Radio link enablers for RRM

2.14.1 General description

In general, radio resource management 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 with 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.

2.14.2 Related state of the art and limits

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 is not allowed to disturb the cellular system performance meaning that cellular communication has priority and D2D links should only be established when the interference introduced is below a certain threshold, 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 conventionally used by LTE needs to be frequently exchanged between UEs and network in particular in mobile D2D scenarios, although a D2D is not always possible or beneficial. 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.

2.14.3 Detailed description of planned research

We assume network-assisted D2D in underlay mode where the focus lies on signaling for RRM including mode selection, power control, and resource allocation. We will evaluate the required RRM enablers from link level perspective and develop a concept for how to derive and exchange link level context information in an efficient manner. 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 of the UE.

Besides the research activity listed above, 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 Summary

This deliverable provides a detailed overview of the radio link research topics and their specific aspects to be investigated as well as a detailed analysis of the related state of the art.

In particular, the document addressed three main objectives:

1. Comprehensive state of the art analysis with respect to the radio link research topics identified in the first deliverable on radio link research D2.1, including current standards and their evolutions as well as academic state of the art. Thus, we reflect the available solutions as well as already known but not yet implemented solutions.
2. Description of the limits of the state of the art and analysis in what respect further research is required to meet the goals of METIS.
3. Identification and detailed description of novel radio link concepts and the specific aspects to be investigated advancing current state of the art.

These objectives are addressed for each of the identified radio link research topics. This document thus motivates the radio link research conducted in METIS from a scientific perspective and connects the proposed radio link aspects and concepts to today's existing solutions as well as to the horizontal topics and the overall research challenges identified in METIS.

In order to achieve the general goal of METIS towards 5G of 1000 times data volume per area and 10 to 100 times user throughput, a threefold approach is chosen leading to a combination of increased spectrum, e.g. by using higher frequency bands up to mmW bands, network densification (UDN) by introducing a large amount of access points and, last but not least, significant improvements of spectral efficiency. In addition, also new approaches and technology enablers for fulfilling the end user requirements are considered in METIS, like moving networks enabling moving relays and D2D for further offloading. Furthermore, also new challenges are addressed like support of MMC and URC. All these challenges are reflected in the radio link research focusing on the PHY and MAC enablers to achieve the goals of METIS as summarized below.

Several air interface aspects relevant for UDN are investigated, like transceiver design for full duplex, medium access control for UDN, and also general aspects such as latency and throughput, wireless backhauling and usage of higher and dynamic frequency bands which are especially suited for dense deployment. To exploit the new opportunities of higher frequency bands and cognitive radio (CR) approaches, possible solutions for an air interface for dynamic spectrum usage, modulation schemes suited also for mmW, multiple access schemes and waveform design for cognitive radio are described. Increasing spectral efficiency is targeted by research activities on new waveforms including related multiple access techniques, non- and quasi-orthogonal multiple access, new modulation and coding techniques and advanced equalizers. Radio link research plans to provide specific RRM enablers and multiple access techniques for D2D. MMC is specifically challenging for the radio link layer. To enable an efficient support of MMC, new multiple access and medium access control schemes, HARQ enhancements, synchronization issues and general signaling aspects for MMC are investigated. In these research topics, also aspects of URC are considered. Moving networks (MN) are an important enabler to extend coverage and reliability of the network and impose a challenge for the radio link as well. Robust solutions designed based on FBMC systems are investigated as well as an air interface designed for moving networks.

With all these requirements and the diversity of solutions, flexible design and interface management become of increasing importance, as most likely a one-fits-all solution will not be able to efficiently address all the demand of the diverse services of future wireless networks. Aspects of flexible design and interface management are also investigated in the radio link research by advanced link adaptation, flexible modulation, coding and HARQ design as well as flexible signaling structures.

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