Contribution to PHY and MAC layers for GFDM in the context of Cognitive Radio

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Abstract

The soaring increase of data consumption in the last ten years has brought communication networks to a saturation point, both in terms of energy consumption and spectrum use. Besides, it has appeared in recent studies that though almost saturated, the spectrum is paradoxically under-used in time because of currently enforced licensing policies. Cognitive Radio (CR) is considered to be the key technology allowing to overcome this issue, as it gives devices and networks more flexibility and intelligence, thus allowing them to adapt to their environment and perform Dynamic Spectrum Access (DSA).

The scenario most commonly depicted for Fifth Generation (5G) networks is a situation where Cognitive Agents (CA) coexist with licensed Primary Users (PUs) in the same geographical areas and on the same frequency bands.

Such a paradigm has repercussions at all layers of the Open Systems Interconnection (OSI) stack. In this work, we focus on the lowest ones. On the PHYsical (PHY) layer, new waveforms have to be designed because the poor spectrum localization of Orthogonal Frequency Division Multiplexing (OFDM) causes too much interference to PUs. On the Medium Access Control (MAC) and Network layers, algorithms have to be deployed to distribute power among subcarriers used by CA to make the best use of the available power budget.

In this dissertation, we first point out the expectancies for 5G, and what waveforms the community has proposed to answer to them so far. Then, we focus on one of them, namely Generalized Frequency Division Multiplexing (GFDM). Its principles and performances are exposed, and we investigate theoretical expressions of its Fourier Transform (FT). Afterwards, power loading related problems are presented. A formerly proposed algorithm is extended to the asynchronous scenario and tested with GFDM. Eventually, further ways to improve the GFDM scheme are presented.
Acknowledgements

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**ADSL** Asymmetric Digital Subscriber Line ........................................ 5
**AP** Access Point ........................................................................ 49
**AWGN** Additive White Gaussian Noise ........................................ 21
**BS** Base Station ........................................................................ 49
**BSSID** Basic Service Set Identifier ............................................... 50
**CDMA** Code Division Multiple Access ........................................... 11
**CBS** Cognitive Base Station ........................................................ 33
**CA** Cognitive Agents ................................................................... 12
**CFO** Carrier Frequency Offset ...................................................... 30
**CR** Cognitive Radio ...................................................................... 11
**CP** Cyclic Prefix ........................................................................... 19
**DSA** Dynamic Spectrum Access .................................................... 9
**DVB-T** Digital Video Broadcasting - Terrestrial ............................... 7
**ED** Energy Detector ...................................................................... 28
**FCC** Federal Communications Commission ..................................... 6
**FDMA** Frequency Division Multiple Access ..................................... 7
**FT** Fourier Transform ................................................................... 1
**FBMC** Filter Bank Multi Carrier .................................................... 17
**FHSS** Frequency Hopping Spread Spectrum .................................. 11
**GFDM** Generalized Frequency Division Multiplexing ....................... 17
**GSM** Global System for Mobile Communications ............................. 5
**HD** High Definition ..................................................................... 1
**ISM** Industrial, Scientific and Medical .......................................... 6

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<td>ICI</td>
<td>Inter Carrier Interference</td>
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<td>ISI</td>
<td>Inter-Symbol Interference</td>
<td>22</td>
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<tr>
<td>IFFT</td>
<td>Inverse Fast Fourier Transformation</td>
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<td>IoT</td>
<td>Internet Of Things</td>
<td>7</td>
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<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
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<td>MAB</td>
<td>Multi Armed Bandit</td>
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<td>MAC</td>
<td>Medium Access Control</td>
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<td>MF</td>
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<td>MMSE</td>
<td>Minimum Mean Square Error</td>
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<td>MTC</td>
<td>Machine Type Communication</td>
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<td>M2M</td>
<td>Machine To Machine</td>
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<td>OQAM-OFDM</td>
<td>Offset Quadrature Amplitude Modulated-Orthogonal Frequency Division Multiplexing</td>
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<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
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<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
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<td>OOB</td>
<td>Out Of Band</td>
<td>2</td>
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<td>OSA</td>
<td>Opportunistic Spectrum Access</td>
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<td>OSI</td>
<td>Open Systems Interconnection</td>
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<td>PAPR</td>
<td>Peak-to-Average Power Ratio</td>
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<td>PC</td>
<td>Personal Computer</td>
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<td>PHY</td>
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<td>PLC</td>
<td>Power-line communication</td>
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<td>PU</td>
<td>Primary User</td>
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<td>QoS</td>
<td>Quality of Service</td>
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<td>RC</td>
<td>Raised Cosine</td>
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<td>RKRL</td>
<td>Radio Knowledge Representation Language</td>
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<td>RRC</td>
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<td>RSS</td>
<td>Received Signal Strength</td>
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LIST OF ACRONYMS

SCEE  Signal, Communications et Electronique Embarquée......................... 51
SC-FDMA  Single Carrier Frequency Division Multiple Access.................. 5
SDR  Software Defined Radio.................................................... 13
SMS  Small Message Service .................................................... 5
SNR  Signal to Noise Ratio.................................................... 22
TCP  Transfer Control Protocol.................................................. 49
TDMA  Time Division Multiple Access ........................................... 6
TFL  Time-Frequency Localization ............................................... 17
VDSL  Very high bit-rate Digital Subscriber Line................................... 5
WAP  Wireless Application Protocol................................................ 5
WRAN  Wireless Regional Area Network........................................... 8
ZF  Zero Forcing............................................................... 21
5G  Fifth Generation.......................................................... 49
## Mathematical notations

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<tr>
<td>$T_s$</td>
<td>Time Symbol</td>
</tr>
<tr>
<td>$K$</td>
<td>Number of subcarriers</td>
</tr>
<tr>
<td>$M$</td>
<td>Number of symbols</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of samples per symbols</td>
</tr>
<tr>
<td>$L$</td>
<td>Number of subcarrier significantly affected by each prototype filter</td>
</tr>
<tr>
<td>$\vec{b}$</td>
<td>Binary data train</td>
</tr>
<tr>
<td>$\vec{b}_c$</td>
<td>Binary encoded data train</td>
</tr>
<tr>
<td>$\vec{d}$</td>
<td>QAM mapped data</td>
</tr>
<tr>
<td>$d_k[m]$</td>
<td>$m^{th}$ symbol transmitted on the $k^{th}$ subcarrier</td>
</tr>
<tr>
<td>$A$</td>
<td>Modulation matrix</td>
</tr>
<tr>
<td>$\tilde{x}$</td>
<td>Modulated signal</td>
</tr>
<tr>
<td>$\tilde{x}_c$</td>
<td>Signal after CP addition</td>
</tr>
<tr>
<td>$\tilde{H}$</td>
<td>Channel convolution matrix</td>
</tr>
<tr>
<td>$\vec{w}$</td>
<td>AWGN vector</td>
</tr>
<tr>
<td>$\tilde{y}$</td>
<td>Transmitted signal</td>
</tr>
<tr>
<td>$\tilde{y}_s$</td>
<td>Received signal after synchronization</td>
</tr>
<tr>
<td>$\tilde{y}_r$</td>
<td>Received signal after CP removal</td>
</tr>
<tr>
<td>$\tilde{z}$</td>
<td>Received signal after equalization</td>
</tr>
<tr>
<td>$B$</td>
<td>Demodulation matrix</td>
</tr>
<tr>
<td>$\hat{X}$</td>
<td>Estimated value of $X$</td>
</tr>
<tr>
<td>$g_{\tilde{r}_x}$</td>
<td>Circularly shifted version of the transmission prototype filter</td>
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<tr>
<td>$\alpha$</td>
<td>Roll-off factor</td>
</tr>
<tr>
<td>$I_{th}$</td>
<td>Interference Temperature</td>
</tr>
<tr>
<td>$d_i$</td>
<td>spectral distance between $i^{th}$ subcarrier and $l^{th}$ PU</td>
</tr>
<tr>
<td>$B_l$</td>
<td>frequency width of $l^{th}$ PU band</td>
</tr>
<tr>
<td>$\Phi_i$</td>
<td>PSD of CA $i^{th}$ subcarrier</td>
</tr>
<tr>
<td>$\delta F$</td>
<td>Frequency offset</td>
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1 Introduction

1.1 Motivation and scope

The progresses made in the field of communications in the last century are easily measurable by looking at the increase of allowable data rate on wireless links. The evolutions of data consumption are presented in Figure 1.1. It appears clearly that the part of data greedy applications has been soaring in the last years. This denotes a fundamental change in the way phones have been used during the last years. This change of behaviour has been allowed by the advent of 3G. The data consumption should keep increasing, as 4G Long Term Evolution (LTE) now allows downlink speeds approaching hundreds of \(Mb/s\) and enables applications such as live High Definition (HD) video streaming or online gaming over the air interface.

Today networks rely on very rigid principles, both at the scale of network organization
and the waveforms that are used to transmit data. The spectrum is shared in a fixed way under the licensing model among telecom operators. This organization is no longer thought to be the most able to make the best use of the spectrum as it leads to a paradoxical situation where licensed users fight to get exclusive rights to parts of the spectrum which are in turn underused on the time and geographical scale [1, 2].

This paradox has given birth to the idea of DSA in which the spectrum is dynamically shared. Sweeping from licensed sharing to this new paradigm involves bringing a lot of new abilities to communication networks and devices. CR, which refers to a number of techniques bringing a certain degree of intelligence to radio devices, is presented as a good way of enabling these newly needed abilities.

This thesis tackles the questions raised by the advent of DSA at different layers. On the physical layer, the crucial choice of a waveform adapted to new scenarios where opportunist users coexist with incumbent ones is tackled. OFDM is the leading multicarrier waveform today, as it is very flexible and can be processed with little complexity through the use of Inverse Fast Fourier Transformation (IFFT) blocks. It has been proposed as a solution for CR systems [3]. However, it suffers from high Out Of Band (OOB) emissions due to the rectangular windowing of the symbols in time domain [4, 5]. This is not adapted to the narrow spectrum masks that CA have to comply with, and there has therefore been a soaring research on new waveforms. We particularly focus on the study of GFDM, a new modulation technique which has much in common with OFDM but abandons subcarriers orthogonality. On the MAC layer, dealing with new, so far unfaced situations involves designing new algorithms. One of the main constraints of CA is to produce little interference onto the bands of the incumbent users. Produced interference computation or analytical expressions is not an easy task, as it depends both on the waveform used and the time [6] and frequency [7, 8] desynchronization between the CA and the PU. Filter Bank Multi Carrier (FBMC) has proven to be a good alternative to OFDM as far as OOB emissions are concerned [4, 6, 7, 9] and therefore being able to achieve a better capacity under same interference constraints. This thesis evaluates GFDM under such a scenario and points out its strengths and weaknesses as a possible candidate for 5G networks.
1.2 Organization of this dissertation

This dissertation tackles the choice of a waveform for 5G networks. The aim is to give a tutorial summary of today challenges in the field of digital communications, give a review of good quality of GFDM and test the latter in comparison with former work. The rest of this dissertation is organized in four chapters which all depict a different aspect of the work I led during these five last months.

- **Chapter 2.** This chapter draws a history of digital communications and details some key features about current networks organization and used waveforms, such as OFDM. 5G expected applications are then presented, as well as the impact they have on the design of future networks. Then, CR is presented as a way to enable them. Finally, different proposed multi-carrier techniques are introduced.

- **Chapter 3.** This chapter aims to draw a state of the art on GFDM by presenting its core principles and system model as well as some implementation and performance issues. Major contributions of this chapter consist of derivation of theoretical expression of GFDM FT.

- **Chapter 4.** This chapter tackles the issue of power loading in CR systems. We present a low-complexity algorithm optimizing power which was introduced in previous work and applied to OFDM and FBMC based systems. We extend it to the asynchronous scenario and apply it to GFDM as a major contribution.

- **Chapter 5.** This chapter sums up our bibliographical reviews and contributions. A general conclusion on the interest of GFDM for 5G is given. Besides, open research fields are pointed out and plans for future work and publications are presented.
2 From analog communications to 5G: evolution of techniques and challenges for the future

2.1 Current paradigm of communication systems

2.1.1 A brief history of communication techniques

Since the democratization of digital communications, the successive generations of technologies have been designed according to the foreseen applications that they were hoped to enable. The first generation, which was solely aiming at transmitting voice signals, made use of purely analog transmission techniques. The second generation, widely known as Global System for Mobile Communications (GSM), made use of digital modulation in order to introduce data transmission services such as Small Message Service (SMS) and Wireless Application Protocol (WAP) protocols in addition to traditional voice communication. With the third generation, transmission techniques achieved data rates suitable for web browsing. Finally, Long Term Evolution (LTE), by making use of OFDM in the downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) in the uplink increased data rates like never before and brought the performances of cellular networks, in terms of throughput, at the level of the wired networks, such as those based on Asymmetric Digital Subscriber Line (ADSL) and Very high bit-rate Digital Subscriber Line (VDSL).

If giving a comprehensive history of communications techniques is in no way the scope of this thesis, it is important to bear in mind that transmission technologies have always been designed according to their expected applications. Therefore, before tackling 5G related issues, it is a good policy to recall in the following lines some key
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2.1.2 Licensed spectrum policy

Today, the spectrum is, with the exception of the Industrial, Scientific and Medical (ISM) band, a rare and expensive resource. Though the cellular nature of networks, as well as sharing schemes such as Time Division Multiple Access (TDMA) have made it possible to reuse the same frequency bands for different users, this policy will never be able to fully use the spectrum resource for two main reasons. The occupation of the spectrum is not homogeneous as most of the transmissions are done on the same bands, which tends to saturate some parts of the spectrum while deserting some others. This is mostly due to the fact that the assignment of frequencies over a national territory cannot optimise its use at all the geographical areas of the said territory. This is shown on Figure 2.1, which represents the spectrum use at a particular geographical area over a wide spectrum band and timespan. A disparity clearly appears, with areas of the spectrum being heavily used whereas other ones are little or even not used.

Besides, the frequencies are currently assigned to users over extended periods of time, whereas the communications are of bursty nature. This involves that during the

Figure 2.1: Spectrum use over large frequency band and timespan [2]
timespan users are assigned a specific band, they are not transmitting 100% of the time. Therefore, a lot of time slots, coined as "white spaces" are free to use, even when there is actually someone transmitting on a certain band. This situation is shown on Figure 2.2. A quick estimation of the time occupation based on this figure gives an approximate use rate of 20%, which is coherent with the conclusions of Federal Communications Commission (FCC) [11].

Therefore, opposed to the common idea that the spectrum is going extinct, there is available spectrum. The question is what assignment policy to adopt to make the best use of it.

### 2.1.3 OFDM: some words on the currently leading multi carrier technique

Today, an important number of communication protocols rely on multicarrier systems. It has indeed numerous advantages: by dividing the signal in multiple spectrum bands, called subcarriers, which are narrower than the channel coherence bandwidth, it is possible to assume a flat channel on every subcarrier, and therefore perform one-tap equalization. It also gives more flexibility to the systems by dividing the spectrum resources into equal parts which can be easily shared among users under some Frequency Division Multiple Access (FDMA) schemes. It is expected that 5G will make extensive use of this kind of techniques. OFDM is currently used in most of the main communication standards, including Digital Video Broadcasting - Terrestrial (DVB-T), ADSL, Power-line communication (PLC), Wi-Fi a/g/n as well as LTE. As such, it is fair to say that OFDM is the currently leading multicarrier technique.

OFDM [12] relies on rectangular shaping of the time symbols, which results in a
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Figure 2.3: Application challenges for 5G [5]

sinus cardinal in the frequency domain. In order to prevent Inter Carrier Interference (ICI), the subcarriers have to be separated by \( \frac{1}{T_s} \), which ensures orthogonality by placing the zero crossings of the sinus cardinal function at the frequencies \( \frac{k}{T_s} \forall k \neq 0 \). Such a scheme is achievable with low complexity through the use of FFT/IFFT blocks. This low complexity implementation is of great interest and explains the success of the OFDM scheme. Besides, Orthogonal Frequency Division Multiple Access (OFDMA) is estimated to be one of the best existing techniques for multiusers scenario [13].

OFDM being so thoroughly implemented in today networks, it has naturally been proposed as a solution for 5G and CR related issues [3]. We now list the expected applications of future networks in order to be able to evaluate the pertinence of using OFDM in those upcoming scenarios.

2.2 Drivers for 5G

The driving applications are manyfold, and as it is presented on Figure 2.3, future networks will probably have to deal with many different use-cases, and therefore many different standards. Throughout the bibliography, five envisioned applications make a consensus, namely Internet Of Things (IoT), tactile Internet, Gigabit connectivity, Fragmented Spectrum management and Wireless Regional Area Network (WRAN) [1,
2.2 DRIVERS FOR 5G

5, 14]

2.2.1 Internet Of Things (IoT)

In this scenario, hundreds or even thousands of small and cheap devices are deployed. A typical application is the building of wide and dense Machine To Machine (M2M) communication networks. All of these devices would therein communicate in a Machine Type Communication (MTC) way. Such communications are usually very sparse and bursty.

That involves a lot of challenges:

- Spectrum sharing, either in a centralized or distributed way, will be very complex due to the very high number of devices possibly wanting to communicate at the same time.

- Such devices should be very cheap and energy efficient, which prevents from using computationally complex procedures or non-energy efficient transmission techniques.

- Synchronization is a major problem in such networks: as complexity should be kept low, heavy synchronization procedures should be avoided. Besides, these devices are supposed to be idle most of the time and wake up only when they have data to transmit - the idle time between two emissions probably ranging from hundreds of milliseconds to seconds. Therefore, they will have to resynchronize with the Base Station (BS) at every wakeup, which emphasizes the need for relaxed synchronization constraints.

2.2.2 Tactile Internet

In this scenario, new interfaces allowing real-time Internet browsing on tactile devices are envisioned. In such a situation, the main constraint is the round trip delay between the user impulse and the answer provided by the network. It should be kept below 1 ms to give the sensation of real-time browsing [5], which is an important challenge. It can only be achieved through low-complexity transmission techniques that mitigate the computation delay.
2.2.3 Gigabit Connectivity

The soaring of ever more data consuming applications such as video streaming - and even envisioned 3D content streaming - should trigger a need for wireless data rates as high as \(10 \text{ Gb/s}\). Future networks should therefore be able to provide such data rates. One possible way to achieve such performances is the use of carrier aggregation, which is a technique that future devices should be able to process.

2.2.4 Management of fragmented spectrum

Though not constituting a proper use case at the application layer, the management of fragmented spectrum, also known as "Digital agenda" is a task future devices and networks should be able to pursue in order to optimize the spectrum use.

2.2.5 WRAN

WRAN [15] is a direct application of the former. WRAN are networks able to cover cells of a diameter of approximately \(100 \text{ km}\) and which take advantage of the white space in the TV bands, according to the FCC recommendations [16]. They are expected to answer the need for long reach wireless networks in rural areas.

In order to fulfil these very diverse tasks, future devices will need to embed three main characteristics:

1. Ability to dynamically access the spectrum.
2. Capability to adapt to their environment and answer different performance requirements.
3. Physical layer techniques capable of supporting the above.

2.3 Dynamic Spectrum Access

As defined earlier in this dissertation, Dynamic Spectrum Access (DSA) refers to the ability of radio devices to dynamically access and share the spectrum. This can be achieved under different models, which have been classified by Zhao et al.[17] in a way visible on Figure 2.4. This classification is still valid, but as the frontiers between each
model tend to blur, they should not be opposed, but considered as complementary solutions. Besides, it is likely that future networks will make use of not only one but several models mentioned here according to the situation they face.

2.3.1 Dynamic Exclusive Use Model

This refers to a model where the spectrum is still licensed to exclusive operators but the latter may adopt two behaviours. In the Spectrum Property Rights model, they trade spectrum to each other to introduce flexibility. A typical application of this model would be the reciprocal lending of licensed but unused frequency bands between two operators. Going further into that direction, a model known as Dynamic Spectrum Allocation is also proposed. Whereas in the Spectrum Property Rights model, operators have the property of designated spectrum bands, the Dynamic Spectrum Allocation model puts all paying operators on an equity level, none of them owning a part of the spectrum, but all of them being allowed to access it. They benefit from a fast varying spectrum allocation based on spectrum use spatial and temporal statistics supposed to guarantee them a minimal Quality of Service (QoS) at all times.

However, those two models, by following a scheme where the allocation is decided in a central way according to statistical data, it is unlikely to fully mitigate the under use of the spectrum. Indeed, if we refer to Figure 2.2, there is no chance that such an open loop model can successfully use the white spaces which are in the order of $10 \text{ ms}$. Such a reactivity involves that the devices perform spectrum sensing, which is not proposed in the two aforementioned models.
2.3.2 Open Sharing Model

This is the boldest proposal, aiming at abandoning licenses and building systems where peer users dynamically share the spectrum, either in a centralized or distributed way. In such a model, users cooperate in order to achieve a fair sharing of the spectrum. It would involve a complete restructuration of communication networks and bring a lot of both technological and economical questions. Therefore, the research on this field is hardly existing and this solution is not considered as credible.

It is not, as one could think, what is already used on the ISM band. Indeed, on the latter, there is no cooperation between users. They simply transmit and hope that they will not cause or suffer interferences. In order to keep the bit loss under a ratio made acceptable by channel coding, most devices operating in this band make use of Frequency Hopping Spread Spectrum (FHSS) techniques [18] and will simply retransmit if data is lost. Such a policy is not scalable to the 5G scenarios, e.g IoT where thousands of nodes are expected to share the spectrum.

2.3.3 Hierarchical Access Model

This model relies on a scenario where unlicensed (secondary) users are allowed to communicate in incumbent licensed (primary) users bands unless they interfere with the latter. This may be achieved in two ways:

**Spectrum Underlay or Ultra Wide Band model**

In this scenario, secondary users operate below primary users’ noise level by using spectrum spreading techniques. Such techniques spread the data on a wide frequency band so that at every frequency, the signal is both undetectable and insignificant. The receivers then integrate the spread message to reconstitute it. A technique commonly used to achieve this is Code Division Multiple Access (CDMA). This type of transmission has the advantage of being already well developed. It is in particular used by the military to hide their communications into the noise. Besides, such techniques do not take advantage of spectrum white spaces, and do not need so-called intelligent devices. However, though they can enable very high data rate in short range, they fail to transmit data over long range. Moreover such techniques suffer from very difficult hardware implementation as they need long filters.
Spectrum Overlay or Opportunistic Spectrum Access (OSA) model

This model defines a scenario where secondary users act in an opportunistic way, trying to communicate in spectrum white spaces and preventing themselves to interfere onto incumbent users. It is the most studied model today, not because of performances considerations, but because it is the most credible proposal, as it can easily be grafted onto preexisting networks without altering their structure. This scheme involves using waveforms with limited OOB emissions in order to make the best use of available white spaces. However, in order to transmit efficiently in the spaces that are granted to them, opportunistic users need to embed sufficient intelligence. Therefore, the need for Cognitive Radio (CR) arises.

2.4 Cognitive Radio: bringing intelligence to networks

2.4.1 A definition of Cognitive Radio

Joseph Mitola III defined CR for the first time in his PhD. dissertation as follows: "The term CR identifies the point at which wireless personal digital assistant (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer to computer communication to:

1. Detect user communication needs as a function of use context, and
2. Provide radio resources and wireless services most appropriate to these needs."

Following this definition, radio devices must embed some intelligence and decide in regards to different constraints, such as the environment and the user needs. Such radio devices are named Cognitive Agents (CAs).

Basically, a CA needs to be able to hear to its own environment, and adapt its characteristics to its observations, which is summed up in [2] in two main functionalities: Cognitive Capability and Reconfigurability. These functionalities have repercussions on all aspects of radio devices, and involve a compulsory cross-layer design. As such, in [2], Akyildiz et al. define four functions that CA must implement and that are supported by the whole Open Systems Interconnection (OSI) stack (see Figure 2.5):
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- Spectrum sensing: detect unused spectrum and avoid interferences.
- Spectrum management: select a satisfying part of spectrum in regard of desired QoS.
- Spectrum mobility: assure unchanged QoS during transitions to better areas of the spectrum.
- Spectrum sharing: assure equity among users.

On Figure 2.5, it appears clearly that in order for CA to work, there must be a cooperation of all the layers: the "cognitive part" of the system cannot be handled at the physical level only. E.g. during error-rate sensitive communications, packets should be queued during frequency hops in order to avoid any loss. Therefore, upper layers should be informed by the lower ones of the current state of the system. Hence, CA have to be cross-layer designed, and it would not make any sense to design CR application layer without prior definition of the underlying physical layer.

All the layers interact together in what is referred to as the cognitive cycle, which summarizes the different steps processed in a CA. This cycle can be summarized by the following sentence: the observation of the constraints (environment, user needs, device state, etc.) is computed through the cognitive engine, which leads to a decision itself leading to an act on the environment. The consequences of this act being then observed,
the obtained satisfaction can be estimated, which in turn can be used to learn and tune the decision algorithms.

We propose Figure 2.6 to represent this process. On one hand, the CA observes the Resources space, which is the representation of the resources and constraints it has to deal with. On the other hand, the comparison between the objectives space, which is the translation of QoS expectations, is compared with the current, actual performances in order to compute a satisfaction metrics. In order to increase its satisfaction and according to its observations, the CA decides of an action by using the most adapted
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Figure 2.7: Adapted decision making techniques as a function of a priori knowledge [19]

decision making technique it disposes of. The decision is transmitted to the Software Defined Radio (SDR) system which supports the CA and will in turn reconfigure the radio system. The consequences of this action on both the resources space and the performances of the system are measured. In the mean time, the CA keeps trace of its past states and is therefore able to learn from its decisions. This learned information can then be used to tune the decision making algorithms.

2.4.2 Decision making techniques for CR

On Figure 2.6, it is shown that CAs base their decisions on sets of rules designed by decision making techniques and tuned by learning algorithms. Knowing what technique to use in what situations is a very important goal to pursue. In order to do that, it has been proposed to use the "a priori information", which represents the available knowledge of environment constraints, user requirements and device capabilities [19].

It appears that when the system is well known, it is possible to express it in Radio Knowledge Representation Language (RKRL) and apply deterministic models to make a decision. On the contrary, when there hardly is any prior knowledge, learning approaches, such as Multi Armed Bandit (MAB), where random decisions are simply evaluated in regards of their obtained gain have to be performed.

2.4.3 Spectrum opportunities detection by CR in the context of OSA

As shown on Figure 2.6 environment knowledge is an important part of the resources the CA observes, and is of the highest importance when it comes to OSA. Two ways to obtain this knowledge can be used. On one hand, a geolocalisation database of equipments not to be interfered with can be maintained and polled. This technique is used for some
Figure 2.8: Detection problems: (a) Receiver uncertainty and (b) Shadowing uncertainty [2]. Here, xG is equivalent to CR.

devices operating in TV white spaces [16]. On the other hand, it is possible to sense the spectrum in order to detect incumbent receivers which might be affected by signal emitted by a CA transmitter. Though, as this is particularly difficult to do, most CR systems rely on the detection of primary transmitter. This, however, can lead to two problems:

1. The secondary user can be in the range of a primary receiver, but not of a primary transmitter.

2. The secondary user can be in the range of the primary transmitter but be shadowed by a natural obstacle

Different sensing solutions as well as their ability to mitigate the two aforementioned problems are presented:

**Non-cooperative detection**

This type of detection cannot mitigate the two considered problems, as it is based on the observations of only one user. The three different techniques that a user can implement to detect signals are still depicted here.

- **Matched Filter Detection**: when the transmission technique used by the Primary Users (PUs) is known and an Additive White Gaussian Noise (AWGN) channel is faced, this technique performs well
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- **Energy Detection** [19]: this technique solely relies on measurements of average energy over a frequency band. Therefore, there is no need to have prior knowledge on the incoming signals. However, this technique is very sensitive to noise.

- **Cyclostationary Feature Detection** [20]: this technique takes advantage of communication signals inherent cyclostationarity.

### Cooperative Detection

In such schemes, different users try to detect PUs by using one of the aforementioned techniques. Then, the different measurements are computed in order to try to obtain a better knowledge of the PUs location. However, the performances of such techniques directly depend on the distribution of the CAs. In order to achieve good results, they should extensively cover the geographical area of interest. Moreover, a major bottleneck of such techniques is the overhead signalling, which can finally be counterproductive. Besides, in order to communicate their observations, CAs should be aware that they will not interfere with PUs, which is exactly what they are trying to know.

### Interference-based Detection

In interference-based detection, it is proposed that PUs embed a system emitting an alarm signal when they suffer from interference higher than a certain tolerated level $I_{th}$.

To conclude on spectrum sensing, ways to directly detect primary users still constitute an open research field. Besides, the less samples developed techniques need, the better, which should be a top concern in coming research.

Moreover, though it is not treated here, secondary users need of course to sense other secondary users. However, it is understood that this is less problematic than primary user detection, as secondary ones share the same network and therefore communicate to each other.

In conclusion, CR, by bringing intelligence, adaptability and flexibility to the networks, is able to answer many of 5G related issues. However, as it has been pointed out, CR systems must be cross-layered designed, and in particular supported by an adapted physical layer. Therefore, to sustain the upper layers functionalities necessary for 5G systems, a number of waveforms has been proposed to adapt the physical layer to the foreseen 5G scenarios.
2.5 Proposed waveforms for 5G

The former sections of this chapter have presented the characteristics of today networks, as well as the expectations for future ones. Two of their main characteristics, ability to perform OSA and cognitive capability have been presented.

It is therefore now possible to point out some requirements on the waveforms that should be used in 5G: in order to enable OSA, the used waveforms need to have good spectral localization. Besides, in the context of CR, it is wished that the waveforms grant flexibility to the system by being easily tunable and adaptable. Finally they should enable power savings in order to mitigate the exponential soaring of the amount of energy used per bit to transmit in the past years.

2.5.1 OFDM

In [3] OFDM is proposed as a credible option to support future networks. OFDM is indeed an easily adaptable transmission technique, which allows for carrier aggregation, spectrum sharing and easy adaptation to the environment. However, it is understood that the need for perfect synchronization and orthogonality is an important drawback in the conception of CR systems [14].

Indeed, the rectangular pulse shaping in time inducing high sidelobes and therefore OOB emission, OFDM suffers from a very bad spectral localization which results in important interference to other networks that has to be coped with important guard bands or the use of cancellation techniques [4, 6, 21]. This obviously is an important drawback when it comes to optimizing spectrum use as well as using low complexity techniques.

Besides, OFDM strong need for synchronization [5, 9], involves an important overhead signalling as well as bulky procedures. This is bound to increase complexity, power consumption and in the mean time decrease the part of spectrum used for effective data transmission. It has been shown [1] that signalling now represents almost half of the transmitted data. This trend has to be dramatically slowed down, and too strict synchronisation needs do not allow that.

Finally, it is known that OFDM suffers from high Peak-to-Average Power Ratio (PAPR) which prevents amplifiers to work at their most effective point. This represents an important energy waste at BSs, and so far prevents OFDM from being used in the uplink mode, as is proven by the use of SC-FDMA on LTE uplink mode. A number
of PAPR reduction techniques exist but they are once again complex procedures which do not satisfy the need for simplicity of 5G.

### 2.5.2 Some proposed multicarrier techniques for 5G

The first naturally proposed technique consists of filtering OFDM to cope with side-lobes production. This is known as Offset Quadrature Amplitude Modulated-Orthogonal Frequency Division Multiplexing (OQAM-OFDM) [22], in which subcarriers are pulse shaped in order to achieve a Time-Frequency Localization (TFL) close to that of the channel. However, achieving both time and frequency localization in the mean time as maximum spectral efficiency is not possible under the Balian-Low theorem [23].

Filter Bank Multi Carrier (FBMC) constitute the most studied technique so far. In FBMC, subcarriers are filtered through a very selective filter. In order to achieve good spectral localization, the symbols are made very long and overlap on each other. This makes FBMC spectrally efficient and robust to asynchronism [24]. However, the use on long filters does not cope with the need for low latency.

A special kind of FBMC, called Fast Convolution based FBMC (FC-FBMC) [25] takes advantage of consecutive overlapping FFT-IFFT blocks to implement linear convolution. It can achieve high tunability and lower complexity. Some proposed multirate implementations of it use FFT blocks of different lengths to divide a wide band into multiple narrow bands.

Generalized Frequency Division Multiplexing (GFDM) [26], which can be seen as a corner case of FC-FBMC, is a type of block multicarrier technique where subcarriers are not orthogonal. It is now presented and evaluated in details.
3. Generalized Frequency Division Multiplexing: a new non-orthogonal waveform for 5G

3.1 The philosophy behind GFDM

The fundamental hypothesis of GFDM systems is that it is not possible to achieve 5G requirements by keeping so rigid standards on both orthogonality and synchronization [14]. In the GFDM scheme, orthogonality between the subcarriers is abandoned as they are separately filtered through a so-called "prototype" pulse shape filter [26, 27].

![GFDM block structure](image)

Figure 3.1: GFDM block structure [28]
3. GENERALIZED FREQUENCY DIVISION MULTIPLEXING : A NEW
NON-ORTHOGONAL WAVEFORM FOR 5G

The data is divided in blocks which span the transmitted signal onto $K$ subcarriers and $M$ time slots during which symbols are sampled $N$ times. A Cyclic Prefix (CP) is then added to this $M \times K$ block. The structure is visible on Figure 3.1.

In the following sections, the system model for GFDM is presented. GFDM performances are evaluated and recently proposed modifications to the scheme are exposed. Finally, implementation issues are discussed.

3.2 System model

3.2.1 GFDM transceiver

In this work, we focus on GFDM modulation and demodulation. The overall structure of the GFDM transceiver is depicted on Figure 3.2. The first blocks refer to classical channel coding and QAM Mapping which are not in the scope of this dissertation. Besides, there is still little work on synchronization in the context of GFDM, except in [30].

GFDM is part of the Fast Convolution Based techniques, which means that it takes advantage of cyclic convolution with the synthesis filter at the transmitter. This was first nicknamed "tail-biting" [26, 31] as it indeed prevents the up and down ramps of the signal which normally limit the efficiency of transmissions. The modulated signal is expressed in the following way:

$$\forall n \leq MN, \quad x[n] = \sum_{m=0}^{M-1} \sum_{k=0}^{K-1} d_k[m] \times \tilde{g}_k[n - mN] e^{j2\pi \frac{k}{K} \times n} \quad (3.1)$$

Equation 3.1 shows that the GFDM signal is the superposition of the result of the convolution of the incoming QAM symbols with circularly shifted versions of the same prototype filter. In order to help the understanding, the representation of the GFDM signal during one time slot and on one subcarrier are respectively presented on Figure 3.3.
3.2 SYSTEM MODEL

Figure 3.3: GFDM signal during one time slot [29]

Figure 3.4: GFDM signal on one subcarrier

and Figure 3.4. On these figures, $M = 5$ and $K = 4$ and a raised cosine filter with 0.3 roll-off factor is used as the prototype filter.

By serializing the datablock presented on Figure 3.1 to a vector $\vec{d}$, it is possible to express the modulation process under a matrix form $\vec{x} = A\vec{d}$ [27, 28]. Under such formulation, we have the following formulation of the modulation matrix:

$$A = \begin{pmatrix} g_0^T & g_1^T & \ldots & g_K^T \end{pmatrix}^T$$  \hspace{1cm} (3.2)

Because of this matrix representation, it is possible to easily apply classical receiver schemes to the GFDM schemes [31].

**Matched Filter Receiver**

In Matched Filter (MF) reception, the incoming data is demodulated in the following way: $\hat{\vec{d}} = A^H \vec{y}$. This expression denotes the fact that the receiver is the reciprocal of
the transmitter. This is the simplest way of reception, and classically performs well on Additive White Gaussian Noise (AWGN) channels.

However, in the context of GFDM, the received signal is highly polluted by Inter Carrier Interference (ICI). In order to overcome this problem, Interference Cancellation (IC) techniques have to be used [32–34] which rely on the same principle depicted on Figure 3.5

It relies on an iterative algorithm where for each step $i$, every subcarrier $k$ undergoes the following algorithm:

- The symbols $d_{k+1}^i - 1$ and $d_{k+1}^i + 1$ which correspond to the former estimated symbols of the $k - 1^{th}$ and $k + 1^{th}$ subcarriers are fed to the IC unit
- They are remodulated in order to simulate the interferences they are responsible for.
- Their sum is subtracted to the initially received subcarrier $y_k$.

The complexity and the latency of the system are of course increased with the implementation of such a system. This will be depicted later in this chapter.

Figure 3.5: Interference cancellation scheme [34]
3.2 SYSTEM MODEL

Figure 3.6: Time response of different proposed prototype filters

Zero Forcing Receiver

In order to suppress ICI, it is possible to use Zero Forcing (ZF) reception, which, by definition cancel interference between subcarriers. In this reception scheme, \( \tilde{d} = (A^H A)^{-1} A^H y_s \), which corresponds to inverting the modulation matrix. Therefore, in the absence of noise, ZF is able to fully invert the effect of ICI. However, the modulation matrix has to be well conditioned in order to be able to invert it.

Minimum Mean Square Error Receiver

Finally, Minimum Mean Square Error (MMSE) reception is capable to minimise the error at the receiver by computing \( \tilde{d} = \frac{\sigma_d^2}{\sigma_s^2} I + A^H A \)\(^{-1} A^H y_s \). However, this scheme is obviously the most complex to implement as it needs to compute Signal to Noise Ratio (SNR) at each cycle of reception. Besides, at high SNR, the term \( \frac{\sigma_d^2}{\sigma_s^2} \) converges to 0, and MMSE becomes equivalent to ZF.

3.2.2 Prototype filters

GFDM is of particular interest because of the degree of freedom it offers by giving the choice of the used prototype filter on every subcarrier. It is even possible to use different filters on different subcarriers, but there has not been any incentive to do so yet, as the interest of doing it has not been justified so far.
In the case where MF reception is used, the prototype filter should respect Nyquist criteria in order to cancel Inter-Symbol Interference (ISI). On the opposite, if ZF reception is considered, the choice of filter is much more open. Indeed, if the modulation matrix $A$ can be successfully inverted, ISI can be effectively cancelled. Therefore, a number of Nyquist and non Nyquist filter have been considered in the context of GFDM. They are listed in the following lines and their time response is depicted on Figure 3.6, where $M = 15$.

- **Rectangular filter**: using it makes GFDM similar to OFDM
- **Raised Cosine (RC)**: one of the most studied Nyquist filters, it takes advantage of its roll-off factor to tune the temporal secondary lobes.
- **Root Raised Cosine (RRC)**: its frequency response is the square root of RC filter’s one. Therefore, it is thoroughly used in communications using MF reception, as the global filter is in that case a Nyquist filter.
- **Xia [35, 36]**: those filters which have so far had a limited success implement the same roll-off principle as RC and RRC. Their main interest rely in the fact that they are ISI-free, whether MF is applied or not. Their frequency response is the following:

$$G(\omega) = \begin{cases} 
1 & |\omega| \leq \frac{(1-\alpha)\pi}{T_s} \\
\frac{1}{2}(1 + e^{j\pi\nu(\frac{T_s}{2\alpha})}) & \frac{(1-\alpha)\pi}{T_s} \leq \omega \leq \frac{(1+\alpha)\pi}{T_s} \\
\frac{1}{2}(1 - e^{j\pi\nu(\frac{T_s}{2\alpha})}) & \frac{-(1+\alpha)\pi}{T_s} \leq \omega \leq \frac{-(1-\alpha)\pi}{T_s} \\
0 & |\omega| \geq \frac{(1+\alpha)\pi}{T_s} 
\end{cases} \quad (3.3)$$

$\nu(x)$ is the continuous function of the form $\nu(x) = x^\beta(P_{\beta-1}(x))$, where $\beta$ is the order of the function (e.g. Xia4 refers to a Xia filter using a $\nu$ function with $\beta = 4$ and $P(\beta - 1)(x)$ a polynomial function of order $\beta - 1$ such that

$$\begin{cases} 
\nu(x) = 0 & x \leq 0 \\
\nu(x) = 1 & x \leq 1 \\
\nu(x) + \nu(1-x) = 1 & x \in \mathbb{R} 
\end{cases} \quad (3.4)$$

We derived the expressions of the coefficients of the polynomial $P_{\beta-1}(x)$ and found that, if we define $a_i$ its coefficient for the $i^{th}$, in order to find their values, it is
sufficient to solve the following equation system:

\[ \forall j \in [0, \beta - 1], (-1)^j \left[ \sum_{i=0}^{\beta-1} a_i \left( \frac{j}{i + \beta} \right) \right] = 0 \]  \hfill (3.5)

The detail of the calculation is available in Appendix B.

- **Dirichlet**: this filter is the reciprocal of rectangular shaping in the time domain, and performs rectangular shaping in the frequency domain. Therefore, this filter does not provoke ICI. However, it is both very sensitive to timing offsets, and is only theoretical, as such a perfect shaping in the frequential domain would involve an infinite transmission in the time domain.

- **Gauss**: the well-known Gaussian pulse is a credible choice, as it is particularly well localized, both in time and frequency. However, this is not a Nyquist filter and should only be used with ZF receiving.

- **Half-cosine**: the impulse response of this filter is defined equal to 0 everywhere except from \(-T_s\) to \(T_s\) where its expression is \(g(t) = \cos(2\pi f T_s)\)

The choice of one of those filters will have a major effect on GFDM signal behaviour in the frequency domain. We now focus on this aspect and try to describe the GFDM Fourier Transform

### 3.2.3 Fourier Transform expression of GFDM

Because we found that GFDM spectral behaviour is neither well explained or understood though it is of great interest to study it, e.g. to calculate OOB emissions, we decided to formally express the Fourier Transform of GFDM. Here, we consider a GFDM signal \(x\) where data is spanned on \(K\) subcarriers and \(M\) time slots. We denote \(x_k(t)\) the signal on the \(k^{th}\) subcarrier, represented on Figure 3.4 so that

\[ x(t) = \sum_{k=1}^{K} x_k(t) \]

In the context of this analysis, we consider an impulse response, and do not take into account the effect of the transmitted symbols \(d_{k,m}\). Therefore, we have the following
expression:

\[ x_k(t) = \sum_{m=-M/2}^{M/2} \tilde{g}_k(t - m \times T_s) \times e^{2i\pi f_k t} \]

Where:

- \( T_s \) is the time-symbol
- \( \tilde{g}_k(t - m \times T_s) \) is the filter used on the \( k^{th} \) subcarrier, circularly shifted by \( m \times T_s \)
- \( f_k \) is the frequency of the \( k^{th} \) subcarrier

Besides, as the term \( e^{2i\pi f_k t} \) only consists of a translation in the frequency domain, we consider, from this point on, \( f_k = 0 \) without loss of generality.

### Fourier Transform of the impulse response for one data block

Here we define \( X_k(f) \) the Fourier Transform of \( x_k(t) \), which represents the signal transmitted by the \( k^{th} \) subcarrier in the frequency domain.

\[
X_k(f) = \int_{-M \times T_s/2}^{M \times T_s/2} \sum_{m=-M/2}^{M/2} \tilde{g}_k(t - m \times T_s) \times e^{-2i\pi f t} d(t)
\]

Here, \( X_{k,m} \) represent the Fourier Transform of the \( m^{th} \) symbol transmitted on the \( k^{th} \) subcarrier. It is a complex number and can therefore be represented by defining \( \rho_{X_{k,m}} \) its absolute value and \( \Theta_m \) its phase as:

\[
X_{k,m} = \rho_{X_{k,m}} \times e^{i\Theta_m}
\]

However, \( \forall m, X_{k,m} \) represent the Fourier Transform of the same, circularly shifted signal. Therefore, \( \forall m, \rho_{X_{k,m}} = \rho_{X_{k}} \).
By naming $X_{k,0}$ the Fourier Transform of the centered, symmetric symbol, which is therefore real, we can then write:

$$X_k(f) = X_{k,0}(f) \times \sum_{m=-\frac{M-1}{2}}^{\frac{M-1}{2}} e^{i\Theta_m}$$

$\Theta_m$ is the phase of the Fourier Transform resulting from a circular shifting of $m \times T_s$, which leads to: $\forall m, \Theta_m = 2\pi \frac{m}{M} f$.

Therefore, we have

$$X_k(f) = X_{k,0}(f) \times (1 + \sum_{m=-\frac{M-1}{2}}^{\frac{M-1}{2}} e^{2i\pi \frac{m}{M} f} + e^{-2i\pi \frac{m}{M} f})$$

So that, finally:

$$X_k(f) = X_{k,0}(f) \times (1 + \sum_{m=-\frac{M-1}{2}}^{\frac{M-1}{2}} 2 \times \cos(2\pi f \frac{m}{M}))$$

Which we eventually generalize to:

$$X_k(f) = \underbrace{X_{k,0}(f - f_k)}_{\text{Fourier transform of the prototype filter}} \times (1 + \sum_{m=-\frac{M-1}{2}}^{\frac{M-1}{2}} 2 \times \cos(2\pi (f - f_k) \frac{m}{M})) \quad (3.6)$$

Therefore, we see that, in order to find the Fourier Transform of a GFDM data block, one only needs to know $M$ and the Fourier transform of the prototype filter used on each subcarrier.

**Fourier transform of prototype filters**

Deriving the expression of prototype filters Fourier transform is the bottleneck to overcome in order to obtain the GFDM one. Whether the prototype filters are time-limited to a duration smaller than $M \times T_s$ determines the complexity of this calculation:

- If they are, obtaining the Fourier transform of the prototype filter is a straightforward problem.
3. GENERALIZED FREQUENCY DIVISION MULTIPLEXING : A NEW NON-ORTHOGONAL WAVEFORM FOR 5G

Table 3.1: Inventory of so far calculated prototype Fourier Transforms

<table>
<thead>
<tr>
<th>Time domain filter</th>
<th>( X_{k,0}(f) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{rect}_{T_s}(t) )</td>
<td>( T_s \times \text{sinc}(\pi f T_s) )</td>
</tr>
<tr>
<td>Half-cosine</td>
<td>( \frac{\pi}{T_s} \times \frac{\cos(2\pi f T_s)}{\gamma^2 + 4\pi^2 f^2} )</td>
</tr>
</tbody>
</table>

- If they are not, we have the following:

\[
X_{k,0}(f) = \bar{X}_k(f) \otimes (MT_s \text{sinc}(MT_s \pi f))
\]

Where \( \bar{X}_k \) represents the non time-limited version of the prototype filter and \( \otimes \) represents the convolution product. This implies computation the integral of the \text{sinc} function, which is not possible to express with regular functions.

We advise that this work is still in progress and is still undergoing simulation verification. Besides, it should be extended to take into account the effects of the use of multiple blocks as well as of CP insertion.

3.3 Achieved performances

This section tries to give a good overview of GFDM flaws and advantages. It is hard to say with accurate precision what exact performances GFDM can boast of, as they highly depend of the tested configuration. However, we try in the following part to give the reader a good understanding of GFDM strengths and weaknesses regarding two different criteria : digital agenda related performances and transmission quality performances.

3.3.1 Digital Agenda related performances

In order to evaluate the pertinence of GFDM for achieving Digital Agenda, we bring the light on three different metrics : OOB emissions, Incumbent user protection and signal detection.

OOB emissions

Though first papers on GFDM were promising important gains in terms of OOB [38], the increased comprehension of its behaviour shows that because of the rectangular
windowing, the inherent OOB emissions can not go more than 15 to 20 dB deeper than OFDM, before applying any OOB limitation technique [29].

A first way to lower them is to use a certain number of guard subcarriers between the CA and the PU. In [37], the effects of the used filter on OOB emissions is presented, and it is shown that for all of them, using a guard band of 6 subcarriers allows to lower them to around -70 dB. However, using such a technique is not satisfying, as it dramatically decreases the spectral efficiency of the system.

Another way to achieve this goal is introducing guard symbols on both sides of the data block. It has been firstly introduced in [27] and formalized in [29]. Some results regarding this are presented on Figure 3.7, where we see that the addition of two guard symbols (one on each side of the data block) decreases OOB emissions by around 4dB, which is not very satisfying. The defenders of this idea claim that the relative spectrum loss of efficiency can be mitigated by increasing $M$. However, this is bound to increase latency of the system, which is not wished. Besides, they claim that these guard symbols could be used to transmit pilots or synchronization signals. However, this would diminish the gains on OOB emissions, which are already not sufficient. Therefore, at this stage of the research, we do not consider that the insertion of guard symbols is a credible or pertinent technique to lower OOB emissions of GFDM.

Another proposal is to remedy to the major flaw of GFDM which is the rectangular shaping in the time domain. Time windowing has been recently proposed, as part of a synchronization scheme in [30] and extended to OOB reduction in [29]. However, as this is a very new proposal in the field of GFDM, we still lack of background on the subject and do not present results here. However, we find it likely that this idea will significantly decrease OOB emissions of GFDM by mitigating the convolution with the sinus cardinal function in the frequency domain.

Finally, it has been recently proposed to use cancellation subcarriers for GFDM [39]. The presented results are very impressive, as the authors announce OOB reduction in the order of 30 to 50 dB compared to traditional GFDM. However, it is so far the only paper on the subject, so that these results need to be confirmed. Besides, the insertion of cancelling carriers is known to rely on complex computation [40], which is not wished in the context of 5G.

**Signal detection**

On another field, if GFDM is ever to be released as a waveform used by CR systems, it must be able to sustain signal sensing. Two main detectors [20] can be used to achieve
3. GENERALIZED FREQUENCY DIVISION MULTIPLEXING: A NEW NON-ORTHOGONAL WAVEFORM FOR 5G

Figure 3.7: Guard symbols influence on OOB emission. $M_{on}$ refers to the number of used symbols, out of $M = 15$. Here $N = 2048$ and $K = 1024$ [27].

this task:

1. Energy Detector (ED), simple but not resilient to noise uncertainty.

2. Generalized Cyclostationary Detector, which can detect cyclostationary signals in the spectrum.

The performances of ED in the context of GFDM have been investigated in the QoSMOS project and summed up in [41]. Though they show in that paper that in the case of perfectly synchronized transmitter and receiver, there is no real difference between GFDM and OFDM, they found out that for more realistic scenarios where this is not respected, GFDM outperforms OFDM as a receiver. It is even shown that a GFDM sensor is more able to detect OFDM signals than an OFDM receiver.

However, ED is not reliable when the amount of noise is not perfectly known. In such cases, cyclostationary detectors, though much more computationally complex, may be preferred. This has been investigated for GFDM in [20] where the authors take advantage of GFDM cyclostationary features to detect the signal. Their conclusions are twofold:
• With a CP as long as in the OFDM case, GFDM can not compete on this field of comparison: it is even not achieving the theoretical performances of an ED with $0.1dB$ uncertainty.

• When increasing the Cyclic Prefix to 25% of the useful payload length GFDM achieves the same detection performances as OFDM. However this is an important drawback as far as spectrum efficiency is concerned.

Once again, it seems that GFDM may have to sacrifice efficient use of the spectrum in order to improve its other performances. However, in the OSA policy, the priority is not to guarantee good QoS to the secondary user but to protect the PUs, which GFDM can achieve in a satisfying way.

**Incumbent user protection**

The problem of GFDM coexistence with OFDM PUs has been tackled by Michailow et al. in [38] where two setups are compared. Both consider a primary user using OFDM; the first considers a secondary user using OFDM too, whereas on the other hand, the secondary user of the second setup used GFDM. The parameters used for the simulation are those specified in IEEE 802.11a and a RC filter is used for GFDM (roll-off and block size are unfortunately not specified) and the channel is AWGN. The results are shown on Figure 3.8

This graph shows that, as instinctively thought, the primary user encounters less BER when sharing spectrum with a secondary user using GFDM. However, it also appears that the secondary user sees their BER increase when using GFDM. In this simulation though, GFDM uses a MF receiver, in which IC scheme is used, which could mitigate this last problem.

### 3.3.2 GFDM transmission quality performances

Two criteria are studied here to evaluate GFDM transmission performances: bit error rate performances and asynchronism sensitivity.

On the former, it is interesting to compare the performances of the three aforementioned receiver types. Different simulations are led in [31], both in AWGN and Rayleigh Channel. We have successfully reproduced the pursued simulations in the AWGN case. Let us interpret those results: under low roll-off, ICI is contained and MF therefore keeps behaving relatively well. However, it is still outperformed by ZF and MMSE for
3. GENERALIZED FREQUENCY DIVISION MULTIPLEXING : A NEW NON-ORTHOGONAL WAVEFORM FOR 5G

Figure 3.8: BER comparison of the two setups [38].

high SNR. With high roll-off though, ICI becomes preponderant and MF is no more suitable at all. ZF and MMSE keep performing well though a little affected by induced self-interference.

As it has been discussed earlier on, MF can be coupled width serial IC in order to improve its performances. This has been shown in [42] where the application of Double-sided Serial IC allows MF to outperform ZF. However, in [28] it is shown that the number of IC loops to perform increases approximately as quickly as the used QAM order, in an even more significant way on Rayleigh channels. This is bound to increase latency in the GFDM devices, which is an important drawback for 5G.

Another major expectation regarding GFDM is that it would allow devices to relax synchronization constraints, as those imposed by OFDM do not enable the deployment of hundreds of very cheap devices communicating together in a MTC scheme. The subcarrier filtering reducing the side lobes, GFDM will indeed instinctively behave in a better way than OFDM in the context of Carrier Frequency Offset (CFO).

Some results regarding this problem have been obtained in [41] and are presented on Figure 3.10.
3.3 ACHIEVED PERFORMANCES

Figure 3.9: Receiver comparison on AWGN channel: RRC filter, $K = 128$, $M = 5$, uncoded 4-QAM

Figure 3.10: GFDM error rates in the presence of CFO [41].
However, these results are not to be taken as granted, as no informations on the used filter is given in the paper. It only shows that under certain circumstances, GFDM can well resist to up to 5% CFO if some CFO cancellation mechanisms are used. This is quite interesting as allowed CFO in the context of OFDM is usually around 0.1%.

Still, GFDM resilience to desynchronization remains an open research field which deserves much attention as it could probably be one of GFDM main assets. This field of research could make an important use of the work led on GFDM FFT theoretical expressions described earlier in this dissertation.

3.4 Implementation techniques

The example of OFDM showed that no matter how theoretically effective a waveform can be, it has to be easily implementable to encounter success. Therefore, there has been ongoing research for low complexity implementations of the GFDM scheme [27, 28] which even led to an FPGA proof of concept [29].

The low complexity techniques developed so far take advantage, both at the transmitter and receiver, of the spectral sparsity of used prototype filters. A parameter, called $L$, corresponding to the number of significant samples of the prototype filters, is introduced in order to reduce complexity. Besides, Equation 3.1, after some arithmetical transformations detailed in [27] results in the following:

$$x_k[n] = \text{IDFT}_{NM}(\text{DFT}_{NM}(d_k[m] * \delta(n - mN)) \times \text{DFT}_{NM}(g_{T_{x}})[n] \otimes \text{DFT}_{NM}(e^{j2\pi \frac{k}{N} n}))$$

(3.7)

Three simplifications can then be made to this equation according to Michailow et al.:

1. The left part consists of $N$ captures of $\text{DFT}_{M}d_k[m]$, which can be achieved through upsampling in the time domain.

2. Applying the aforementioned consideration allows to perform no more $N$, but only $L$ multiplications

3. The right part only consist of frequency shifts.

The structure of the corresponding transmitter is presented on Figure 3.11. The corresponding receiver has as well been described but is not presented here as it uses
3.5 Conclusion on GFDM

GFDM most important specificity lies in the use of circular convolution with pulse shape, non-orthogonal filters at the transmitter. This loss of orthogonality produces ICI, and MF receivers can therefore only be used in cooperation with IC techniques which add complexity.

Though the pulse shaping of each subcarrier lowers OOB emission, the rectangular windowing of data blocks in time is very harmful, and it seems that GFDM will have to implement some time windowing techniques to compete with proposed alternatives.
Even though the research on GFDM is now well under way, with the unveiling of the first FPGA working prototype, we regret the lack of theoretical analysis on this waveform and propose to derive arithmetical expressions of its properties, most of all of its Fourier transform which is crucial for the study of OOB emissions and can serve as input for MAC layer algorithms, a field that we tackle in the next chapter of this work.
4 Power allocation for opportunist systems

4.1 Objectives

4.1.1 Considered scenario

In the former section, we have presented GFDM modulation scheme in details. Though its physical layer characteristics have been thoroughly analysed in the literature, very little work has been made on the field of MAC layer for GFDM or GFDM application in CR scenarios. Here, we propose a novel work by considering a situation where a GFDM CA network coexists with an incumbent LTE-A network and tackling the issue of optimizing the power distribution on the subcarriers of the CA network.

We consider a simple situation, where only one CA tries to communicate in uplink mode to the Cognitive Base Station (CBS). For the incumbent network, we consider the downlink scenario, in which the Base Station (BS) communicates with the users using OFDM. We will consider, in a first approach, a very simple spectrum distribution, in which the incumbent user uses $N_{PU} = 32$ subcarriers on a continuous band, whereas the CA uses $N_{CR} = 32$ subcarriers as well, but distributed equally on each side of the PU band.

![Figure 4.1: Spectrum distribution. The GFDM CA tries and communicate on the free red spaces](image)

Figure 4.1: Spectrum distribution. The GFDM CA tries and communicate on the free red spaces
Besides, we consider that there is no exchange of information between the CR and the PU networks, which results in possible timing and frequency offsets. The scenario is ruled by the following constraints:

1. The PU only tolerates a certain amount of interference, known as Interference temperature and symbolized by $I_{th}$

2. The CA disposes of a certain amount of Power, $P_t$

3. The CA tries to distribute the available spectrum resource in the most efficient way possible, in order to maximize its capacity.

This configuration, where the objective is to maximize a certain function while respecting some constraints of resources is particularly fit to be modeled by an optimization problem [43]. We define the latter in the following subsection.

### 4.1.2 Considered optimization problem

We denote:

- $P_i$ the allocated power on each subcarrier
- $h_i$ and $\sigma_i$ the flat gain and the noise level on each subcarrier
- $I_{max}^j$ the maximum tolerable amount of interferences on the $j^{th}$ subcarrier of the PU
- $\delta F, \delta T \in ] -0.5, 0.5]$ the relative frequency and time offsets between the PU and the CA

Therefore, the problem we are dealing with is expressed in the following form:

$$\begin{align*}
\text{maximize} & \quad \sum_{i=1}^{N_{CR}} \log_2(1 + P_i \frac{|h_i|^2}{\sigma_i^2}) \\
\text{subject to} & \quad \sum_{i=1}^{N_{CR}} P_i \leq P_t \\
& \quad P_i \geq 0, \quad i = 1, \ldots, N_{CR} \\
& \quad \sum_{i=1}^{N_{CR}} I_i^j \leq I_{max}^j, \quad j = 1, \ldots, N_{PU}.
\end{align*}$$

(4.1)
As this consists of maximizing a convex function onto a convex set of parameters, it corresponds to a convex optimization problem [43]. Similar optimisation problems under similar scenarios, both for FBMC and OFDM, have been studied in the literature [7, 8, 44]. In the following section, we present the mathematical expressions derived by Shaat et al., as well as a low-complexity algorithm they developed to answer these optimisation problems.

4.2 Previous work on the subject

The aforementioned optimisation problem has been studied, in the synchronous case, for both OFDM and FBMC. It has been shown that its direct solving is computationally complex, as it would involve the computation of an important number of Lagrange coefficients. Therefore, a low complexity algorithm, coined as Power Interference constrained Algorithm (PI-Algorithm) has been proposed [7, 8]. Without entering into details that are not in the scope of the discussion, we briefly detail its workflow:

1. Only the interference constraint is considered, and the maximum allowable powers for each subcarrier $P_{i}^{max}$ is processed.

2. If $\sum_{i} P_{i}^{max} \leq P_t$, then the algorithm assigns $P_{i}^{max}$ on each subcarrier and has finished.

3. In the more likely other case, powers are granted to subcarriers under a so-called cap-limited waterfilling process, which ensures that no subcarrier enforces the maximum interference constraint.

4. Then, as in this case the maximum interference constraint has not been reached, it is possible to update the maximum allowable power constraints. I.e, the subcarriers where $P_{i}^{max}$ is not achieved do not interfere as much as what had been initially
planned. Therefore, the amount of allowable power on other subcarriers can be increased.

5. Finally, another step of cap-limited waterfilling is performed

The principle of PI-Algorithm is depicted on Figure 4.3. On this figure, the set A corresponds to the set of subcarriers achieving the maximum allowable power after the first round of cap-limited waterfilling.

As this algorithm has proven both to outperform most of other alternatives and low complexity, we take it as a basis for our scenario, and we test it for OFDM, FBMC and GFDM under desynchronisation.

### 4.3 Extension to the asynchronous scenario

In order to extend the work of Shaat et al. to our scenario where time and frequency synchronization between networks are not guaranteed, we need to model the interference in a way allowing to translate this desynchronization. Two models for interference are evaluated in this section.
4.3 EXTENSION TO THE ASYNCHRONOUS SCENARIO

4.3.1 PSD based model

It is the model used by Shaat et al. It defines interference caused by the CA to the PU as the integral of the PSD of the signal transmitted by the CA over the PU band. Formally, interferences introduced by \(i^{th}\) subcarrier to \(l^{th}\) PU are therefore described as:

\[
I_l^i(d_i, P_i) = \int_{d_i-B_i/2}^{d_i+B_i/2} |g_i|^2 \Phi_i(f) df
\] (4.2)

Where we have:

- \(d_i\) : spectral distance between \(i^{th}\) subcarrier and \(l^{th}\) PU
- \(B_l\) : frequency width of \(l^{th}\) PU band
- \(\Phi_i\) : PSD of the \(i^{th}\) subcarrier

This model can be easily used to take frequency desynchronisation into account. With \(\delta F \neq 0\) Equation 4.2 becomes:

\[
I_l^i(d_i, P_i) = \int_{d_i-B_i/2+\delta F}^{d_i+B_i/2+\delta F} |g_i|^2 \Phi_i(f) df
\] (4.3)

However, as this model relies solely on frequency representation, there is no means to take into account time desynchronisation between networks. We present a model remedying to this drawback in the following subsection.

4.3.2 Mean Interference table

The concept of mean interference tables has been introduced by Medjahdi in his PhD. [6] both to be able to take into account time desynchronisation between two mutually interfering systems and also to remedy to the fact that as the PSD based model assumes perfect time synchronisation, it tends to underestimate interference. This is visible for CP-OFDM on Figure 4.4.

In the mean interference table model, interference is calculated by its pure definition, through time domain integration. Besides, the variable \(\delta T\) is assumed to be uniformly distributed on \([-0.5, 0.5]\). The value given by this model is then the mathematical expectancy of interference according to \(\delta T\). Here, we give the first steps of the derivation of mean interference caused by the the \(i^{th}\) subcarrier of a GFDM transmitter to \(j^{th}\) subcarrier of an OFDM receiver:

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Figure 4.4: Interference caused by CP-OFDM according to the two models [6]

\[ I_i^I = \mathbb{E}_{x_{m,n}}[|y_{tot}(\tau, \phi)|^2] \]

\[ |y_{tot}(\tau, \phi)|^2 = \sum_{m=1}^{m_{NCR}} y_{m_0,n_0}^m(\tau, \phi) \]

\[ y_{m_0,n_0}^m(\tau, \phi) = \sum_{n=-\infty}^{n=+\infty} \frac{x_{m,n}}{\sqrt{T}} \ast e^{-j \frac{2\pi}{T} m\tau - \phi} \ast \int_{n_0(T+\Delta)+\Delta}^{(n_0+1)(T+\Delta)} f_T(t - nT - \tau) \ast e^{j \frac{2\pi}{T} [(m-m_0)\ast t + (m_0\ast n_0-m\ast n)T + m_0\ast n\ast \Delta]} \, dt \]

We see that the complexity of arithmetical expressions rapidly increases. Besides, they are strongly dependent of the used prototype filter, and the calculations should therefore be led for each of them. Moreover, the effects of time desynchronization on our
considered scenario are only quantitative and do not affect the core findings that we could make with the PSD based model. For those two reasons, in our first approach, we restrict our initially proposed scenario to a situation where there is no time desynchronisation, but still a frequency offset between the two networks.

4.4 Simulations, first results and conclusions

The goal of our study is to compare the behaviours of GFDM and OFDM under the considered scenario, when using PI-algorithm under frequency desynchronization between PU and CA. The main metric that we aim for is therefore the achievable capacity of the CA vs frequency offset. Besides, this allows us to estimate the pertinence or pursuing frequency synchronisation in the case we study. In this section, we present the simulations we led and the interpretations we propose of them.

4.4.1 OFDM

In this subsection, we apply PI-algorithm to our scenario and assume that the CR system uses OFDM. This allows us both to describe precisely the behaviour of PI-algorithm when it faces frequency desynchronization and to have reference performances to compare GFDM to.

Computing caused interference

As described in the former section, the main input needed by the PI-algorithm is the interference caused by each subcarrier on the PU band. Besides, as we are interested in the effect of frequency desynchronization, we compute this value for different frequency offsets, from $-0.5 \times W_f$ to $0.5 \times W_f$ where $W_f$ represents the width of one subcarrier. Besides, we also compute the overall interference caused by the CA onto the PU band in function of frequency offset, which gives a good idea of the optimal frequency offset to achieve, which, instinctively should be 0.

The interference in dB caused by the OFDM CR onto the PU band is presented in Figure 4.5. With no surprise, the closer the subcarriers are to the PU band, the more they interfere. Besides, the represented matrix has central symmetry because of the inherent symmetry of the considered scenario: when the frequency offset is negative, the lower band of the CA introduces less interference onto the PU, at the opposite of its band, and the situation is reversed when the frequency offset becomes positive. This
4. POWER ALLOCATION FOR OPPORTUNIST SYSTEMS

Figure 4.5: Interference in dB caused by each subcarrier of an OFDM CR to the PU band, for different frequency offsets

Inherent symmetry results in a surprising outcome, visible in Figure 4.6. It appears that, though synchronization is preferable, any frequency offset comprised between $-20\%$ and $20\%$ of subcarriers width has no effect on the total introduced interference. Indeed, in this interval the latter varies by approximately $1\text{mW}$. This is the first sign that, opposed to what the instinct leads to think, perfect frequency synchronization between CA and PU may not be, in the particular scenario we are depicting here, of great importance.

**PI-algorithm performances**

Now that we have computed the interference caused by the CR system onto the PU, which serves as the input of the PI-algorithm, we are able to apply the latter and interpret the results. We present the capacity achieved by an OFDM based CR system in function of the interference constraint and the frequency offset, when it disposes of a total power of $1\text{mW}$ in Figure 4.7. This figure shows that for very low interference constraint, the frequency desynchronization has no effect. This is due to the fact that in such a situation, the interference constraint can be respected with equality, without using the total available power. Therefore, it is always possible to achieve the same capacity whatever the frequency offset is. Then, for interference constraints higher than $6\mu\text{W}$ the frequency offset starts influencing the achieved capacity to a small extent.

To better represent this, we zoomed in Figure 4.8 on the zone corresponding to interference higher than $10\text{mW}$. In this situation, the power constraint is now prominent, as the interference constraint is relaxed. We see that for a given level of allowed interference, the achieved capacity in function of the frequency offset follows a pattern inverse
4.4 SIMULATIONS, FIRST RESULTS AND CONCLUSIONS

Figure 4.6: Total interference caused by OFDM based CA onto the PU band in function of frequency offset

Figure 4.7: OFDM CR achieved capacity versus Interference constraint and Frequency offset with available CR power = 1mW
4. POWER ALLOCATION FOR OPPORTUNIST SYSTEMS

Figure 4.8: OFDM CR achieved capacity versus Interference constraint and Frequency offset with available CR power = 1mW

to the total caused interference visible in Figure 4.6. Therefore, the teachings of this simulation are twofold:

- When interference constraint is low, PI-algorithm is able to almost perfectly cope with frequency offset and the latter does not have any significant influence on the achieved capacity of the CR system.

- When the interference constraint cannot be respected with equality without respecting the total power constraint, the latter has higher impact. However, the effect on the achieved capacity still stays fairly limited.

Finally, we simulated the situation with different power constraints in order to confirm the conclusions this first simulation led to. The results are presented in Figure 4.9. We clearly see that for low interference constraints, the two curves superpose, as the total available power does not have any effect on the achievable capacity. But from $I_{th} = 4\mu W$ on, the two curves separate: the blue one enters in the power constrained zone, whereas the red one never reaches this point. Besides, we point out that the red curve is coherent with the results to be found in the existing literature [7], which validates our simulation results.
Figure 4.9: Capacity achieved by the OFDM CA under different total power constraint vs interference constraint. Curves represent the mean capacity in function of the frequency offset, intervals the variation between the minimal ($\delta F = \pm 0.5$) and maximal ($\delta F = 0$) achieved values.

Moreover, once again, the impact of desynchronization seems very limited, as it is responsible for a variation of the achieved capacity ranging from 0.02 to 0.06 Bit/s/Hz. Therefore, we can conclude by saying that under the considered scenario, with an OFDM based CA, there is no point in pursuing frequency synchronization between the PU and the CR network.

4.4.2 GFDM

We now focus on applying PI-algorithm to the same scenario as before, but with a GFDM-based CA. It is hoped that by decreasing OOB emissions, the GFDM CR will achieve more capacity that its OFDM equivalent under the same scenario.

Simulation process

In the study we led, we adopted the parameters summed up in Table 4.1. We sweep the parameters $I_{th}$ and $\delta F$ for two different values of $P_t$ and simulate for each of this point
Table 4.1: GFDM PI simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Min value</th>
<th>Max Value</th>
<th>Step</th>
<th>Number of points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency offset</td>
<td>$\delta F$</td>
<td>-0.5</td>
<td>0.5</td>
<td>0.005</td>
<td>201</td>
</tr>
<tr>
<td>Interference constraint</td>
<td>$I_{th}$</td>
<td>1$\mu$W</td>
<td>20$\mu$W</td>
<td>1$\mu$W</td>
<td>20</td>
</tr>
<tr>
<td>Total power budget</td>
<td>$P_t$</td>
<td>1mW</td>
<td>1W</td>
<td>/</td>
<td>2</td>
</tr>
<tr>
<td>Number of iterations for each point ($\delta F, I_{th}, P_t$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

the caused interference and the PI algorithm output for 100 random realisations of a Rayleigh channel. The presented values are the means of these 100 iterations for each of those points.

**Interference matrix aspect**

Computing interference in the GFDM case is a much more complicated task as for OFDM, as for the latter, its PSD expression is well known and easily expressed by the sinus cardinal function. In this study, as we have not yet been able to derive arithmetical expressions of GFDM with enough certainty, we use Matlab simulations to compute the interference matrix. This is not completely satisfying, as it is more likely to add errors into our results. Therefore, the results presented in this section will hopefully later be compared to those obtained with theoretical expressions of GFDM PSD.

Though the interference matrix is highly dependent of the filter used, we expect that they will all have the following common characteristics. The interference caused onto the PU is expected to be concentrated on the $16^{th}$ and $49^{th}$ subcarriers. Depending on the filter, those two subcarriers are even expected to interfere more than in the OFDM case, as they naturally span on the PU because of the roll-off of the pulse shape filter. However, we expect that the interference will decrease more rapidly than in the OFDM case, allowing the CA to use more efficiently the bands separated from the PU by a certain number of subcarriers. In consequence of this, the PI-algorithm should naturally form a guard band very close to the PU.

The computed interference matrices for different filters are presented in Figure 4.10. Only the 16 first subcarriers are represented, interference caused by subcarriers 49 to 64 being obtained by a simple symmetry. This figure confirms the a priori expectation that we had on the aspect of interference matrices, as the interference caused by the $16^{th}$ subcarrier is predominant. Besides, the effect of the frequency offset is naturally mostly seen on the subcarriers close to the PU band.
Achieved capacity

The mean achieved capacity in function of the frequency offset for different filters and two different power constraints is presented in ??.

For $P_t = 1\, mW$, GFDM based CA are constrained by the available power only, except for the half-cosine based CA which is in the interference constrained regime until $I_{th} = 3\, \mu W$. They therefore all achieve very similar mean capacity. We also see that OFDM performs as well as GFDM for $I_{th} > 1\, mW$. This is a very interesting teaching: there is no point in worrying in the used waveform after a certain point where the interference constraint is not predominant any more, so that, quite surprisingly, when the available power is low, one might as well use OFDM or GFDM. However, when the available power increases, the interference constraint becomes much more important, as it can prevent the CA to use all its available
power. This is exactly what happens on ?? for $P_t = 1W$. All the GFDM based CAs, except the one based on half-cosine filter, are only constrained by the total power, and their performance is almost independent of $I_{th}$. The fact that the half-cosine performs much less satisfyingly is consistent with its interference matrix, which shows a slower decrease of the amount of caused interference than the other filters.

To conclude on this, we showed that under the considered scenario, there is sometimes no need to use a complex waveform. Its choice should be motivated by the amount of available power: from the moment that the considered waveforms cause interference little enough to be able to use this given amount, they will achieve equivalent performances. We can therefore model the performance of each waveform by a curve $P_{\text{max}} = f(I_{th})$ giving the maximum usable power under a certain constraint. Then, the choice of a waveform to use for a given couple of constraints $(P_t, I_{th})$ is binary and consists of picking one for which the $P_{\text{max}}(I_{th}) > P_t$.

**Impact of asynchronism**

We previously showed that the frequency offset between the primary and secondary users had little impact when using OFDM, with a variation around 0.1 Bit/s/Hz. However, considering the fact that the variation of caused interference seems much more important in the case of GFDM because of the subcarriers adjacent to the PU band naturally spanning onto it, the effect of frequency desynchronisation on achieved capacity can be more important for GFDM than OFDM, as presented in Figure 4.11.

For GFDM, the achieved capacity can encounter variations of around 0.4 Bit/s/Hz because of the frequency offset. This is especially the case when using acute filters such as Dirichlet, because they face a steep increase of their caused interference when a frequency offset appears between the PU and the CA. We also see that the sensitivity
to frequency offset is much less important when $P_t$ is small. This is due to the fact that when the power constraint is predominant, the interference constraint is not respected with equality, so that the algorithm can adapt its power allocation to cope with the interference overhead caused by the frequency offset.

### Assigned power profile

To conclude on this analysis, we show the profile of assigned power in function of the interference constraint for the two regimes the CA can face, power constrained or interference constrained. This is shown in figures 4.12 and 4.13, where the red curve represents the minimal interference constraint $I_{th} = 1\mu W$. When the interference constraint is predominant, the profile is homogeneously diluted as $I_{th}$ increases. The formation of a guard band on subcarriers 14 to 16 is visible, as almost no power is assigned to these subcarriers.

On the other hand, the behaviour is much more surprising when the power constraint is predominant: as the interference constraint is respected with equality, the guard band tends to disappear as $I_{th}$ increases, and we observe an homogenisation of the assigned power on each subcarrier. However, it is very likely that such a behaviour would not be observed if there was a constraint on the interference caused to each subcarrier of the PU. Indeed, in our scenario, $I_{th}$ is the interference constraint for the whole PU band, which means that our simulation allows high interference on subcarriers adjacent to the CA. Adding more accurate interference masks to our scenario would be an interesting direction to investigate.
4.4 SIMULATIONS, FIRST RESULTS AND CONCLUSIONS

Figure 4.13: Variation of assigned power profile from $I_{th} = 1\mu W$ to $I_{th} = 20\mu W$ for a CA in the power constrained regime (Half-cosine, $P_t = 1mW$)

4.4.3 Summary on PI-algorithm for GFDM

In this chapter, we compared the performances of PI-algorithm for OFDM and GFDM. It appeared that there is no point in choosing GFDM when the total available power is small, as the interference constraint has then little impact. However, when the latter becomes predominant, GFDM, as expected, performs better than OFDM because of its smaller OOB emissions. However, it seems to be a little more affected by frequency offsets than OFDM, but this is also highly dependent on the used filter. Finally, we also showed that the PI-algorithm naturally creates a guard band of around two subcarriers when using GFDM, which tends to disappear in situations where the small amount of available power removes the effect of the interference constraint.
5 Conclusion and future work

5.1 Contributions of this work

In this dissertation, we have first recalled the leading requirements for the future communication networks: beyond the never stopping soaring of data rates to sustain, 5G is envisioned to enable scenarios which need to redefine the way today communication networks are designed and thought.

From a centralized, rigid, strictly orthogonal organisation, networks need to evolve into a flexible, intelligent, adaptable behaviour. This has repercussions on all conception layers. On the physical layer, newly designed multicarrier waveforms have to be spectrally and energy efficient. GFDM proposes to do so by abandoning orthogonality between subcarriers.

We provided a review of the state of research on GFDM, highlighting the flaws of this scheme that have to be investigated. We stated that the knowledge of GFDM behaviour in the frequency domain is crucial to evaluate its performances, and provided the first arithmetical expressions of its Fourier transform.

On the MAC layer, we presented the issues related to power loading of CAs. We extended previous work to the case where PU and CA are not frequency synchronized. We applied this formulation to GFDM and analyzed the performances of this scheme under this scenario. We quantified the effects of frequency desynchronization on CAs capacity, and measured the interest of achieving perfect synchronism between CAs and PUs.

In the end, we improved the understanding of GFDM, and used this new knowledge to simulate GFDM based CAs performances in typical CR scenarios.
5. CONCLUSION AND FUTURE WORK

5.2 Future Work

The challenges related to 5G, and especially to GFDM, are still manyfold. As we developed a knowledge of GFDM frequential behaviour, we propose to use the latter as a pillar stone of our oncoming work.

We propose to thoroughly study GFDM OOB emissions in order to give models and closed forms for the different possible configurations of the GFDM scheme. OOB emissions are such a crucial metric in CR systems that it could be used to pursue many different goals.

We aim at investigating the effects of asynchronism on GFDM BER and proposing ways to make this waveform more robust to CFOs and time offsets.

We are also interested in studying the links between GFDM and future networks scenarios, such as multi-user situations, and designing a kind of Generalized Frequency Division Multiple Access.
Appendices
A. MAKING NETWORKS GREENER : DEMONSTRATING THE IMPACT OF USER LOCALISATION

A Making networks greener : demonstrating the impact of user localisation

A.1 Context

One of the biggest concerns for Fifth Generation (5G) networks lies in decreasing significantly the energy consumption, which has exploded even faster than data rates over the years. Among multiple ways to achieve these goals, such as using Peak-to-Average Power Ratio (PAPR) reduction techniques, the idea of localizing users in order to manage Base Station (BS) power distribution in a more efficient way has been increasingly investigated in the last few years.

Some current SCEE members have been doing research in this field, and developing algorithms for cluster detection and localization. Relevant references can be found in [45–47]. In the course of the International Chair on Green Radio led by Honggang Zhang ending in October 2014, it has been decided to develop a demonstration of a network in which a central server is able to shut down BS when no user needs it. The architecture of the deployed network is visible on Figure A.1.

For the sake of the demonstration and for feasibility reasons, BS are emulated by Wi-Fi Access Points (APs). Each of them is equipped of a switch controllable over Ethernet, which allows them to be turned off and on in a software way. An Ethernet hub links all APs together with the central server which runs a Python software in charge of the treatments. The different terminals, whether mobile phones or Personal Computers (PCs), communicate their measurements to the server over Transfer Control Protocol (TCP) sockets.

At a predefined frequency, the users sense their environment and save the data couples
A. MAKING NETWORKS GREENER: DEMONSTRATING THE IMPACT OF USER LOCALISATION

Figure A.1: Architecture the deployed network

(Basic Service Set Identifier (BSSID), Received Signal Strength (RSS)) and transmit it to the central server. The latter uses these measurements to update its RSS matrix of dimensions $N_{users} \times N_{BSSID}$. According to these values, it can be decided to turn off a BS if no user is attached to it or to turn one on if a user suffers from low RSS incoming from every BS. These measurements can also be transmitted to Matlab and processed by the algorithms formerly developed to extract user clusters and positions.
A.2 DEVELOPED APPLICATION

Though this project is not directly linked to the rest of my work, I have been asked to develop an Android application capable of achieving the required measurements and data transmission, as I had realized a similar software during an undergraduate project. A synoptic chart of the developed application is presented on Figure A.2. As one can see, the process is easily cut into three different steps: at each cycle, the user goes through the following cycle:

1. Initialization: ensure that Wi-Fi is on on the mobile and the mobile is connected to the network.

2. Management of terminal moves: if the phone jumped to a new BSSID of the same network since last cycle, it informs the server with due data.

3. Scan and feedback: the results of a Wi-Fi scan are parsed into a JSON array and fed to the server over TCP.

Figure A.2: Flowchart of the developed mobile application
This work is still under progress, and the mobile application as well as the server software under active development. At this point of the process, the server is able to gather informations on all nodes connected to the network and process algorithms on their respective RSS. However, it must also be able to control nodes and ask them, for example to leave a particular BS and attach to another in order to turn the former off. This part still remains to be developed.

It is hoped that this work will be presented as a demonstration at the IEEE Online GreenComm 2014 conference. Besides, the developed application being easily deployed on Android phones of Signal, Communications et Electronique Embarrquée (SCEE) research members and Supélec students, it could represent a useful research tool in the future.
B Calculation of Xia filter roll-off function

In this appendix, we present the derivation we made of the \( \nu \) function used in Xia filters to define their roll-off.

\[
\forall x \in [0, 1], \nu(x) = x^\beta \left( \sum_{i=0}^{\beta-1} a_i x^i \right)
\]

\[
\forall x \in [0, 1], \nu(x) + \nu(1 - x) = 1
\]

Therefore

\[
\forall x \in [0, 1], \sum_{i=0}^{\beta-1} a_i x^i + (1 - x)^\beta \left( \sum_{i=0}^{\beta-1} a_i (1 - x)^i \right) = 1
\]

\[
\forall x \in [0, 1], \sum_{j=0}^{\beta-1} a_i x^i + \sum_{j=0}^{\beta-1} \binom{j}{i+\beta} (-x)^j = 1
\]

\[
\forall x \in [0, 1], \sum_{j=0}^{2\beta-1} a_{j-\beta} x^j + \sum_{j=0}^{2\beta-1} (-1)^j \left[ \sum_{i=0}^{\beta-1} a_i \binom{j}{i+\beta} \right] x^j + \sum_{j=0}^{\beta-1} (-1)^j \left[ \sum_{i=0}^{\beta-1} a_i j i + \beta \right] x^j = 1
\]

\[
\forall x \in [0, 1], \sum_{j=0}^{\beta-1} (-1)^j \left[ \sum_{i=0}^{\beta-1} a_i \binom{j}{i+\beta} \right] x^j + \sum_{j=0}^{\beta-1} (-1)^j \left[ \sum_{i=0}^{\beta-1} a_i j i + \beta \right] x^j = 0
\]

Therefore

\[
\forall j, b_j = 0
\]
As it appears that the expressions of $b_j$ for $j \in [\beta \ 2\beta - 1]$ are linear combinations of those for $j \in [0 \ \beta - 1]$, this last equation is equivalent to:

$$\forall j \in [0 \ \beta - 1], (-1)^j \sum_{i=0}^{\beta-1} a_i \binom{j}{i+\beta} = 0$$

This last equation describes the system of equations that the coefficients $a_i$ of the $\nu$ function has to respect.
Bibliography


