5G WIRELESS COMMUNICATION SYSTEMS:
PROSPECTS AND CHALLENGES

5GNOW: Non-Orthogonal, Asynchronous Waveforms for Future Mobile Applications

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ABSTRACT

This article provides some fundamental indications about wireless communications beyond LTE/LTE-A (5G), representing the key findings of the European research project 5GNOW. We start with identifying the drivers for making the transition to 5G networks. Just to name one, the advent of the Internet of Things and its integration with conventional human-initiated transmissions creates a need for a fundamental system redesign. Then we make clear that the strict paradigm of synchronism and orthogonality as applied in LTE prevents efficiency and scalability. We challenge this paradigm and propose new key PHY layer technology components such as a unified frame structure, multicarrier waveform design including a filtering functionality, sparse signal processing mechanisms, a robustness framework, and transmissions with very short latency. These components enable indeed an efficient and scalable air interface supporting the highly varying set of requirements originating from the 5G drivers.

WHAT DRIVES 5G?

Bigger, faster, higher? The appetite for broadband has clearly fueled the development of mobile cellular networks. On the other hand, the successful deployment of killer applications in the past 20 years has had a major impact on the markets as well: First and foremost, the need for untethered telephony and, with it, wireless real-time voice communication has dominated the success of cordless phones, followed by the first generation (1G) of cellular communications. Soon, incorporated in (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) and the widespread market adoption of laptop computers, Internet data connectivity became interesting to anyone, opening up the opportunity for creating a market for the next killer application in 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, offering high bandwidth access to wireless users with the world's information at their fingertips everywhere and at any time. This is the scenario of the current 4G, so called Long Term Evolution-Advanced (LTE-A). Smartphones are undoubtedly the focus of service architectures for future mobile access. Now, is there a killer application for 5G on the horizon?

5G APPLICATION REQUIREMENTS

Fundamental research for 5G is well underway.[1] The main drivers are:

- **Internet of Things (IoT)**: The IoT will certainly play a key role, but business models have not started off yet. The main challenge is the scalability problem with more than, say, 100,000 machine-type communication (MTC) nodes in a cell under the premises of low cost (below \$10 per radio module) and long lifetime (greater than 10 years). The IoT could change the way we see the Internet as a human-to-human interface toward a more general machine-to-machine platform.
- **Gigabit wireless connectivity**: For example, users might request quick downloads of 3D streaming content (e.g., from a wireless data kiosk) with data rates on the order of ~100 Mb/s. Thereby, download times are expected to be 100

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[1] *METIS project (https://www.metis2020.com) and 5GNOW project http://www.5gnow.eu)*

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The main hypothesis of this article is that the underlying design principles — synchronism and orthogonality — of the PHY layer of today's LTE-A radio access network constitute a major obstacle for the envisioned service architecture.

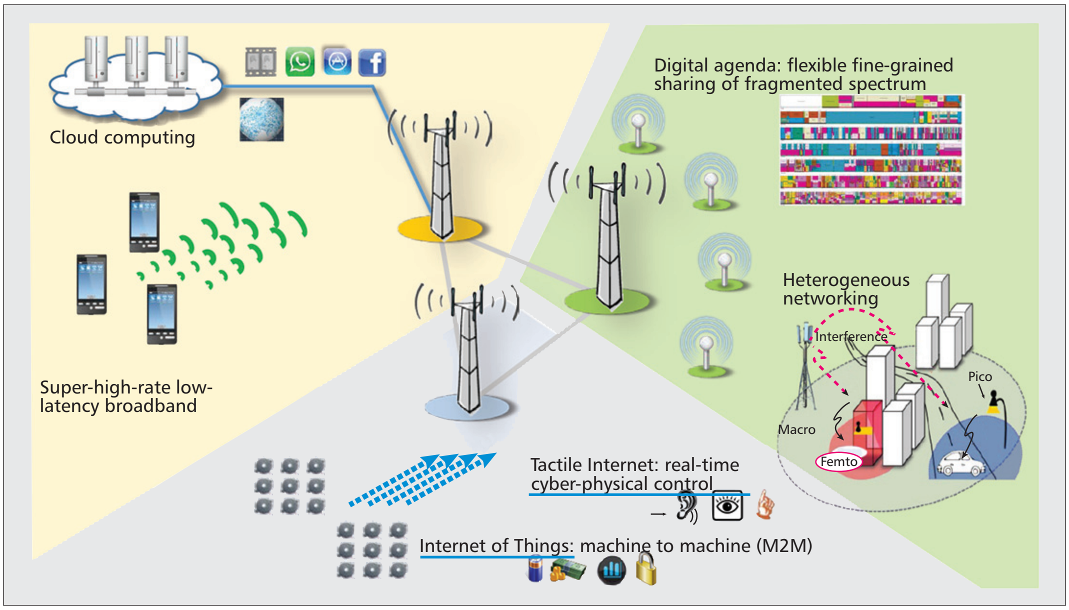

Figure 1. *Exemplary 5G application scenario where the radio access must cope with very different requirements.*

times faster, thus on the order of ~10 Gb/s. Gigabit wireless connectivity is also expected in large crowd gatherings with possibly interactively connected devices (smartphones, tablets, etc.).

•**Tactile Internet**: It comprises a vast amount of real-time applications with extremely low latency requirements. Motivated by the tactile sense of the human body, which can distinguish latencies on the order of 1 ms accuracy, 5G can then be applied to steering and control scenarios, implying a disruptive change from today's content driven communications; popular ideas range from virtual overlay of context information on a display, through robotics and health care to vehicle safety and smart city applications. As derived in [1], a 1 ms round-trip time for a typical tactile interaction requires a time budget of maximum 100 µs on the physical (PHY) layer. This is far shorter than current wireless cellular systems allow, missing the target by nearly two orders of magnitude.

… and probably many more. The envisioned 5G service architecture is depicted in Fig. 1.

From a technical perspective, it seems to be the utmost challenge to provide uniform service experience to users under the premises of heterogeneous networking or future small cell scenarios. Not only must the network operators be well prepared to take on the challenge of a much higher per-user rate and increasing overall required bandwidth, but also to realize service differentiation with very different (virtually contradictory) application requirements. Consequently, the radio access has to be *flexible*, *scalable*, *content-aware*, *robust*, *reliable*, and *efficient in terms of energy and spectrum*. Actually, with the limitations of current 4G systems outlined below, the requirements will put further pressure on the common value chains on which the operators rely in order to compensate for investment costs for future user services. Hence, there is a clear motivation for an innovative and in part disruptive redesign of the PHY layer.

Before we discuss in the following section why LTE-A orthogonal frequency-division multiplexing (OFDM) waveforms fall short in view of 5G requirements, let us briefly comment on the architectural view (which is not the focus here). As schematically addressed in Fig. 1, a densification of cellular systems as well as a deployment of light base stations (BSs) together with resource pooling and data aggregation (*cloud computing*) will take place in the future. It is important to note that 5G application requirements and cloud-based architectural elements are not fully independent. For example, the tactile Internet with its extremely low latency requirements requires baseband processing unit(s) relatively near the terminals with its *real-time app*. This means that for such an application the cloud cannot be in a remote area but must be within a certain radius of the application (hence, by the speed of light and the 100 µs budget on the PHY layer, the real-time constraints results in a maximal cell radius of 30 km).

WHY DO WE NEED NEW WAVEFORMS?

The main hypothesis of this article is that the underlying design principles — synchronism and orthogonality — of the PHY layer of today's LTE-A radio access network constitute a major obstacle for the envisioned service architecture. Synchronism means that the senders operate with a common clock for their processing. Orthogonality means that no crosstalk occurs in the receivers' waveform detection process. Often, both are related such that some "rough" synchronization is required to establish orthogonality. LTE-A OFDM modulation keeps the subcarrier waveforms orthogonal even after the channel, provided the discrete Fourier transform (DFT) window can be properly adjusted by a suitable synchronization mechanism, which is then near optimal processing in a single cell if a capacity achieving scheme such as superposition coding is used per subcarrier. However, as soon as the orthogonality is destroyed (e.g., due to random channel access or multi-cell operation), the distortion accumulates without bounds in OFDM. This is due to the so-called reproducing Dirichlet kernel $sin(Nx)/sin(x)$ of OFDM, which quickly approaches the $sin(x)/x$ kernel for large N where N is the number of subcarriers. For such a kernel, it is well known that the amplification of small errors (e.g., due to sampling or frequency offsets) is *not* independent of N and can grow with order $\log(N)$. Hence, we believe it is better to abandon strict orthogonality partially or altogether and control the impairments instead.

Let us discuss several intriguing examples.

SPORADIC TRAFFIC

Sporadic traffic generating devices (e.g., MTC devices in the IoT) should not be forced to be integrated into the bulky synchronization procedure of LTE-A PHY layer random access, which has been deliberately designed to meet orthogonal constraints. Instead, ideally, they awake occasionally, and then should transmit their messages right away and only coarsely synchronized. By doing so, MTC traffic would be removed from standard uplink data pipes with drastically reduced signaling overhead. Therefore, alleviating the synchronism requirements can significantly improve operational capabilities and network performance as well as user experience and lifetime of autonomous MTC nodes.

Interestingly, sporadic access poses another significant challenge to mobile access networks due to an operation known as *fast dormancy*. Fast dormancy is used by smartphone 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. A rough estimation yields that 2000 control resource elements (i.e., a subcarrier) can be necessary to deliver one data resource element.

We conclude that sporadic traffic must be carried by non-orthogonal waveforms for asynchronous signaling in the uplink and specifically in an uplink random access channel (RACH). We outline later a suitable *sparse signal processing concept* together with new waveforms to efficiently deal with the sporadic traffic and control signaling problem. In fact, the ratio of control and data can actually be reversed by such a concept to approach a value below 5 percent within a single sub-frame.

SPECTRAL AND TEMPORAL FRAGMENTATION

Due to fragmentation, spectrum is scarce and expensive but also underutilized: this is commonly referred to as the *spectrum paradox*. Therefore, carrier aggregation will be implemented to achieve much higher rates by variably aggregating non-contiguous frequency bands [2]. Carrier aggregation implies the use of separate RF front-ends accessing different channels, thereby reinforcing the attraction of isolated frequency bands such as the L-Band. Actually, the search for new spectrum is very active in Europe and the United States 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. Moreover, techniques to detect and assess channel vacancy using cognitive radio could well make new business models possible in the future. The first real implementation will start with the exploration of TV white spaces in the United States. Combined with the preparation of the ongoing regulatory framework in Europe, opportunistic use of spectrum can address a 5G market if it overcomes, with spectrum agility, the rigorous implementation requirements of low out-of-band radiation for protection of legacy systems [2].

The LTE-A waveform imposes generous guard bands to other legacy networks 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. Moreover, in a scenario with *uncoordinated interference* from pico- or femtocells and highly overlapping coverage, it seems illusive to provide the degree of coordination to maintain synchronism and orthogonality in the network calling for new waveforms as well. In addition to spectral fragmentation, temporal fragmentation is another key issue (e.g., due to sporadic access in the asynchronous uplink RACH). Notably, asynchronous signaling also matters in the downlink in the context of cooperative multipoint (CoMP).

In conclusion, such 5G scenarios where multiple users are allocated a pool of frequencies with relaxed (or even no) synchronization in time must be addressed by new waveforms. Such waveforms must implement sharp frequency notches and tight spectral masks in order not to interfere with other legacy systems, and must be robust to asynchronous signalling and handle uncoordinated interference. Traditional OFDM schemes are not suited due to the inflexible handling of guard intervals (GIs) — cyclic prefixes (CPs) or cyclic suffixes (CSs) — as well as poor spectral localization. In a later section we discuss waveforms achieving 100× better localization (e.g., 35 dB side lobe with LTE-A OFDM compared to 55 dB side lobe with filter bank multicarrier (FBMC) [8]), which thus makes a real difference in fragmented spectrum and CoMP scenarios.

REAL-TIME CONSTRAINTS

Fourth-generation systems offer latencies of multiple 10 ms between terminal and BS that originate from resource scheduling, frame processing, retransmission procedures, and so on. However, future application scenarios such as the tactile Internet scenario require ultra-low latency matched with the human tactile sense. In such an environment, a massive number of dis-

Sharing the medium becomes an additional challenge and imposes short wake up cycles on the nodes and the use of burst transmission. Instead of consuming spectrum and power resources by introducing sophisticated algorithms to reach synchronism, an asynchronous approach appears promising.

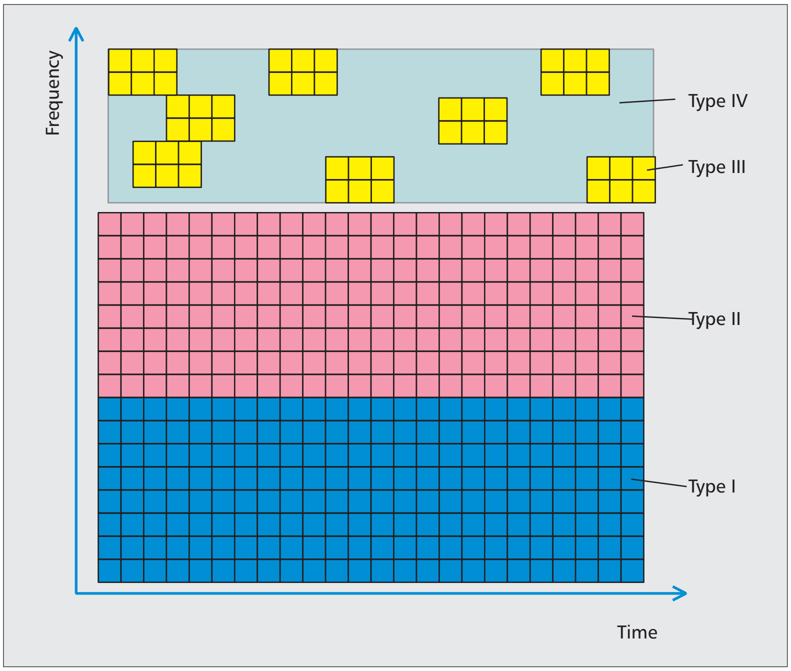

Figure 2. *The 5G vision of a unified frame for different types of traffic. Types I and II represent high rate data for video with possible non-orthogonal advanced receiver processing for cell edge or CoMP users for the second type. Type I possibly also carries real-time traffic. Types III and IV is sporadic asynchronous MTC traffic, possibly containing an energy-efficient spreading element, for example, for sensors in the case of Type IV, as schematically indicated by the green shade.*

tributed sensors and actuators will be connected to enable real-time tactile interaction in an augmented way. Sharing the medium becomes an additional challenge and imposes short wake-up cycles on the nodes and the use of burst transmission. Instead of consuming spectrum and power resources by introducing sophisticated algorithms to reach synchronism, an asynchronous approach appears promising.

In order to achieve ultra-low latency, each and every element of the communication and control chain must be optimized. Focusing on the PHY layer, an LTE-A system supports different granularity of scheduling resources in a fixed transmission time interval (TTI) of 1 ms. TTI represents an inherent lower bound of the LTE-A system's PHY latency. Clearly, as the time budget on the PHY layer in the tactile Internet scenario is 100 μs maximum, frame duration must be reduced, and LTE-A with its OFDM symbol duration of 67 μs is not an option. In order to discuss possible alternatives, assume 20 μs symbol duration. This means that a frame is composed of five symbols, allowing for an appropriate frame structure for random channel access. Considering, say, a 1 km cell range, the expected delay spread is around 3 μs; thus, 4 μs CP is required to ensure an intersymbol interference (ISI)-free scenario. Hence, use of conventional OFDM entails 20 percent loss in spectral efficiency. A non-orthogonal waveform that allows for transmitting multiples symbols with a single CP relaxes such strict time domain requirements.

Another major drawback caused by short frames is the fixed bandwidth increment required to keep a given throughput. A flexible non-orthogonal multicarrier waveform also allowing for intercarrier interference (ICI) can use non-proportional subcarrier spacing to accommodate the necessary bandwidth. Alternatively, non-contiguous spectrum can be aggregated, again enabled by the low out-of-band emissions of the non-orthogonal waveform.

Short frames also have a positive impact on mobility support and operational frequencies. LTE-A has been designed to support Doppler spread of 100 Hz caused by 50 km/h mobility. By reducing the frame duration, it is possible to either support higher mobility or operate in a higher frequency range. Finally, a short frame brings benefits to upper protocol layers: although the latency requirements of real-time applications demand a robust PHY layer to avoid retransmissions of the frame, applications may desire acknowledged signaling. A short frame will enable the implementation of less time-consuming retransmission algorithms.

Summarizing, although OFDM could be tuned to address different granularity of scheduling resources, there is no mode in the current LTE-A standard that can adapt to the latency requirements of real-time services running on top. If the symbol duration is reduced to achieve very short round-trip delays, the GIs cannot be scaled accordingly without severely compromising spectral efficiency or cell size. Required flexibility can only be achieved with new waveforms, as shown in a later section.

ELEMENTS OF 5G PHYSICAL LAYER ARCHITECTURE

In this section, we describe selected PHY elements that can overcome the technological challenges.

UNIFIED UPLINK FRAME STRUCTURE VISION

A 5G approach must be able to efficiently support different traffic types, which all have to be part of future wireless cellular systems. Our vision of a unified frame structure concept, depicted by Fig. 2, aims to handle the large set of requirements in a single 5G system. A filtered multicarrier approach will enable the mix of synchronous/asynchronous and orthogonal/non-orthogonal traffic types, where the reduced side-lobe levels of the waveform seek to minimize ICI and ISI. The classical bit pipe traffic (type I) with high-volume data transmission and high-end spectral efficiency still exploits orthogonality and synchronism wherever possible (e.g., when serving cell center users). This bit pipe might also be a potential real-time carrier. Vertical layering at common time-frequency resources generates a non-orthogonal signal format supporting heterogeneous cell structures and cell edge transmissions more efficiently. For high-volume data applications in those cell areas (type II), a multi-cell multi-user transceiver concept is required. The principle of interleave-division multiple access (IDMA), initially published in [3], is a very appealing approach to generating these signal layers, and an elegant receiver and coding concept for it.

MTC is expected to be one dominant application of 5G systems. For this sporadic traffic type (type III), a contention-based access technique is attractive, saving overhead by dropping the strict synchronism requirement. For sensor-type traffic (type IV), the open Weightless initiative (http://www.weightless.org/) has shown that, from an energy-efficiency perspective, it is beneficial to stretch the transmissions in time by spreading. This additional signal layer, again, can be handled by an IDMA-like approach.

Dealing with Heterogeneous Traffic Types

Universal filtered multi-carrier (UFMC) is a recently introduced technique [10] generalizing filtered OFDM [8], where the filtering is done over the entire frequency band, and FBMC (staggered multitone, SMT) [8], where the filtering is done on a subcarrier level. One of the design criteria of UFMC is to collect the advantages of filtered OFDM and FBMC while avoiding the respective disadvantages, thereby trading off the filtering functionality between the two techniques. Typically, UFMC filtering is performed per sub-band comprising multiple subcarriers, for example, per physical resource block (PRB), which suppresses the spectral side-lobe levels and thus the ICI between different resource blocks stemming from, say, lack of synchronism or carrier frequency offsets (CFOs). Another advantageous effect of filtering per sub-band instead of per subcarrier is that the filter length may be significantly shorter than that of FBMC due to the larger sub-band bandwidth (e.g., in the order of the OFDM cyclic prefix). Hence, the UFMC waveform is also an appealing technique for communication with short bursts, as in MTC. Additionally, quadrature amplitude modulation (QAM) may be efficiently used instead of offset QAM, compulsively adopted by FBMC.

In the unified frame structure vision, illustrated in Fig. 2, different traffic types are served by the network, both synchronous and asynchronous. In order to effectively deal with ICI and ISI at the allocation edges of those traffic types, a new waveform and frame structure approach beyond OFDM is required. For that purpose, Fig. 3 provides simulation results for a two-user (one is at the cell edge) uplink FDMA scenario, demonstrating the superiority of UFMC over OFDM for allocation edges with different timings, as appear in the universal frame structure. UFMC uses filters that are Dolph-Chebyshev-shaped (with 40 dB side-lobe attenuation which comes on top of the sinc-shaped spectral side-lobe level attenuation). For delays outside the CP, UFMC clearly outperforms OFDM. Furthermore, it has a symmetric characteristic of MSE vs. delay. This allows, in the absence of closed-loop timing control (which costs energy and signaling overhead, being undesirable e.g., for MTC) better support of open-loop timing control mechanisms. The device uses the downlink pilot signals by the BS for a rough synchronization and applies further corrections based, for example, on estimated cell size. Device signals arriving "too early" cause much less degradation in UFMC than in OFDM. Thus, in this scenario at the allocation edge between two traffic types, UFMC shows clear advantages over OFDM. Furthermore, the UFMC technique was already successfully demonstrated in an uplink CoMP scenario [10].

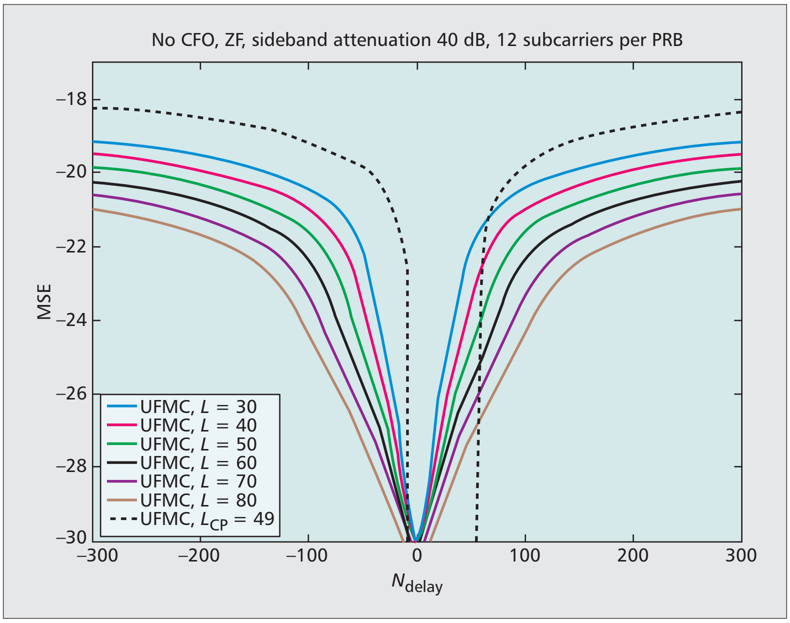

Figure 3. *Comparison of UFMC with different filter lengths (30–80) against CP-OFDM: mean squared error (MSE) in the presence of two allocated asynchronous users on adjacent bands, each using three PRBs, having a timing offset of* N_{delay} *(in samples), with FFT length 1024.* L *denotes the UFMC filter length in samples,* L_{CP} *the OFDM cyclic prefix length.The MSE is caused by both ISI and ICI.*

Sparse Signal Processing

The application of sparse signal processing methodology for detection and demodulation of MTC traffic in the PHY layer RACH benefits from the "bursty" nature of signals that are in a mathematical sense "sparse," that is, they can be described by a small set of parameters within a much larger set of observables [12, 13]. Similar to the mobile channel, a typical realization of a doubly dispersive channel is described by only a limited number of time-frequency shifts. It is then a fundamental question of how many observables the BS needs to recover 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 [11]. Moreover, recent results suggest that beyond conventional thinking in compressed sensing, joint "sparsity" of the messages and channels is additive rather than multiplicative [15]. One of the intriguing ideas is to make sparse signal processing available for 5G RACH, exploiting joint "sparsity" of messages, mobile channels, and user activity.

In our system concept, RACH dimensioning in the uplink can be basically the same as in LTE-A (1.08 MHz of 20 MHz total bandwidth). In contrast to LTE-A, the RACH performs terminal identification, channel estimation, as well as equalization and demodulation at the same time within a single subframe. Thanks to the sparse structure of channels, the underlay control signaling over the whole uplink bandwidth, and sparse signal processing at the receiver, the BS is able to process all signals including the payload traffic (of different classes; Fig. 2) over the whole uplink bandwidth (Fig. 4). Indeed, our results and analysis show that terminals can be identified with very high probability (on the order of LTE-A) and, additionally, can transmit payload data within a single subframe over the full bandwidth with reasonable "raw" symbol error rates. The actual supported number of terminals then depends on the cell size, actual channel profiles, and actual user activity.

CoMP Robustness Framework

In cellular systems, cell edge users suffer from high distances from their serving BS and strong interference from neighboring cells, drastically impacting the total cell throughput. Cooperation between neighboring cells (CoMP), where users at the border of the cell are served by at least two BSs, is an efficient way to deal with this issue and allows exploiting the available spatial degrees of freedom (DoF) more efficiently, leading to increased system capacity in future cellular wireless communication networks [4]. However, such an approach entails huge additional overhead in terms of backhaul message sharing, BS synchronization, feedback of channel state information (CSI), forwarding of control information, and so on. On top, the approach is known to lack robustness against the actual extent to which 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, even constraining the potential services in the network due to extensive uplink capacity use for control signaling [4]. The CoMP robustness framework for new waveforms is a means to overcome current limitations.

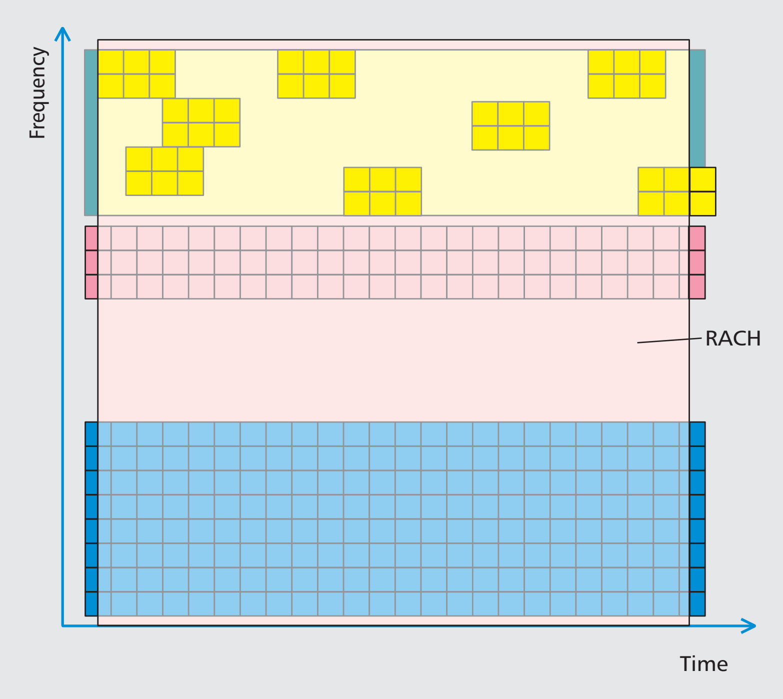

Figure 4. *The unified frame structure shall be controlled by an advanced 5G RACH that is able to "illuminate" the full available uplink bandwidth by observing a small observation window and using underlay signaling as well as sparse signal processing (schematically indicated by the red shade).*

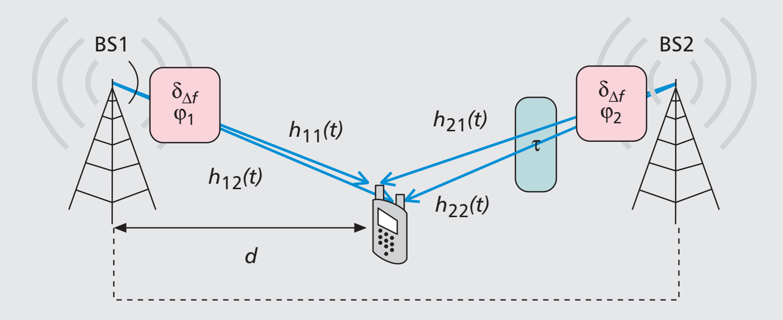

Figure 5. *The CoMP downlink synchronization problem.*

Time and Frequency Synchronization — The first major issue with CoMP is time and frequency synchronization between the serving BSs and the user equipment (UE). Figure 5 describes the problem with two BSs. We focus here on the downlink, but the same kind of synchronization issues arise in the uplink. The signal from BS2 is received at the UE with a delay τ compared to the signal from BS1, reflecting the over-the-air propagation delay. $\delta_{\Delta f}$ is the carrier frequency offset (CFO) between each BS and the UE. ϕ_i is a random initial phase, and $h_{ij}(t)$ is the channel response (exponential decay model) between BS antenna i and UE antenna j.

OFDM requires a CP at least as long as the delay τ to efficiently compute channel estimation and perform equalization, leading to a loss of spectral efficiency. By contrast, due to the length of the prototype filter (typically several times the length of the OFDM window), FBMC symbols can deal with high delays without the use of a CP. In [9], it was demonstrated that with the LTE-A 10 MHz parameters and an overlapping factor of 4, delays τ up to 7.8 μs can be tolerated with FBMC without loss of performance. To reach such a performance, OFDM would require a CP longer than 120 samples, which is 11.7 percent of the symbol length! In order to deal with longer delays, τ must be estimated at the UE and corrected at the BSs. For this aim, [9] proposes a robust algorithm with very low feedback that is able to manage delays up to 230 time samples.

The estimation and compensation of the CFO (i.e., frequency synchronization) can be entirely realized at the receiver without any need for feedback information to the BSs. Thanks to the very good frequency localization of the FBMC prototype filter, CFOs up to 15 times the carrier spacing (considering an overlapping factor of 4) can be estimated in two steps [9]. The first step is a low-complexity energy detection mechanism performed on the carriers of the received preamble; the second step schematically consists of an estimation of the phase of the scalar product of two vectors of N carriers. The residual CFO after estimation and compensation with this method was shown to be lower than 0.15 percent of the carrier spacing with N high ($N = 560$) and lower than 0.3 percent with a

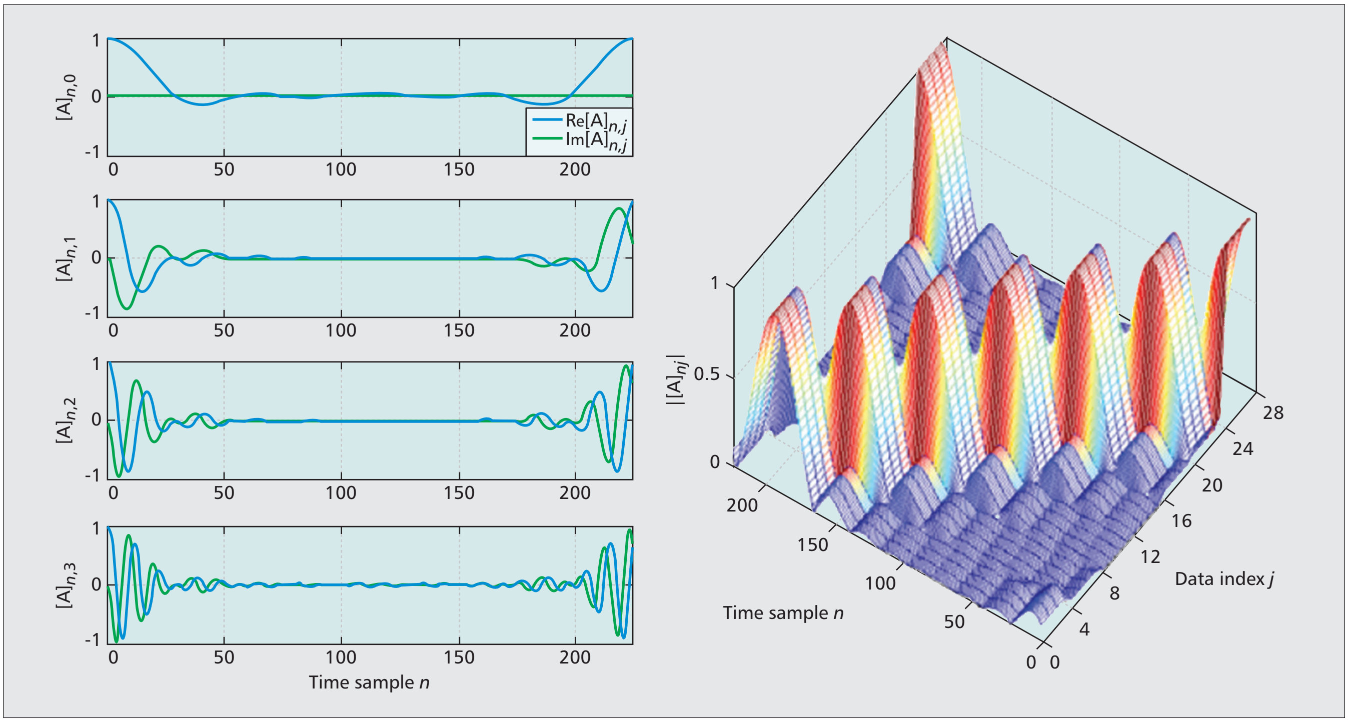

Figure 6. *View of the GFDM frame structure based on the self-contained block for four subcarriers and seven time slots. The left part shows the transmit filter impulse responses for each subcarrier of the first time slot, while the right side shows the transmit matrix A where it is possibe to observe the time slot blocks with* K *subcarriers. A contains all* MK *impulse responses used to transmit the data symbols of the GFDM frame.*

smaller complexity ($N = 140$), even with high delay τ.

Imperfect CSI — Another major problem is the limited feedback problem and corresponding imperfect channel state information for CoMP scenarios. The limited feedback problem has been considered for multiuser multiple-input multiple-output (MU-MIMO) communications [5] as well as for joint transmission and interference alignment [14], all of them in the infinite signal-to-noise ratio (SNR) regime, thereby essentially carrying out a system's DoF analysis. Even though analytic treatment has made significant progress in the past, the DoF approach cannot really account for the throughput degradation experienced in practice. The main reasons for this are:

1. Infinite SNR regime where achieving DoF is optimal (in this operational regime interference mitigation instead of signal enhancement is the primary goal)
2. No user selection (the optimal scheduling decision is known)
3. Ideal link adaption (rate allocation is always considered optimal)

Altogether, this renders the performance analysis overly optimistic, motivating new waveform analysis for the limited feedback problem.

In [5] a new direction is developed that bears great potential for the envisioned robustness framework. The main idea in this work is to exploit the structure of the transmit signals (in this case the spatial transmit codebook) and 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 [5] in a non-cooperative multicell network. In [14] the work was generalized to CoMP, introducing new metrics using non-standard (and robust) alignment conditions better suited to deal with the practical impairments of a 5G PHY layer. In this generalization other MAC-related "asynchronisms" (e.g., outdated CSI) can be collected easily and incorporated as well.

ACHIEVING VERY SHORT LATENCY

Generalized frequency-division multiplexing (GFDM) [6, 7] is a recent PHY layer scheme designed to overcome the major broadband and real-time challenges for 5G systems. The basic idea of GFDM lies in the transmission of a block frame composed by M time slots with K subcarriers. Each subcarrier is filtered within a GFDM block, and the filter impulse response plays an important role in the system (Fig. 6). Since the transmit filter impulse response is not restricted to be rectangular, there might be ICI among adjacent subcarriers, and ISI might arise if the combined transmit and receive filters do not fulfill the Nyquist criteria. However, the proper choice of the pulse shape and appropriate interference canceling algorithms in the receiver enable GFDM to match the performance of OFDM in additive white Gaussian noise (AWGN) channels and even outperforms OFDM in severe frequency-selective channels

From a base station point of view, new dimensions of processing capabilities are enabled by a change from mere transistor scaling to 3D integration of chips with wireless high-speed interconnection among the chips outperforming todays processing by a factor of at least 10E5.

when a frequency domain equalizer is employed. In order to avoid long filter tails and keep the GFDM frame contained within *MN* samples, a technique called tail biting is employed. This means that GFDM uses circular convolution in the filtering process instead of the linear convolution used by FBMC. This procedure leads to several advantages. The block frame structure allows adding cyclic prefix and suffix, relaxing the requirement of time domain synchronization. Also, a single CP protects the information contained in *M* time slots and results in higher spectral efficiency compared to OFDM.

The low latency requirement, which is the major challenge in the tactile Internet scenario, can be fulfilled by GFDM due its flexibility and block structure, which can be seen as a datagram. Since the amount of information to be transmitted in this scenario is small, a GFDM frame can be designed to fit the 100 μs time budget; and if the throughput must be increased, non-continuous subcarrier allocation or non-proportional subcarrier spacing can be used to accommodate the extra data rate. It is important to notice that GFDM can still efficiently employ CP and CS even with a 100 μs time budget for the frame duration. The use of CP and CS in GFDM relaxes the frame synchronization demands between multiple users and also in a CoMP scenario. The GFDM block structure also brings an important benefit in the random access channel scenario. In an asynchronous real-time network, the capacity to correctly detect when a new communication process has started is mandatory. Special sequences with impulse self-correlation properties can be used as preamble of the GFDM frame, allowing for an efficient communication initialization procedure. Therefore, GFDM is a key candidate for the PHY layer of the next generation cellular system, capable of addressing all types of communications foreseen for the 5G networks.

CONCLUSIONS

The basic concepts presented in this article dismiss the widely unquestioned credo of strict synchronism and orthogonality in cellular networks, and instead introduces a broader non-orthogonal robustness concept incorporating the overall required control signaling and the applied waveforms in a joint framework. 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 control these impairments by a suitable transceiver structure and transmission technique. Several waveform approaches such as UFMC, FBMC, and GFDM — all of them with disruptive advantages over OFDM — are presented and put in exemplary scenarios such as service differentiation, spectrum agility, CoMP, and real-time transmission. For these scenarios we have clearly outlined the benefits of non-orthogonal asynchronous waveforms over conventional OFDM modulation. Corresponding advanced sparse signal processing and robustness framework complement the new concepts.

We are aware that the technological challenges are manifold and require advanced and, most likely, more complex transceiver designs. Fortunately, due to the evolving silicon processing capabilities, following Moore's law, it is self-evident that 5G inner receivers will have plenty of headroom for complexity increases, compared to 3.5G–4G, as needed for processing non-orthogonal asynchronous signals. Moreover, from a base station point of view, new dimensions of processing capabilities are enabled by a change from mere transistor scaling to 3D integration of chips with wireless high-speed interconnection among the chips outperforming today's processing by a factor of at least 10E5.

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