

5G NOW

Consistent 5G Radio Access Architecture Concepts

D2.2

'5G NOW_D2.2_v1.0.docx'

Version: 1.0

Last Update: 22/12/2014

Distribution Level: CO

- **Distribution level**

PU = Public,

RE = Restricted to a group of the specified Consortium,

PP = Restricted to other program participants (including Commission Services),

CO= Confidential, only for members of the 5G NOW Consortium (including the Commission Services)

The 5GNOW Project Consortium groups the following organizations:

Partner Name	Short name	Country
FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	HHI	Germany
ALCATEL LUCENT DEUTSCHLAND AG	ALUD	Germany
COMMISSARIAT À L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	CEA	France
IS-WIRELESS	ISW	Poland
NATIONAL INSTRUMENTS	NI	Hungary
TECHNISCHE UNIVERSITÄT DRESDEN	TUD	Germany

Abstract:

This deliverable is a pre-final summary of the approach and achievements of the 5GNOW project. It summarizes the key communications scenarios that are relevant for the PHY and MAC layer design of 5G cellular radio access architecture, describes the corresponding asynchronous, non-orthogonal waveforms approaches of 5GNOW and finally evaluates the performance with respect to selected scenarios compared to LTE benchmark.

“The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 318555”

Document Identity

Title:	Consistent 5G Radio Access Architecture Concepts
WP:	WP2 - System Requirements, Specifications and Overall Concepts
WP Leader	Priv.-Doz. Dr. Gerhard Wunder
Main Editor	Priv.-Doz. Dr. Gerhard Wunder
Number:	D2.2
File name:	5GNOW_D2.2_v1.0
Last Update:	Monday, December 22, 2014

Revision History

No.	Version	Edition	Author(s)	Date
1	0.1		Gerhard Wunder (HHI)	29.10.14
	Comments:	Template edition and insertion of initial content and input all		
2	1.0		Gerhard Wunder (HHI)	19.12.14
	Comments:	Final polishing		
3				
	Comments:			
4				
	Comments:			
5				
	Comments:			
6				
	Comments:			
7				
	Comments:			
8				
	Comments:			
9				
	Comments:			
10				
	Comments:			
11				
	Comments:			
12				
	Comments:			
13				
	Comments:			
14				
	Comments:			
15				
	Comments:			

Table of Contents

1	INTRODUCTION	7
1.1	KILLER APPLICATIONS.....	7
1.2	APPLICATION CHALLENGES.....	7
1.3	STATUS AND DEVELOPMENTS OF LTE.....	10
1.4	5GNOW APPROACH.....	11
2	KEY COMMUNICATION SCENARIOS	14
2.1	MTC.....	14
2.1.1	<i>Burst communication and sparse signal processing</i>	<i>15</i>
2.1.2	<i>M2M: Sensing, monitoring, collecting</i>	<i>15</i>
2.1.3	<i>Driving technology by human needs: Real-Time.....</i>	<i>16</i>
2.2	FRAGMENTED SPECTRUM	17
2.3	COMP/HETNET.....	18
2.3.1	<i>Time and frequency synchronism.....</i>	<i>19</i>
2.3.2	<i>Imperfect channel state information</i>	<i>19</i>
3	5GNOW OBJECTIVES, BENCHMARK SYSTEM AND KPI'S DESCRIPTION	20
3.1	5GNOW OBJECTIVES FROM THE DESCRIPTION OF WORK	20
3.2	LTE-A BENCHMARK SYSTEM	21
3.3	KEY PERFORMANCE INDICATORS	21
4	5GNOW ARCHITECTURE CORE ELEMENTS.....	25
4.1	WAVEFORMS.....	25
4.1.1	<i>Gabor signalling</i>	<i>25</i>
4.1.2	<i>5GNOW waveforms</i>	<i>26</i>
4.2	UNIFIED FRAME STRUCTURE, ONE SHOT TRANSMISSION AND AUTONOMOUS TIMING ADVANCE.....	26
4.3	TEMPORAL AND SPECTRAL FRAGMENTATION	28
4.4	NETWORKING INTERFACE – ROBUSTNESS FRAMEWORK	30
4.4.1	<i>Robust CoMP with relaxed time and frequency synchronization.....</i>	<i>30</i>
4.4.2	<i>Robust cellular iterative interference alignment</i>	<i>31</i>
4.5	LOW LATENCY	32
5	5GNOW REFERENCE SCENARIOS.....	33
5.1	PRACH SCENARIO	33
5.1.1	<i>Performance evaluation.....</i>	<i>34</i>
5.2	GENERALIZED FREQUENCY DIVISION MULTIPLEXING (GFDM)	34
5.2.1	<i>Performance evaluation.....</i>	<i>35</i>
5.3	UPLINK COMP WITH JOINT RECEPTION	35
5.3.1	<i>Performance evaluation.....</i>	<i>36</i>
5.4	MULTIUSER UPLINK ON FRAGMENTED SPECTRUM WITH FBMC.....	38
5.4.1	<i>Performance evaluation.....</i>	<i>38</i>
5.5	DOWNLINK COMP WITH FBMC	39
5.5.1	<i>Performance evaluation.....</i>	<i>41</i>
6	INTERMEDIATE CONCLUSIONS	45
7	ABBREVIATIONS	46

Executive Summary

This deliverable is part of WP2, specifically Task 2.1, and describes key scenarios and key performance indicators (KPIs) which have been investigated during the course of the project in WP3, WP4 and WP5 and which have guided the partners in the evaluation of their waveform proposals. It further collects and summarizes baseline (waveform) requirements from a technical and an application perspective with respect to the 5G cellular radio access architecture, addresses the LTE-A reference system and provides the corresponding performance results. HHI is the main editor of this document.

1 Introduction

This section is setting the stage for the 5GNOW research project: it briefly reviews communication history from an application point of view and highlights challenges in terms of data rates, signalling and spectrum. Finally, it relates these challenges to state-of-the-art LTE-A and the corresponding 5GNOW approach.

1.1 Killer applications

The successful deployment of killer applications in wireless communications technology allow its rapidly development in the past 20 years, with a major impact in modern life and in the way societies operate in politics, economy, education, entertainment, logistics & travel, and industry.

First and foremost the need for un-tethered telephony and therefore wireless real-time communication has dominated the success of cordless phones, followed by first generation (1G) of cellular communications. Soon, incorporated in the second generation (2G), two-way paging implemented by short message service (SMS) text messaging became the second killer application. With the success of wireless local area network (WLAN) technology (i.e. IEEE 802.11), http internet browsing, and the widespread market adoption of laptop computers internet data connectivity became interesting for anyone, opening up the opportunity for creating a market for the third killer application in third generation (3G), wireless data connectivity. The logical next step has been the shrinkage of the laptop, merging it with the cellular telephone into today's smartphones, and offering high bandwidth access to wireless users with the world's information at their fingertips everywhere and every time. This is the scenario of the current fourth generation (4G), so called LTE-A (Long Term Evolution - Advanced). Hence, smartphones are, undoubtedly, in the focus of service architectures for future mobile access networks. Current market trends and future projections indicate that smartphone sales will keep growing and overtook conventional phones [TIA's 2009/2010/2011/2012 ICT Market Review and Forecast] to constitute now the lion's share of the global phone market: the smartphone has become a mass market device.

The next foreseen killer application is the massive wireless connectivity of machines with other machines, referred to as machine-type-communication (MTC), where machine-to-machine (M2M) or the Internet of Things (IoT) is the more prominent subset. During the past years a multitude of wireless M2M applications has been explored, e.g. information dissemination in public transport systems or in manufacturing plants. However, fast deployment of M2M through a simple 'plug and play' connection via cellular networks is not a reality and the commercial success has been somewhat limited, yet. The availability of cellular coverage needs to be combined with simplicity of handling, in both software and hardware aspects, i.e. avoiding having to setup and connect as in a ZigBee or WLAN hot-spot but at the same time allowing longer battery life time and cheap devices. These principles can stimulate subscribers to buy M2M sensors and participate in the collection of monitoring data. M2M can be employed by communities (social network) to share monitoring information about cars, homes and environment, which could lead to a number of connected devices orders of magnitude higher than today.

1.2 Application challenges

The typical use of a smartphone goes beyond simple voice calls as seen in Figure 1. The variety of services ask for covering a much wider range, i.e., bandwidth-hungry applications such as video streaming, latency-sensitive applications such as networked online gaming, and in particular sporadic machine-type-like

applications due to smartphone apps which are most of the time inactive but regularly access the internet for minor/incremental updates with no human interaction (e.g. weather forecasts, stock prices, navigation position, location-dependent context information etc.).

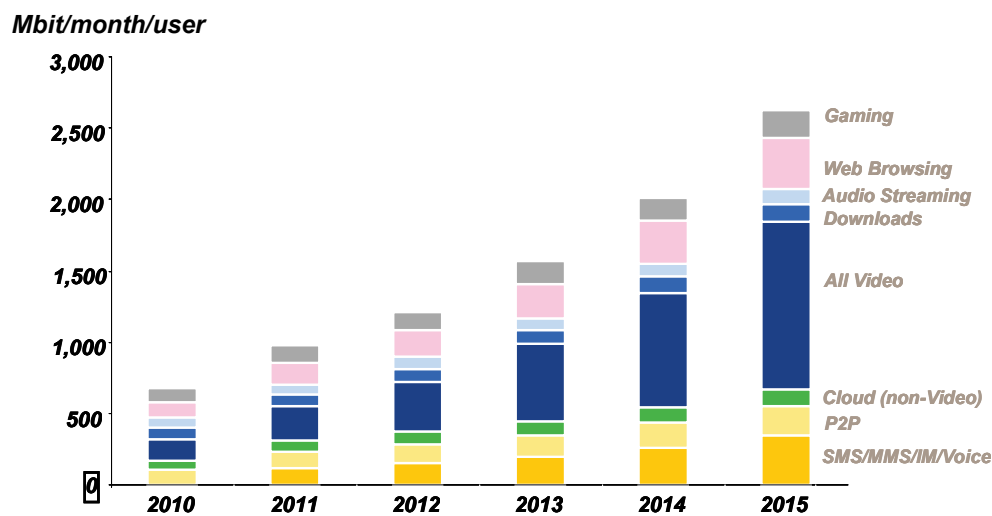


Figure 1: Mixture of traffic types (internal study by ALUD)

Hence, the operators have to be well prepared to take on the challenges of a much higher per-user rate, increasing overall required bandwidth and service differentiation threatening the common value chains on which they rely to compensate for investment costs of future user services [Cis10]. From a technical perspective it seems to be utmost challenging to provide *uniform service experience* to users under the premises of heterogeneous networks.

As can be also seen in Figure 1, more than 50% of the data volume measured in cellular networks is already generated by users consuming streaming applications. As high definition 3D streaming with user enabled vision angle control requires on the order of 100Mb/s, and users expect even higher data rates for the simple transference of such files, it is possible to see *10-100 Gb/s wireless connectivity* coming up as a target in future. Obviously this does not lead to a need for a continuously sustainable very high bandwidth for one user over long periods of time. Instead, data rates of 100 GB/s will be shared via the wireless medium.

Somewhat surprisingly, sporadic access poses another second significant challenge to mobile access networks due to an operation known as *fast dormancy* [Nok11][Hua10]. Fast dormancy is used by handheld manufacturers to save battery power by using the feature that a mobile can break ties to the network individually and as soon as a data piece is delivered the smartphone changes from active into idle state. Consequently, when the mobile has to deliver more pieces of data it will always go through the complete synchronization procedure again. Actually, this can happen several hundred times a day resulting in significant control signalling growth and network congestion threat, see Figure 2. Furthermore, with M2M on the horizon, a multitude of (potentially billions) MTC devices accessing asynchronously the network will dramatically amplify the problem. Such huge number of MTC devices will eventually pose a significant challenge in cellular networks for the envisioned higher density cells with thousands of low cost and energy efficient devices.

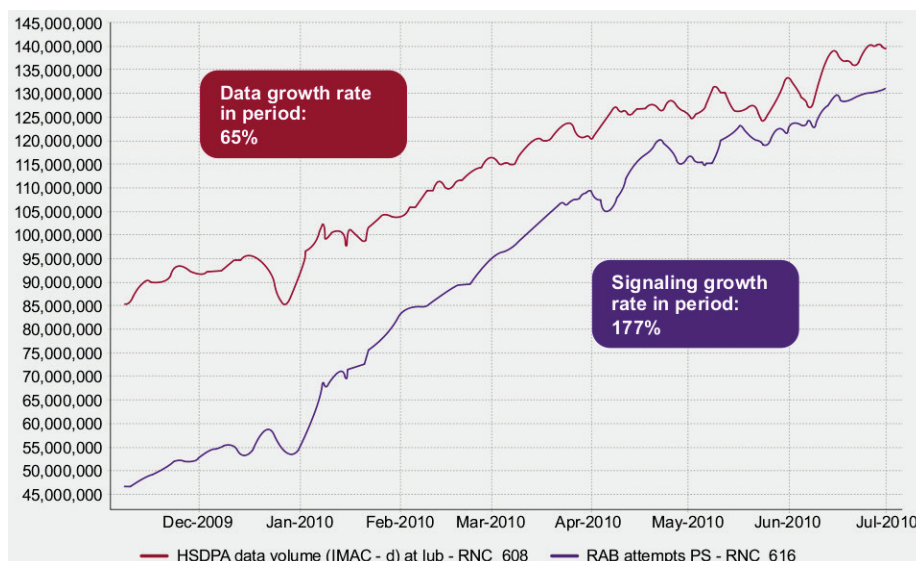


Figure 2: Comparisons of data and signalling traffic [Nok11]

A third challenge for cellular networks is the variable usage of aggregated non-contiguous frequency bands, so-called *carrier aggregation* implemented to achieve much higher rates. Carrier aggregation can imply in the use of separate radio frequency (RF) front ends accessing different channels and can provide higher data rates in the downlink, reinforcing the attraction of isolated frequency bands such as the L-Band. Actually, the search for new spectrum is very active in Europe and in the USA in order to provide mobile broadband expansion. It includes the opportunistic use of spectrum, which has been an interesting research area in wireless communications in the past decade.

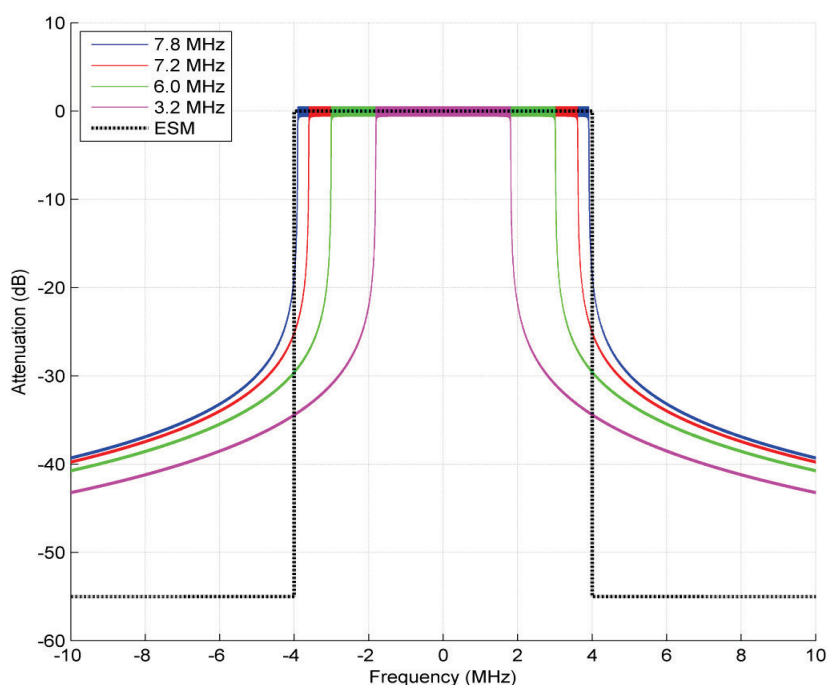


Figure 3: OFDM+CP vs. ESM, original picture [NGB11]

Techniques to assess channel vacancy using cognitive radio could well make new business models possible in the future and the first real implementation will start with the exploration of TV white spaces (TVWS) in USA. Combined with the preparation of the regulatory framework in Europe, TVWS exploration can represent a new niche markets if it overcome, with spectrum agility, the rigorous implementation requirements of low out of band radiation for protection of legacy systems. In [NGB11] this scenario is detailed and Figure 3 exhibits the loss of efficient of traditional orthogonal frequency-division multiplexing (OFDM) with cyclic prefix (CP) to fit in an emission spectrum mask (ESM) due its non-negligible side lobes. The picture helps to see how the partial use of the available spectrum can alleviate the need of additional filtering process, which in the analog case also represents less insertion loss on the output of the transmitter.

1.3 Status and developments of LTE

The most important feature of cellular is to provide coverage, i.e. connectivity no matter where the customer is positioned. Once connectivity is available and a connection has been established, the speed of data communications becomes the next prominent feature to be provided. LTE will be used over the coming years with its new orthogonal frequency-division multiple access (OFDMA) transmission scheme acting as a stepping stone for providing higher data rates in future improvements which will enter the standardization process later. Initially it will have the data rates of the same order that HSPA+ within the same carrier bandwidth (BW). This repeats the case seen at the time of 3G UMTS (universal mobile telecommunications system) introduction, which was also done at data rates compatible with previous second-generation enhancements of 384kb/s EDGE (enhanced data rates for GSM evolution).

LTE Release 8 (R8) and Release 9 (R9) ideally offer data rates of up to 300Mb/s in the downlink and 75Mb/s in the uplink at the physical (PHY) layer without high level signalling. The push for higher data rates in the subsequent standard update R10 is mostly addressed by going from 4 to 8 transmit antennas in the downlink, and from 1 to 4 transmit antennas in the uplink. R10 is thus compliant to the IMT-Advanced requirements and is known as LTE-Advanced (LTE-A). Even higher data rates (over 1 GB/s in downlink, and over 500Mb/s in uplink) will be possibly achieved through carrier aggregation. Inter-cell coordination like ICIC (inter-cell interference coordination, R10) as well as joint processing enabled by CoMP (Coordinated Multipoint) transmission/reception (R11) will further increase spectral efficiency. All such schemes seek for an evolutionary approach within a synchronous/orthogonal physical layer framework. In 10 years, following the progression of wireless throughputs in Figure 4, speeds in the order of 10 GB/s must be able to be addressed.

Specific traffic needs of access devices such as smartphones, multimedia tablets or MTC devices have not been addressed in LTE R10 yet. Moreover, particularly MTC devices are currently viewed as a threat to network stability due to signalling overhead, and thus, restrictions are considered upon bringing in such devices into the network (network overload protection). MTC devices may have other special requirements such as low power operation, low data transmission, bursty and sporadic traffic profiles. Therefore a dedicated study group has been formed within the 3rd Generation Partnership Project (3GPP) to which plans to work out signalling and protocol schemes to include MTC traffic into a future standard update (release candidate R12) which enables creation of multimedia sensor networks at the service level. This contribution could be realized in terms of proposing specific definition of services, requirements, features, options, signalling, and many more. MTC, as a specific type of communication, has its special requirements, such as for example a strong need to minimize the power consumption at the end device. Other example features of MTC to be proposed and evaluated include mobile-only originated calls, low data transmission, low power transmission, low mobility scenarios (e.g. surveillance cameras), periodic data transmission, and

delay tolerant services. Also here, a fundamental issue for working on MTC is to have an adequate and detailed model of the physical (PHY) and medium access (MAC) layers of the system. So far only the basic features and concept of MTC are included [3GP11a] at the level of stage 1 specification. Physical layer techniques, however, as one of the main focus of the 5GNOW project proposal, are not within the scope of such activities. Some MAC amendments may be considered. Both offer a great opportunity to exceed (PHY) or contribute (MAC) to the specifications for R12 and beyond.

Finally, LTE-A is, in one way or another, dealing with some spectrum agility as a requisite to allow worldwide interoperability of devices in a fragmented spectrum, fuelled by ongoing spectrum auctions, license renewals and re-farming initiatives across a wide range of frequency band [3GP09]. LTE is already implemented in many frequency bands: 700 MHz and AWS (Advanced Wireless Spectrum) bands in the USA, 800, 1800 and 2600 MHz in Europe, 2.1 GHz and 2.6 GHz in Asia. It is expected that the 2.6 GHz, 1800 MHz and 800 MHz bands to be the most widely used in Western Europe for 4G deployments. As a conclusion, the lack of spectrum harmonization is forcing vendors to find contour solutions to deliver, as far as possible, globally compatible LTE chipsets and devices (and OFDM spectrum property is not helping much to alleviate the analog signal processing challenges in the front-end).

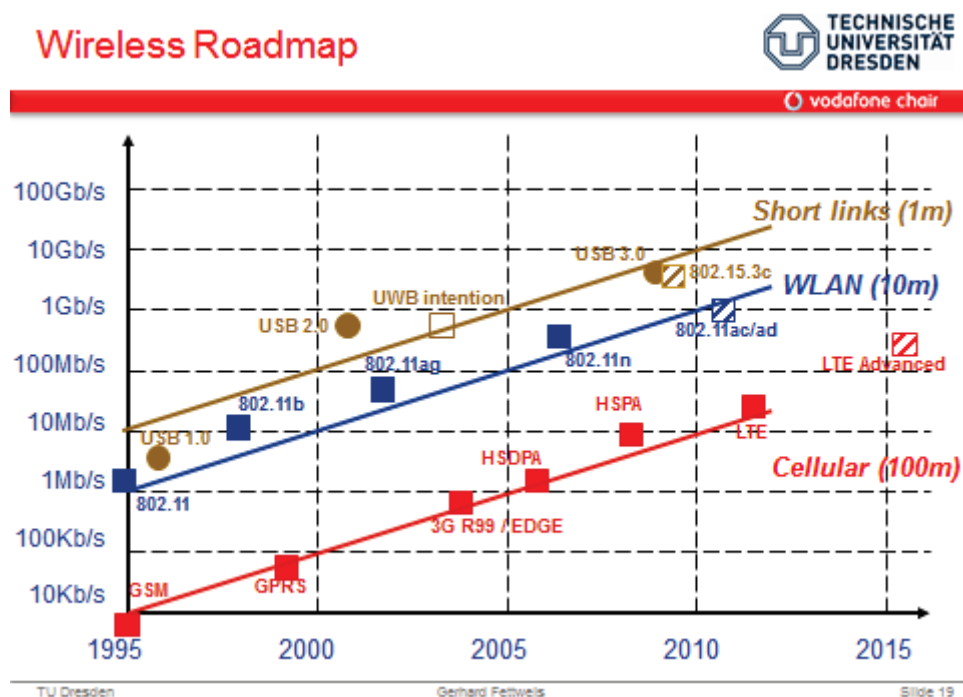


Figure 4: Wireless roadmap

1.4 5GNOW approach

5GNOW identifies and questions orthogonality and synchronism as common design principles of the underlying system architecture. For example, MTC traffic generating devices (including smartphones) should not be forced to be integrated into the bulky synchronization procedure which has been deliberately designed to meet orthogonal constraints. Instead, they optimally should be able to awake only occasionally and transmit their message right away only coarsely synchronized. By doing so MTC traffic would be removed from standard uplink data pipes with drastically reduced signalling overhead. Therefore,

alleviating the synchronism requirements can significantly improve operational capabilities and network performance as well as user experience and life time of smartphones and autonomous MTC nodes. 5GNOW will follow up on this idea and develop non-orthogonal waveforms for asynchronous signalling in the uplink (and specifically random access channel (RACH)) to enable such efficient MTC traffic.

MTC traffic and the corresponding network congestion problems are primarily concerned with synchronism and orthogonality constraints on the LTE-A PHY layer uplink channels. However, LTE-A downlink is also involved when Coordinated Multipoint transmission [3GP11] is considered. CoMP is driven by the appealing idea to exploit the superior single-cell performance of the underlying synchronous orthogonal air interfaces enabling both uniform coverage and high capacity. However, such an approach entails huge additional overhead in terms of message sharing, base station synchronization, feedback of channel state information, forwarding of control information etc. On top, the approach is known to lack robustness against the actual extent to what the delivered information reflects the current network state - in fact, it turns out that the achieved gains by CoMP transmission are still far away from the theoretical limits while even constraining the potential services in the network due to extensive uplink capacity use for control signalling [Wil11]. In addition, in a heterogeneous networking scenario (HetNet) with uncoordinated pico or femto cells and highly overlapping coverage, as in today's networks, it seems illusive to provide the required information to all network entities. Evidently, if the degree of coordination to maintain synchronism and orthogonality across layers (PHY, MAC/networking) is not attainable the LTE-A PHY layer should not be forced into such strict requirements, calling for 5GNOW non-orthogonal waveforms for asynchronous signalling and also improved robustness in the downlink.

Finally, interference within the network is overlaid by certainly likewise inherently uncoordinated interference from other legacy networks due to carrier aggregation. Current systems impose generous guard bands to satisfy spectral mask requirements which either severely deteriorate spectral efficiency or even prevent band usage at all, which is again an artefact of strict orthogonality and synchronism constraints within the PHY layer. 5GNOW will address carrier aggregation by implementing sharp frequency notches in order not to interfere with other legacy systems and tight spectral masks.

Summarizing, the main hypothesis of this explorative research proposal is that, specifically, the underlying design principles –synchronism and orthogonality– of the PHY layer of today's mobile radio systems constitute a major obstacle for the envisioned service architecture, so there is a clear motivation for an innovative and in part disruptive re-design of the PHY layer from scratch.

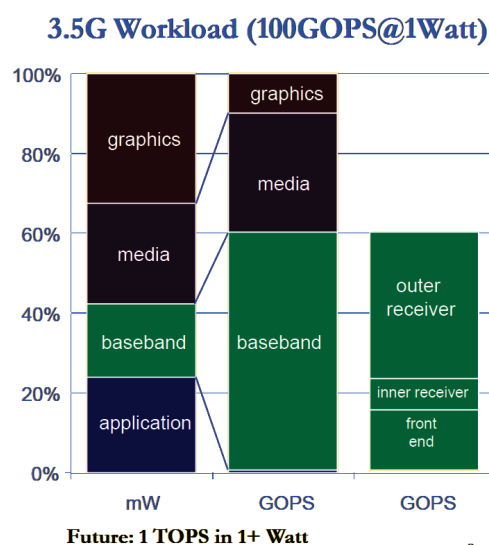


Figure 5: Workload of current mobiles (outer receiver consists of channel decoder and de-interleaver)

To enable the 5GNOW approach the basic concept of this proposal is to dismiss the widely unquestioned credo of strict synchronism and orthogonality in the network and, instead, to introduce a broader non-orthogonal robustness concept incorporating the overall required control signalling effort and the applied waveforms in a joint framework. At the core of this paradigm is the introduction of new non-orthogonal waveforms that carry the data on the physical layer. The idea is to abandon synchronism and orthogonality altogether, thereby admitting some crosstalk or interference, and to control these impairments by a suitable transceiver structure and transmission technique. The technological challenges are manifold and require advanced and, most likely, more complex transceiver designs. Due to the evolving silicon processing capabilities, according to Moore's law, today's receiver complexity is about one order of magnitude less constrained than it was several years ago, when LTE Release 8 was being designed. Current LTE baseband signal processing, according to Figure 5, consumes less than 20% of the overall mobile phone power budget, with the 'inner receiver', consisting of signal detection and parameter estimation, consuming less than 10% of the overall baseband operations. With a boost from Moore's law, it is self-evident that 5G smartphones will have plenty of headroom for inner receiver complexity increases, compared to 3.5G, as needed for processing non-orthogonal, asynchronous signals.

5GNOW investigates the inherent trade-offs between possible relaxation in orthogonality and synchronism and their corresponding impact on performance and network operation/user experience versus the required signal processing capabilities. The research proposal will make use of the natural emerging technological possibilities suitable for 5G communication. All partners will use their previous experience from former projects (e.g. EU FP7 PHYDYAS) to address the non-orthogonal, asynchronous approach within the trinity of the corner scenarios MTC, CoMP/HetNet, carrier aggregation.

It is important to note that the 5GNOW approach stands in clear contrast to (potentially competing) approaches where the challenges are met by applying higher bandwidths and/or increasing the number of antennas. In such approaches the network cost of establishing and maintaining orthogonality and synchronism is mostly overlooked devouring much of the promised gains. A more comprehensive system view is necessary, though, to enable more scalable network architectures.

2 Key Communication Scenarios

The key scenarios MTC, CoMP and fragmented spectrum are summarized in Figure 6. In the following a collection of research problems, major shortcomings in LTE-A, and requirements on PHY/MAC will be addressed in each scenario.

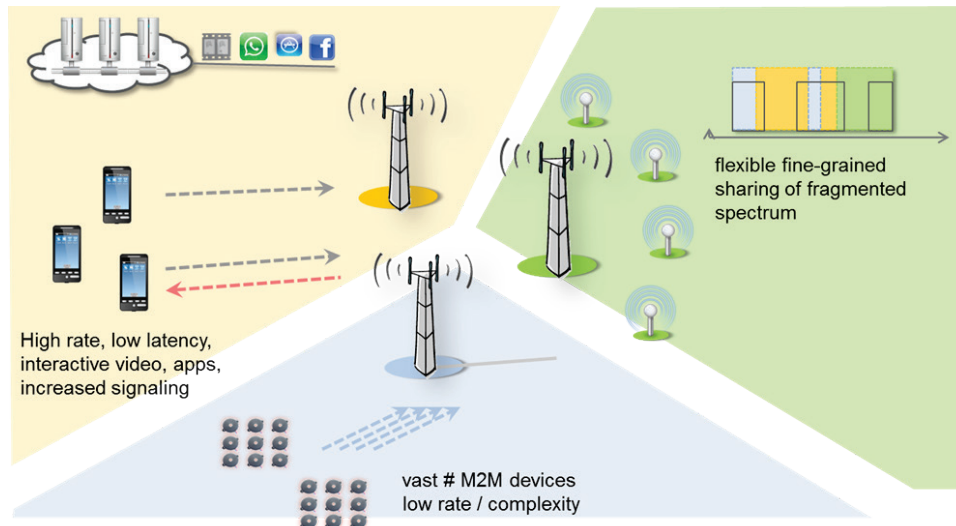


Figure 6: Application challenges for 5G

2.1 MTC

Current cellular networks of the 2nd to 4th generation are optimized for H2H (Human-to-Human) interaction. Current M2M solutions are based on a variety of (proprietary) adaptations built on the pre-defined functionality of these networks, with limited scalability. Most of these solutions use the short message service (SMS) of the widely-deployed Global System for Mobile Communications (GSM) standard (2nd generation) and standardization activities have been started to integrate M2M functionality into the existing networks by adding functionality to higher OSI layers while keeping the functionality of the lower layers (in particular of the PHY, for the benefit of downward compatibility of existing devices and base station hardware). 3GPP has started to investigate how an increasing number of cellular M2M devices can be supported in the existing cellular standards [Jun11] and the studies for the enhancement of the LTE to support both M2M and high-speed H2H applications is being carried out in the project EXALTED (Expanding LTE for Devices) [<http://www.ict-exalted.eu/>]. One interesting insight considered is to reduce the M2M device complexity by moving major parts of the signal processing from the M2M devices to the base station (as far as this is possible within LTE). The 5GNOW project aims to catch upon the idea above but take a step forward by defining new physical layer concepts, based on non-orthogonal modulation, that will further reduce the M2M device complexity in terms of synchronism and improve the spectral efficiency through better frequency localization.

The motivation for a new non-orthogonal PHY concept is that the reuse of existing cellular standards to serve an increasing number of cellular M2M devices will eventually waste radio resources. The reason is that all of the existing standards require full synchronization between the terminals and base stations. This requirement will dramatically increase the signalling overhead when huge amount of M2M devices are

connected to the network, each transmitting only a very small amount of uplink data once in a while. This issue will limit the number of M2M devices that can be supported without deteriorating the quality of service of the H2H applications. The specifics of MTC are already addressed by 3GPP by definition of features of stage 1 documents. However the details are not yet present, here the input from 5GNOW could be useful.

Another issue that is closely related to the signalling overhead is the complexity and power consumption of the M2M devices. The more signalling the cellular standard requires the more complex and power-hungry will be the devices. Considering state-of-the-art device technologies, a power reduction of at least two orders of magnitude is still required [FDM+11]. The design of new physical layer techniques can facilitate the required reduction device complexity and power consumption and support heterogeneous connectivity, with various degrees of M2M device mobility and different data rate / bandwidth requirements in an optimal way. Some concepts related to these interests will be presented below and can be used to further development of flexible ideas.

2.1.1 Burst communication and sparse signal processing

The application of sparse signal processing methodology for detection and demodulation of MTC traffic in PHY layer RACH (Random Access Channel) benefits from the bursty nature of signals which are in a mathematical sense “sparse”, i.e. they can be described by a small set of parameters within a much larger set of observables. Similar for the mobile channel, a typical realization of a doubly dispersive channel is described only by a limited number time-frequency shifts. It is then a fundamental question of how many observables the base station needs for recovering the MTC message in a robust manner. Recent results in Compressed Sensing show that this number is far below the Nyquist rate exploited by suitably reduced measurements in the digital domain [SJW11, THE+10]. An analogue signal perspective has been established under the name “Xampling” see for example [ME11]. Moreover, recent results in signal processing for single-user signals suggest that, beyond conventional thinking in Compressed Sensing, joint “sparsity” of the message and the channel is additive rather than multiplicative [HB11]. Generalizations to the multiuser case are an open problem to be targeted in this project.

2.1.2 M2M: Sensing, monitoring, collecting

When addressing the need for M2M sensing it must be translated into technical requirements specification which serves as a design goal. As the M2M sensing requirements differ widely from one application scenario to another, a specification must be found which serves the needs of a dominating majority. An example solution would be a device which could be activated, runs for e.g. 10 years on an AAA battery, and transmits e.g. 25 Bytes of information in a duty cycle of every 100 seconds. This duty cycle could be an average, as it is moderated according to the instantaneous need. However, the question which needs to be answered is whether the power budget is reasonable.

Taking the communication need of 25B/100s, the resulting average data rate equals 2b/s. Assuming a 2MHz channel with a net capacity of 0.1bit/s/Hz (roughly GSM, and 5% of LTE) this results in an average of 100K M2M devices per cell. If every device would be billed by the operator with \$1/year this would result in \$100k/cell addressable revenue. Assuming 16-QAM (quadrature amplitude modulation) modulation with net 2bit/symbol (after error correction coding) this results in 4Mb/s within the 2MHz channel. Each 25B (200bit) packet would then have a duration of 0.5ms, adding preambles and ramp-up/down of the transceiver roughly 1ms duration per packet can be assumed. Assuming 25B for uplink as well as for downlink packets, this results in 2ms transceiver uptime per duty cycle, or $2 \cdot 10^{-6}$.

Assuming a AAA battery with 1000mAh @1V, and 10 years of M2M battery life operations, this roughly leads to 10 μ W average power available. Dividing this average by 2*10⁻⁶ results in a power budget of 5W during transmit and receive, allowing for 1W transmit power. Even when taking a standby power of 1 μ W into consideration, the numbers only change marginally.

All the calculations above clearly further improve when taking energy scavenging into consideration. Therefore, the good news is that this kind of M2M Things 2.0 vision is technically possible. However, not with current cellular systems, as their protocols require too much communications overhead for synchronization and channel allocation that 10 years of operations off a AAA battery is far more than one order of magnitude away, an issue that could be addressed in the new 5G standard.

2.1.3 Driving technology by human needs: Real-Time

The Wireless Roadmap clearly shows how technology continues to drive data rates. However, other forms of human interaction besides internet browsing and multimedia distribution can be analyzed to understand basic needs which will be serviced by drastically new innovations over the next decades. For this, real-time experience can be analyzed in more detail. Obviously, real-time is experienced whenever the communication response time is fast enough when compared with the time constants of the application system environment.

Humans have the ability to react to sudden changes of situations with their muscles, e.g. by hitting the breaks in a car due to an unforeseen incident, or by touching a hot platter on a stove. The sensing to muscular reaction time typically is in the range of 0.5-1 seconds. This clearly sets boundaries also for technology specification in comparable situations. An example is web browsing. The page buildup after clicking on a link could be in the same order of time. Henceforth real-time browsing interaction is experienced, if new web pages can be built-up after clicking on a link within 0.5 seconds. A shorter latency, i.e. a faster reaction time of the web is not necessary for creating a real-time experience. This reaction time has been serviced by initial 802.11b and 3G cellular systems.

The next shorter real-time latency constant is experienced when analyzing the hearing system. As humans it is known that real-time interaction is experienced in conversations, if the corresponding party receives the audio signal within 70-100ms. This means when standing more than 30m (100ft) apart, due to the speed of sound real-time discussions cannot be carried out. Since the speed of light is 1 million times faster, many applications have been designed which adhere to this restriction. E.g. for engineering system specifications the impact has been that speech delays on telephone lines have to be in that order of magnitude. Also, lip synchronization between the video stream and the sound track needs to be within the same time lag, otherwise the sound seems disconnected to the moving image. The 4th generation cellular standard LTE meets this requirement, as well as modern 3rd generation systems, making internet video conferencing (e.g. Skype) viable over cellular. The eyes, the visual sensing system of human beings, have a resolution slower than 100Hz, which is why modern TV sets have a picture refresh rate in the order of 100Hz. This allows for seamless video experience, translating into 10ms latency requirement.

The toughest real-time latency is given by the tactile sensing of human bodies. It has been noted that humans can distinguish latencies of the order of 1ms accuracy. Examples are the resolution of tactile sensing when moving fingers back and forth over a table with a scratch. By high sensing resolution humans can experience the scratch in the same position. Also, tactile-visual control is in the same order of magnitude, e.g. when moving an object on a touch screen. Humans move hands with e.g. 1m/s, i.e. when 1ms latency can be achieved the image follows the finger with approximately 1mm displacement. A latency of 100ms would create a 100mm (4") displacement. A similar experience can be made by moving a mouse and tracking the cursor on the display. Since humans see a differential signal over a static background, a

screen update resolution finer than 10ms is necessary. More extreme situations where the 1ms latency requirement can be experienced are when moving a 3D object with a joy stick, or in a virtual reality environment. A real-time cyber physical experience can only be given if the electronic system adheres to this extreme latency time constraint. This is far shorter than current wireless cellular systems allow for, missing the target by nearly two order of magnitude.

Summarizing, each and every element of the communications and control chain must be optimized for latency. Clearly, as the time budget on the physical layer is 100 μ s maximum, LTE with OFDM symbol duration of 70 μ s is not going to be the solution.

2.2 Fragmented spectrum

Although OFDMA-access schemes have been considered for Filter Bank Multi-Carrier (FBMC) [MTR+11], fragmented spectrum has yet not been considered. Fragmented spectrum may be viewed as the consequence of relaxed extension of channel aggregation for mobile communications. A user may access more than one frequency band being contiguous or not in frequency at any given time. In the asynchronous context of 5GNOW, where multiple users may not necessary be synchronized in time, this could lead to the generation of a heavily fragmented spectrum both in time and frequency. An example of the resulting spectrum in time and frequency is depicted in Figure 7. This phenomenon should be further exacerbated by machine-to-machine communications as shorter message size may lead to further fragmentation.

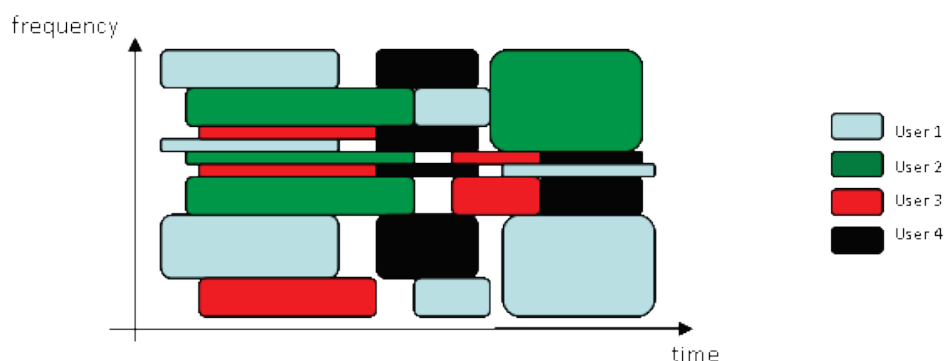


Figure 7: Example of fragmented spectrum in an asynchronous network

Scenarios of fragmentation, where a single user is allocated a pool of frequencies with a relaxed synchronization in time should be addressed. This scenario should have strong implications for the receiver architecture of the base stations (BS) as the different users may not be synchronized. A specific synchronization per user should be explored while containing the complexity of the overall receiver in order to avoid unrealistic implementation proposals. The study could take as a starting point the channelization proposed by current LTE standards, while adapting it to the MTC scenarios. The impact of channel bonding schemes (carrier aggregation vs. spectrum pooling) must be studied at different levels including PAPR (peak-to-average power ratio) requirements, emitted spectrum adjacent channel leakage and requirements on finite precision dynamic and digital-to-analog conversion. Therefore, the added value of the hardware implementation is to provide realistic limits of what can be expected from a fragmented scheme.

The possibility of any single user to access multiple frequency pools of a fragmented spectrum is expected to serve more users and/or provide higher data rates. The concept of frequency pooling first described in [WJ04], seem to be particularly efficient for frequency localized and non-orthogonal waveforms such as FBMC [NGB11]. However, very little investigations have been put so far on the effect the concept will have (for instance on synchronization or equalization) on the algorithms of the receiver but also on the related implementation issues. For instance, currently proposed synchronization algorithms such as proposed by [FPT09], would not perform well in the context of fragmented spectrum. Therefore new innovative algorithms and implementations will be proposed and quantified. These will then be extended to the fragmented asynchronous multi-user environment. [MTR+11] only considered the impact of asynchronous OFDMA schemes on the integrity of the transmitted signal. However new areas may be investigated in order to simultaneously receive asynchronous fragmented multi-user FBMC signals.

2.3 CoMP/HetNet

Cooperation among base stations allows exploiting the available spatial degrees of freedom more efficiently leading to an increased system capacity in future cellular wireless communication networks [FKV06], see [MF11] for an overview. An inherent requirement for the communication between a BS and an user equipment (UE) is the time and frequency synchronization in order to avoid inter-carrier interference (ICI) as well as inter-symbol interference (ISI). In state-of-the-art OFDM systems it must be ensured that the discrete Fourier transform (DFT) window at the receiver is always aligned to the cyclic prefix (CP) which serves as guard interval to avoid ISI between consecutive OFDM symbols, but also to avoid ICI. An unaligned carrier frequency will cause ICI as well.

OFDM time and frequency synchronization for point-to-point links is a well investigated research area (see e.g. [MKP07]). However, the transition to multi-point to multi-point transmission systems is not straight forward due to the physical limitation of the wave propagation speed which is usually equal to the speed of light (see e.g. [ZMM+08]). If, for instance, two BSs jointly transmit signals to one UE the UE could only place the receiver DFT window w.r.t. to the timing reference of one BS. A time difference of arrival (TDOA) between the two transmits signals, caused by the different distances between the BSs and the UE, will inevitably cause ISI and ICI if it is larger than the CP duration. A detailed ISI and ICI analysis for cooperating base station systems is presented in [KF10]. Consequently, the CP must either be chosen sufficiently long in order to cover all possible TDOAs in the network or advanced signal processing techniques for ISI and ICI cancellation must be applied at the receiver, in addition to multi-user reception. However, a long CP, containing only redundant information, leads to a reduced spectral efficiency. Therefore, minimizing the CP length is major system design goal. A similar problem arises if the BSs are not fully frequency synchronous. The main difference compared to the TDOAs is that the frequency offsets are not distance dependent and are constant everywhere within the network. Furthermore, the TDOAs could also occur if the BS network itself is not synchronous so that the transmit timing is not aligned.

Another major problem addressed in 5GNOW is the limited feedback problem and corresponding imperfect channel state information for CoMP/HetNet scenarios. The limited feedback problem has been a very active research area e.g. in multi-user MIMO (multiple input multiple output) communications [LHL+08, CJK+10]. However, research on the limited feedback problem in more general scenarios such as CoMP or coordinated beam-forming for e.g. interference alignment is still at a very early stage. A summary paper of transmission techniques in multi-cell MIMO cooperative networks is given in [GHH+10]. The impact of limited feedback on CoMP is described e.g. in a very recent paper by [Ker11]. Interference alignment for cellular systems was first considered in [ST08], where a scheme called subspace interference alignment was introduced for a limited system setting. Interference alignment with user selection in general cellular

networks was considered in [SW11, SW12a/b]. While these transmission schemes are widely developed, limited feedback is an open problem for cellular systems [LSC10].

2.3.1 Time and frequency synchronism

A possible solution to achieve time and frequency synchronism among all base stations is to use global positioning system (GPS) receivers [JWS+08]. Stringent synchronization requirements in OFDM systems, however, require expensive oscillators. The IEEE 1588 precision time protocol could be used as an alternative to GPS based synchronization. It entails lower synchronization accuracy but is more flexible. If the base station network serves as time and frequency reference, the terminals must align their timing and oscillators in the downlink. This is typically achieved using dedicated training signals for estimating the time and frequency offset parameters. In the uplink the expected time and frequency mismatch is pre-compensated at the UE so that is ensured that the signal at the base station receive antenna is aligned. An overview about current state of the art synchronization algorithms is e.g. given in [MKP07].

The approach described above is not capable of solving the TDOA problem because UE timing synchronization is only possible to one BS which is usually the serving one with the highest receive power level. Regarding other cooperating BSs at least the time and frequency mismatch can be estimated. These estimates can be used to re-modulate the asynchronous interference at the receiver, followed by interference suppression or cancellation. An overview about techniques of asynchronous interference cancellation and suppression is e.g. given in [KRF12]. Using these techniques it is possible to mitigate the impact of asynchronism, at the cost of a high receiver complexity.

2.3.2 Imperfect channel state information

In contrast to OFDM systems, the FBMC waveform should be less sensitive to timing errors between the different cells, due to better frequency localization of the prototype filter [MTR+11]. This feature will be used to investigate the feasibility of downlink (DL) CoMP in a multi cell scenario (DL multi cell MIMO in 3GPP/LTE terminology [3GP10]) including FBMC waveform at the physical layer. For instance, non-coherent joint transmission where each base station computes the local precoders based on UE feedbacks will be studied. If perfect channel state/quality information (CSI, CQI) is assumed, FBMC presents higher energy efficiency with respect to OFDM since it does not require a cyclic prefix. However, in the imperfect CSI/CQI case, the opposite may occur since it may imply ISI and ICI for FBMC systems [PPN10]. Thus, the accuracy of CSI feedback and the impact on performance of refresh rate of CQI feedback on the precoding techniques will be also taken into account. Therefore new multi-cell operation scheme will be carefully designed to support asynchronism and a reduced level of control information (backhaul and CSI feedback).

With respect to robustness framework there have been very recent approaches to deal with the limitations of the feedback link [JCC+10, SP10, WS10, WS12]. Particularly, in [WS10, WS12] a new direction is developed which bears some great potential for the envisioned robustness framework. The main idea in this work is to use the structure of the transmit signals (in this case the spatial transmit codebook) and to incorporate as much information as possible in the design of the control channels. The collection of all information is the key to tailor the metrics used in the network to generate control messages as close as possible to the underlying performance indicators (rather than close to e.g. the mobile channel coefficients). This approach has been proven to drastically increase the rates [WS12] in a non-cooperative multi-cell network. It is of interest a generalization of this framework to CoMP or coordinated beam-forming schemes such as interference alignment using non-standard (and robust) alignment conditions. In this generalization other MAC-related “asynchronisms” (e.g. outdated CSI) shall be collected and incorporated as well.

3 5GNOW Objectives, Benchmark System and KPI's description

The 5GNOW approach stands in clear contrast to (potentially competing) approaches where the challenges are met by applying higher bandwidths and/or increasing the number of antennas. In such approaches the network cost of establishing and maintaining orthogonality and synchronism is mostly overlooked devouring much of the promised gains. At the core of this proposal is the investigation of ways to alleviate the synchronism requirements of existing systems and support all the service requirements for future mobile access networks. These approaches will be listed in the following research topics, reference scenarios and a summarizing table of KPI (Key performance Indicator) will conclude this section.

3.1 5GNOW objectives from the description of work

The conceptual paradigm shift from synchronous and orthogonal to asynchronous and non-orthogonal systems with increased robustness pose a number of research challenges. The design of a new PHY layer for 5G systems using non-orthogonal waveforms will be addressed through the following main research areas and their corresponding technical objectives:

- 1) Design of non-orthogonal PHY layer RACH channel to enable asynchronous MTC traffic by using state-of-the-art sparse MIMO signal processing methodology at the base station. The integration of MTC communication into the network can be highly simplified making the system more capable to serve uncoordinated sporadic access of many nodes and to handle unforeseen events when many nodes abruptly access the network concurrently, e.g. in case of emergency situations. This will be measurable by a reduced congestion probability within the heterogeneous scenarios and other appropriate measures to be developed, e.g. such as life time of MTC nodes, infrastructure costs etc.
- 2) Provision of CoMP/HetNet with relaxed time/frequency synchronization requirements and imperfect channel state information. The objective is measured in terms of reduced signalling effort and backhaul traffic while maintaining some benchmark performance as well as scalability of the whole system in terms of e.g. rate, waveform properties (e.g. peak-to-average power ratio), out-of-band radiation, ability to seamlessly accommodate many sporadic, low rate users and high rate users; the objective also entails the definition of indicators measuring the allowable degree of asynchronism by non-orthogonal system design and extraction and abstraction of physical layer parameters to be used by upper layers for system operation.
- 3) Provision of carrier aggregation/fragmented spectrum transmission techniques with relaxed (or completely omitted) synchronization requirements. The objective will be measured in terms of increased bandwidth efficiency in white spaces.
- 4) Scenario-dependent (channel profile etc.) waveform adaption along key scenarios described before for seamless system operation. The objective is measured in terms of relative gains to a static setup.
- 5) Adaption of the MAC layer to enable efficient and scalable multi-cell operation within heterogeneous environment. This specifically implies a re-design of (selected) MAC/networking key functionalities for the underlying new PHY layer targeting MAC-related impairments.

The developed non-orthogonal PHY layer waveforms and their specific structure will be incorporated into the design of the control signalling on MAC layer leading to different designs for different waveforms. Such approach (see e.g. [WS12] incorporating spatial transmit codebooks) differs significantly from state-of-the-art methodology where typically the transmitted signals have no impact on the design of the control channel. The objective is measured in terms of reduced control signalling and appropriate metrics for the system's sensitivity to mobility, capacity limitations etc.

Provision of non-orthogonal scheduling framework measurable in terms of scheduler performance gains along sum throughput and standard fairness metrics.

- 6) Provision of a proof-of-concept for the non-orthogonal physical layer techniques/algorithms by means of a hardware demonstrator and over-the-air transmission experiments. The feasibility and potential benefits of selected 5G core concepts shall be demonstrated using a hardware platform.

3.2 LTE-A benchmark system

LTE-A enhances previous releases of LTE in order to fulfil 3GPP requirements of the fourth generation systems. The focus of LTE-A is to increase throughput in order to reach higher peak data rates up to 3Gbps in DL and 1.5Gbps in UL. Such improvement is made possible by increased spectral efficiency up to 30 bps/Hz and aggregating active carriers which allow transmitting data in 100 MHz bandwidth.

LTE-A is used in 5GNOW project as a benchmark. Obtained results are compared to the performance of a 3GPP LTE-A system. The project focus is to improve characteristics of current system in six main areas which are gathered in Table 6, namely:

- Signalling overhead (downlink),
- Signalling overhead (uplink),
- Capacity (downlink),
- MTC signalling overhead (uplink¹),
- Out-of-band radiation,
- Local oscillator accuracy requirement.

Detailed description of KPIs can be found in following section. Table 6 contains description of the performance of current system used as a benchmark (LTE-A) and expected improvement in relation to this benchmark.

3.3 Key performance indicators

The performance of the approaches will be compared to a standard LTE-A air interface using the indicators summarized in the KPI table below.

¹ In physical layer random access channel (PRACH)

Table 1: Measurability of objectives: performance Indicators and corresponding figures

Measurable quantity related to the objectives	Description of the baseline performance	Improvement In [%] or by [factor]	Comments on the used reasoning and methodology
(K1) Signalling overhead (downlink)	The percentage of physical layer control signalling overhead equals to 32% for representative system settings (BW=20 MHz, 3 OFDM symbols per Control Region, normal CP, 2 e-NodeB (eNB) antennas). This means that only 68% of the theoretical physical layer capacity can be used to carry PDSCH data.	50%	The area for improvement with non-synchronized signalling is in removing the control region (i.e. PDCCH), which would shift control signalling overhead from 32% to a minimum of around 10–12% (however a complete removal of the region might not be possible). For a CoMP/HetNet system the same figures is taken as a reference compared to state of the art (SOTA) system.
(K2) Signalling overhead (uplink)	For the uplink analogical percentage of physical layer control signalling overhead equals to 17% for representative system settings (BW=20 MHz, normal CP, 1 PRACH per frame). This means that 83% of the theoretical physical layer capacity can be used to carry PUSCH data.	25%	The area for improvement with non-synchronized signalling is in removing the PUCCH, which would shift control signalling overhead from 17% to around 15%. However the largest overhead in uplink stems from the DRS, thus the more optimistic figure results from improvements in the channel estimation procedure. For a CoMP/HetNet system the same figures is taken as a reference compared to SOTA system.

(K3) Capacity (Downlink)	<table><tr><th>System</th><th>Average throughput</th><th>Cell edge throughput</th></tr><tr><td>LTE-A (Rel. 10) 8x8, reuse 1</td><td>27.0 Mbit/s</td><td>9.6 Mbit/s</td></tr><tr><td>LTE-A (Rel. 10) 8x8, reuse 3</td><td>12.5 Mbit/s</td><td>3.8 Mbit/s</td></tr></table>	System	Average throughput	Cell edge throughput	LTE-A (Rel. 10) 8x8, reuse 1	27.0 Mbit/s	9.6 Mbit/s	LTE-A (Rel. 10) 8x8, reuse 3	12.5 Mbit/s	3.8 Mbit/s	100% relative to the same signalling overhead defined before	Reference numbers are taken from ISW (Partner 3) system simulations. The target is to make cell edge throughput close to the current average throughput, i.e. more than 100% improvement. This is motivated by the use of CoMP, which considered as macro diversity feature solves the problem of poor SNIR at the cell edge
	System	Average throughput	Cell edge throughput									
	LTE-A (Rel. 10) 8x8, reuse 1	27.0 Mbit/s	9.6 Mbit/s									
	LTE-A (Rel. 10) 8x8, reuse 3	12.5 Mbit/s	3.8 Mbit/s									
	<u>Assumptions:</u> <ul style="list-style-type: none">- Urban area scenario with 20Mhz bandwidth @2GHz (Ref. is: 3GPP TS 36.942)- Throughput is calculated for 1 UE (UE gets all resources)- For reuse 3 each sector is assigned 1/3 of 20MHz (6.67MHz); 100% of assigned spectrum utilization- No interference coordination, no channel-aware scheduler- MIMO increases throughput only near eNB (peak throughput increase)- Cell edge throughput is calculated for 5% of the area with worst SNIR- Signalling resources not excluded, throughput estimated at PHY (after FEC)											
(K4) MTC RACH signalling overhead	Sporadic uplink message of typical MTC devices are expected to contain around 100 information bits. Using a robust modulation-and-coding scheme, e.g., QPSK with code rate 1/2, 100 resource elements (REs), e.g. subcarriers of one OFDM symbol, would be required to transmit one MTC uplink message. In LTE, the control signalling spent for an uplink message that occupies 100 REs easily adds up to more than 2000 additional REs.		200% for the transmission of MTC uplink messages	This tremendous overhead can be significantly reduced through non-synchronized signalling. That is, by avoiding random access procedures, channel sounding and uplink control signalling for MTC devices, e.g., through pre-scheduled MTC uplink transmission, the signalling overhead can be drastically decreased, such that the total signalling overhead might be reduced to at most 100 REs for an MTC uplink message of 100 REs. This reduces the uplink overhead to 5% as compared to synchronized signalling in LTE. Thus, with a dedicated PHY design that supports non-synchronized uplink signalling, it appears feasible to improve the energy-efficiency of MTC uplink data transmission by a factor of 20 (the reduction is then a compromise between such ideal situation and optimized MTC over RACH/PUSCH). This can significantly improve the lifetime of battery-driven MTC devices in cellular networks. That is, a lifetime of 1-10 years may become feasible with a typical battery used in MTC devices (2.4Ah, 3.6V)								
(K5) Out-of-band radiation	OFDM		Factor 100	Using GFDM and specific pulse designs								
(K6) Local oscillator	Required terminal LO accuracy in LTE-A: 0.1 ppm		Factor 10 (reduction of	Self-Interference has to be accounted for within receiver algorithms anyway. The relaxation of factor 10 will								

5G NOW	D2.2
---------------	-------------

accuracy		the required terminal LO accuracy)	approximately cause the same interference as it is inherent in GFDM
----------	--	------------------------------------	---

4 5GNOW Architecture Core Elements

4.1 Waveforms

4.1.1 Gabor signalling

The ability to explore time and frequency dimensions is one core element of a flexible waveform. To better understand how these domains can be engineered, consider a signal s . Its time-domain representation $s(t)$ provides exact information about the behaviour at any time instant. However, no information about frequency components at these positions is available. Instead, we can look at the Fourier transform (FT) of the signal, which provides exact information about frequency components, but no information on time-domain behaviour is obtained. It is possible to gather information about frequency components of a signal at certain positions in time by looking at the FT of the multiplication of the signal with a window function, which leads to the short-time Fourier transform (STFT). But the output of the STFT can be highly redundant if the time and frequency parameters are kept independent.

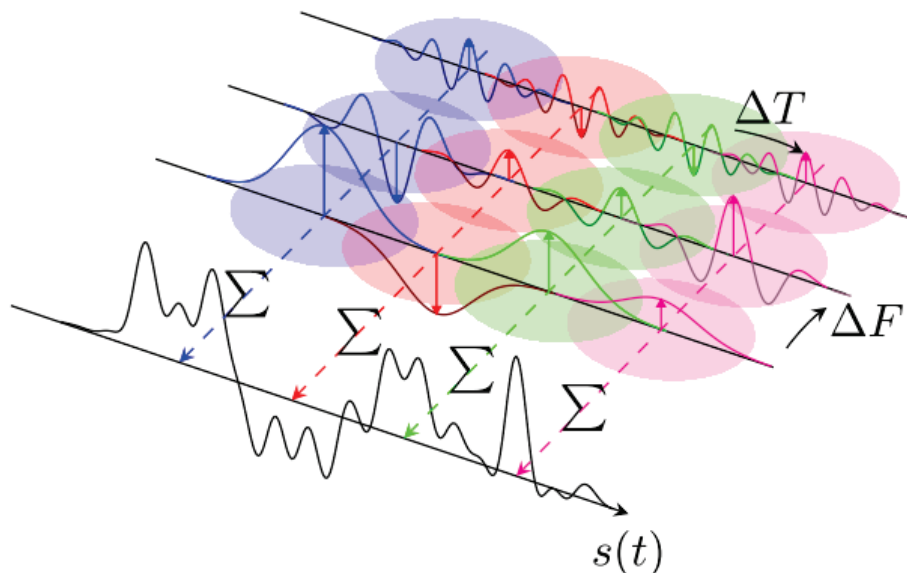


Figure 8: Illustration of Gabor expansion. The expanded signal is the sum of scaled time-frequency shifts of a prototype window. The scaling factors are given by the Gabor expansion coefficients

In 1947, Dennis Gabor proposed to represent a signal as a linear combination of Gaussian functions that are shifted in time and frequency to positions in a regular grid, see Figure 8. He chose the Gaussian function because it has the best localization in time and frequency simultaneously, so that local behaviour of the signal is most accurately described. Gabor concluded that the original signal is fully characterized by the coefficients multiplying the Gaussian functions, establishing the foundation of time-frequency analysis [Gröc01]. Later it was shown that the uniqueness and existence of such an expansion critically depends on the density of the grid of time-frequency shifts, which is defined as the product of spacing in time ΔT and frequency ΔF . Densities larger than 1 imply non-unique expansions whereas with densities smaller than 1, expansion coefficients only exist for certain signals. Nowadays, the linear combination of time-frequency shifted windows is known as a Gabor expansion and the calculation of the STFT with a certain window at a regular grid is known as a Gabor

transform [BHW98]. Expansion and transform windows are in a dual relation, i.e. the coefficients which are used to expand to a certain signal with a given window are provided by the Gabor transform of that signal with the dual window. In case the window and its dual are equal, the window is said to be orthogonal and expansion and transform reduce to well-known orthogonal expansion series.

A prominent example is OFDM, which performs a Gabor expansion using a finite discrete set of rectangular window functions with length T S in time and shifts of $1/T$ S in the frequency grid. In discrete Gabor expansion and transform, which in the OFDM case is the discrete Fourier transform (DFT), all signals are assumed to be periodic in time and frequency. However, non-periodic time-continuous scenarios can be approximated by choosing long frames and appropriate sampling frequencies.

4.1.2 5GNOW waveforms

In 5GNOW the following waveform approaches have been developed [Wun14][5GNOWD3.1][5GNOWD3.2]:

- GFDM [MMG+14] can be seen as a more generic block oriented filtered multicarrier system that follows the Gabor principles. Basically, the parameterization of the waveform directly influences i) transmitter window; ii) time-frequency grid structure; as well as iii) transform length and can hence provide means to emulate a multitude of conventional multi-carrier systems.
- FBMC-OQAM [Farh11][DBC+14] belongs to the family of filterbank based waveforms. The principles revolve around filtering the subcarriers in the system while retaining orthogonality. As the name suggests, the essence of this candidate waveform is offset modulation, which allows avoiding interference between real and imaginary signal components.
- BFDM [KWJ+14][WJW14] directly relates to the theory of Gabor frames. Signal generation can be considered a Gabor expansion while the bi-orthogonal receive filter constitutes a Gabor transform.
- In UFMC [VWS+13], a pulse shaping filter is applied to a group of conventional OFDM subcarriers. This approach can be also represented in the context of the Gabor frame.

These waveforms have been thoroughly investigated within 5GNOW, each particularly related to certain scenarios as described in detail in the next section.

4.2 Unified frame structure, one shot transmission and autonomous timing advance

The unified frame structure concept, depicted by Figure 9 provides a flexible multi-service supporting solution in one single integrated 5G air interface [Wun14]. The underlying basis of the universal frame structure is formed by the 5G candidate multi-carrier waveforms in [5GNOWD3.2]. Each square in Figure 9 represents a single resource element, a single subcarrier of a single multi-carrier symbol.

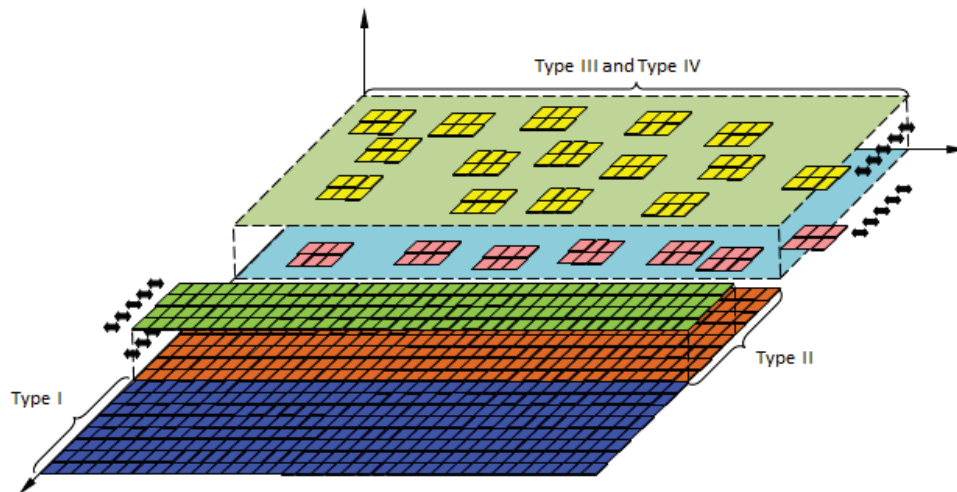


Figure 9: Unified frame structure

For supporting the heterogeneous 5G system requirements, the frame is divided into different areas as discussed in [5GNOWD3.1]:

- The type I area carries classical “bit pipe” traffic. High volume data transmissions are served here. High spectral efficiency is the key performance indicator to be pursued. A high degree of orthogonality and strict synchronism is kept in this service type.
- Type II traffic is rather similar to type I traffic. Basically the same service and device classes are supported. In contrast to type I users being confronted with a higher degree of interference from adjacent cells are assembled here. Key building block for efficient multi-user separation is vertical layering (see next section). Synchronization and orthogonality requirements are not as tight as with type I traffic.
- Type III traffic includes sporadic sensor/actor messages requiring low latencies. As outlined above, closed-loop synchronization is less suited, here. Instead transmissions are only loosely synchronized (open-loop) and a contention-based access technique is used.
- Type IV traffic includes sporadic sensor/actor messages tolerating high latencies. Multiple signal layers are used, either using spreading or IDMA [PLK06][CSW14].

The unified frame concept shall be main part of the standardization processes to be initiated in the future. In that context, exemplary scheduling/multiple access schemes are defined as follows:

- a) Dynamic, channel adaptive resource scheduling for traffic Type I using standard or advanced resource scheduling mechanisms.
- b) Semi-static/persistent scheduling for traffic Type II. From MAC point of view it is necessary to decide on the amount of resources allocated for this type of traffic, since schedulers will not adapt to specific parts of the frequency (may also be used for high speed terminals).
- c) “One shot transmission” [Wun14][KWJ+14][WJW14] using contention-like based approaches for random access in conjunction based on “sparse” signal processing methodology and waveform design to enable payload (Type III and IV) transmission in PRACH. Clearly, by doing so, sporadic traffic is removed from standard uplink data pipes resulting in drastically reduced signalling overhead. Another issue that is closely related to the signalling overhead is the complexity and power

consumption of the devices. Notably, waveform design in such a setting is necessary since the OFDM waveform used in LTE cannot handle the highly asynchronous access of different devices with possible negative delays or delays beyond the CPs. Clearly, guards could be introduced between the individual (small) data sections, however, which make the approach again very inefficient.

The design problem is as follows: terminals seek access to the system over the PRACH. We assume that in the presence of a common broadcast channel some rough synchronization is available. Each user has a data and control signal part which overlap in time with each other to allow for "one shot" detection. Obviously, loosely speaking, to allow for channel equalization, the control must be "close" to the data to probe the channel conditions "nearby". Conversely, detectability becomes erroneous the more control is interfering with the data, i.e. when separation between pilots and data cannot be achieved in a stable sense. This seems a contradicting, irresolvable task at first sight. However, with sparse signal processing methodology we can cope with that task thanks to the sparse structure of 1) user activity, 2) channel impulse response, 3) spatial correlations 4) sparse topology etc. A possible configuration is shown in Figure 10. Here we spread the signalling over the whole signal space, so-called underlay signalling, and collect it back within the observation window.

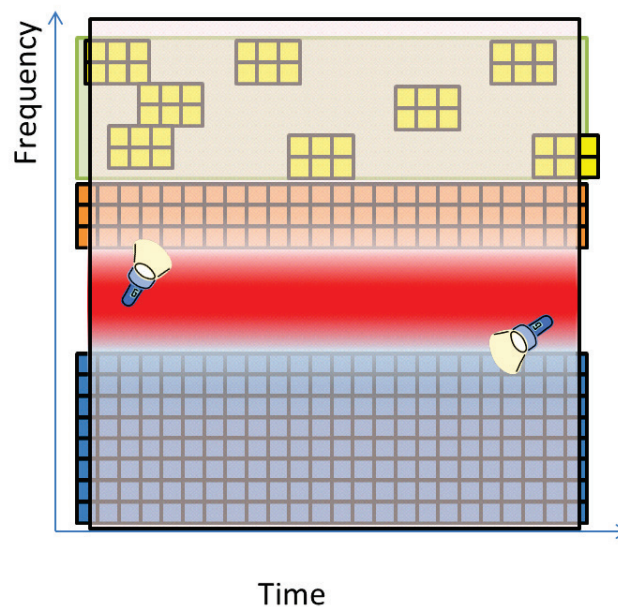


Figure 10: Underlay signalling in "one shot transmission" concept

d) Notably, traffic types II and III rely on open-loop synchronization. The device listens to the downlink and synchronizes itself coarsely, based on synchronization channel and/or reference symbols, similar to 4G systems. Furthermore, the devices may apply some autonomously derived timing advance which we call autonomous timing advance (ATA) [SW14] relevant also particularly for MTC in 5G NOW.

4.3 Temporal and spectral fragmentation

Relaxed synchronization and access to fragmented spectrum are considered essential for future generations of wireless networks in order to reduce physical channel signalling. In 5G NOW, a high performance FBMC receiver has been implemented which allows relaxed frequency and time synchronizations [CKD13][DBC+14]. It is described on Figure 11. The receiver is based on the

‘asynchronous FFT’ assumption: it is able to efficiently demodulate the signal in the frequency domain without a priori knowledge of the FFT timing alignment. In that case, time synchronization is performed independently of the position of the FFT. This is realized by combining timing synchronization with channel equalization, which allows the possibility to have asynchronous multiuser reception with only one FFT. Indeed when considering time domain correction of synchronization, then the duplication of FFTs is mandatory hence increasing the complexity of the receiver. This is not adapted if many users with small frequency fragments are simultaneously decoded.

An asynchronous FFT of size KN is processed every blocks of $N/2$ samples generating KN points, i.e. a KN -point FFT is computed for samples $k = (n + m \times N/2)$ with $n = 0, 1, \dots, NK - 1$. These successive KN points are stored in a memory unit. The detection of a start of burst is then achieved on the frequency domain (i.e. at the output of the FFT) using a priori information from the preamble. Carrier frequency offset (CFO) is first estimated using the pilot subcarrier information of the preamble by computing the phase of the product between two consecutive FBMC symbols at the location of the pilot subcarriers. The propagation channel is assumed static for the duration of the burst. CFO compensation is then performed in the frequency domain using a feed-forward approach. The channel coefficients are then estimated on the pilot subcarriers before being interpolated on every active subcarrier. Once the channel is estimated on all the active subcarriers, a one-tap per subcarrier equalizer is applied before filtering by the FBMC prototype filter. Demapping and Log-Likelihood Ratio (LLR) computation complete the inner receiver architecture. A soft-input Forward Error Correction (FEC) decoder recovers finally the original message.

The asynchronous frequency domain processing of the receiver combined with the high stop-band attenuation of the FBMC prototype filter provides a receiver architecture that allows for multiuser asynchronous reception [DBC+14].

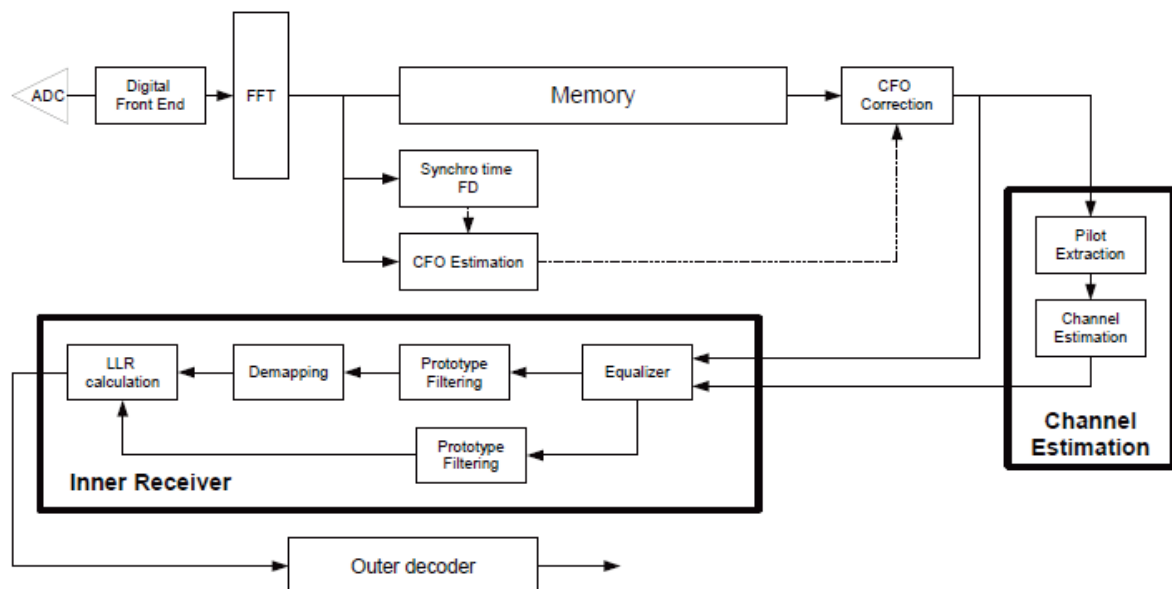


Figure 11. Block diagram of the FBMC receiver architecture

It should be mentioned that the complexity of this receiver is increased compared to the classical FBMC receiver based on time domain PPN (PolyPhase Network) [Bel10]. The FFT processor works on KN points while N points are required for PPN+FFT architecture. As the sampling frequency is small compared to current circuit clock processing the complexity of a KN -point FFT is close to a N -point FFT. However, the memory resources required are K times more important for the proposed architecture.

4.4 Networking interface – Robustness framework

4.4.1 Robust CoMP with relaxed time and frequency synchronization

Cooperation between cells in the DL (i.e. CoMP) aims at improving the QoS of users at cell edges. Fourth generation of cellular systems can benefit from the presence of the OFDM Guard Interval (GI) to deal with different times of arrival of eNBs' signals at the UE. Nevertheless, the further the eNBs are from the UE, the longer must be the GI, reducing the system capacity dramatically. For the next generation of cellular systems, non-orthogonal waveforms are strong candidates. FBMC is one of these waveforms. In addition to the excellent frequency localization of its prototype filter, it does not require the use of a GI. The system capacity is thus increased (for long enough frames). However, for CoMP, a robust design of a receiver against time delays between eNBs' signals becomes crucial.

A receiver with robust algorithms, for both time and frequency synchronizations, have therefore been proposed for DL CoMP with FBMC. The chronology of the synchronization process is illustrated on Figure 12 (bottom) and the system on Figure 12 (top). Here $\delta_{\Delta f}$ is the Carrier Frequency Offset between the BSs and the UE; τ is the delay at the UE of eNB2 compared to eNB1 and φ_i is the initial phase of eNBi.

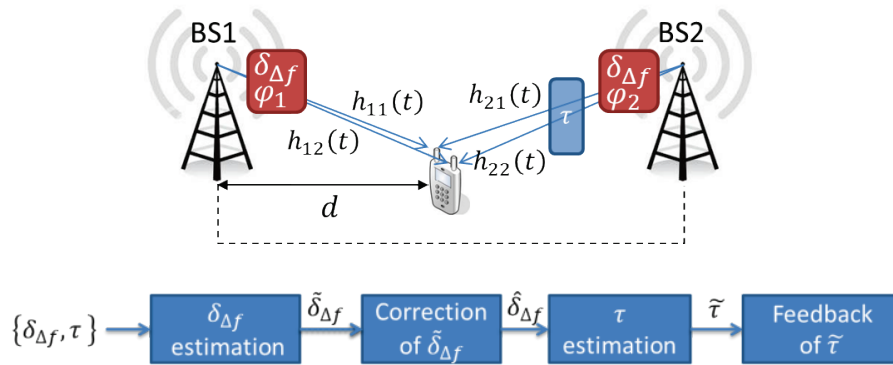


Figure 12 (Top) DL CoMP system. (Bottom) Chronology of the proposed time and frequency synchronization process

Delays up to 120 samples, i.e. $7.8 \mu\text{s}$ (2340 meters with the LTE parameters) can be tolerated at the UE without any estimation or correction, with the proposed pilot scheme [CKD13] [CKW+14]. Delays higher than $7.8 \mu\text{s}$ are unlikely to occur in most of cooperative systems. Nevertheless, in order to decrease the effects of phase rotations of the channel due to high delays, an algorithm was proposed to estimate the delay. The algorithm was demonstrated to be very robust to non-detections and false alarms with very limited feedback information.

Frequency synchronization (estimation and compensation of the CFO) with FBMC can be entirely realized at the UE in the frequency domain. Thanks to the very good frequency localization of FBMC carriers, the most part of the CFO can be easily and accurately estimated thanks to a simple energy detection algorithm on the preamble carriers. The residual part of the CFO after this estimation is lower than $100/(2K)\%$ of carrier spacing (with K the FBMC overlapping factor) [CKD13]. The same method applied to OFDM would lead to a much higher residual CFO of 50 % at maximum. The proposed algorithm for estimation of the residual part was shown to have good performance with reduced complexity. The correction of the CFO requires no feedback from the UE to the BSs.

4.4.2 Robust cellular iterative interference alignment

The major limiting factor in 4G CoMP (OFDM) systems is properly sharing channel state information (CSI) and other overhead among cells. This so-called limited feedback problem has been greatly analysed for multiuser MIMO [CJK+10], as well as for joint transmission [KG12] in terms of the rate distance Δr_m of node m to capacity subject to some offset independent of SNR. Hence, these results essentially provide a systems' degrees-of-freedom (DoF) analysis assuming infinite SNR regime. It is now highly relevant how the overall throughput scales with the feedback overhead for both practical systems in more relevant regimes.

Classical analyses in literature reveals a scaling of the throughput degradation in the number of feedback bits in the order of $2^{-b(p)/(N_T-1)}$ where N_T denotes the number of transmit antennas while p and $b = b(p)$ denote the SNR and feedback budget per user and resource block (in bits/channel use) as a function of SNR, respectively. 5G NOW studies [SWJ13][SWJ14] indicate that these results are fragile and that, in fact, the trade-offs actually behave very differently in more practical regimes. Classical analysis of the scaling of per-node capacity in the number of feedback bits falls short due to several reasons: (i) it assumes an infinite SNR regime where achieving DoF is optimal. In this operational regime, interference mitigation instead of signal enhancement is the primary goal; (ii) it asserts that the transmitter can optimally allocate rates while, in practice, the transmitter allocates rates according to the available CSI and corresponding scheduler decisions (real versus ideal link adaption); (iii) the optimal scheduling decision is known a priori, which is unrealistic since limited feedback not only affects the choice of spatial precoding but also user selection and resource allocation.

In [SWJ13][SWJ14] it is shown that for any finite SNR point p and for any scaling in b the per-node capacity degradation is actually in the order of $2^{-b/(2(N_T-1))}$, which actually doubles the required number of bits. In addition, in [SWJ13, SWJ14] a scheme termed *robust cellular iterative interference alignment* generalizing the algorithms in [SW11, SW12a/b] which actually achieves this scaling has been developed.

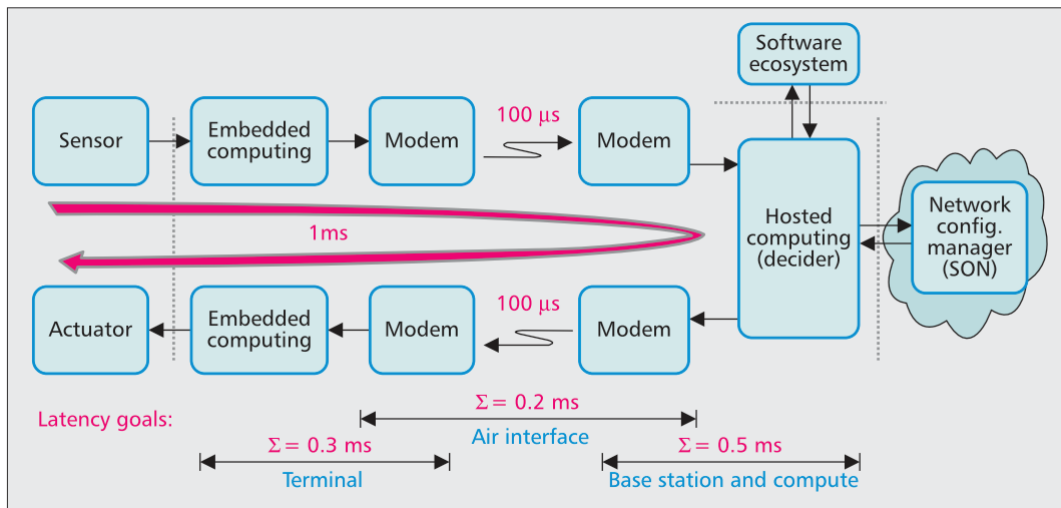


Figure 13: The impact of breaking down the 1 ms round-trip delay

4.5 Low latency

Real time is a highly subjective term and depends on the use case. We define a service to be real time when the communication response time is faster than the time constants of the application. While today all major applications are hosted and run in the cloud, users want to maintain the responsiveness of locally executed software. Current wireless cellular systems miss this target by nearly two orders of magnitude. Figure 13 shows one possible latency budget over a communications chain, taking into account the latencies from the sensor through the operating system, the wireless/cellular protocol stack, the physical layer of terminal and base station, the base station's protocol stack, the trunk line to the compute server, the operating system of the server, the network within the server to the processor, the computation, and back through the equivalent chain to the actuator.

In 5GNOW we use the GFDM waveform for low latency transmission, because it facilitates the use of shorter packets. The main enabling ingredients are:

- The circular signal structure enables efficient DFT-based block processing and eliminates filter tails that increase the latency of a data packet.
- The two-dimensional resource grid allows adjusting subcarrier bandwidth and sub-symbol duration independently. A configuration with short sub-symbols can be easily realized.
- A per-subcarrier frequency selective channel can be still easily equalized in the frequency domain, because each subcarrier is represented by multiple samples in the frequency domain.
- While one cyclic prefix is required per block, no cyclic prefix is added between the sub-symbols within a block. This allows using frequency domain equalization, while keeping the redundancy in the signal low and the packet duration short.
- An orthogonal GFDM configuration either with specific filters or in combination with OQAM modulation eliminates the need for time-consuming interference cancellation on the receiving side.

5 5GNOW Reference Scenarios

5.1 PRACH scenario

Similar to the implementation in UMTS the goal is to transmit small user data packets using the PRACH thereby not maintaining a continuous connection. So far, this is not possible in LTE, where data is only carried using the physical uplink shared channel (PUSCH). The goal of the PRACH reference scenario is joint link acquisition and the transmission of “sparse data” in the total number of dimensions within 1 to X sub-frames. Within a sub-frame, out of the total 20 MHz bandwidth of the uplink frame of LTE as shown in Figure 14, the PRACH occupies a bandwidth of 1.08 MHz and 1 ms in time. Table 2 lists the relevant parameters. The goal is to achieve the same link acquisition key performance (regarding misdetection probability in a multi user scenario and time and frequency offset estimation errors) as LTE-A. For MTC communications, a rate of 20kbit/s is anticipated.

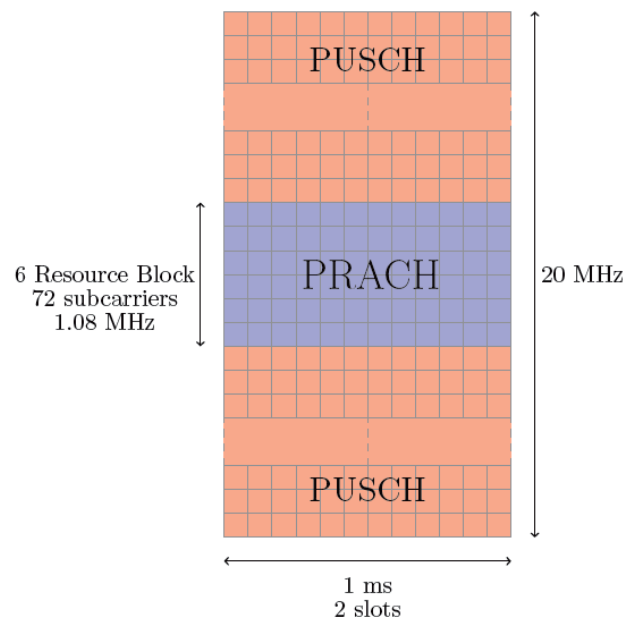


Figure 14: LTE Uplink FrameStructure

Table 2: Channel specification in PRACH reference scenario

Simulation Parameter	Value (PUSCH/PRACH)
Modulation	SCFDMA / OFDM
Bandwidth	20 MHz / 1.08 MHz
Symbol duration T_u	0.67 μ s / 800 μ s
Subcarrier spacing Δf	15 kHz / 1.25 kHz
Sampling frequency f_s	30.72 MHz / 30.72 MHz
Length of FFT N_{FFT}	2048 / 24576
Number of subcarrier L	1200 / 839
Cyclic prefix length N_{CP}	144 / 3168
Guard time	0 / 2976

In PRACH the 1.08 MHz bandwidth is anticipated to be used for data transmission.

5.1.1 Performance evaluation

This will be part of the final Deliverable D2.3.

5.2 Generalized frequency division multiplexing (GFDM)

Table 3: GFDM reference scenario specification

Simulation Parameter	Value	“LTE- like” format for 2.5MHz bandwidth 256 points IFFT with sample rate 3.84 Msamples/s)
Subcarrier spacing Δf	240kHz (with 16 symbols per sub-carrier*)	
Subcarriers per “PRB”	1	
FFT size	256	
No. of used “PRBs”	10*	
Block (=subframe) duration	$1/240k * 16 = 67\mu s$	
Modulation	64QAM	
GFDM CP-length	1 symbol of the subcarrier, $1/240k \sim 4\mu s$	
Receiver	MF, ZF or MMSE	
Channel	AWGN / Veh A block fading	
Freq. offset (*)	$[0 \dots 0.1\Delta f]$	
Timing offset	$[0 \dots 0.1T_s]$	

*Approximately 16 slots * 6bits each*10 subcarriers allocation = 960 bits (<100 μs burst)

The focus of the GFDM reference scenario is also uplink MTC communication. The cell size considered in the scenario is around 1km in ratio, so multipath in the order of less than 4 μs duration is expected (1 μs delay corresponds to 300 meters deviation). The scenario includes low effort in synchronism and the transmission of data in bursts of 1kbit in at most 100 μs (thus at a rate of 10 Mbit/s). Due to the “low effort” in synchronism (10 ppm) at the receiver “poor” synchronicity in frequency together with the effect of propagation delay and delay spread occurs (few μs , up to guard interval). The 10 ppm corresponds to a frequency offset of $0.1 \Delta f$.

The reference scenario investigates how well these asynchronisms can be supported in a MTC setting with the GFDM approach. Timing and frequency offsets are also treated in the scenario. The total frequency offsets are caused by the M2M transmitters, while the BTS are synchronized. Further, for MTC the relaxed oscillator requirements are expected to be beneficial in terms of not only price, but also in terms of the settling time required for awakening of a device in sleep mode.

The most relevant parameters of the GFDM reference scenario are listed in Table 3. The bandwidth of 2,5 MHz will be divided in 10 subcarriers with 240kHz each (matching the coherence bandwidth of the channel). Each 240kHz will be represented by 16 coefficients (16 symbols in time domain). The spectrum resolution can be calculated by 10 subcarriers with 240kHz multiplied by 16 coefficients per subcarriers with 240kHz leading to 160 coefficients. To allow proper up-sampling and filtering, zero stuffing coefficients need to be added. The next power of two greater than 160 is 256, so $256 - 160 = 96$ null coefficients (6 null subcarriers) will be considered. Moreover, the following SNR

conditions are considered in the scenario. The model initially considers high order QAM (64QAM) and high SNR (i.e. 25dB). In low SNR conditions (i.e. 10dB) lower constellation (QPSK) can be transmitted by more subcarriers to transmit 1000bits in less than 100 μ s, but this requires the use of more spectrum and more complex hardware (bigger FFT).

5.2.1 Performance evaluation

This will be part of the final Deliverable D2.3.

5.3 Uplink CoMP with joint reception

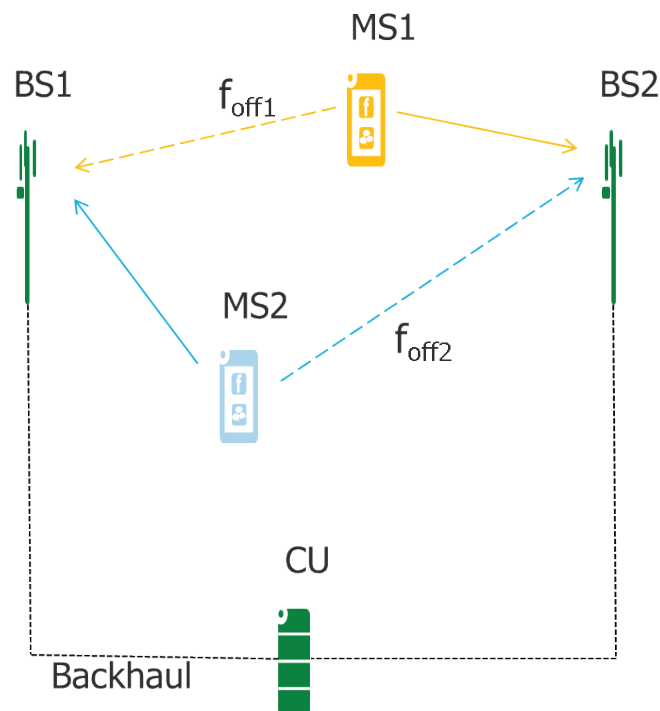


Figure 15: Uplink CoMP reference scenario

The third reference scenario deals with uplink CoMP with joint reception. It is illustrated in Figure 15, and comprises 2 cells and 2 users. The scenario again deals with timing and frequency offsets. Sources of timing offsets can be the following. Uplink timing advance control mechanisms can align receive signals of a single cell, but, due to propagation delay differences, Uplink CoMP joint reception across multiple cells has inherent timing offsets. At the receiver, the cumulative effects of propagation delay, synchronicity and delay spread occur. Furthermore, the 5G NOW system vision aims at an asynchronous uplink. This scenario checks how well asynchronisms can be supported in a CoMP setting.

Regarding frequency offset remarks, the total frequency offsets are caused by both transmitter and receiver. For MTC it has to be checked whether relaxed oscillator requirements (like those in WLAN instead of LTE) are significantly beneficial for the price of cheap devices (e.g. as a mass of small “internet-of-things” sensor-like devices have to be supported by 5G). This would push multi-carrier

waveforms with lower side lobe levels, as higher frequency offsets could be tolerated due to reduced ICI. Table 4 summarizes the relevant parameters.

5.3.1 Performance evaluation

BS1 is the serving base station for MS1 (primary base station), while BS2 is the secondary base station for MS1. For MS2 the relations are accordingly (BS2 primary, BS1 secondary). The scenario assumes a LTE-like ranging procedure. So, MS1 is aligned (timing and carrier frequency) to BS1 while MS2 is aligned to BS2. Though different base stations within a given single-frequency network (SFN) are synchronized with respect to their carrier frequency, there still may occur fractional carrier frequency differences. (MS1 and MS2 synchronize themselves to the downlink signals of their respective serving base station, then they do uplink transmission based on this time-frequency synchronization outcome. In this whole chain, any phase jitter, oscillator inaccuracy, etc. will lead to carrier frequency offsets between the signals of MS1 and MS2 received at one of the BS.)

So, as a given mobile only may be aligned to a single base station (its serving basestation), the respective transmission to the secondary base station suffers from a carrier frequency offset (CFO, Δf_{12} and Δf_{21}). Similarly, the transmission to the secondary base station suffers from time delay (ΔT_{12} and ΔT_{21}) as the propagation delays (MS1 to BS1 and MS1 to BS2, MS2 accordingly) are typically different. Both CFO and time delay are introducing inter-carrier interference degrading the performance.

The detailed mathematical system model and the used joint reception scheme are described in [5GNOW-D3.1] and are treated in a similar manner in [VWS+13].

The transmissions between BS_i ($i = [1, 2]$) and the CU via fronthaul is assumed to be ideal (error free and with sufficient resolution, so that any quantization effects are negligible; e.g. using a CPRI interface).

Ultimate target of this reference scenario is to compare the capabilities of different waveforms to harvest on the gains UL CoMP is promising under realistic synchronization assumptions.

Simulations have been carried out in order to assess the performance gains of UPMC over OFDM. For now, the considered timing offsets are still $\Delta T_{12} = \Delta T_{21} = 0$, so, only the impact of frequency offsets on the cross-links are considered, yet. The simulation settings are depicted in Table 4.1.1. The receiver is assumed to have perfect channel state information. The simulation results are depicted in Figure 16.

Depending on the SNR operation point, performance gains of several dBs for UPMC over OFDM can be observed, because of better inter-carrier interference suppression by the reduced side-lobe levels of the waveform. This demonstrates that UPMC is a powerful candidate 5G waveform in the CoMP scenario in case of synchronization mismatch. This allows that synchronization requirements can be relaxed and in the case of MTC devices transmitting in CoMP joint reception systems, a better support of low-end devices with relaxed oscillator requirements can be provided by the help of UPMC.

This directly addresses the KPI target (K6) from Table 1: The chosen frequency offset of $0.1 \Delta f$ is 1.5kHz for the selected subcarrier spacing. 5GNOW target is 1 ppm LO accuracy, corresponding to a carrier frequency of 1.5 GHz. Furthermore, KPI target “(K5) Out-of-band radiation” with a factor 100 improvement is easily fulfilled by the UPMC waveform – see spectrum plot in D3.3.

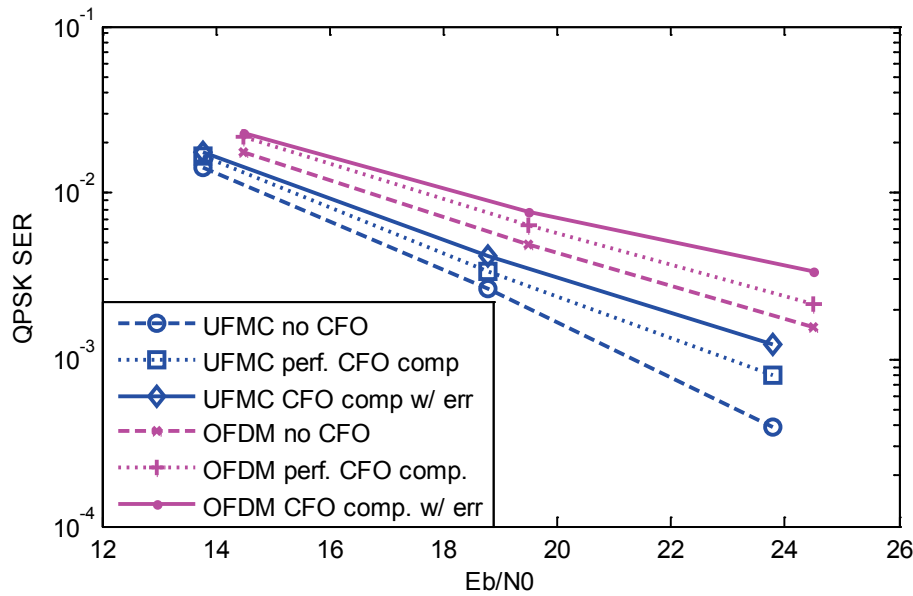


Figure 16: SER vs E_b/N_0 – comparison between UPMC and OFDM for absence of carrier frequency offset (no CFO), perfectly known and compensated carrier frequency (per. CFO comp) and a CFO compensation with a residual mismatch of 10% of the total CFO.

Table 4:UL CoMP reference scenario specifications.

Simulation Parameter	Value	
Subcarrier spacing Δf	15 kHz	LTE format for 1.4 MHz bandwidth with sample rate 1.92 Msamples/s
Subcarriers per PRB	12	
FFT size	128	
No. of used PRBs	6	
Block (=subframe) duration	1 ms	Other schemes have to compare at the same overall data symbol rate
Modulation	QPSK	
OFDM CP-length	16	
Receiver	ZF	Adapt range until significant effect occurs (*) Put in relative perspective to oscillator requirements: LTE UE/MacroBS 0.1/0.05 ppm, [3GPPTS36.521], WLAN device 20 ppm
Channel	AWGN / Veh A block fading	
Freq. offset (*)	[0 ... 0.1 Δf]	
Timing offset	[0 ... 0.1 T_s]	
Path loss	Start with cell edge case: Equal path gains to both cells	
Performance metric	BER/SER vs E_b/N_0	
Backhaul constraints	Start with ideal backhaul	

5.4 Multiuser uplink on fragmented spectrum with FBMC

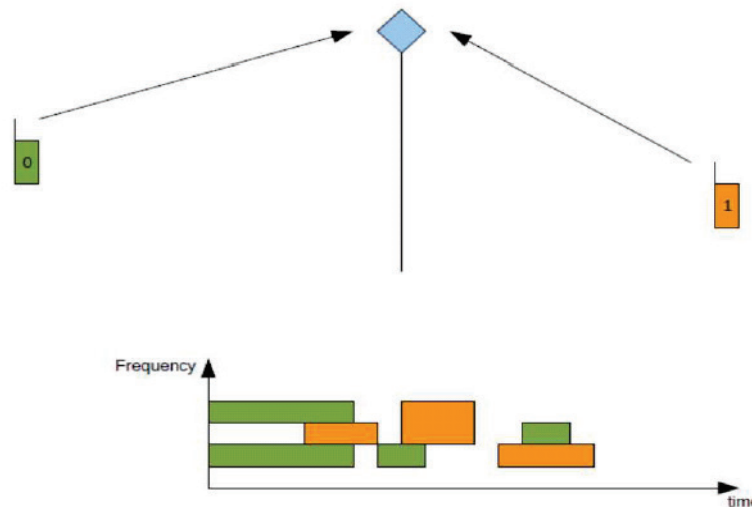


Figure 17: Multiuser uplink reference scenario for fragmented spectrum with FBMC

The advent of the Digital Agenda and the introduction of carrier aggregation are forcing the transmission system to deal with fragmented spectrum. 3GPP/LTE-A is already dealing with some spectrum agility as a requisite to allow worldwide interoperability of devices in a fragmented spectrum. In this context, the scenario under consideration is uplink (UL) asynchronous multi-user access on fragmented spectrum [DBK14] for 5G with non-orthogonal waveform. The objective is to allow relaxing both time/frequency synchronization constraints while enabling flexible fine-grained sharing of fragmented spectrum. If the spectral needs are not met in a contiguous space of spectrum, then some form of aggregation should be realized. The specific nature of the fragmented spectrum and the stringent requirements on adjacent band leakage are suggesting a new approach for the PHY using FBMC and spectrum pooling techniques.

Both OFDM and FBMC may theoretically be suited to multicarrier-based spectrum pooling. However, high adjacent channels' rejection cannot be met without a very complex and programmable band-pass transmit filter in the CP-OFDM case, whereas FBMC would simply requires "switching on and off" the appropriate carriers at the transmitter. The main shortcoming of the OFDM waveform identified here originates from the large side-lobes because of the rectangular shaping of the temporal signal whereas the FBMC built-in filtering feature adapts to spectrum availability even in the fragmented case.

Despite its prominence in modern broadband radios, CP-OFDM has some drawbacks for the intended scenario operation. Indeed, CP-OFDM side lobes make it inappropriate in adjacent channels, unless expensive rejection filters are used. Spectrum pooling is an appealing approach to virtually elaborate wider channels, but again CP-OFDM is not applicable because of unaffordable out-of-band leakage. FBMC is as a valid alternative to CP-OFDM, as it achieves both adjacent coexistence and spectrum pooling. Figure 17 illustrates the scenario which comprises one base station and 2 users while Table 4 summarizes the most important parameters

5.4.1 Performance evaluation

This will be part of the final Deliverable D2.3.

Table 5: Uplink multiuser fragmented spectrum reference scenario specification

Simulation Parameter	Value	
Subcarrier spacing Δf	15 kHz	LTE format for 10 MHz bandwidth with sampling rate 15.36 MHz
Subcarriers per PRB	$12p + 1$	
FFT size	1024	
No. of used carriers	13 to 601 (depending on p)	
No. of used PRBs	configurable	
Block (subframe) duration	1.6 ms	Adaptative data rate
FBMC Filter	$K=4$ (optimized for ACLR)	
Modulation	QPSK to 64-QAM	
Coding rate	$1/2, 2/3, 3/4, 5/6$ (CC $K=7$ / LDPC 802.11n)	
OFDM CP-length	N/A	Adapt range until significant effect occurs
Channel	Exponential decaying	
Freq. offset	$[0 \dots 0.1\Delta f]$	
Timing offset	Random (uniform distribution)	
Performance metric	(BER,PER) vs SNR (/Freq offset)	

5.5 Downlink CoMP with FBMC

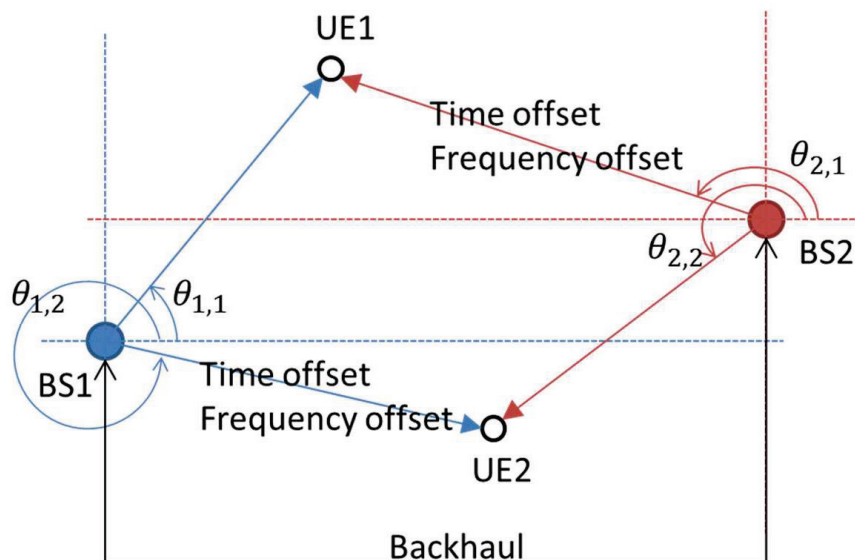


Figure 18: Downlink CoMP reference scenario for FBMC

The reference scenario for FBMC deals with downlink CoMP with joint reception, its objective: is to demonstrate the feasibility of downlink CoMP for 5G with non-orthogonal waveforms. As illustrated in Figure 18, 2 cells and 2 users are included. Timing and frequency offsets are again considered, the sources of the offsets can be characterized as follows:

Received signals from multiple cells may not be aligned in time at the receiver due to propagation delay differences and due to possible time de-synchronization between cooperating BSs. This offset causes pilots rotations at the receiver that make the estimation of the channel difficult. Thus high time delays will be studied. Clocks at the BSs and at the UE side may not be perfectly synchronized in frequency, causing Carrier Frequency Offset (CFO) at the receiver, therefore, the impact of the CFO will be studied. The reference scenario investigates the level of tolerance to asynchronism in the downlink CoMP scenario using the FBMC waveform.

Concerning the return link, in order to deal with different time of arrivals from different BSs, the receiver may estimate the delay and feedback the information to the BSs. The cost of this operation, in term of UL bandwidth, will be studied. Furthermore multiuser CoMP implies CSI knowledge at the transmitter side. Therefore the necessary information to be fed back to the BSs will be investigated as well. The studies will be carried out with respect to reducing the level of control information compared to OFDM solutions (backhaul and CSI feedbacks). The most important parameters are summarized in Table 6.

Table 6: Downlink CoMP FBMC reference scenario specifications

Simulation Parameter	Value	
Subcarrier spacing Δf	15 kHz	} LTE format for 10 MHz bandwidth with sampling rate 15.36 MHz
FFT size	1024	
No. of used carriers	601	
Block (subframe) duration	1.6 ms	} Other schemes have to be compared at the same overall data symbol rate
Modulation	16-QAM	
Coding rate	3/4 (CC / LDPC)	
OFDM CP-length	N/A	
Receiver	ZF	} Adapt range until significant effect occurs
Channel	- Exponential decaying - SCM(E)	
Freq. offset	[0 ... 0.1 Δf]	
Timing offset	Up to several micro seconds	
Path loss	NLOS, function of distance	
Performance metric	BER vs SNR, throughput vs distance	
Backhaul constraints	Start with ideal backhaul, then relaxed backhaul bandwidth.	

5.5.1 Performance evaluation

It was previously demonstrated in this project that the UE can robustly estimate very large delays and arbitrary high carrier frequency offsets. The correction of the delays required only a few bits of feedback when the compensation of the offset can be realized at the UE side. The aim here is to go one step further by investigating the robustness of FBMC in DL CoMP scenarios with respect to the feedback link and MAC related asynchronisms such as outdated CSI, as investigated in [CKW+14]. The parameters can be found in Table 7 and Table 8.

In order to avoid having to carry out actual signal processing, in system level simulations usually a link-to-system (L2S) interface comprising a suitable PHY layer abstraction is used. The goal of this PHY layer abstraction is essentially to obtain a block error rate (BLER) for a transport block (given particular subcarrier channel realizations) without having to carry out real signal processing. This is usually implemented in form of a look-up table where packet or block error rates are given for a certain effective quality measure, often the SINR, taking into account modulation and coding, power control, resource allocation, HARQ, etc. However, the SINR measure, which is usually applied in the evaluation of OFDMA systems, cannot capture the mutual dependencies between subcarriers of non-orthogonal multicarrier schemes. To cope with this issue, we used the Signal to Noise plus Interference and Distortion Ratio (SNIDR) model, as proposed in [OIG+13], where the “D” stands for the residual distortion. The SNIDR on subcarrier k is defined as:

$$\text{SNIDR}_k = \frac{P_s}{P_i + P_n + P_d}$$

Thereby P_s , P_i , and P_n denote the signal power, interference power, and noise power, respectively. P_d denotes the residual distortion power.

In simulations presented above, the CSI feedback and the throughput computation is done on a RB basis. The following steps are then realized to assess the users' throughputs:

- Computation by each user of the preferred precoder(s) depending on the channel at the current time t_0 .
- Reporting by each user of the preferred precoder(s).
- Measurement by link level simulations of the SNIDR of each user on each carrier of the RB at time $t_0 + \tau$. τ is a parameter modelling the time between feedback at the UE and the reception of the signal. The SNIDR takes into account inter-user interference due to MU-MIMO, residual distortion power and SNR. It is computed with the channel at time $t_0 + \tau$.
- Computation of the mean SNIDR on the RB. The choice to use the mean SNIDR instead of the ESM mechanism is justified by the high coherence bandwidth of the channel.
- Choice of the PER corresponding to the MCS and the mean SNIDR in LUT. The MCS must maximize the throughput while ensuring $\text{PER} < 10^{-1}$.
- Assessment of the throughput as $R(1-\text{PER})$ with R the rate of the MCS.

LUT are presented on Figure 19. As stated in [WKB+13], the gain in FBMC from abandoning the cyclic prefix can be clearly observed in these LUTs.

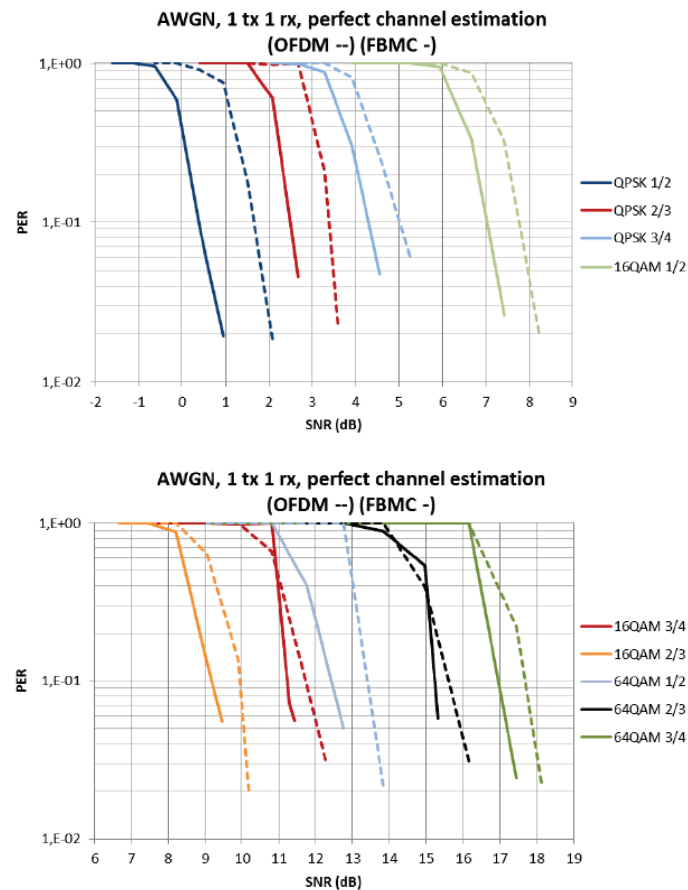


Figure 19. BLER vs SNR in AWGN Channel

Figure 20 shows the distribution of the throughputs of UEs for FBMC and OFDM (OFDM with dashed lines, FBMC with continuous lines), for a feedback of the two preferred precoders. Two-antenna BSs are used for the figure. On each figure and for each modulation, three curves are plotted, corresponding to $\tau = \{0, \Delta(t), 2\Delta(t)\}$ ms. The correspondence between $\Delta(t)$ and the speed of the UEs is given in Table 7.

The red curves are for an instantaneous feedback. The blue curves are for $\tau = \Delta(t)$ and the grey curves are for $\tau = 2\Delta(t)$, whatever the speed of the UE. For example for a UE moving at 3km/h (resp. 20km/h) the blue curves are for $\tau = 90$ ms (resp. $\tau = 13.5$ ms) and the grey curves for $\tau = 180$ ms (resp. $\tau = 27$ ms).

Two observations can be made from this figure. First, FBMC outperforms OFDM whatever the feedback delay τ . These gains from FBMC to OFDM are primarily caused by the removal of the cyclic prefix. Second, the degradation of the throughput when $\tau = \Delta(t)$ compared to $\tau = 0$ is significant. At 20km/h ($\Delta(t) = 13.5$ ms), the precoders must therefore be updated frequently.

Table 7: Error over velocity

velocity [km/h]	$\Delta(t)$ [ms]
1	270
3	90
10	27
20	13.5

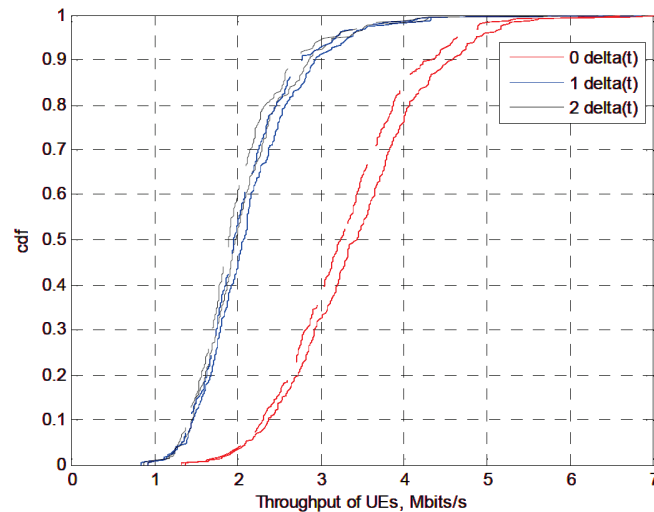


Figure 20. CDF of the throughput of UEs. (OFDM: dashed lines, FBMC: continuous lines)

The total throughput of the UEs vs. the feedback rate per UE was plotted in Figure 21 for the same configuration. The feedback per RB per codebook is N_T bits for the preferred weight and four bits for the MCS. As two preferred precoders are fed back, the feedback is $2(N_T+4)$ bits per RB per UE. Two UEs are scheduled on each RB and fifty RBs are available.

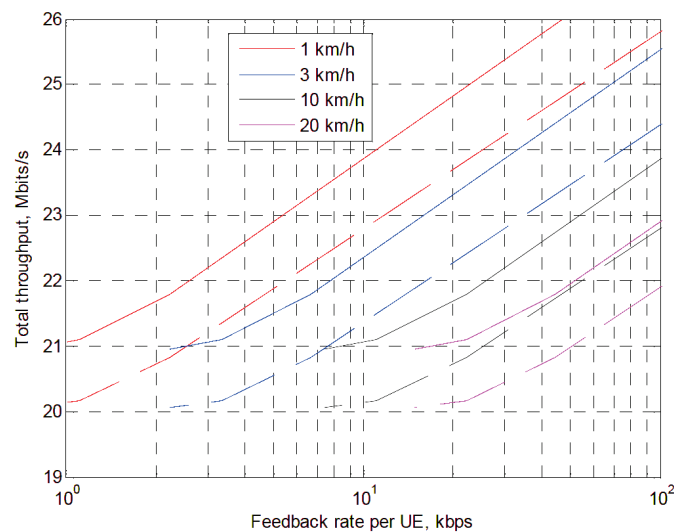


Figure 21. Total throughput as a function of the feedback rate. (OFDM: dashed lines, FBMC: continuous lines)

It must be noted that FBMC once again outperforms OFDM, for example:

- Regarding “Signalling overhead” Key Performance Indicator, to reach the same throughput of 22Mbps, FBMC requires 3 (resp. 10, 30 and 55) kbps lower feedback rates than OFDM for a speed of 1 (resp. 3, 10 and 20) km/h.
- Regarding “Capacity” Key Performance Indicator, with a feedback rate of 20 kbps, FBMC UEs moving at 1 km/h allow a throughput of 24,7Mbps whereas OFDM UEs only allow 23.6Mbps.

As intuitively expected, the speed of the UEs has a significant impact on the necessary amount of feedback: to ensure a throughput of 24.7 Mbps, 60 kbps are necessary at 3 km/h and more than 100 kbps at 10 km/h. Further, it can be observed, that the FBMC curves have a slope similar to the slope

of the corresponding OFDM curves. Thus, FBMC shows a comparable robustness against limited feedback.

Table 8: Downlink CoMP FBMC reference scenario specifications

Simulation Parameter	Value
Subcarrier spacing	15kHz
FFT size	1024
Number of transmit antennas	2
Number of receive antennas	1
Codebook	LTE
N° of used carriers	600
N° of RBs	50
Modulation	From QPSK to 64QAM
Number of users	Two per RB
Coding rate	From 1/3 to 3/4
Channel	SCM(E)
Feedback delay	Up to 540ms
Path LOS	NLOS
Performance metrics	PER vs SNR Throughput vs feedback delay
Backhaul constraints	Non instantaneous

6 Intermediate conclusions

This deliverable has the objective of presenting a clear definition of cellular communications scenarios to be addressed with an asynchronous 5G cellular radio access architecture consolidation of the partners' perspective on the PHY and MAC layer requirements, degrees of freedoms and models for the design of a 5G radio access architecture based on non-orthogonal modulation.

A harmonized definition and numerical specification of the relevant KPIs for all investigations, design efforts and implementations carried in the project is presented in this document.

This document provides the basis for further investigations in the project. The specified 5G communications scenarios, system requirements and design constraints will be passed in particular onto WP3 and WP4. The KPI specifications and the investigations of the design degrees of freedom will be conducted collaboratively with T3.1, T4.1 and T5.1 to feed into joint specifications established there.

7 Abbreviations

3GPP	3rd Generation Partnership Project
1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
5GNOW	5th Generation Non-orthogonal Waveforms for Asynchronous Signalling
BS	Base Station
BW	Bandwidth
CoMP	Coordinated Multipoint
CFO	Carrier Frequency Offset
CP	Cyclic Prefix
CQI	Channel Quality Information
CSI	Channel State Information
DFT	Discrete Fourier Transform
DL	Downlink
DRS	Demodulation Reference Signal
eNB	e-NodeB
EXALTED	Expanding LTE for Devices
FBMC	Filter Bank Multi-Carrier
FEC	Forward Error Correction
FP7	7th Framework Programme
GFDM	Generalized Frequency Division Multiplexing
GPS	Global Positioning System
GSM	Global System for Mobile Communications
H2H	Human-to-Human
HetNet	Heterogeneous Networking
ICI	Inter-Carrier Interference
(I)FFT	(Inverse) Fast Fourier Transform
ISI	Inter-Symbol Interference
KPI	Key Performance Indicator
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
M2M	Machine-to-Machine
MAC	Medium Access (layer)
MIMO	Multiple Input Multiple Output
MTC	Machine Type Communication
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PHY	Physical (layer)
PRACH	Physical Random Access Channel
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel

QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RACH	Random Access Channel
RE	Resource Element
RF	Radio Frequency
SMS	Short Message Service
SNIR	Signal to Noise and Interference Ratio
SOTA	State Of The Art
TDOA	Time Difference Of Arrival
TVWS	TV White Spaces
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
WLAN	Wireless Local Area Network

References:

- [3GP09] http://www.3gpp.org/ftp/workshop/2009-12-17_ITU-R_IMT-Adv_eval/docs/pdf/REV-090006.pdf, last access 13.11.2012
- [3GP10] 3GPP TR 36.814, Further Advancements for E-UTRA Physical Layer Aspects, v9.0.0, Mar. 2010
- [3GP11] 3GPP TR 36.819 V11.1.0, Coordinated Multi-point Operation for LTE Physical Layer Aspects, December 2011
- [3GP11a] Technical Specification 22.368 V11.2.0 (2011-06) Stage 1 (Release 11), <http://www.3gpp.org/ftp/Specs/html-info/22368.htm>
- [Cis10] Cisco, "Architectural Considerations for Backhaul of 2G/3G and Long Term Evolution Networks", White Paper, 2010 [Available: http://www.cisco.com/en/US/solutions/collateral/ns341/ns973/white_paper_c11-613002.pdf]
- [CJK+10] G. Caire, N. Jindal, and M. Kobayashi, and N. Ravindran, Multiuser MIMO Achievable Rates with Downlink Training and Channel State Feedback, IEEE Trans. on Information Theory, vol. 56, no. 6, pp. 2845–2866, June 2010
- [CKD13] N. Cassiau, D. Ktésas and J-B. Doré, "Time and Frequency Synchronization for Downlink CoMP with FBMC", ISCWCS (International Conference on Wireless Communication Systems), 28th August 2013, Ilmenau, Germany
- [CKW+14] N. Cassiau, D. Ktésas, G. Wunder and M. Kasparick, "Feedback scaling for Downlink CoMP with orthogonal and non-orthogonal waveforms", in proceedings of European Conference on Networks and Communications (EuCNC'14), Bologna, 23.6. - 26.6.2014
- [DBC+14] J-B. Doré, V. Berg, N. Cassiau and D. Ktésas, "FBMC receiver for multi-user asynchronous transmission on fragmented spectrum", EURASIP Journal on Advances in Signal Processing 2014, 2014:41
- [DBK14] J-B. Doré, V. Berg and D. Ktésas, "Performance of FBMC Multiple Access for Relaxed Synchronization Cellular", 10th IEEE BWA Workshop, IEEE Globecom 2014, 9-12 December 2014, Austin, Texas, USA.
- [FDM+11] G. P. Fettweis, F. Denzin, N. Michailov, K. Schlöder, D. J. Seul, I. Wolff, E. Zimmermann, Wireless M2M – Wireless Machine-to-Machine Communications, VDE Position Paper
- [FKV06] G. J. Foschini, K. Karakayali, and R. A. Valenzuela, Coordinating Multiple Antenna Cellular Networks to Achieve Enormous Spectral Efficiency, IEE Proceedings Communications, vol. 153, no. 4, pp. 548-555, 2006
- [FPT09] T. Fusco, A. Petrella, and M. Tanda, Data-Aided Symbol Timing and CFO Synchronization for Filter Bank Multicarrier Systems, IEEE Trans. on Wireless Communications, Vol. 8, May 2009 for OFDM/OQAM, Vehicular Technology Conference, 57th IEEE Semiannual VTC Spring, vol. 3, pp. 1581–1585, 2003
- [GHH+10] D. Gesbert, S. Hanly, H. Huang, S. Shamai Shitz, O. Simeone, and W. Yu, Multi-cell MIMO Cooperative Networks: a new Look at Interference, IEEE Journal on Selected Areas in Communications, vol. 28, no. 9, pp. 1380-1408, Oct. 2010
- [HB11] C. Hegde and R. G. Baraniuk, Sampling and Recovery of Pulse Streams, IEEE Transactions on Signal Processing, vol. 59, no. 4, 1505-1517, April 2011
- [Hua10] Huawei Technologies, Behaviour Analysis of Smartphone, White Paper, 2010 [Available: <http://www.huawei.com/en/static/hw-001545.pdf>]
- [JCC+10] M. Joham, P. M. Castro, L. Castedo, and W. Utschick, "Robust Precoding with Bayesian Error Modeling for Limited Feedback MU-MISO Systems". IEEE Trans. on Signal Processing, vol. 58, no. 9, pp. 4954-4960, Sep. 2010

- [Jun11] Juniper Networks White Paper, Machine-to-Machine (M2M) – The Rise of the Machines, 2011, [Online Available: <http://www.juniper.net/us/en/local/pdf/whitepapers/2000416-en.pdf>]
- [JWS+08] V. Junnickel, T. Wirth, M. Schellmann, T. Haustein and W. Zirwas, „Synchronization of Cooperating Base Stations“, in Proc. IEEE International Symposium on Wireless Communication Systems (ISWCS), 2008.
- [Ker11] P. de Kerret and D. Gesbert, The Multiplexing Gain of the Network MIMO Channel with Distributed CSI,” Aug. 2011, arXiv Preprint 1108.3742, [Available online]: <http://arxiv.org/abs/1108.3742>
- [KF10] V. Kotzsch and G. Fettweis, "Interference Analysis in Time and Frequency Asynchronous Network MIMO OFDM Systems", in Proc. IEEE Wireless Communications and Networking Conf., (WCNC'10), April 2010.
- [KRF12] V. Kotzsch, W. Rave and G. Fettweis, Interference Cancellation and Suppression in Asynchronous Cooperating Base Station Systems, in Proc. International Workshop on Smart Antennas, (WSA'12), February 2012, accepted
- [LHL+08] D. J. Love, R. W. Heath, V. K. N. Lau, D. Gesbert, B. D. Rao, and M. Andrews, An Overview of Limited Feedback in Wireless Communication Systems, IEEE Journal on Selected Areas in Communications, vol. 26, no. 8, pp. 1341-1365, Aug. 2008
- [LSC10] N. Lee, W. Shin, and B. Clerckx, Interference Alignment with Limited Feedback on Two-cell Interfering Two-User MIMO-MAC, www.arxiv.org/pdf/1010.0933, 2010.
- [ME11] M. Mishali and Y. C. Eldar, Xampling: Compressed Sensing of Analog Signals, Compressed Sensing: Theory and Applications, Cambridge University Press 2011
- [MF11] P. Marsch and G. Fettweis, Editors, Coordinated Multi-Point in Mobile Communication, Cambridge University Press, 2011
- [MKP07] M. Morelli, C.-C. Kuo, and M.-O. Pun, "Synchronization Techniques for Orthogonal Frequency Division Multiple Access (OFDMA): A Tutorial Review", Proc. IEEE, vol. 95, no. 7, July 2007
- [MTR+11] Y. Medjahdi, M. Terre, D. Le Ruyet, D. Roviras, D., and A. Dziri, Performance Analysis in the Downlink of Asynchronous OFDM/FBMC Based Multi-Cellular Networks, IEEE Trans. on Wireless Communications, Vol. 10, Aug. 2011
- [NGB11] D. Nogu  t, M. Gauthier, and V. Berg, Advances in Opportunistic Radio Technologies for TVWS, EURASIP Journal on Wireless Communications and Networking, Nov. 2011
- [Nok11] Nokia Siemens Networks, Understanding Smartphone Behavior in the Network, White Paper, 2011, [Available: http://www.nokiasiemensnetworks.com/sites/default/files/document/Smart_Lab_WhitePaper_27012011_low-res.pdf]
- [PPN10] M. Payaro, A. Pascual-Iserte, and M. Najar, Performance Comparison between FBMC and OFDM in MIMO Systems under Channel Uncertainty, European Wireless, pp. 1023-1030, April 2010
- [SP10] D. Sacrist  n-Murga and A. Pascual-Iserte, Differential Feedback of MIMO Channel Gram Matrices Based on Geodesic Curves, IEEE Trans. on Wireless Communications, vol. 9, no. 12, pp. 3714-3727, Dec. 2010
- [ST08] C. Suh and D. Tse, Interference Alignment for Cellular Networks, Proc. 46th Annual Allerton Conference on Communication, Control, and Computing, pp. 1037-1044, Sep. 2008
- [SJW11] J. Schreck, P. Jung, and G. Wunder, Compressed Sensing Based Channel State Feedback for Cooperating MIMO-OFDM systems, in 16th International OFDM Workshop, pp. 1-5, Hamburg, Aug. 2011
- [SW11] J. Schreck and G. Wunder, Distributed Interference Alignment in Cellular Systems: Analysis and Algorithms, Proc IEEE European Wireless, pp. 1-8, April 2011

- [SW12a] J. Schreck and G. Wunder, Iterative Interference Alignment for Cellular Systems with User Selection, to appear in IEEE 37th International Conference on Acoustics, Speech, and Signal Processing (ICASSP), pp. 1-4, March 2012
- [SW12b] J. Schreck and G. Wunder, Interference Alignment Over Limited Dimensions for Cellular Networks: Feasibility and Algorithms, IEEE ITG Workshop on Smart Antennas, Dresden, March 2012
- [THE+10] G. Taubock, F. Hlawatsch, D. Eiwen, and H. Rauhut, Compressive Estimation of Doubly Selective Channels in Multicarrier Systems: Leakage Effects and Sparsity-Enhancing Processing, IEEE Journal of Selected Topics in Signal Processing, vol. 4, no. 2, pp. 255-271
- [Wil11] T. Wild, Comparing coordinated multi-point schemes with imperfect channel knowledge, in Proceedings of IEEE VTC Fall 2011, San Francisco, Sep. 2011
- [WJ04] T. A. Weiss and F. K. Jondral, Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency, IEEE Communications Magazine, vol. 42, no. 3, pp. 8-14, Mar. 2004
- [WS10] G. Wunder and J. Schreck, A Robust and Efficient Transmission Technique for the LTE Downlink, Proc. 44th Annual Asilomar Conference on Signals, Systems, and Computers, Monterey, USA, Nov. 2010
- [WS12] G. Wunder, J. Schreck, and P. Jung, Nearly Doubling the Throughput of Multiuser MIMO Systems Using Codebook Tailored Limited Feedback Protocol, IEEE Trans. on Wireless Communications, Dec. 2013, www.arxiv.org/pdf/1107.2101
- [ZMM+08] H. Zhang, N. Mehta, A. Molisch, J. Zhang, and H. Dai, Asynchronous Interference Mitigation in Cooperative Base Station Systems, IEEE Trans. Wireless Communications, vol. 7, no. 1, Jan. 2008
- [Gröc01] K. Gröchenig, Foundations of Time-Frequency Analysis. Birkhäuser, 2001
- [BHW98] J. J. Benedetto, C. Heil, and D. F. Walnut, "Gabor Systems and the Balian-Low Theorem," in Gabor Analysis and Algorithms, H. G. Feichtinger and T. Strohmer, Eds. Birkhäuser, 1998, ch. 2, pp. 85–122.
- [MMG+14] Michailow, N.; Matthe, M.; Gaspar, I.S.; Caldevilla, A.N.; Mendes, L.L.; Festag, A.; Fettweis, G., "Generalized Frequency Division Multiplexing for 5th Generation Cellular Networks," Communications, IEEE Transactions on , vol.62, no.9, pp.3045,3061, Sept. 2014
- [Farh11] B. Farhang-Boroujeny, "OFDM versus filter bank multicarrier," IEEE Signal Processing Magazine, April 2011, pp. 92-112.
- [KWJ+14] Kasparick, Martin; Wunder, Gerhard; Jung, Peter; Maryopi, Dick, "Bi-orthogonal Waveforms for 5G Random Access with Short Message Support," European Wireless 2014; 20th European Wireless Conference; Proceedings of , vol., no., pp.1,6, 14-16 May 2014
- [Wun14] Wunder, G.; Jung, P.; Kasparick, M.; Wild, T.; Schaich, F.; Chen, Y.; Brink, S.T.; Gaspar, I.; Michailow, N.; Festag, A.; Mendes, L.; Cassiau, N.; Ktenas, D.; Dryjanski, M.; Pietrzyk, S.; Eged, B.; Vago, P.; Wiedmann, F., "5GNOW: non-orthogonal, asynchronous waveforms for future mobile applications," *Communications Magazine, IEEE* , vol.52, no.2, pp.97,105, February 2014
- [PLK06] Ping, Li; Liu, Lihai; Wu, Keying; Leung, W.K.; "Interleave-Division Multiple-Access," IEEE Trans. Wireless Commun., Vol. 5, No. 4, pp. 938–947, Apr. 2006.
- [CSW14] Y. Chen, F. Schaich, T. Wild, "Multiple Access and Waveforms for 5G: IDMA and Universal Filtered Multi-Carrier", IEEE VTCs'14, Seoul, Korea, May 2014
- [SW14] F. Schaich and T. Wild, "Relaxed Synchronization Support of Universal Filtered Multi-Carrier including Autonomous Timing Advance," ISWCS Workshop on Advanced Multi-Carrier Techniques for Next Generation Commercial and Professional Mobile Systems, Aug. 26-29, 2014, Barcelona, Spain

- [Bel10] M.Bellanger, et al. "FBMC physical layer: a primer," <http://www.ict-phydyas.org>, 2010
- [VWS+13] V. Vakilian, T. Wild, F. Schaich, S.t. Brink, J.-F. Frigon, "Universal-Filtered Multi-Carrier Technique for Wireless Systems Beyond LTE", 9th International Workshop on Broadband Wireless Access (BWA) @ IEEE Globecom'13, Atlanta, GA, USA, December 2013.
- [WJW14] G. Wunder, P. Jung, C. Wang, „Compressive Random Access for Post-LTE Systems“, IEEE ICC Workshop on Massive Uncoordinated Access Protocols, Sydney, Australia, June 10-14, 2014
- [SWJ14] J. Schreck, G. Wunder, and P. Jung, "Robust Iterative Interference Alignment for Cellular Networks with Limited Feedback", IEEE Transactions on Wireless Communications, to appear 2015, available at <http://arxiv.org/abs/1308.6750>
- [SWJ13] G. Wunder, J. Schreck, and P. Jung, "Distributed Interference Alignment with Limited Feedback for Cellular Networks", International Workshop on Emerging Technologies for LTE-Advanced and Beyond-4G, IEEE Globecom'13, Atlanta, GA, USA, Dec. 2013

--- End of Document ---