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Abstract

This deliverable provides the conclusions of the action by pointing out the key scientific results achieved in FANTASTIC-5G and provides the set of recommendations we can draw from those for the definition of 5G New Radio. Additionally, the deliverable provides a summary of the exploitation and dissemination activities and the impact of the project.

In agreement with the project officer we have combined the two project deliverables D6.2 and D1.2 into a single document as they are both covering the same period (the whole project) and are covering complementary areas: the overview of the results and their exploitation and dissemination, the conclusions of the action and the socio-economic impact of the action.

Keywords

5G, New Radio, Air Interface, MBB, MMC, mMTC, MCC, URLLC, BMS, V2X, PHY, MAC, RRM

[1] CO = Confidential, only members of the consortium (including the Commission Services)

PU = Public

Executive Summary

As specified by the proposal this document is issued by work package 1 and work package 6 and constitutes the final report as required by the grant agreement of the project. Its purpose is to provide the reader a global overview about the work being done during the course of the project without having the intention to provide details. Those are covered within the respective deliverables of the technical work packages to be found at http://fantastic5g.eu/ ([FAN16-D2.1, FAN16-D2.2, FAN17-D2.3, FAN16-D3.1, FAN17-D3.2, FAN16-D4.1, FAN17-D4.2, FAN16-D5.1, FAN16-D5.2, FAN17-D5.3]) and within the references given in those.

The document starts with an outline of the scientific core results of the project and the recommendations we have drawn from those. We have structured this part following the lines of the project itself (link technologies, multi-node/multi-antenna technologies, overall air interface design, lessons learnt from the Proof of Concept (PoC) activities). The project has provided significant outcomes and related recommendations in 18 sub-categories covering the lower layers of the air interface (PHY, MAC and RRM). Some exemplary sub-categories are waveform and frame design, multi-node connectivity, efficient massive access protocols, system level integration of enhanced MIMO, etc.

Subsequently, we present the achievements of the project related to exploitation, dissemination, standardization and innovation.

Finally, we close this deliverable with the assessment of the impact of the project and provide the conclusions.

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List of Acronyms and Abbreviations

5G-NORMA	5G Novel Radio Multiservice adaptive network Architecture
ACK	ACKnowledgement
AI	Air Interface
ARP	Access Reservation Protocol
BF	Beamforming
BF-OFDM	Block-Filtered OFDM
BMS	Broad- and Multicast Services
BS	Basestation
CB	CodeBlock
CDF	Cumulative Distribution Function
CoMP	Coordinated Multipoint
CP-OFDM	Cyclic Prefix OFDM
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Check
C-RNTI	Cell Radio Network Temporary Identifier
CRPLNC	Coded Random Access with Physical Layer Network Coding
CSI	Channel State Information
D2D	Device to Device
DCI	Downlink Control Information
DFT	Discrete Fourier Transformation
DIR	Dominant to rest of Interference ratio
DL	Downlink
DTX	Discontinuous Transmission
EC	European Commission
EuCNC	European Conference of Networks and Communications
EVM	Error Vector Magnitude
EW	European Wireless
FANTASTIC-5G	Flexible Air iNTerfAce for Scalable service delivery wiThin wIreless Communication networks of the 5th Generation
FQAM	Frequency and Quadrature Amplitude Modulation
FBMC	Filter-Bank Multi-Carrier
FC-OFDM	Flexibly Configured OFDM
FDPC	Frequency Domain Partial Construction
FEC	Forward Error Correction
FFT	Fast Fourier Transformation

FS-FBMC	Frequency spreading FBMC
GoB	Grid of Beams
H2020	Horizon 2020
HARQ	Hybrid Automatic Repeat reQuest
ICC	International Conference on Communications
ICI	Inter-Carrier Interference
ICIC	Inter-Cell Interference Coordination
ICT	Information and Communication Technologies
IDMA	Interleave-Division Multiple Access
IoT	Internet of Things
IPR	Intellectual Property Rights
IR	Incremental Redundancy
ISD	Inter-Site Distance
ISWCS	International Symposium on Wireless Communication Systems
JT	Joint Transmission
KPI	Key Performance Indicator
LDPC	Low Density Parity Check
LOS	Line of Sight
LTE	Long Term Evolution
LTE-A	LTE Advanced
MAC	Medium Access Control
MBB	Mobile Broadband
MBMS	Multimedia Broadcast and Multicast Service
MC	Multi-Carrier
MCC	Mission Critical Communications
MCS	Modulation and Coding Scheme
MIB	Master Information Block
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
MMC	Massive Machine Communications
mMIMO	Massive MIMO
mmMAGIC	mm-Wave based Mobile Radio Access Network for 5G Integrated Communications
MMSE	Minimum Mean Squared Error
MU	Multi-User
MUD	Multi-User Detector
mMTC	massive Machine Type Communications

MRT	Maximum Ratio Transmission
MWC	Mobile World Congress
O	Orthogonal
ONE5G	E2E-aware Optimizations and advancements for the Network Edge of 5G New Radio
NACK	Non-ACKnowledgement
NLOS	Non Line of Sight
NOMA	Non-Orthogonal Multiple Access
NO	Non-Orthogonal
NR	New Radio
NUC	Non-Uniform Constellations
OFDM	Orthogonal Frequency Division Multiplexing
OQAM	Offset-QAM
PAPR	Peak-To-Average Power Ratio
PDCCH	Physical Downlink Control CHannel
PHY	Physical Layer
PMI	Precoding Matrix Indicator
PoC	Proof of Concept
P-OFDM	Pulse Shaped OFDM
PPN	PolyPhase Network
PRACH	Physical Random Access CHannel
PS	Priority aware Scheduling
PSS	Primary Synchronization Signal
P-TRP	Primary Transmission Point
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RA	Random Access
RACH	Random Access CHannel
RAN	Radio Access Network
RB	Resource Block
R&D	Research and Development
RF	Radio Frequency
RMa	Rural Macro
RRC	Radio Resource Control
RRM	Radio Resource Management
RS	Reference Signal

SAW	Stop-And-Wait
SDR	Software Defined Radio
SFN	Single Frequency Network
SIB	System Information Block
SIC	Successive Interference Cancellation
SINR	Signal to Interference and Noise Ratio
SMARTER	Study on New Services and Markets Technology Enablers
SME	Small and Medium-sized Enterprises
SNR	Signal to Noise Ratio
SotA	State-of-the-Art
SPEED-5G	quality of Service Provision and capacity Expansion through Extended-DSA for 5G
SSS	Secondary Synchronization Signal
STR	Specification Transparency Requirement
TA	Timing Advance
TDD	Time Division Duplexing
TFL	Time-Frequency Localization
TTI	Transmission Time Interval
UE	User Equipment
UF-OFDM	Universal Filtered OFDM
UID	User-ID
UL	Uplink
UMa	Urban Macro
URLLC	Ultra-Reliable Low Latency Communications
V2X	Vehicle-to-Anything
V2V	Vehicle-to-Vehicle
VTC	Vehicular Technology Conference
WG	Working Group
WOLA	Weighted OverLap and Add
WP	Workpackage
ZF	Zero Forcing
ZT-DFT-s-OFDM	Zero-Tail-spreading OFDM

1 Introduction

1.1 Objective of the document

The objective of this document is to collect and summarize the essence of the work being done in FANTASTIC-5G. Here, we collect the major recommendations being developed during the course of the project and the key lessons learnt related to the design of the air interface of 5G for bands below 6 GHz to achieve its ambitious targets.

WP1 and WP6 – the originators of this document – have no resources allocated to actual research. So, the material provided in the following is completely based on the work being done in the technical work packages of the project as reported in their respective deliverables. This document is to provide an overview of those outcomes without having the intention to go into detail. Those are to be found within the respective deliverables of the other work packages.

1.2 Structure of the document

We start with outlining the scientific results of the project and the recommendations we have drawn from those. This is followed by the presentation of the achievements of the project related to exploitation, dissemination, standardization and innovation. We end this deliverable with outlining the impact of the project and the conclusions of the action.

2 Scientific results and project recommendations

The project's intention has been to ultimately providing recommendations on how to design the air interface of 5G for bands below 6 GHz to achieve its ambitious targets. Following the original intentions of the project, we have focused on signal processing aspects related to the complex baseband of the air interface covering PHY, MAC and RRM.

5G will be confronted with a high degree of heterogeneity in various aspects, e.g. related to use cases being supported and thus requirements to be met by the system (e.g. latency, reliability), the wide range of deployment types and link characteristics. For being able to cope with this high degree of heterogeneity and the ambitious targets of 5G with respect to capacity and coverage and to make 5G future-proof, i.e. easing the introduction of new features, we have developed a set of design targets we obey to when identifying and designing potential candidate technologies to be used in 5G:

To have a high degree of flexibility/versatility for supporting the broad class of services with their associated (broad class of) KPIs and to enable efficient multi-service support (i.e. meeting the high heterogeneity of requirements) while dealing with high heterogeneity of deployment types (dense urban vs rural; train lines …), operating frequencies and link characteristics (e.g. Doppler, delay spread).

To be highly scalable to efficiently support a high number of devices and a wide range of antenna system designs, bandwidth and carrier frequency configurations.

To allow for **satisfactory service quality** where and when needed both related to consistent service quality (e.g. by introducing special means to improve cell edge performance such as interference mitigation techniques) and related to the provision of capacity peaks in respective areas (e.g. by the introduction of high capacity links in crowded areas).

To be highly efficient to support the requirements on energy consumption and resource utilization and to enable high spectral, energy, and cost efficiency in general.

To be future-proof/forward compatible to support easy integration of new services and functionalities, and new frequencies, without the need of redesigning the AI.

We started in the beginning of the project with an assessment of the anticipated ecosystem of use cases (out of the 5 families: Mobile BroadBand (MBB), Mission Critical Communications (MCC, 3GPP equivalent: URLLC), Massive Machine Communications (MMC, 3GPP equivalent: mMTC), Broad- and Multicast Services (BMS) and Vehicular-to-anything (V2X)) 5G will potentially to be required to support. We have based this assessment upon external sources such as the NGMN whitepaper [NGMN-5G], deliverable D1.1 from the FP7 project METIS [METIS13-D1.1] and the outcomes of the 3GPP activity SMARTER (Study on New Services and Markets Technology Enablers) [22.891]. Additionally, we have refined our selection in cooperation with other 5G PPP phase 1 projects and with the help of the advisory board of the project

Following this activity, the technical work packages have analyzed and parameterized the identified candidate technologies accordingly. Additionally, we have produced a set of proof of concepts for some selected technologies. Furthermore, we have implemented some key enabling technologies into the available system level simulators and have assessed their performance. Those system level simulators have been calibrated according to the procedures being defined by 3GPP and thus are aligned to those. The following sections provide the major outcomes related to those activities.

2.1 Link technologies

The first set of technologies being covered in the following are related to the physical layer. Those technologies are required to efficiently setting up the links between network and user equipment (UE) and between several UEs.

2.1.1 Waveform design

One of the key enablers on link level is the selected waveform. The baseline to compare waveform proposals against has been CP-OFDM as e.g. applied in 4G. While CP-OFDM is a reasonable selection in general, some of its characteristics can be improved considerably. The project has followed two different variants for improving CP-OFDM with various flavours for both. The first category applies a filtering function per subcarrier. Investigated variants have been: FC-OFDM (Flexibly Configured OFDM), P-OFDM (Pulse shaped OFDM), Frequency spreading Filter-Bank Multi-Carrier/Filter-Bank Multi-Carrier (FS-FBMC/FBMC), FBMC with QAM signalling (QAM-FBMC) and Zero-Tail-spreading OFDM (ZT-DFT-s-OFDM). The other line we have followed has been per subband filtering: Universal Filtered OFDM (UF-OFDM), Block-Filtered OFDM (BF-OFDM). Following 3GPP the partners in the project have extended these investigations by including windowed variants of OFDM (WOLA – Weighted OverLap and Add). The project has both made a simulation based comparison of a selected set of candidates and has provided improvements for the different options related to various aspects:

- transceiver implementations with reduced complexity
- concurrent support of different subcarrier spacings
- support of transmissions with relaxed synchronization
- performance in frequency-selective/delay spread channels
- coexistence between different waveforms
- support of MIMO (PHY aspects)
- support of high mobility scenarios
- parameter optimizations for various scenarios

We have conducted a major simulation campaign with calibrated simulators to directly compare the candidates. According to 3GPP both windowed and sub-band filtered variants based on CP-OFDM are selected as options under the constraint of having transparent transmitters. While per-subcarrier filtering is currently not considered, the next phase of 3GPP might still allow for those. In the following we provide the key outcomes of the project and the related conclusions to be drawn.

General note: 3GPP NR requires the spectral confinement techniques, e.g. windowing/filtering to be transparent to the receiver. We call this specification transparency requirement (STR), which naturally compromises the spectral confinement of the radio signal.

Advantages and drawbacks of windowing and sub-band filtering:

- Subcarrier-wise filtering (aka. windowing)
    - Advantages:
        - Windowing at TX and RX can be implemented with low complexity, e.g. complexity increase is less than 2% for FC-OFDM and P-OFDM windowing operation.
        - Windowing reflects a per-subcarrier filtering, hence window design is independent of allocated sub-band location and bandwidth
        - Windowing operation only needs to be run once, both for contiguous as well as for distributed sub-band allocation
        - Windowing does not cause sub-band edge EVM (Error Vector Magnitude) regrowth, rendering it suitable especially for narrow-band transmission

        - Transparent windowing (verifying STR) is doable for window lengths not substantially exceeding the symbol interval
    - Drawbacks:
        - Transparent windowing constrains the window length and results in compromised spectral confinement.
        - OQAM-based scheme does not allow a straightforward reuse of certain MIMO-OFDM schemes, e.g. SFBC and non-linear MIMO.
- Sub-band-wise filtering
    - Advantages:
        - Transparent filtering (verifying STR) is always doable without restrictions
        - For constant filter tail length, sub-band filtering can achieve a steeper slope of the power at the sub-band edges compared to windowing
        - Filter length is less constrained by STR than windowing, since interference imposed by the filter tails on surrounding symbols is minor or negligible (filter matched at the receiver is not mandatory to suppress interference). This leads to enhanced spectral confinement.
    - Drawbacks
        - Sub-band filter design depends on the allocated sub-band location and bandwidth, i.e. specific set of filter coefficients are needed for each sub-band location and bandwidth
        - Sub-band filtering schemes have relatively higher implementation complexity compared to windowing; however, the gap varies depending on specific filtering schemes (e.g. UF-OFDM, F-OFDM and BF-OFDM)
        - Sub-band filtering causes EVM re-growth at the edges of the sub-band; however, precoding can be used to alleviate this issue.

Conclusions:

Note that the conclusion is drawn from our waveform comparison results, which are based on the project simulation assumptions, although, we cannot guarantee that the simulation cases cover all aspects relevant for 5G. We aim at giving some important insights and helping to select the suitable waveform schemes.

- Under the STR condition, sub-band filtering-based schemes allow for steeper slopes at the sub-band edges in frequency-domain, yielding better spectral confinement than windowing-based schemes
- OQAM signaling based FBMC with overlapping symbols provides best confinement and highest spectral efficiency, but it cannot meet the STR and suffers a compatibility loss with OFDM (e.g. not MIMO-friendly)
- Sub-band filtering-based schemes require relatively high Tx-Rx modem complexity compared to windowing-based schemes (except for FBMC-OQAM, where the symbol rate is doubled and thus two FFTs are required).
- From our comparisons: for small guard bands, sub-band based schemes clearly outperform windowing schemes. However, for larger guard bands, the performances of both schemes converge. Hence, eventually the size of guard bands needed to attain the desired interference isolation is decisive for selecting the appropriate waveform.

Recommendations

- OQAM signalling, according to the latest SoTA, still requires re-design of MIMO, synchronization sequence and some control signals. Thus, we think that it is not ready for 5G yet.
- We recommend to consider both sub-band filtering-based and windowing-based schemes for 5G in various situations
    - Sub-band filtering should be considered in the following cases,

    - enhanced spectral confinement level is required; (especially if small guard bands are desired to be used at high spectral efficiency)
    - allocated sub-band is contiguous; (sub-band size should be larger than a minimum size)
    - sub-band allocation is almost static (allowing to change / update filter coefficients rarely)
    - reasonable amount of TX antennas (since the signal at each antenna needs to be filtered individually)
  - Windowing should be considered in the following cases,
    - Moderate spectral confinement level is needed
    - Larger guard bands are a reasonable choice, either if spectral efficiency is not the main target or if high interference isolation is desired
    - Allocated sub-bands are distributed in the system band; (support of narrow-band transmissions)
    - Dynamic sub-band allocation is needed (note that here we refer to sub-bands assigned to different services and thus need isolation, aiming to avoid inter-service interference due to e.g. time miss-alignment or different numerology, and not classical multi-user isolation. For example, MBB certainly needs only one filter for service isolation, which may be adapted, though, should the band allocation between MBB and other services change).
    - large amount of antennas

2.1.2 Channel coding

The main focus in this area has been on improving convolutional turbo coding to be better suited for the scenarios being anticipated for 5G. We have worked on enhancements both related to code termination and on avoiding malicious interactions between the interleaver and the puncturing functionality by performing a joint optimization. Besides improving turbo codes to be a reasonable candidate for 5G, we have compared the currently discussed candidates from the 3 families (LDPC, Polar Codes, Convolutional Turbo Codes).

We consider Polar codes as a strong candidate for low latency applications. Although it is a relatively new technology, Polar code show excellent performance for short message lengths with no error floors, and their scalable decoder complexity (depending on the decoder parameters) allows them to be used in simple and complex receivers. This also allows the decoder performance to improve with technological improvement without changing the codes defined in the standard.

When targeting low rates and short frame sizes for URLLC, polar and turbo codes emerge as the most promising candidates from the error correcting performance point of view. In fact, LDPC codes cumulate the drawbacks of short cycles and of complexity (increasing with lower rates). To identify the best technical choice, in-depth complexity comparisons going beyond simple computational complexity, would have to be carried out at comparable performance. The framework for such comparisons should be clearly set and agreed between the parties proposing these coding solutions (e.g. within the discussions at 3GPP).

Finally, the selection process for 5G coding solution has launched a wave of new proposals for the 3 families of codes. Current studies are focusing on improving the decoding efficiency of turbo decoders when targeting high throughput scenarios. A large number of studies are also focusing on the design and implementation efficiency of polar codes/decoders. Therefore, important improvements are being made and a thorough investigation taking into consideration performance and hardware complexity between these two strong candidates represented by turbo and polar codes should be performed when the selection process should take place.

2.1.3 Enhanced modulation

Related to this area we have investigated FQAM (as a candidate to improve the performance of cell-edge users) and the use of NUC (non-uniform constellations for improving spectral efficiency). Both are outperforming current modulations schemes used in LTE, and bring advantages for the 5G system. It is recommended to use FQAM to serve users that suffer from high interference levels (such as cell-edge users) and QAM for users with good channel conditions (cell-centre users) concurrently. The inactive subcarriers in each FQAM symbol can be utilized to serve another user with relatively lower transmission power as detailed in D3.2. A user feedback (similar to CQI in LTE) can be used to determine the interference level at the user and decide which modulation to be used (FQAM or QAM). Also, it is recommended to use FQAM in uplink for grant-free and random access schemes to enable blind detection at the base-station.

For BMS and MBB services, it is recommended to utilize NUC for at least high modulation orders (64QAM, 256QAM, etc.) to enhance the achieved throughput. As it is not expected to have high modulation orders for MMC, MCC and V2X, NUC may not be very beneficial for these services.

2.1.4 MIMO – physical layer aspects

MIMO is seen as one of the key enablers for both achieving very high capacities (spatial multiplexing), high reliability (diversity schemes) and reasonable cell edge performance (beam forming). For the various waveforms we have dealt with in the project and in the light of extreme scenarios (high mobility) we have made dedicated investigations. In a nutshell:

- All the new waveforms proposed by the project (except FS-FBMC OQAM) in the current deliverable are compatible with the enhanced MIMO schemes proposed in D4.2.
- Regarding high mobility, in general, thanks to the predictor antenna, the networks hits the "wall of speed" (i.e. stops using adaptive MIMO) at higher velocities. Simulation results show that, for 256x2 ZF-MIMO and 256x1 MRT-MISO, respectively, speeds or carrier frequencies which are 3 and 4 times higher, respectively, can be supported thanks to the predictor antenna.

The following recommendations have been derived:

- Regarding high mobility, the use of more advanced prediction will push even further the "wall of speed" to higher carrier frequencies and higher speeds.
- First studies indicate that the wall of speed and its sensibility to parameters such as the number of antennas or the propagation environment need to be characterized for all MIMO techniques being studied at the 3GPP.
- Regarding the longer term evolution of 5G, massive MIMO is identified as a potential enabler to mix service-specific waveforms. For instance, single carrier modulation links with high data rates (Mbits/s) could be introduced for high data rate connected objects. The interference due to partial overlapping in frequency between single carrier and multi-carrier modulations would be reduced by transmit/receive beamforming.

2.1.5 PAPR reduction techniques

We have investigated various options related to PAPR reduction. The main differences between those options is the required processing effort and the signal quality at the output. While some use cases required a very high signal quality (e.g. as they apply higher order modulation formats), some are not able to support extensive processing. Consequently, for 5G it is worth to identify which technique would be the best selection based upon the service being considered and the related device class.

Based on the analysis in D3.2 [FAN17-D32], we propose the following selection rules related to PAPR reduction mechanisms depending on the service specific requirements:

Table 2-1: Rules for selecting the appropriate PAPR reduction method:

Use case specific requirements	Service type	Prioritized technique
High modulation order used, high complexity allowed	MBB, BMS	Multicarrier modulation with PAPR reduction • Allow for complex algorithms Example: • FDPC (Frequency Domain Partial Construction) • mSLM / Two Stage
Low/medium modulation order used, medium complexity tolerated	MCC, V2X	Multicarrier modulation (for sub-6 GHz), Single carrier modulation (for high-frequency comm.). • Depending on the application, single carrier may be favorable even in sub 6 GHz band Example • MC (Multi-Carrier) with Soft Clipping
Low modulation order used, low complexity required	MMC	Low complex algorithms + use case specific: • For narrowband transmission: DFT-spreading based modulation • For MC: low complex algorithms (e.g. OFDM with clipping) for PAPR reduction
high reliability required, multicarrier signalling used	MCC	FDPC: • allows for degradation-free on reference signals • controlled processing latency

2.1.6 Fundamental signal and frame design characteristics

We have discussed fundamental signal and frame design characteristics to be selected as follows.

Sampling rate, bandwidth support, numerology options, relative timing:

1. Sampling rate, number of subcarriers covering the bandwidth and corresponding subcarrier spacing should be integer multiples of a given basis, to keep system complexity and testing efforts at a reasonable level.

In D3.1 (section 6.5 [FAN16-D31]) we have presented reasonable options for selecting the triple of (1) covered bandwidth, (2) sampling rate and (3) the respective FFT length for various sub carrier spacings. We have kept the list of options rather wide, ranging from 0.2 MHz up to 320 MHz. Which ones are to be applied will in the end depend on the availability of bands and roll-out scenarios. The lower end of these options (e.g. 0.2 MHz) are for example candidates for spectral refarming of 2G bands, while the higher end of this list is more relevant for the capacity layer of the network and potentially need to be applied at carrier frequencies above 6 GHz. The coverage layer of 5G will most likely make use of a similar set of options as 4G did (10 MHz, 20 MHz, 40 MHz) with the potential of going up to 80 MHz or even 160 MHz.

2. The base sampling rate should be aligned with the base sampling rate of LTE, to ease interworking and multi-link functionalities and enable hardware reusability and sharing.

The options we have proposed in D3.1 (section 6.5 [FAN16-D31]) follow this rule for improved coexistence (even in-band), interworking and multi-link processing. Additionally, this helps the reuse of design activities happened in the era of 4G.

3. Reasonable amount of supported bandwidth: 5 MHz, 10 MHz, 20 MHz, 40 MHz and up to 160 MHz (for small cell capacity hot spots), to keep system complexity and testing

efforts at a reasonable level, while supporting all reasonable scenarios. Smaller bandwidth options might be envisaged in later standard releases.

As given in point 1 above (and detailed in D3.1, section 6.5 [FAN16-D31]) we have decided to keep the set of options rather wide. The actual down-selection in 5G New Radio (NR) depends on various aspects being outside of the project such as available bands, roll-out strategies and selected carrier frequency.

4. Means to support narrow-band devices by dedicated design of in-band structures are required (e.g. introduction of complementary narrow-band synchronization signals), to successfully integrate MMC services while still enabling MMC devices to be low-cost and long-lasting with a single set of energy sources.

While allowing low-end devices (e.g. sensors) to skip parts of the time- and energy-consuming procedures related to accessing the system (e.g. message exchange during network entry), these devices still need to be able to detect close-by cells and synchronize on frame level. For this it needs to detect the respective synchronization signals regularly being broadcasted by the basestations (in LTE: primary and secondary synchronization signals, PSS and SSS) and detect the general cell configurations (in LTE: Master Information Block (MIB) and System Information Block (SIB)). While for conventional broadband devices in 4G (and potentially in 5G NR as well) PSS and SSS have been transmitted in the center of the band covering about 1 MHz, the wide bandwidth is less suitable for low-end devices. Instead it is beneficial to broadcast another set of synch signals covering a smaller bandwidth as this allows these devices to be more cost- and energy efficient. In section 6.6.3 of D3.1 [FAN16-D31] we have investigated this feature. Naturally, with relying on a smaller bandwidth only, the synchronization accuracy degrades. We have provided means to improve the accuracy without extending the bandwidth. Additionally, the work on filtered waveforms has shown that a reduced accuracy with respect to symbol timing and carrier frequency can be tolerated (e.g. sections 6.1.1.3, 6.1.4.3, 6.1.5.4 in D3.1).

5. The basic 5G subframe length should follow LTE (i.e. have a duration of 1 ms), to ease interworking and multi-link functionalities and enable hardware reusability and sharing. To enable low latency transmissions, special subframes with lengths being fractions x of 1 ms should be supported (e.g. $x=2^N$ with integer N, e.g. N = [0, 1, 2, …]).

In section 6.5.2.2 and 6.5.3 of D3.1 [FAN16-D31] we have proposed a set of resource block definitions following a more general rule as given above (i.e. the TTI length options are N multiples/divisions – N being integer – of the baseline of 1 ms). Additionally, the tiling concept being presented in 6.5.1 of D3.1 follows this criterion as well. Applying this rule simplifies the definition of the set of available tile/sub-tile configurations. Being aligned to LTE improves coexistence and simplifies cooperation between 4G and 5G. The actual gain the system can make use of when allowing the use of various TTI lengths has been investigated and presented in section 2.4.1 and 2.4.2 of D4.2 [FAN17-D42].

6. Subframe bundling needs to be supported (for longer transmission opportunities), to increase the signalling efficiency (less control signalling required) and to support coverage extension.

The tiling concept as proposed in 6.5.1 of D3.1 [FAN16-D31] has a granularity in time of 1 ms as baseline. Shorter TTI lengths are supported via the selection of sub-tiles and by allowing pre-emptive scheduling. Longer TTI lengths are supported by bundling consecutive tiles. This means the scheduler of sub-frame n+1 needs to take into account, if in sub-frame n it has been decided to bundle. This imposes some restrictions to the tile scheduler. Additionally, this requires to use asynchronous HARQ mechanisms to avoid SAW channels (Stop-And-Wait) to be blocked (or vice versa tile-bundling being blocked by active SAW channels). This item is allowing a more efficient inclusion of low-end devices and to make signaling more effective. The actual gain the system can make use of when allowing the use of various TTI lengths has been investigated and presented in sections 2.2.3.2 in D4.1 [FAN16-D41] (related to overhead reduction with making use of subframe bundling), 2.4.1 and 2.4.2 of D4.2 [FAN17-D42].

7. The support of different subcarrier spacings (following rule 1 above) within a single carrier is one option to be envisaged, to improve respective use cases (e.g. low latency transmissions) and transmissions with extreme channel characteristics (e.g. very high Doppler values), while maximizing multiplexing gains and reducing the number of constraints for e.g. scheduling. For the former an alternative approach is the introduction of minislots containing a lower number of symbols.

The key questions to ask for these items are twofold: (1) How can the system support different subcarrier spacings without imposing severe inter-subband interference and (2) what are the gains the system can make use of with this degree of freedom. The former question is strongly related to our work on waveforms. We have proposed means to efficiently implementing this into a system applying UF-OFDM (though, other waveforms being investigated in FANTASTIC-5G are able to do so in a similar manner). We have shown, that for extreme Doppler scenarios we can gain up to a factor of two/three/four (low SNR/medium SNR/high SNR scenario) with respect to spectral efficiency.

8. Transmission points are aligned to a common time base, to ease collaborative schemes such as interference coordination.

As soon as different cells are to coordinate with each other on a spectral resource basis - e.g. to deal with intercell-interference – it is beneficial, if these cells have a common time base. To name an example, if a given cell is to mute specific resources to protect transmissions in another cells, it only has to mute a single sub-frame, if the sub-frames of these two cells are time-aligned. If the cells are not time-aligned two sub-frames would have to be muted as it is very likely, that the sub-frame to be protected intersects with two sub-frames of the other cell. WP4 of FANTASTIC-5G has worked on mechanisms related to this in the area of intercell-interference handling. The outcomes are given in section 4.2 of D4.2 [FAN17-D42]. Another aspect benefitting of having a common time base is the improved in-band coexistence of 4G and 5G as e.g. outlined in section 6.1.1.5 of D3.1 [FAN16-D31].

Lean channel/signal design, time/frequency confined structures, access procedures:

1. Use of multi-carrier signalling, to allow for simple transceiver mechanisms (e.g. one-tap equalization, frequency selective precoding) and multiple transmissions to share the band.

All waveform candidates being proposed in FANTASTIC-5G are of multi-carrier type (or modifications, e.g. by applying DFT precoding). With applying multi-carrier signaling, the system is able to dedicate the available spectral resources for various means and with differing characteristics concurrently enabling efficient multi-service support. This approach has been shown in earlier generations to be highly efficient and simplifies coexistence and interworking with e.g. 4G. Furthermore, by using a 2-dimensional resource grid other techniques are enhanced (e.g. intercell-interference coordination).

2. The amount of always-on components should be minimized and the actual repetition rate (e.g. for synchronization signals in DL) should be configurable. Apply the on-demand

principle as far as possible (e.g. MIB is always-on while SIB is on-demand), to increase energy efficiency especially in low-load scenarios.

While cell-specific control-plane messaging per se is not part of the project, the contribution in section 4.2.3 of D4.1 [FAN16-D41] (intercell coordinated small-cell on/off) is related to this item. Additionally, being able to deactivate certain signaling components as required improves forward compatibility and makes the system more energy efficient. DL reference symbols in 4G are an example for always-on signals constraining the system in that respect. WP3 has provided a novel approach dealing with this matter (coded CSI reference signals).

3. Highly flexible TDD configurations required for efficiently following the actual traffic/service needs.
4. Subframe options supporting both UL and DL components (control, data, reference signals) should be envisaged (for latency optimized scenarios) in addition to subframe configurations purely containing either DL or UL components.

We have addressed items 3 and 4 in section 3.5.3 in D3.1 [FAN16-D31]. Here, we have proposed four different subframe types (pure UL, pure DL, DL control + data and UL control, DL control and UL control and data). All types include respective reference signals. By dynamically selecting the respective subframe the system is able to follow efficiently the actual traffic needs. WP4 has taken up this in D4.2 [FAN17-D42] section 2.4.1 for the design of efficient scheduling mechanisms.

5. The radio frame (with radio frames consisting of an integer number of subframes) should support different kinds of access mechanisms (scheduled access, contention based access, beam guided access), to support various use cases related to e.g. MBB and MMC concurrently.

We have investigated different kinds of access mechanisms to support the different kinds of services in D4.1 [FAN16-D41] and D4.2 [FAN17-D42]. These mechanisms range from scheduled access e.g. making use of adaptive TTI lengths and in-band control channels, efficient massive access mechanisms (protocols and detection mechanisms), D2D and beamforming aided procedures. Besides unicast mechanisms, we also have investigated broad- and multicast solutions. For allowing the frame to efficiently support different kinds of access mechanisms concurrently in parallel (e.g. scheduled access, massive access and broad/multicast) the tiling concept can be used by defining respective tile types. Overall, this flexibility allows the system to support different kinds of use cases efficiently.

6. Reference signal design should be configurable to meet various design targets (e.g. to be optimized towards the respective transmission mode; to enable frequency resource blanking – i.e. avoid 'almost blanked subframes' as e.g. in LTE).
7. Reference signal design should natively support a wide range of number of antenna ports, to enable later extensions without requiring fundamental redesigns.

The work being reported in section **Error! Reference source not found.** of D3.2 [FAN17-D32] follows items 6 and 7, describing our approach for the design of DL reference signals. The sub-tiling concept in combination with the use of a respective code strategy (e.g. Walsh Hadamard) allows to easily scale the system according to the number of antenna ports/beams available without introducing excessive overheads. Depending on the state of the device (e.g. related to time variance and frequency selectivity of its channel towards the basestation) it can use the relevant reference symbols to conduct its measurements.

8. Time frequency confined user-specific control channel design to enable multi-service support and frequency resource blanking and to make 5G forward compatible.
9. Control channel structure, allowing for devices to go immediately to the sleep mode (micro-sleep), to maximize energy efficiency at the device side.
10. Control channel design enabling energy efficient reception without putting severe restrictions to the search space, to minimize energy consumption without putting heavy restrictions to e.g. the scheduling mechanism.

Those three design principles are connected. As presented in sections **Error! Reference source not found.** of D3.2 [FAN17-D32] and 2.4.1 in D4.2 [FAN17-D42] FANTASTIC-5G promotes to apply in-band user specific control channels for user specific control messages (e.g. DCIs – Downlink Control Information - carrying the selected resource configuration, scheduling grants …). The aspects making this a valuable choice (as e.g. in contrast to the PDCCH design in 4G) is the fact, that the actual control messages can use different formats (as e.g. a eMBB services requires different control means than a MCC service does). Additionally, by not multiplexing control messages of multiple users into a single structure and instead appending it to the respective data transmission allows to use the same link enhancing methods (e.g. interference coordination, rank 1 precoding, etc. as e.g. described in section 4.2 of D4.2 [FAN17-D42]). Furthermore, it does not require to configuring the transmission mode according to the weakest link and allows to sharing reference symbols between control and data. So, with applying this means the system is more efficient in general and the respective control elements can be designed according to the respective use case. Finally, the inclusion of new use cases and features is improved as the number of constraints is minimized. The work related to the user-ID signals (UIDS), as it is presented in section 6.6.1 of D3.1 [FAN16-D31], is targeting a control channel structure with 3 parts: 1) UIDS (specific preamble), 2) fixed-sized FEC block (basic control) carrying the beginning of the DCI and 3) variable-sized FEC block (main control) carrying the remainder of the DCI (and the start of user data if any). The UIDS allows the device to quickly and efficiently detect its messages. As the device only requires to scan for its preamble instead of having to fully decode all control messages down to the CRC check (as e.g. in LTE) the search space is not required to be restricted (i.e. the device is able to check all possible positions) and thus does not restrict the scheduler.

11. Avoid non-elastic transmission mechanisms (e.g. configurable asynchronous HARQ instead of fixed synchronous HARQ as e.g. used in LTE UL), for the system to be more flexible e.g. related to dynamic TDD and deployments with centralized structures.

Non-elastic transmission mechanisms have the advantage of lower overheads (as the non-elasticity provides implicit knowledge about relevant characteristics of the transmission, which not have to be communicated). At the same time, they add constraints to the system (e.g. to the scheduler) preventing it to fully make use of the flexibility options described earlier (e.g. related to variable TTI definitions and dynamic TDD configurations). Asynchronous HARQ has been tackled in FANTASTIC-5G in section **Error! Reference source not found.** of D3.2 [FAN17-D32]. The application of this is for example described in section 2.4.1 of D4.2 [FAN17-D42]. Given the necessity of supporting diverse services and network implementations, HARQ can significantly benefit from a flexible timing of the control loop. Envisioned 5G ultra-low latency applications may require the usage of an early feedback to be transmitted prior to finalizing the decoding. Further, the concept of the feedback is expected to take a leap forward from its Boolean nature and provide further information for optimizing the retransmissions. In particular, the enriched feedback can be used for indexing specific code block retransmissions, avoiding retransmission of the entire transport block and therefore improving resource utilization. Such resource saving can be also achieved by exploiting the variable IR concept (Incremental Redundancy), i.e. using the enriched feedback to signal the redundancy version of a transport block which is likely to ensure correct decoding given the already accumulated mutual information at the receiver.

12. Allow for specific traffic types with highest priority (e.g. related to MCC) to ‘hijack’ allocations originally being dedicated to other traffic types (e.g. MBB), to avoid wasting resources, while still supporting MCC services with highest efficiency.

Having to occasionally transmit messages requiring ultra-high reliability with very low response times (use cases in the area of MCC; respective 3GPP terminology: URLLC, ultra-reliable low latency communications) while having at the same time a constant flow of ‘conventional’ MBB traffic to support, opens up the potential issue of inefficient use of the available resources. A straight-forward but inefficient solution is to persistently keep parts of the transmission band reserved for potential MCC messages. As they may or may not occur a reasonable wastage of resources is unavoidable. A more advanced way of treating this is discussed in section 2.4.3 of D4.2 [FAN17-D42]. Here, all spectral resources are available for non-latency critical transmissions. When a request to transmit a latency critical message occurs, the system is allowed to ‘hijack’ resources already being scheduled to carry ‘conventional’ traffic. This can be done by either puncture the less critical message (i.e. in DL not modulate the respective resource elements with the data related to the less critical message) or to allow the latency critical message to be superimposed using a much higher transmission power to ensure successful transmission (e.g. in UL by allowing both devices to transmit their data). As both mechanisms increase the chance for failed transmissions of the ‘conventional’ message, means to recuperate this have to be applied (see section 2.4.3 in D4.2 [FAN17-D42]). With allowing the system to make use of this mechanisms both the multi-service support is improved and the overall system is more efficient.

13. Enable robust and scalable contention based access, to integrate MMC services with highest efficiency.

Robust and scalable contention based access requires both efficient protocol design, advanced code design and sophisticated PHY layer processing mechanisms to detect and separate the transmitted messages. FANTASTIC-5G has worked on all these items. Details are included in section 3.2 of D4.1 [FAN16-D41] and of D4.2 [FAN17-D42] and in related appendices. The overall system is more efficient with serving the different services according to their respective needs and characteristics. Sequence design for random access opportunities has to be revisited compared to the usage in 4G. While Zadoff-Chu sequences have specific characteristics having made them a reasonable choice for the random access channel in 4G their periodic behaviour after correlation makes them less of a good choice for 5G which requires for efficiency reasons a much higher number of available sequences per allocation. Instead the project has identified m-sequences with circular Delay-Doppler shifts as a reasonable alternative.

2.2 Multi-node/multi-antenna technologies

The second set of technologies being covered in the following are related to the higher layer aspects (MAC, RRM). Those technologies are required to efficiently manage the diverse set of devices accessing the system concurrently. Additionally, means to coordinate between different cells are treated (e.g. inter-cell interference coordination). Finally, technologies being used to maximize spectral efficiency are treated (e.g. system level integration of massive MIMO).

2.2.1 Radio resource control (RRC) state machinery

For enabling low end devices (e.g. from the use case family MMC) to access the system, the air interface needs to be designed to allow those to stay at highest energy efficiency both during the transmission of data and in-between. The former is tackled later, the latter is achieved by allowing the device to go to sleep mode when no data is transferred. 4G already has such a functionality implemented. Here, devices are either in connected mode (during data is to be transmitted) or in idle mode. In the latter most functionalities of the device are powered down and the basestation “forgets” about the device. This means any resources the device has been allocated to are released (e.g. C-RNTI, Cell Radio Network Temporary Identifier) and the data related to the access stratum is discarded. Every once in a while the device reads the DL paging channel to check, if data is available at the basestation to transmitted for this device. In this case the device wakes up and shifts its state to connected mode. Unfortunately, this transition includes a high number of measurements and message exchanges between device and basestation. For 5G low end devices we propose to add another state having similar characteristics as the idle state of 4G once the device is in this respective state. However, in this state the basestation assigns a temporary identifier to the device and keeps the relevant configuration parameters related to the access stratum within a local database attached to this identifier. When the device is to transfer to connected state it can use its temporary identifier to revoke the configuration being stored within the data base instead renegotiating them. For mobility reasons the relevant database entries need to be exchanged between respective basestations (i.e. the former basestation of the device and the new basestation the device is trying to connect to).

The project has named this new state ‘RRC Extant’. Industrial partners of the project have contributed respective Tdocs toward 3GPP. 3GPP has in the meantime adopted this principle using the term ‘RRC Connected Idle’.

2.2.2 Multi-node connectivity

Multi-node connectivity in general is available already for 4G, however, with a restricted set of options. In 4G dual connectivity is typically used for capacity reasons to be able to use the resources of several bands (carrier aggregation), each being below 6 GHz. We propose to enhance this mechanism for 5G both for capacity reasons (data split, e.g. dual-connectivity to a low-band macro cell acting as control anchor and to a high-band (mmW) small cell providing a significant higher capacity for data transmission) and for reliability reasons (data duplication). This functionality is one enabler to achieve the high reliabilities of URLLC use cases. Another means multi-connectivity can be used for is to increase the link robustness. For doing so several RRC entities are instantiated instead of only one as done in 4G. This way a losing the connection to e.g. the primary cell does not lead to losing the link between device and network. Naturally, any form of CoMP is to be seen as a type of multi-connectivity as well. Our recommendations related to this are presented in a later section covering the system level integration of massive MIMO.

2.2.3 Mobility enhancements

We have worked on mobility enhancements both for the single-connection case and in case of multi-connectivity. For the former we propose as already indicated earlier to have basestations to be time-aligned. This way the device is able to skip the RACH-procedure as it is used to measure the timing misalignment towards the new cell. If the cell the device is currently active and the new cell are time-aligned the timing mismatch between device and new cell is rather small (depending on the difference between the travel times of the signal from the device to both basestations).

The benefits of the proposed synchronous RA-less handover functionality, as compared to that supported for legacy LTE networks, is the significant reduction of the data interruption time during handovers, approaching virtually zero. Moreover, the handover execution process is reduced as compared to that of LTE, as there is no RA at the target cell at every handover. Measurements from LTE network shows that the RA procedure typically takes on the order of ~10 ms. The faster handover execution process for the synchronized RA-less functionality translates to increased mobility robustness, as the system is able to react faster (i.e. resulting in even lower handover failure probabilities). Finally, the fact that the handover process no longer requires RA translates to savings in the required RA access resources for the system. For example, the handover rate per UE is found to typically vary from few handovers per minute to handovers every second depending on the network topology and velocity of the device. Thus, especially for scenarios with high-speed users such as the highway scenario studied in, the use of synchronous RA-less handover also offers significant reductions of the required RA resources.

For multi-connectivity cases, we propose to adopt a UE autonomous cell management approach for the small cell layer (instead of network controlled as in 4G), while still having the primary cell management (handover) on the macro-layer being fully network controlled. By adopting such a scheme, the signalling overhead and network burden of having to frequently manage UE small cell associations is significantly reduced. As primary cell management actions happen less frequently, and typically requires interaction (signalling) with the core network, such actions are assumed to continue being fully network controlled and UE assisted.

The performance of UE autonomous secondary cell management has been evaluated by means of extensive system level simulations. For the highway scenario studied in, we found that the average number of required RRC signaling per UE per second is reduced from 4.9 to 0.35 by using UE autonomous secondary cell management. Similarly, the associated X2 signalling is reduced by approximately 50%. Those are attractive gains in terms of both reduced RRC and X2 signaling.

2.2.4 Dynamic resource allocation

With 5G the ecosystem of use cases accessing the network for exchanging data is growing tremendously. This puts a high burden to network to distribute the available resources in a fair and efficient manner, while keeping the various use case specific particularities (e.g. to achieve the stringent requirements of URLLC transmissions with respect to latency and reliability). Further means complicating resource allocation is the support of multiple carriers concurrently with various characteristics (e.g. in case of multi-connectivity including low-band and high-band carriers) and the paradigm change to asynchronous and adaptable HARQ as outlined earlier. Finally, inter-cell interference coordination (ICIC) adds further constraints the packet scheduler has to take into account. To be able to follow all those requirements and constraints the context awareness of this functionality needs to be improved compared to 4G. The scheduler for example requires knowledge about the use case and the respective requirements to be followed for each single connection is to manage. He needs to know about any resource reservations, and requires a tight integration with the HARQ manager and the link adaptation manager and needs full awareness about the configuration of the different carriers.

For the allocation of the resources the scheduler makes use of the degrees of freedom we have presented earlier related to physical resource blocks, numerology options and TTI lengths. For setting up the frame we have investigated and proposed various design criterions:

- Downlink control channel and data channel transmissions are multiplexed per user, with the control channel (front loaded) always appearing in the start of the transmission. This corresponds to a user-centric design, as also studied in the earlier FANTASTIC-5G Deliverable D4.1 – Chapter 2.
- In line with earlier 3GPP NR agreements, the NR physical-layer design should be such that devices with different bandwidth capabilities can efficiently access the same NR carrier regardless of the NR carrier bandwidth.
- For a UE scheduled with a longer TTI (e.g. by using flexible slot duration or concatenation of slots, or subframes), the corresponding downlink control channel grant/allocation is sent once only, such that benefits of lower control channel overhead when using transmission with longer TTIs are maintained.

In line with the 3GPP NR agreements, the timing for the proposed scheduling framework is furthermore assumed to be highly dynamic and flexible to efficiently support different network implementations and dynamic TDD. Among others, this means that both, the timing between a

DL assignment and corresponding DL data transmission, as well as the timing between UL assignment and corresponding UL data transmission is indicated by a field in the DCI. Also the timing between DL data reception and corresponding acknowledgement is indicated by a field in the DCI. This timing flexibility allows advanced network implementations where the MAC is implemented in one physical location (e.g. in a centralized unit), while the RF is located at distributed basestation sites, using fronthaul connections of variable latency depending on it implementation.

A simple option to both support MBB traffic and URLLC traffic with much more stringent latency requirements is to statically assign parts of the band to each traffic type. However, as the actual number of requests and thus the required amount of resources related to those two kinds are very dynamic and thus either significant resource wastage or shortage might occur with this kind of static assignment. So, we propose to both allow a semi-static reconfiguration of the resource distribution based upon measured traffic flows and to if the available resources being dedicated towards URLLC services are insufficient, we propose to introduce a functionality to allow the system to instantly realocate a given set of resource being already assigned towards a MBB transmission towards the URLLC user. Naturally, the performance of the MBB transmission is reduced. Therefore, we have proposed various means to reduce the damage (e.g. by informing the victim device and by retransmitting the punctured data either directly after the original transmission or as a HARQ retransmission).

2.2.5 Service classification

Service classification methods, applying machine-learning techniques to identify, extract and monitor the key QoS parameters of the different ongoing services have been developed. Various machine learning mechanisms has been investigated and compared. It is found that the so-called Decision tree, Random Forest and Gradient Boosting algorithms yields the highest accuracy, outperforming the other machine learning algorithms. Moreover, our results of using the concept of confusion matrix show that the Decision Tree and the Random Forest algorithms result in extremely good results as they miss-classify less than 0.5% of the traffic flows. Therefore, these two classification mechanisms have been chosen as the most appropriate algorithms for the service classification. The output of these service classification techniques, together with the QoS requirements requested by the higher network layers for each user and respective service, serve as input to the resource management framework.

2.2.6 Downlink non-orthogonal multiple access

The Non-Orthogonal Multiple Access (NOMA) technique addressed consists of multiplexing multiple users in the power-domain at the transmitter side, on top of the OFDM layer, and in separating the multi-user signal at the receiver side using Successive Interference Cancellation (SIC). The main objective of our studies is to use NOMA in order to boost the spectral efficiency by combining the potential gain achieved by power multiplexing with a proper optimization of the amount of used bandwidth, while respecting a set of traffic requirements.

Two cases were studied: The first scenario tries to minimize the required bandwidth to achieve a particular target data rate per user. In this context, the target is to serve users their required data rate at the minimum bandwidth and power costs. The second scenario corresponds to the extension of the classical case of power and resource allocation adopted in LTE to take into account the multiplexing of multiple users in power domain for NOMA support. In this context, all users, including cell-edge ones should be served as fairly as possible without largely sacrificing total cell throughput. The resulting problem consists of striking an appealing balance between total cell throughput and user fairness.

Under the first scenario, the problem of optimum power and resource allocation leads to a non-linear system that was solved using a numerical solver. A new suboptimal power allocation technique based on waterfilling was introduced to increase the total achieved system throughput in a downlink transmission scenario with respect to the equal power case. The results of the first scenario can be summarized as follows:

- Although NOMA increases the overall capacity of the system (NO-WF, Non-orthogonal Waterfilling) when compared to the orthogonal signaling system (O-WF, orthogonal waterfilling), it does not provide an increase in spectral efficiency in all subbands. Indeed, in some cases, the loss in data rate experienced by one user sharing its subband with a second user is larger than the data rate gain achieved by the latter. Therefore, the implementation of an adaptive switching to orthogonal signaling mechanism (NO-O-WF and NO-O-xxx curves) is highly recommended to make better use of the NOMA technique.
- The NOMA technique allows the amount of used bandwidth to be reduced compared to the conventional orthogonal signaling system: a smaller total number of subbands is needed to achieve the data rate targets.
- When optimizing the cell-edge user throughput in crowded areas, equal power repartition may perform as good as an optimized repartition using waterfilling.

The second step of the work consisted of proposing once again an improved power allocation technique based on waterfilling that can still be implemented with a reasonable complexity that should improve achieved spectral efficiency and user fairness. It is based on an iterative algorithm that would distribute allocated power recursively while taking into account the channel gains of allocated users and the changes of what is called the water level.

As a conclusion, we have investigated the introduction of NOMA in power domain as a possible way to improve total cell throughput under two different scenarios, one with target rates and under bandwidth constraints, and the other aims for a balance between throughput and fairness. It was shown that by applying adapted power allocation solutions, important gains in throughput can be achieved. It was also shown that some resource allocation algorithms/metrics are not fully adapted to NOMA and that specialized solutions could enable yet larger gains especially in a classical LTE context.

2.2.7 Device-to-device (D2D) communications

Several aspects of Device-to-Device (D2D) Communications have been developed which take advantage of the available degrees of network assistance. For Device-to-Device (D2D) communications to take place, they require mechanisms that enable proximity discovery and communication mode selection. The latest results are focused on proximity discovery in cellular, ad-hoc and V2X settings, where the use of full duplex and interference cancellation receivers have been found to be enablers of fast device discovery. Furthermore, a novel discovery scheme has been proposed in V2V proximity discovery, which provides a balance between discovery speed and energy consumption. We proposed various sensing schemes suited to pedestrian UEs, which the goal is power consumption minimization. Still in the V2X D2D setting, it was proposed how to take advantage of the geo-location information of neighbouring vehicles to aid on the radio-resource selection. Moreover, options for D2D aided relaying where devices can act as relays and therefore extend the coverage and potentially the cell capacity have been explored. It was shown that there is a 25% gain in network throughput performance when offloading the network using D2D and content caching.

Furthermore, to reduce the required assistance from the network, a concept for joint resource identification and channel estimation was developed based on compressed sensing in the advanced receiver section of D4.2, enabling passive listening for devices in the D2D use case to identify free resources without assistance from the network.

2.2.8 Efficient massive access protocols

Several efficient massive access protocols for Massive Machine Communications (MMC) have been developed, leveraging the benefits of (non-)contention based random access versus scheduled access. We have classified random-access schemes in three types: one-stage, two-stage and multi-stage. Several physical layer and medium access layer techniques have been considered for the one- and two-stage protocols. The physical layer techniques include multi-user detection using compressive sensing techniques, collision resolution and harness of interference using physical layer network coding and non-orthogonal access with relaxed time-alignment. The medium access layer techniques include coded random access and signature based access, one- and two-stage random access and fast uplink access protocols with a focus on latency reduction. A common evaluation framework was defined and a comparison provided, with the goal of highlighting which kind of approach is best suited for a given access load considering the different MMC KPIs. These results provide a first step towards the design of a robust massive access solution, by identifying which techniques lead to higher protocol performance. Hence, the project has achieved a consolidated overview of a broad selection of efficient random access protocols that provides first recommendations on the protocol design for the NR in 3GPP. Especially, it was shown that all the proposed protocols outperform the LTE baseline access in at least one of the considered KPIs (e.g. the access latency was reduced by one order of magnitude, the throughput increased by at least one order of magnitude for high access loads, among others). In addition, a generic energy evaluation methodology for MMC was proposed, and the optimal power control and link adaptation strategy (using repetitions) for low SINR machine type communication (MMC) use cases was investigated and finalized.

2.2.9 Efficient and flexible support for broadcast and multicast transmissions

Related to Broadcast/Multicast communications, the project has developed communication protocols for efficient and flexible support for localized distribution of data/content via broadcast and multicast transmissions. Different alternatives to increase system efficiency and flexibility for broadcast and multicast transmissions has been designed. One of these focuses on the extension of non-orthogonal transmission approaches to broadcast/multicast scenarios, where alternative techniques to NOMA schemes are considered. Namely, we explored channel coding based approaches and spatial multiplexing techniques based on beamforming. Another promising approach is allowing the use of feedback (in the form of ACK/NACK) to introduce flexibility into the system. In this way, higher MCS can be selected for the broadcast phase to serve most users and compensate worst channel state users with optimized unicast retransmissions. Results have shown that the combined approach improves the delivery time, especially for moderate number of active users. The flexibility of the scheme translates into aggressive approaches in the selection of the MCS

2.2.10 System level integration of enhanced MIMO with and without cooperation

The studies related to the integration of MIMO on System level have resulted in several valuable findings. System level MIMO integration, begins with a new over-the-air hardware calibration procedure which is essential to enable channel reciprocity in TDD mode and can provide more than 50% throughput gains at high SNR compared to the state of the art. Additionally, advanced robust MIMO precoding can be used to mitigate the residual errors that might remain after the calibration procedure. Next a fully scalable framework concept has been developed flexibly supporting a range of network and UE capabilities, backhaul/fronthaul availability, different antenna arrays sizes, UE processing with/without channel prediction, etc. It scales from a 2x2 to a massive 512x8 MIMO setup and starts from a limited intra site only JT (Joint Transmission) CoMP configuration for combating intra cooperation area interference up to a full interference mitigation framework performing JT CoMP over three sites. The proposed concept utilizes MIMO with cooperation and has indicated an 8-10 times higher average cell spectral efficiency capability compared to 4x4 MIMO LTE in system level simulations. The basis for the flexible adaptation to available backhaul and UE capabilities is the beam based operation of the system, i.e., the GoB per cell solution. UEs report their relevant channel components, i.e., those received above a certain power threshold, either for a single cell, site or a nine cell cooperation area. Non orthogonal CSI reference signals – so called Coded CSI RS – exploit the sparsity as a results of the massive MIMO antennas and allow for accurate CSI estimation per relevant channel component, even in case of several hundreds of Tx-beams. Note, without cooperation, these Coded CSI RSs will ensure low inter cell interference for the channel estimation. As the UEs report explicit feedback per relevant channel component, they are agnostic to the location and the beam shape of the Tx-beams. This provides full network flexibility in setting up cooperation areas, defining the number beams per cell and the angle of departure for each beam. Semi static scenario adaptations are possible and the level of cooperation can be flexibly changed by the basestation.

MIMO with and without cooperation is supported by the traffic light concept, where UEs report more accurate CSI feedback in case of a 'red' = overload light so that the basestation can apply JT CoMP precoding. In 'green' mode a more limited CSI feedback with lower UL overhead will be transmitted per UE. Similar the basestation can decide in case of moderate or low load to restrict cooperation to a single site or even switch off JT CoMP. Also conventional mode switching from diversity to MU MIMO modes are inherently supported as here, explicit CSI feedback is being assumed. The benefit over LTE like PMI feedback is that explicit CSI feedback avoids the need for a Tx- precoder of interference hypothesis at the UEs.

Further work enhancing the main 'grid of beam' ingredient enable user specific beam adjustment, overcoming losses due to the inherent course quantization. With a marginal 1-bit feedback per user, more than 2.5 times gain from the 'GoB beam selection scheme' baseline was demonstrated. As a complementary solution to the previous approach, an interference coordination scheme based on two-step beamforming/precoding is proposed and evaluated in D4.1. The first stage precoding effectively reduces the spatial degrees of freedom and at the same time each basestations is allowed to transmit only in a certain direction on the current time-frequency resource. These directions may change over time/frequency.

2.2.11 Network based interference coordination

A plurality of promising multi-cell interference coordination schemes has been developed. In the uplink, the problem of pilot contamination is addressed by proposing schemes exchanging sequence indices among basestations. By doing so a given basestation is able to reconstruct the transmissions from adjacent cells for mitigating the interference. Enhanced methods for discontinuous transmissions on cell level (cell DTX) based on fuzzy Q-learning has been developed, including both cases with a distributed architecture as well as scenarios with a centralized controller. This allows the network to dynamically switch of/on small cells depending on the respective load conditions. A new approach for inter-cell coordination is to allow for interference aware rank adaptation (RA). Here the rank is selected to maximize the total system throughput. Novel solutions fulfilling three main criteria, namely: altruism, robustness, and fast convergence have been proposed. Finally, agile on-demand interference coordination schemes exploiting coordinated muting, power boosting, as well as macro-scopic transmissions have been developed. The proposed solutions for network-based ICIC are generalized so they are applicable for both centralized and distributed network architectures, tailored to offer benefits for the KPIs most important for the service that requires interference protection. As an example, attractive throughput gains for mobile broadband users are observed, as well as reduced latency and improved reliability for mission critical communications. The following table summarize the developed network-based ICIC schemes with respect the needs towards the network and the UE, respectively, allowing us to identify the needs for standardization.

Table 2-2: Overview of network coordination techniques and specification needs.

Scheme	Dir	Primary Services	Network coordination	UE requirements
Inter-cell coordinated small cell DTX	DL	**MBB** & MCC	LTE-alike dormant cell discovery signal	There are no special requirements to the UE
On-demand power boost and cell muting	DL	MBB & **MCC**	Xn negotiation of the protected PRBs Xn activation of the muting	As part of the CSI, the UE reports Dominant to rest of Interference ratio (DIR) Measures of the signal and interference under given hypotheses
Inter-cell coordinated rank adaptation	DL	**MBB** & MCC	Xn negotiation of the rank limitation	As part of the CSI, the UE reports Dominant to rest of Interference ratio (DIR)
Inter-cell interference shaping	DL	**MBB & MCC**	Xn of the channel covariance matrices corresponding to the channels from each of the BSs in the network to their users	No special requirements apart from the CSI
Flexible macroscopic combining	DL	**MCC**	Xn signalling among cooperating cells to activate/deactivate the combining feature. P-TRP (Primary Tramsmission Point) acts as the master	Multi-CSI depending on the operation option
Inter-cell coordination of uplink pilot RS sequence configuration	UL	**MBB & MCC**	Xn exchange of sequence indices	There are no special requirements to the UE

2.2.12 Advanced multiuser detection

In the context of Advanced Receivers, a promising set of novel receiver options have been derived and evaluated. This include three receiver concepts on multi user detection: (i) An IDMA receiver for uplink, flexibly supporting both MBB and MMC types of traffic and an achievable rate of 300% or more over the LTE baseline. (ii) An iterative FQAM MUD receiver capable of improving the uplink performance of NOMA by 5dB over a non-iterative receiver. NOMA is required in 5G to support increasing number of users in the system, namely with MMC. (iii) A Linear multi-stage receiver for FBMC, providing a Signal to Noise plus Distortion gain of 4dB and rate increase of approximately 30% when targeted at MBB and MMC use cases. Based on linear processing means it lends itself well to massive MIMO scenarios. This topic proceeds to present further enhancement and evaluation on code design. Enhancements in iterative multiuser detection allow for individual code design tailored for the conditions of each user and can be applied to all NOMA schemes based on iterative receivers, currently under discussion for future 5G systems. Furthermore, the need to manage inter user interference with NOMA for Multiple Access Multiple Relay Channels in uplink is addressed with work on practical distributed coding and relaying functionality. The topic is continued with resource identification and channel estimation concept based on passive listening and compressed sensing techniques for D2D use cases. Here it was shown that the resource map can be identified in a multi-user scenario just through observation, eliminating the need for costly overhead to establish link quality. This topic is finalized with a large system analysis used to study FBMC/OQAM mMIMO (Zero Forcing and Linear MMSE) receivers. The obtained results in a large system regime were shown to be exploitable in real life finite size systems. Depending on the particular receiver, significant gain versus the LTE baseline was observed and detailed along with the required complexity increase. This large system analysis was finally extended to a multi-cell scenario, whereby the use of multiple Basestations is considered in order to increase the global system throughput. Results have been able to shed some light on the tradeoff between additional spatial diversity and increased channel frequency selectivity due to the larger spatial dispersion. The obtained results provide a powerful tool in order to establish whether it is better to cooperate or not, and to determine the optimum number of sites that need to be considered in the CoMP architecture, based on macroscopic (average) channel measurements. The investigation of advanced receivers has led to the significant enhancement of the performance of the proposed technologies (IDMA, NOMA, FBMC etc); thus enabling these technologies to achieve the desired requirements set out by the core project use cases.

2.3 Overall air interface design and evaluation

The technical solutions elaborated in Sections 2.1 and 2.2 are integrated in the FANTASTIC-5G air interface structure as illustrated in Figure 2-1. For each component, we highlight how these innovations contribute to the measurable air interface characteristics that were defined as part of our original project goals. In particular, the FANTASTIC-5G air interface is aiming at

- high capacity (spectral efficiency per area and link throughput)
- ultra-low latency and high reliability/availability
- support of low-cost and low-energy devices
- massive access (high number of devices)
- ubiquitous coverage and high mobility (seamless access everywhere)
- in-band coexistence of services (multi-service air interface)

The air interface components shown in Figure 2-1 are analysed and discussed in more detail in the WP2 deliverables [FAN16-D2.2] and [FAN17-D2.3].

In order to evaluate the air interface, FANTASTIC-5G (WP2) has carried out system level simulations based on the KPIs and use cases defined at the beginning of the project [FAN16-D2.1]. We have: *KPI 0*: User experienced data rate, *KPI 1*: Traffic density (to achieve high system capacity), *KPI 2*: Latency, *KPI 3*: Coverage (to provide ubiquitous access), *KPI 4*: Mobility, *KPI 5*: Connection density, *KPI 6*: Reliability/availability, *KPI 7*: Complexity reduction, *KPI 8*: Energy efficiency.

In the following, we will describe the seven simulation campaigns that were carried out within WP2. The simulations are carried out at system level, where all relevant functionalities of the air interface are implemented, with 4G (LTE) as baseline. Each campaign evaluates selected FANTASTIC-5G technologies, for a certain use case and for different service types (MBB, MMC, MMC, V2X, BMS, as introduced in the beginning of section 2). Particular emphasis is placed on the objective of multi-service co-existence. The results show to which degree the co-existence of diverse 5G services can be realized by a single air interface including different settings/configurations or component selections.

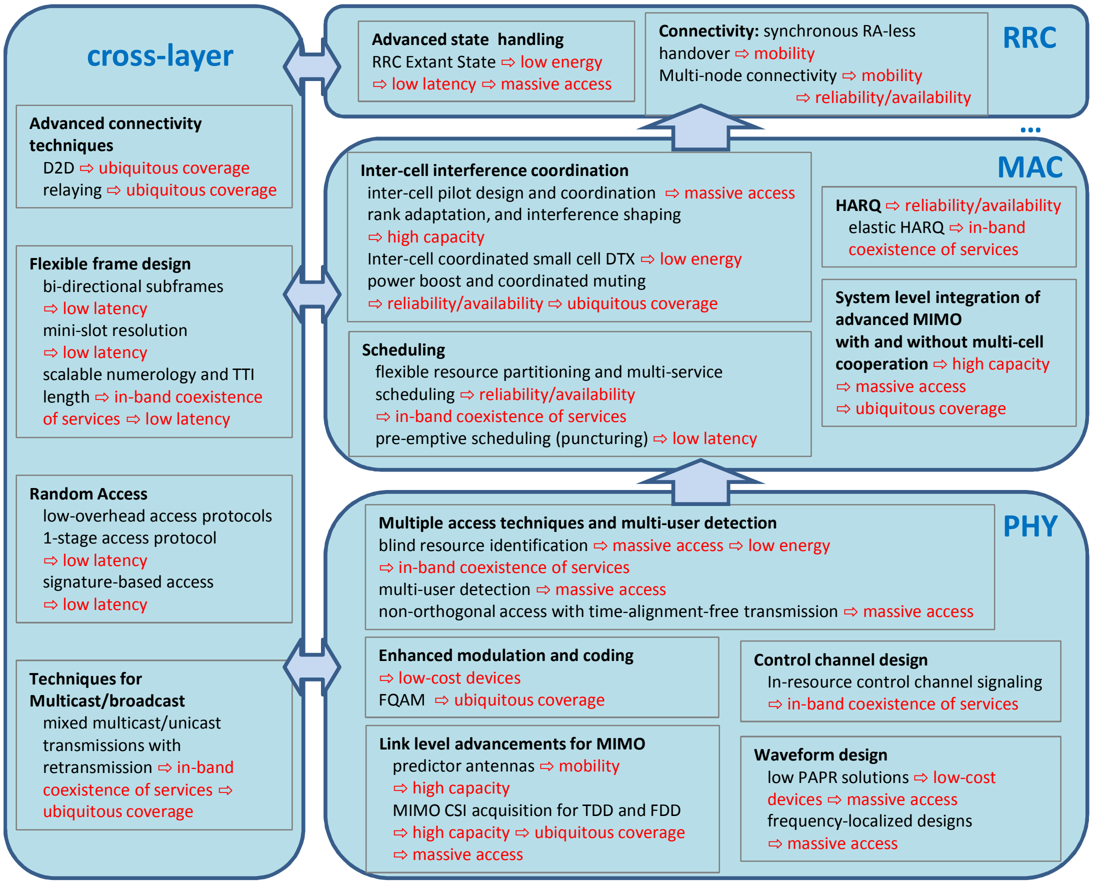

Figure 2-1: Illustration of the FANTASTIC-5G air interface with integrated technical solutions from WP3 and WP4.

2.3.1 Wide area coverage

For this campaign, a massive MIMO configuration has been adopted in macro-cellular environments (UMa/RMa) to provide MBB services to multiple users. Simulations assume a rectangular antenna array with two-stage precoding (regularized zero-forcing on top of a grid-of-beams). An optional inter-cell Coordinated Beamforming (BF) scheme is applied on top of mMIMO. For comparison purposes, a baseline LTE-A system (using 8x8 single-user MIMO) is also evaluated.

Results are reported for three deployment environments: rural (inter-site distance (ISD) = 1000 m, 100 users/km²), suburban (ISD = 600 m, 400 users/km²), and urban (ISD = 200 m, 2500 users/km²). The target value for the average user data rate in this use case is 50 Mbps and simulation results are shown in Figure 2-2 (left). While the LTE-A baseline cannot reach this objective alone, the proposed mMIMO technique can provide at least twice as much as the target. Additionally, the mMIMO with Coordinated BF boost the user data rate from 9.16% (in the rural scenario) up to 19.5 % (in the suburban scenario) comparing to basic mMIMO operations.

Supported traffic density, shown in Figure 2-2 (right), is also greatly increased comparing to LTE-A. With Coordinated BF technique provides an additional gain of 18.0% (in the urban scenario) to 20.8 % (in the suburban scenario) on top of the pure mMIMO gains.

Finally, the availability is shown in Figure 2-3. It is calculated as the percentage of the target throughput achieved by each user, or 100% if higher. While LTE-A is in the 25%-50% range, mMIMO reaches more than 94%. With the additional coordinated BF, results exceed 97%.

For more detail on the evaluated techniques, parameters, and results, see [FAN17-D2.3].

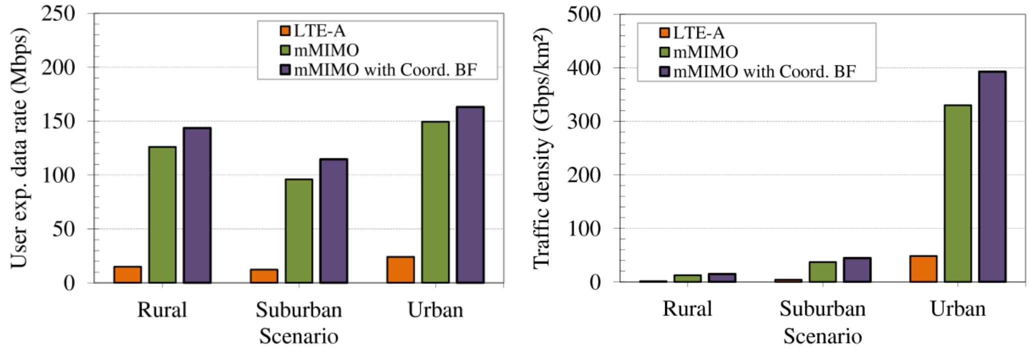

Figure 2-2: User experienced data rate (left) and traffic density (right) for the "Wide area coverage" scenario

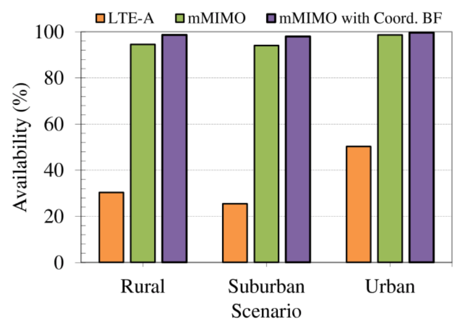

Figure 2-3 Availability for the "Wide area coverage" scenario

2.3.2 Video broadcasting

This simulation campaign represents a scenario in which many users receive the same real-time video stream. Simulations will evaluate specific improvements over the Single-Frequency-Network approach already adopted in LTE. In the context of the FANTASTIC-5G project, the distribution of data in multicast or broadcast mode is captured in the Use case 6, described as "Broadcast like services: Local, Regional, National".

The campaign shows that hybrid broadcast/unicast is a promising new way of dealing with unreliable user channels in SFN networks. Figure 2-4 shows the CDF of the user experienced data rate for video broadcasting, which is considerably improved for cell-edge users when using the adaptive method with HARQ. For more details on the evaluated techniques, parameters and further results, see [FAN17-D23], Sections 3.5 and 3.6.

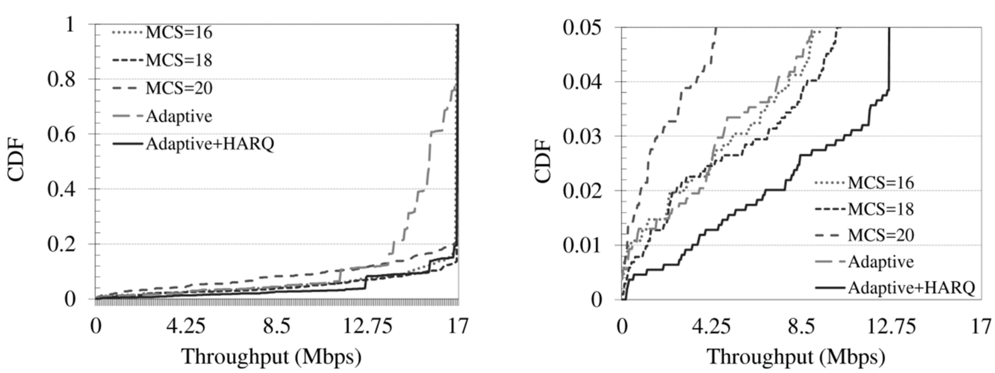

Figure 2-4: CDF of user data rate for video broadcasting

2.3.3 MBB/BMS coexistence

For this campaign, MBB traffic is complemented by video broadcasting which shares the same resources. The same UMa/RMa environment as in the "Wide area coverage" is assumed. For video broadcasting, the bandwidth is limited to 20 MHz and the multicast-broadcast single-frequency networks technique of LTE is adopted. It is also enhanced with a feedback channel in the uplink direction, which allows a dynamic adaptation of the modulation and coding scheme (MCS) based on the channel quality perceive by mobile users. Also, ACK/NACK feedbacks for broadcast packets are introduced, and packets received with errors are retransmitted using dedicated unicast links. The results [FAN17-D2.3] show that the introduction of the BMS service is reducing the data rate for the MBB service by 10-13%, but does not significantly compromise the fulfilment of the target value in the considered scenario.

2.3.4 Massive access

The rapid explosion on the number of IoT devices induce a new challenge for the mobile network. In this direction, new 5G mechanisms that are capable of handling this situation should be integrated and current approaches should be enhanced. The massive access campaign evaluates the system performance by assuming an environment in which a massive number of devices are requesting access and transmitting data. In this campaign a set of massive access protocols proposed and implemented in the 5G-PPP project are evaluated w.r.t. support of a high number of devices and minimizing the average number of retransmissions to minimize the energy consumption of devices.

In the simulation campaign, all devices are assumed to be low-power, low-complexity with limited functionality to support only a fixed modulation and coding scheme of QPSK with code-rate of 0.48. We evaluate the proposed massive access protocols under different request loads. Two new FANTASTIC-5G protocols (two-stage and one-stage) are evaluated and compared to the LTE-A Access Reservation Protocol (ARP). The two-stage access protocols support only single-use detection, while the one-stage protocol support multi-user detection by using the Coded Random Access with Physical Layer Network Coding (CRPLNC) access scheme proposed by FANTASTIC-5G. Further details on the modeling of the different access protocols are captured in [FAN17-D4.2], while the detailed simulation configuration is presented in [FAN17-D2.3] (Section 3.2.2).

Figure 2-5(a) illustrates the reliability performance of the proposed access protocols. The figure shows that the ARP protocol of LTE-A fails to accommodate a high number of requests. The one-stage access protocol shows moderate performance for low SNR values (0 dB), while the performance is improved significantly for higher SNR values. The two-stage tagged access protocol shows gain similar to the one-stage access protocol (0 dB). The two-stage access pooled protocol depicts significant gains for arrival rates up to λ=0.5, while for higher rates retain a noticeable performance.

Figure 2-5(b) presents the protocol throughput in terms of transmitted packets per TTI. Both one-stage (20 dB) and two-stage pooled protocols seems to follow the increase of the arrival rate up to values equal to λ=0.5 and λ=1 respectively. Then the reliability reaches low values so that the throughput starts to decrease (instead of following the arrival rate). The highest throughput (32pkts/TTI) is realized by the one-stage (20 dB) protocol for λ=1.

Figure 2-5(c) illustrates the protocol overhead in terms of average number of retransmissions. The figure illustrate that the one-stage pooled protocol has the lower number of retransmissions for medium arrival rates, while the one-stage protocol (20 dB) has the greatest performance for high arrival rates. From this figure it becomes clear that one-stage protocols are more appropriate for low-power devices since they manage to minimize the total transmissions (low number of retransmissions and simultaneously transmission of control and data information) and therefore the total energy consumption. On the other hand, two-stage protocols generate more transmissions. In order to become comparable to one-stage protocols, two-stage protocols should retain the retransmission numbers in very low values (e.g. in our case the one-stage pooled protocol for arrival rates up to λ=0.5).

Finally, Figure 2-5(d) illustrates the access latency of the proposed protocols which is the secondary KPI for the MMC (a.k.a. mMTC) services. The highest performance is observed in the one-stage (20 dB) protocol and in the two-stage pooled protocol, which depict similar results. The latter, although it is a two-stage protocol, manages to retain low latency values because of the low number of retransmissions.

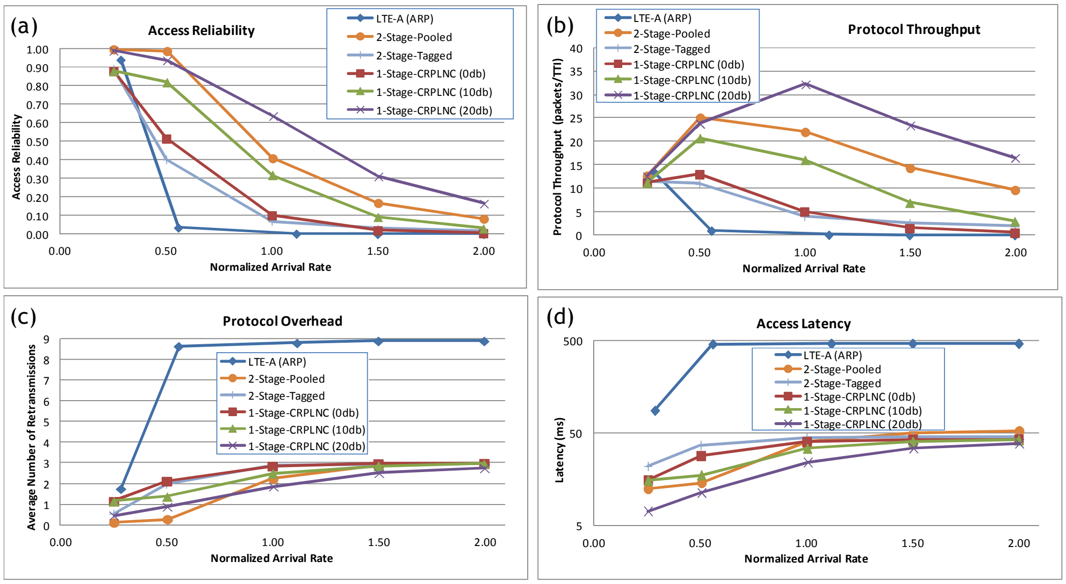

Figure 2-5: Performance of massive access protocols

2.3.5 Diverse device and transmission types (MBB+MMC)

One main limitation of the MMC devices (e.g. sensors) that transmit sporadic data in the uplink direction is that they require to use the downlink channel for synchronization. This is not a major problem in small to medium sized cell environments (e.g., with ISD=500m) and in cases of channel realizations with low delay spread values (e.g., EPA [36.104]), because in these cases the use of cyclic prefix (CP) compensates for any deviations of the transmission from the detection window reference time. But, in cases of large cells (e.g. ISD=1732m) and for channels with high delay spreads (e.g. ETU [36.104], EPB [25.890]), the deviation can become larger, especially for the users far from the basestation, and can exceed the selected CP value. In this case, the transmission is considered asynchronous to the detection window and it produces interference to the transmissions adjacent in frequency. The power of this interference is affected by various parameters (e.g., the size of two bursts, the existence of guard bands between them, etc.). Therefore, in this campaign, we assume a mixture of MBB and MMC traffic. New waveforms with good frequency localization are used to avoid interference due to asynchronous transmission. Figure 2-6 shows the spectral efficiency gains that are achieved with P-OFDM waveforms (see [FAN17-D2.3] for details).

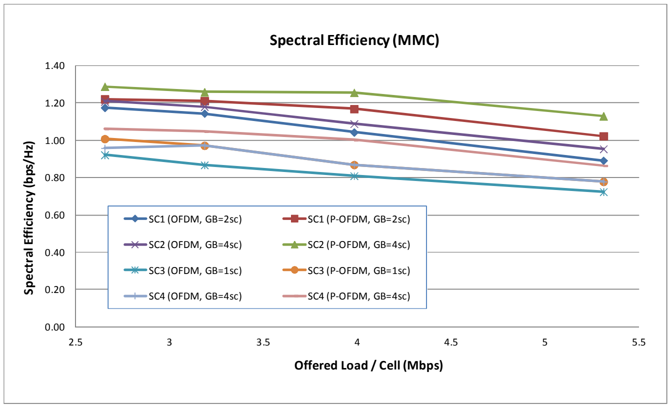

Figure 2-6 MMC service - Spectral efficiency of selected RB positions

2.3.6 Multi-service (MBB, MMC, MCC)

In 5G, a very interesting multi-service scenario is the coexistence of three service types: MBB, MMC and MCC (a.k.a. URLLC). The multi-service simulation campaign evaluates the 5G system performance by assuming a realistic environment reflecting the aforementioned mix of users and devices and by assuming the coexistence of the three aforementioned service types.

In the campaign we define three scenarios in order to evaluate the proposed 5G systems: a) LTE-A scenario (baseline); b) FANTASTIC-5G scenario with flexible TTI, priority scheduling, massive access support and static service clustering (denoted as F5G-FlexibleTTI-PS-MAP); c) similar to (b) with the addition of semi-static service clustering (denoted as F5G-FlexibleTTI-PS-MAP-SSC). In the first scenario the LTE-A case is assumed, in which there is no discrimination between MBB and MCC users, while the MMC user is supported by the LTE ARP. In the second scenario, the available uplink spectrum band of 10 MHz is divided into two clusters: one with 8 MHz bandwidth for MBB and MCC services and the second with 2 MHz bandwidth for MMC services. In the first service cluster a TTI = 0.25 ms is used, while the second service cluster utilize LTE like numerology. In this scenario, scheduling with different TTI sizes is supported Priority aware Scheduling (PS) is applied (higher priority of MCC over MBB services). In addition, the second service cluster (MMC) exploits a 1-stage massive access protocol (MAP) that follows the CRPLNC access scheme. The third scenario is based on the second one, but it permits a small modification of the spectrum assigned to each service cluster. To evaluate the performance of the use case, all three scenarios were assessed under different load conditions. In all scenarios, a 1:4 ratio between the MCC and MBB users is maintained, while the generated files have a size of 1.25 and 100 KB for the MCC and MBB users, respectively. The detailed simulation configuration is presented in [FAN17-D2.3] (Section 3.1.2).

Figure 2-7 (a) illustrates the performance of the MMC services in terms of reliability. From the figure it become obvious that the LTE-A reliability degrades fast when the normalized arrival rate approaches 0.3. The proposed FANTASTIC-5G systems retains high reliability values even when the offered load reach up to λ=0.9, because of the use of the 1-stage massive access protocol (CRPLNC) which supports Multi-user Detection (MUD).

Figure 2-7 (b) presents the total latency (upload time) of the MCC services. The figure is zooming at the performance of the FANTASTIC-5G proposals, while the whole figure (zoom out) is presented in the inlet figure. From the figure, it becomes clear that for medium or high loads the performance of LTE-A is dramatically degraded reaching high latency values (up to 7 s). On the contrary, both FANTASTIC-5G proposals retain low latency values (around 4 ms) for all offered loads. In detail, for low loads, they present a better performance mainly due to the adoption of the new numerology of TTI=0.25 ms. Then, for medium and high load, the adoption of the prioritization scheme during the scheduling process helps the 5G proposals to continue to retain low latency values for the MCC services independently of the volume of the offered load. It is important to stress here that this performance can be further improved by the use of puncturing ([FAN17-D4.2]).

Regarding the MBB users, the three systems under evaluation demonstrate similar results, as indicated in Figure 2-7 (c). The reason behind is that the number of MBB users is higher than the MCC users (1:4 rate), while the generated file size is also higher in MBB users (100 KB instead of 1.25 KB).

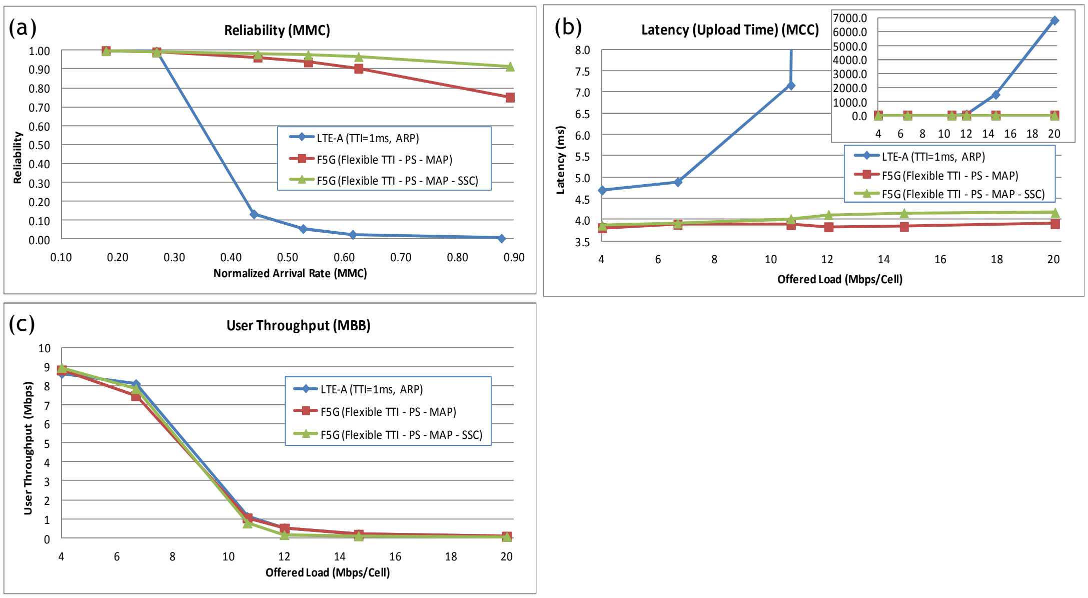

Figure 2-7: Performance of multi-service scenario

2.3.7 High speed train

This simulation campaign represents a scenario where users on fast trains require broadband internet connectivity for entertainment or for work. Users currently experience a limited QoS level due to failures of mobility management, insufficient antenna capabilities and the penetration loss introduced by the train (advanced antenna systems at the roof of the train and relay nodes allow for overcoming the problems of the penetration loss). The quality degradation becomes more severe especially in both rural and mountain areas, where the wireless infrastructure is sparsely populated and the path loss becomes large.

Adaptive MIMO techniques do not work very well with moving receivers. CSI provided by the mobile terminal becomes outdated as it moves along, and the precoding operated by the transmitter is less effective than expected. This is known as the “channel aging” problem, and it gets increasingly worse as the speed increases. In order to mitigate the effect of channel aging, FANTASTIC-5G has proposed the concept of *predictor antennas* [FAN17-D4.2].

Figure 2-8 and Figure 2-9 show the aggregate throughput gains for inter-site distances 1 km and 2 km, respectively.

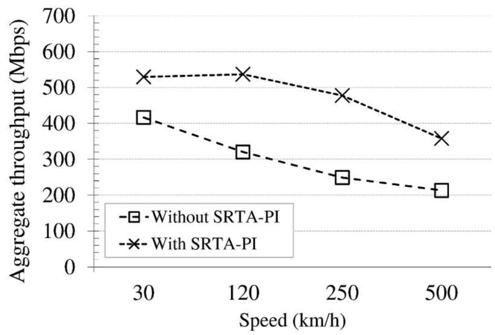

Figure 2-8: Aggr. throughput (ISD=1 km)

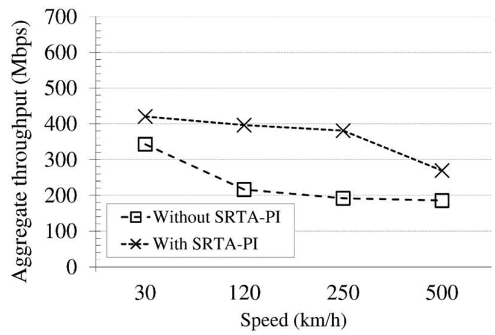

Figure 2-9: Aggr. throughput (ISD = 2 km)

2.4 Key findings and lessons learnt from the PoC activities of the project

Proof-of-concept (PoC) activities in FANTASTIC-5G aim at validating the feasibility and the superiority of some selected technologies being developed by the project. The implementations are categorized into three main categories: (1) Prototyping for post-Orthogonal Frequency Division Multiplexing (OFDM) waveforms, (2) Evaluation of waveform coexistence aspects, and (3) Development of a Software Defined Radio (SDR)-based demonstration for broadcast and multicast transmission. In the following subsections, summary of the main achieved results by the different PoC are provided.

Flexible PoC for Post-OFDM waveforms

Filter Bank Multi-Carrier (FBMC), Flexible Configured (FC)-OFDM, and Universal-Filtered (UF)-OFDM low-complexity transceivers have been implemented in a common real-time hardware platform. In terms of hardware complexity evaluation, the following outcomes can be stated

- UF-OFDM and FC-OFDM uplink have similar synthesis results since the same hardware resources are reused for both transmitters.
- Whereas UF-OFDM is generally considered to be highly complex, an architecture has been proposed and implemented to make it comparable to OFDM in terms of hardware effort.
- The complexity of the FBMC/OQAM transmitter with 1 tap (PolyPhase Network) PPN (for short filters) is comparable to OFDM. When using higher number of taps, the complexity of the FBMC/OQAM becomes much higher than OFDM.
- The required hardware resources in the case of FC-OFDM downlink transmitter are almost two times higher than OFDM.
- The Frequency Spread (FS) implementation can be used with a negligible complexity increase when compared to the PPN implementation for FBMC/OQAM receiver.

These promising candidate waveforms have been also evaluated with respect to state-of-the-art Cyclic Prefix (CP)-OFDM. The evaluation has been performed in Massive Machine Communication (MMC), vehicle-to-everything (V2X) and Machine Critical Communications (MCC) scenarios. The main results can be summarized as follows

- Both UF-OFDM and FC-OFDM uplink (mode 1) are suitable for MMC. Better performances can be achieved with FBMC/OQAM. Particularly, PHYDYAS filter enables to perfectly avoid the inter-user interferences due to its frequency localization.

However, the bottleneck of FBMC/OQAM is the lack of complex orthogonality and thus the difficulty to use e.g. MIMO diversity schemes, while OFDM-based techniques can be reused (Peak to Average Power Ratio (PAPR) reduction, Multiple-Input Multiple-Output (MIMO)), and are perfectly compatible with LTE numerology.

- UF-OFDM and FC-OFDM have slightly better performance in V2X scenario than plain CP-OFDM. For FBMC/OQAM with PHYDYAS filter, the Inter-Carrier Interference (ICI) is clearly reduced since the constellation points are less noisy than OFDM, and no errors are introduced in the received bits when using a code rate of 2/3. When FBMC/OQAM with Time Frequency Localization 1 tap (TFL1) is used, better performance is obtained, since the received constellation is less noisy than when applying the PHYDYAS filter. No errors are introduced when a code rate of 4/5 is considered.
- For the MMC setup, orthogonality is lost in case of plain CP-OFDM resulting in a significant performance penalty. Interference is still present for UF-OFDM, the received QAM symbols are less noisy than with CP-OFDM. For FC-OFDM, better results are achieved than with CP-OFDM, but residual errors remain. Using TFL1 and PHYDYAS filter, no interference is introduced for FBMC/OQAM.

FBMC-MIMO transceiver based on software programmable hardware

To overcome the difficulties of adapting the FBMC waveform to multiple antenna schemes, Block Filtered (BF)-OFDM that combines CP-OFDM and filter bank techniques as applied in FBMC is implemented. Accordingly, 2x2 MIMO BF-OFDM based transceiver is implemented. The main results can be summarized as follows

- Most of the complexity of the implemented BF-OFDM transmitter is found in the inverse FFTs and the complexity of BF-OFDM transmitter w.r.t CP-OFDM is higher due to the filtering function.
- In the receiver side, CP-OFDM and BF-OFDM have the same complexity.
- The implementation of the BF-OFDM confirms the simulation results regarding its good frequency localization properties.
- BF-OFDM was demonstrated to work in a multi-service scenario with mixed numerology.
- BF-OFDM showed compatibility with MIMO and LTE signaling. Peak throughput of up to 195.2 Mbit/s for 2x2 spatial multiplexing MIMO has been achieved (at 20 MHz bandwidth).

Pulse shaped (P)-OFDM for Timing Advance (TA)-free low latency transmission

The key aspect of this PoC is to show that an appropriate waveform design is capable of handling timing offset up to the symbol level. The main results can be summarized as follows

- In an interference-free scenario, both CP-OFDM and P-OFDM achieve comparable link performance.
- In a strong-interference limited scenario, CP-OFDM is subject to severe link performance degradation while P-OFDM exhibits robustness against the interferer; and even in the scenario when the interference level is reduced, CP-OFDM still suffers from the performance degradation compared with interference-free scenario.
- Field trial for single link real-time evaluation is performed in the public streets where the channel between the direct links has experienced both Line of Sight (LOS) and Non Line of Sight (NLOS). It was found that P-OFDM outperforms CP-OFDM attributed to the ICI mitigation due to the pulse-shaping filter with low-out-of-band-leakage as well as due to the improved collection of the receive energy with the matched filter at the receiver.

Post- and parameterized-OFDM waveforms for low latency transmission

Towards fulfilling low latency transmission requirements of MCC services, a parameterized-OFDM transceiver has been developed and implemented. A modification of LTE has been applied to enable the adjustments of the common symbol duration and to redesign the radio frame structure. The real time implementation and measurement shows that end-to-end delay of lower than 1 ms can be achieved with high reliability implementing a flexible numerology and with a round-trip time of less than 2 ms.

Coexistence aspects evaluation

The coexistence of a perfectly synchronized user located with asynchronous interferers, induced by a guard band and/or time asynchronous access is studied. CP-OFDM, UF-OFDM and FBMC/OQAM waveforms are demonstrated under realistic hardware impairments. The experiments are performed by selecting different guard-bands, various time offsets and with mixed numerology. The results confirm that CP-OFDM has the worst performance when the time shift is higher than the CP duration where the best coexistence in that case can be achieved by FBMC/OQAM. UF-OFDM performs better than CP-OFDM.

Broadcast and multicast Joint transmission

Joint broadcast and multicast transmission PoC in implemented by means of Software Defined Radio (SDR), based on the non-orthogonal beam superposition and joint decoding techniques. Real time evaluation is performed to demonstrate the scheme ability to use the entire available bandwidth to transmit several multimedia streams sharing the same frequency and time resources, and to use the spatial dimension to design the coverage of each stream, distinguishing between broadcast and multicast transmissions. It is found that better performance can be achieved when the power is divided equally between the broadcast and the multicast streams. When comparing the implemented technique with LTE MBMS over emulated channels, it can be found that the proposed scheme increases the aggregated throughput without requiring additional power, as it is able to multiplex and serve multiple streams concurrently.

2.5 Exploitation, dissemination, standardization, innovation

The project has been extremely successful in exploiting and disseminating the collected project results:

2.5.1 Dissemination activities

FANTASTIC-5G has initiated a workshop series in the international flagship conferences such as ICC, Globecom and EuCNC from scratch. Well recognized has been the New Air Interface in the VTC 15-16 conference series. Another series is the 5G RAN architecture workshop series collocated with ICC, Globecom 2016-2017 conferences. The workshops have attracted more than 150 submissions from researcher and engineers throughout the world. Within the workshops, reputable key note speakers particularly from the vertical market or content providers such as Bosch, Google etc. have outlined their view on the development and requirements of 5G. The workshops have been advertised over the 5G-PPP channels (website and Twitter) as well as major social networks such as Twitter, LinkedIn, and Youtube etc. To stimulate further technical discussions between the project and the respective academic and industry communities, the project has created a Linked Group with over 500 members! Furthermore, the project has initiated workshops and special session within the EuCNC 16-17 conference series including a final workshop for presenting the major results of the project. The total number of workshops and special session including a special session oversees (Asilomar’15) is nine!

FANTASTIC-5G has actively supported the 5G-PPP inter-project concertation with organizing joint workshops on 5G air interface and architecture on 5G-PPP level (Stockholm, Valencia, Athen). The project has had close ties with other major 5G-PPP flagship projects such as 5G

NORMA, mmMAGIC, SPEED-5G etc. and actively spread, discussed and aligned its research results with the 5G-PPP projects and working groups. FANTASTIC-5G actively contributed to the white papers published at the major MWC'16-17 industry exposition.

The project has showcased its results with booths and proof-of-concept hardware demonstrators to the technical community and policy makers in collaboration with 5G-PPP partners as part of the ICC'15, EuCNC 2017-17 conferences. Proof-of-concept demonstrations have been provided events at major events such as the 5G Global event in Rome.

On top of numerous posters, leaflets, videos etc. the project has published its results in three book chapters (IET, 2xWiley) and two joint journal publications (ETT 2016 and IEEE Access 2017).

2.5.2 Exploitation

FANTASTIC-5G partners have been highly active and published more than 80 publications in all relevant major ICT conferences including ICC, Globecom, ISWCS, EW etc. Industry and SME partners have greatly exploited their results by contributing to 3GPP standardization with more than 70 well documented Tdocs. Additionally, the industrial partners have used the project work for internal collaboration with the respective groups being active in standardization. The SME partners have used the project work to improve their existing solutions build up relevant know-how (e.g. "Sequans Communications (SEQ) is a 4G chipmaker. We are now considering 5G in our roadmap and the work undergone in FANTASTIC-5G was key in helping us to acquire basic know-how about 5G. We were able to contributed into the 3GPP that gave us higher credibility within the ecosystem. This is quite important especially for an SME.").

As part of their activity the universities and companies have trained numerous bachelor, master and PhD students. Additionally, existing lectures have been improved and dedicated lessons have been developed based upon the work in FANTASTIC-5G (e.g. POLIBA: "Dedicated lessons on 5G requirements and use cases, simulation tools, novel technical components, and related performance evaluation have been organized."). 5G technologies have been incorporated as examples and state of the art developments to enhance student awareness and to offer cutting-edge knowledge (e.g. UB: "5G has also been included as an education topic on various levels."). The results from the project research have been included into education programs (e.g. AAU), Eventually, national and international industrial research projects will be fostered through the acquired know-how and supported by the built network of contacts within the 5G field. Partners of FANTASTIC-5G have been able to use the work in FANTASTIC-5G to strengthen their expertise and their standing within the global community (e.g. "The obtained results and dissemination strengthened CEA's position in the 5G and scientific community, enhancing its visibility, and paving the way towards future IPR exploitation").

Altogether, FANTASTIC-5G research results have strengthened the position of European companies in the standardization and overall ICT domain. Finally, the project outcomes will be exploited within the follow-up project ONE5G (E2E-aware Optimizations and advancements for the Network Edge of 5G New Radio). ONE5G has started June 1st 2017 and will build upon the outcomes of FANTASTIC-5G and on the status of 3GPP at this point in time.

2.5.3 Innovation

During the project's lifetime, FANTASTIC-5G initiated dedicated innovation sessions related to innovation management. Several innovation achievements were recognized including IPRs, standards, new tools/products/services and potentially new SMEs. As part of the Innovation Management, we moved from initial concept development and prototypes, towards testing in the production environment and inclusion of the final solutions to standards. This ensured that the results are cost-effective, practical, and tailored to the market needs. As such, for the exploitation of innovation in big companies it is essential to maximize the synergy between corporate strategy/business development and R&D.

FANTASTIC-5G's focus has been on technical enablers for the air interface of 5G related to the lower layers of the protocol stack (PHY, MAC and RRM). To push the innovations towards realization the project has followed upon three different line:

- to produce respective IPR
- to transfer those innovations towards standardization by submitting respective technical contributions
- partner specific innovations (tool improvement, chipset improvement)

The project has produced 13 filings. The filings are still within the embargo phase and thus cannot yet be fully disclosed. In general, those filings are related to various parts of the interface such as waveform design, superposition coding, enhanced receivers, etc.

The relevant body for proposing the project innovations towards standardization is 3GPP (mainly RAN1, to some extent RAN2 and RAN4). The industrial partners of the project have submitted more than 70 contributions (3GPP terminology: Tdocs) to those groups. In the following, we provide the list of topics as discussed/agreed in 3GPP meetings that are aligned with proposals from FANTASTIC-5G. Additionally, we provide a list of items that the project has worked on but are not yet on the agenda of 3GPP and are thus to be submitted in a later stage:

- FANTASTIC-5G has discussed various waveform options being based on OFDM and applying a filtering functionality (both per subcarrier and per sub-band). The latter has been proposed by various industrial partners to be included into the standard. 3GPP has decided to use CP-OFDM as baseline, including those filtering functionalities (per sub-band) as an option. RAN4 is to define the in-band transmission masks. Depending on those the need for those filtering functionalities is determined.
- mMTC (a.k.a. MMC) is not yet on the agenda of 3GPP, however, early discussions indicate 3GPP to follow similar lines as proposed by the project contributions, e.g. related to access protocols (1-stage, 2-stage) and state handling (i.e. the introduction of a 3rd state to allow lean state transitions for battery constraint devices).
- The fundamental frame design considerations (e.g. sub-frame structure, slot configurations, resource block definitions, supported subcarrier spacings, etc.) are in general following the lines as given within the contributions of the industrial partners of FANTASTIC-5G.
- The project partners have proposed various enablers to efficiently implement URLLC (a.k.a. MCC) services into NR (e.g. punctured/pre-emptive scheduling for DL mux of URLLC and MBB transmissions).
- Several enhancements for HARQ (e.g. CB – codeblock - based reTx)
- Enhanced sequence design for PRACH based on modified m-sequences as investigated in the project are currently evaluated in 3GPP as candidate solutions.
- As proposed by the project contributions 3GPP follows the principle of in-resource control channels.
- Not yet on the agenda of 3GPP, but to be contributed in the second phase are enablers for massive MIMO (e.g. reference symbol design, grid-of-beams design, etc.).
- Similarly, aspects related to ICIC are not yet in the focus of 3GPP and thus later to be proposed.

Further innovations were also introduced by SMEs which are not necessarily patented but are related to the creation of new or enhanced products and services. For instance, two SMEs proceeded to the following innovations:

- WINGS introduces a simulation platform that is enhanced with respect to 5G features. WINGS works on projects/contracts targeted to the study of "what if" scenarios. The realization of studies involving 5G will enhance the business opportunities of WINGS. The simulation platform has been existing but the upgrade to 5G technologies is the innovative aspect.
- Sequans also proceeded to enhanced chipset development for facilitating 5G.

The following table summarizes the project's innovations:

Table 2-3: Project's innovations

Type	Number
IPRs	13
Standards	71
Other (e.g. SME innovations)	2

Moreover, in order to promote project's innovations to the broader audience, the project was represented to a special "Workshop on Opportunities and challenges of 5G in the EU" which was organized by the European Parliament with the participation of MEPs. Furthermore, following the main outcomes of the project, VCs and further investors may be engaged (even after the completion of the project) in order to check further exploitation opportunities of the produced solutions.

2.6 Impact

The project had major impact on various levels as already indicated in earlier sections. In the following we provide a global overview.

The project has made significant contributions to the global research efforts in the area of wireless communications. The numerous publications (>80) and workshops the project has organized have significantly enhanced the available knowledge base within the global research community. Additionally, the project outcomes have provided new and superior solutions to current and future communication problems and opened new paths and directions inspiring other researchers on global level.
On European level the project and its participants have actively shaped the activities of the relevant groups such as 5G-PPP. Being a part of 5G-PPP, FANTASTIC-5G has been active in various working groups (e.g. WG Vision and Societal Challenges, WG Pre-Standardization, use cases and performance evaluation) and has shaped their procession. FANTASTIC-5G has been one of the drivers related to various cross-project activities e.g. related to the collaborative design of the Air Interface of 5G. The project manager and the technical manager have actively guided the global activities beyond the borders of the single projects by actively contributing to and directing of the 5G-PPP steering board and the 5G-PPP technical board. FANTASTIC-5G has successfully represented 5G-PPP in particular and Europe in general at various global events such as the Global 5G event (November 2016 in Rome).
By submitting >70 Tdocs to 3GPP RAN meetings the project had significant impact towards the initial release of 5G New Radio. A closer look to the current status of the decisions and agreements in 3GPP show the success of FANTASTIC-5G related to driving its concepts into the standard. As outlined earlier many recommendations given by the project have been incorporated by 3GPP. The partners in the project have generated a very high number of filings (13) increasing the footprint of the European Industry on global level strengthening its position in relation to other areas in the world. The project has been able to strengthen the position of the project partners

compared to other players outside of Europe e.g. by allowing them to enhance existing tools and technologies and by widening their knowledge base. Finally, by incorporating the findings of the project into existing lectures provided by the project partners from academia (e.g. within university courses) the new generation of engineers will be perfectly prepared to compete in the global landscape of wireless communications.

The outcomes of the project enable 5G New Radio to be more than just a simple continuation of 4G (i.e. just providing more of the same). In particular, with applying the project recommendations 5G New Radio is able to revolutionize wireless communications in various aspects by allowing 5G New Radio to be multi-service capable. On business level this allows existing players (e.g. operators) to improve their offer by enhancing business models as of today (e.g. improving quality of experience for web browsing, video streaming, etc.) and by introducing new offers related to new use cases even with new and different customers. Furthermore, it enables new players to enter the market allowing them to enhance their current business by adding communication functionalities (e.g. the car industry) or even by introducing new products/solutions. Industry in general benefits from the possibilities “future factories” (Industry 4.0) are promising enabled by the multi-service capable air interface proposed by FANTASTIC-5G. Adding wireless communication functionalities to industrial processes and procedures is a key ingredient for this. New jobs are created, existing jobs are improved. On societal level everybody is able to enjoy a much wider set of functionalities/technologies/apps, which are strongly improved by having access to a wireless network making the daily life easier and more enjoyable. Cities will be able to ‘become smart’ by adding communication functionalities to existing infrastructures. Environmental monitoring enabled by 5G New Radio will improve everybody’s life by enhancing food production and environment protection.

Although the life time of a project in general and FANTASTIC-5G in particular is finite, it is of absolute necessity to continue on the paths the project has set. For FANTASTIC-5G this happens by the industrial partners continuing to submit the project recommendations towards 3GPP (many of the topics the project has worked on are not yet on the agenda of 3GPP and will be discussed in later phases) and by the execution of ONE5G (horizon 2020 phase 2 project).

Conclusions of the action

FANTASTIC-5G has successfully identified, developed and analyzed the relevant technical enablers for the lower layers of 5G (PHY, MAC, RRM) in the frequency range below 6 GHz to achieve its ambitious targets. So, FANTASTIC-5G has both enhanced the support of the different core services within 5G per se and has enabled 5G to have those to be efficiently multiplexed into a single band. Some examples related to the former are e.g.

- system level integration of massive MIMO for achieving the high data rate requirements of MBB and to achieve full coverage;
- massive access protocols and an enhanced state model to enable massive machine type communications (mMTC a.k.a. MMC) efficiently allowing low end devices to access the system;
- frame design and scheduler related enablers to achieve the stringent requirements of URLLC services (a.k.a. MCC);
- spectrally efficient enablers for broad- and multicast services (BMS) such as unicast support for user specific retransmissions and multi-stream superposition exploiting the beamforming capabilities of the system;
- enhanced support of V2X services by improving the robustness against extreme Doppler channels.

For the latter FANTASTIC-5G has e.g.

- proposed and analysed use case specific adaptation of the waveform and
- introduced use case specific data channel formats dynamically sharing the frame.

So, the project has succeeded in developing a highly flexible, versatile and scalable air interface (multi-service air interface) to enable the in-band coexistence of highly differing services, device types and traffic/transmission characteristics while enabling ubiquitous coverage and high capacity where and when needed. As a consequence, with following the recommendations given by FANTASTIC-5G, 5G New Radio will be able to efficiently introduce new services to be supported efficiently and concurrently. It is possible to have those services to share the available spectrum making the Multi-Service Air Interface a reality. Dedicated mechanisms tailored towards these use cases need to be implemented (e.g. dedicated data channel designs, tailored coding schemes, etc.).

As the system is able to dynamically trade resources between the different use cases energy and resource consumption is minimized.

Dedicated technologies have been proposed rendering 5G to be future-proof such as e.g.

- in-resource control channels and
- a flexible scheduling framework including the respective adaptable frame design.

This allows future releases of 5G to introduce new functionalities, services and use cases, that are not even yet anticipated.

The project has evaluated and validated the developed concepts both with the help of simulations and for selected technologies with the help of proof of concepts.

The industrial partners in the project have developed consensus on selected areas and have had major impacts towards 3GPP by the submission of more than 70 Tdocs.

3 References

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[FAN16-D2.2] FANTASTIC-5G project deliverable D2.2, “Deliverable on the integration of technical components”

[FAN17-D2.3] FANTASTIC-5G project deliverable D2.3, “Deliverable on the final air interface description and system level simulation results”

[FAN16-D3.1] FANTASTIC-5G project deliverable D3.1, “Deliverable on the preliminary results for multi-service support in link solution adaptation”

[FAN17-D3.2] FANTASTIC-5G project deliverable D3.2, “Deliverable on the final results for the flexible 5G air interface link solution”

[FAN16-D4.1] FANTASTIC-5G project deliverable D4.1, “Deliverable on the preliminary results for multi-service support in multi-node/multi-antenna solution adaptation”

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[FAN16-D5.1] FANTASTIC-5G project deliverable D5.1, “Deliverable on identification of the PoC scenarios”

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