Master Thesis

Test of 5G multicarrier schemes using Software Defined Radio

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Abstract

5G aims to be a revolutionary jump in terms of data rates, diminished latency, massive connectivity, the Internet of Things and so on. Right now, multicarrier modulation schemes are widely used because of their great advantages. One particularly famous modulation scheme is Orthogonal Frequency Division Multiplexing (OFDM), which is one of the most adopted technique in the world. We know that wireless channels are frequency selective, meaning that the frequency response of the channel varies according to the variation of the frequency, with a sinusoidal behaviour. By dividing the available bandwidth into smaller bandwidths, we can approximate the channel as flat in each one of them. Moreover, we can also take advantage of the property of orthogonality between the subcarriers. The most famous standards that use OFDM are WiFi and Long-Term Evolution (LTE) networks.

For 5G networks, other modulation schemes are taken in consideration. This is because even if OFDM has lots of advantages, it suffers in particular from a considerable loss of power due to the utilization of Cyclic Prefix (CP), which avoids Inter-Symbol Interference (ISI) and Inter-Carrier Interference (ICI), but also from a very high Peak to Average Power Ratio (PAPR). One of the main goals is to find an alternative solution to this problem to reach a lower PAPR, such as Filter Bank Multicarrier (FBMC) and Universal Filter Multicarrier (UFMC).

FBMC doesn't use any CP. What it does is an operation of filtering before the input to the (Inverse Fast Fourier Transform) IFFT, in general an Inverse Discrete Fourier Transform (IDFT) block. There are two main versions of FMBC: Staggered Multitone (SMT) and Cosine-modulated Multitone (CMT). The one which is taken in consideration in this thesis is the SMT. SMT uses an Offset Quadrature Amplitude Modulation (OQAM) in which the quadrature component (the imaginary part) of the signal is sent with a delay of half the symbol duration. UFMC, on the other hand, slices each sub-carrier into smaller subbands and performs operations of filtering (more specifically a Dolph-Chebyshev filter is used) and IFFT on each of them. Thanks to these strategies we can reach a lower PAPR and other advantages.

In this elaborate an implementation of the transmitter schemes of OFDM, FBMC and UFMC will be illustrated by the software development environment LabVIEW. Furthermore, with the utilization of the NI-USRP, a Software Defined Radio (SDR) by National Instrument, which is the same provider of LabVIEW, and also with the

help of a spectrum analyzer, it has been possible to run a simulation and transmit the three waveforms in the Telecommunications Laboratory located in the ”Universidad Carlos III de Madrid”, the host university that I attended during my Erasmus stay in the city of Madrid, Spain.

The purpose was, after having learned how to work with LabVIEW and USRP, to go deeper to the topic of Multicarrier Systems, have a knowledge about 5G Mobile Networks and study the modulation schemes aforementioned, to implement their transmitter and receiver schemes and eventually to simulate the transmission of the waveforms and collect results such as the PAPR, the Power and the Bandwidth in order to validate the work I've done. My task was a part of a project consisting in the connection between transmitter and receiver of the different modulation schemes by using two USRP.

Dedications

I dedicate this thesis to my mother, Cristina, who has always supported me in everything, believed in me and loved me beyond any imagination; to my father, Emanuele, who is an inspiration for me and who loves me tremendously; to my older sister, Ludovica, who has always been an important person in my life and for whom I will always be there; to my younger sister, Marta, for whom I wish all the best in her life and who will always count on me; to my aunt, Enza, without whom I would be totally lost; my two cousins, Elisa and Simona, an enormous part of my life, for whom I will always be there; my uncle, Marco, who loves me, regardless of the few time spent together and to whom I am grateful; to my other cousin, Miriam, who is tough and smart and for whom I wish all the best; to my other aunt, Pina, who has always loved me unconditionally; and to the rest of my family. My dedications are also to my lost relatives, whom I always bring in my heart. Finally, I want to dedicate this thesis to everyone who has been part of my life and with whom I have had the best moments, especially my friends from high school, from university both in Catania and Turin, from music and from my Erasmus in Madrid. To all of you, I want to say thank you, I always think of you.

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Chapter 1

Introduction

Goals of the Thesis

This Master Thesis aims, in a first moment, to briefly discuss about the state of 5G mobile networks, their requirements and the technology needed to deploy them. After that, the main focus is centered in the multi-carrier modulation schemes that are going to be used to best fulfill all the constraints pursued by 5G. More precisely the attention is focused on three of the most likely contenders that seem to be chosen in the future standard: OFDM, FBMC and UFMC. It is well known that OFDM has a slight disadvantage of spectral inefficiency due to the utilization of Cyclic Prefix, which also leads to other latency problems, and also losses of power. The OFDM symbol contains redundant information, which leads to an inefficient usage of the bandwidth. Moreover, OFDM has a big PAPR, so the trend is to find the best solution to lower it. FBMC and UFMC have pretty good qualities on their side, which are going to be discussed later on. Before directly talking about the three techniques, a general overview about the topic of multi-carrier modulation will be explained, considering all the main aspects that make them extensively used in wireless environment. Afterwards, the topic will be shifted to a waveform simulation performed with a Software Defined Radio (SDR), which is a radio communication system where components that are traditionally implemented in hardware (e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are instead implemented by means of software on a personal computer or embedded system. The software LabVIEW has been utilized, together with a spectrum analyzer. I have done the lab project during my Erasmus stay in Madrid, Spain using the aforementioned LabVIEW, which is a design software for the development of test applications and measurements. OFDM, FBMC and UFMC transmitters have been implemented in this project, together with OFDM and FBMC receivers. UFMC receiver hasn't been possible to implement due to time limitation issues. After the implementation of the architectures in LabVIEW, the waveforms have been transmitted in the laboratory by the means of National Instrument USRP hardware, which the University Carlos III of Madrid have let me borrow, together with a spectrum analyzer provided in the laboratory for the acquisition of the signal. My job consisted in implementing the transmitters and receivers of the three modulation schemes in order to give the means to another project consisting in building the communication between transmitter and receiver of OFDM, FBMC and UFMC by using two USRP: one for the transmitter and one for the receiver. I've been commissioned to provide laboratory results in order to verify the validity of my work.

The overall target of my final work is to describe how 5G networks will operate, to better understand the concept of multi-carrier waveform and analyze its different implementations, and to show the implementation and results of the laboratory project I have worked on, comparing also the three waveforms in terms of PDS (Power Spectral Density) and PAPR (Peak to Average Power Ratio), also by possibly showing that better performance in terms of spectrum efficiency can be achieved with respect to OFDM. Obviously, this work doesn't want to dwarf the advantages of OFDM, which remains one of the best fits in the multi-carrier enviroment.

Chapter 1 is an introduction to my final work. Chapter 2 will deal with 5G networks, talking about the requirements, spectrum, service and key technologies. Then, in chapter 3, the focus will be shifted to multi-carrier systems and three of the potential modulations that will potentially be used in 5G. Afterwards, chapter 4 will talk about the project I've done with LabVIEW and will show the result I've obtained. Eventually, my final conclusions will be discussed in chapter 5.

Chapter 2

5G State of the Art

2.1 Brief Introduction

5G is the fifth generation of cellular mobile networks, directly after 4G (that is LTE). The main targets of 5G are reaching very high data rates, lower latency, energy saving, cost reduction, higher system capacity and massive device connectivity [14]. The main standardization bodies defining 5G are the ITU IMT-2020 and the 3GPP. 5G physical layer is called New Radio (NR) and is going to use new spectrum regions such as mm-wave bands (24-86 GHz), as well as the 600 MHz to 6 GHz currently used in LTE. The theoretical peak download capacity required by ITU IMT-2020 is 20 Gbits. ITU has divided 5G network services into three main categories: enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC) and Massive Machine Type Communications (MMTC). In order to satisfy the targets, 5G needs to implement new technologies, like: Base Station Densification, Massive MIMO (Multiple Input Multiple Output) and work with the already mentioned mm-wave communications.

2.2 5G requirements

5G will have to deal with high speed data rate requirements together with spectral efficiency improvement issues, traffic capacity, latency, reliability and density. For all of each targets we will have to identify a key use case (eMBB, URLLC, MMTC). The table shown in Figure 2.1 illustrates the specific values of the requirements.

2.3 New Radio Spectrum

5G will use new spectrum available in the mm-wave bands, from 24 GHz to 86 GHz, together with the currently existing bands lower 6 GHz (referred to as microwave bands), which have limited bandwidth and heavily used. WRC-15 (World Radiocommunication Conference 2015) approved a certain number of frequency bands in the mm-wave range, which are the followings: 24.25 – 27.5; 31.8 - 43.5; 45.5 – 50.2; 50.4 – 52.6; 66 – 76; 81 – 86 all in GHz. They provide a very big amount of new bandwidth [8].

MINIMUM TECHNICAL PERFORMANCE REQUIREMENTS OF IMT 2020

KPI	Key Use Case	Values
Peak Data Rate	eMBB	DL: 20 Gbps, UL: 10 Gbps
Peak Spectral Efficiency	eMBB	DL: 30 bps/Hz, UL: 15 bps/Hz
User Experienced Data Rate	eMBB	DL: 100 Mbps, UL: 50 Mbps (Dense Urban)
5% User Spectral Efficiency	eMBB	DL: 0.3 bps/Hz, UL: 0.21 bps/Hz (Indoor Hotspot); DL: 0.225 bps/Hz, UL: 0.15 bps/Hz (Dense Urban); DL: 0.12 bps/Hz, UL: 0.045 bps/Hz (Rural)
Average Spectral Efficiency	eMBB	DL: 9 bps/Hz/TRxP, UL: 6.75 bps/Hz/TRxP (Indoor Hotspot); DL: 7.8 bps/Hz/TRxP, UL: 5.4 bps/Hz/TRxP (Dense Urban); DL: 3.3 bps/Hz/TRxP, UL: 1.6 bps/Hz/TRxP (Rural)
Area Traffic Capacity	eMBB	DL: 10 Mbps/m^2 (Indoor Hotspot)
User Plane Latency	eMBB, URLLC	4 ms for eMBB and 1 ms for URLLC
Control Plane Latency	eMBB, URLLC	20 ms for eMBB and URLLC
Connection Density	mMTC	1,000,000 devices/km^2
Energy Efficiency	eMBB	Capability to support high sleep ratio and long sleep duration to enable low energy consumption when there is no data
Reliability	URLLC	$1–10^{-5}$ success probability of transmitting a layer 2 protocol data unit of 32 bytes within 1 ms in channel quality of coverage edge
Mobility	eMBB	Up to 500 km/h
Mobility Interruption Time	eMBB, URLLC	0 ms
Bandwidth	eMBB	At least 100 MHz; Up to 1 GHz for operation in higher frequency bands (e.g., above 6 GHz)

Figure 2.1: 5G requirements of IMT 2020 [8].

2.4 Services

2.4.1 Enhanced Mobile Broadband

Enhanced Mobile Broadband (eMBB) is an extension to 4G broadband services. It's one of the 5G New Radio use cases, which are defined by the 3GPP as part of its SMARTER (Study on New Services and Markets Technology Enablers) project. eMBB is going to make the mobile internet experience faster. It is obviously the most straightforward evolution of what 4G does, enabling newer and better versions of experiences that we can already have, as well as completely new stuff.

eMBB will be among the first 5G services. To enable the early deployment of eMBB services, in March 2017 the 3GPP's RAN Group committed to finalize the Non-standalone (NSA) 5G NR variant, which consists in the usage of the existing 4G network, supplemented by 5G NR carriers to boost data rates and reduce latency. For that reason, eMBB can be seen as the first phase of 5G, which has to be encompassed in the 3GPP Release 15 standards update.

Being the natural evolution of existing 4G networks, eMBB will provide faster data rates and therefore a better user experience than current mobile broadband services. As [6] says, within eMBB we can distinguish three attributes 5G will need to accomplish: higher capacity, in which broadband access must be available in densely populated areas, both indoors and outdoors, like city centres, offices buildings or public areas like stadiums; improved connectivity, in which broadband access must be available everywhere to provide a consistent user experience; higher user mobility, which will enable broadband services in moving vehicles including cars and others. Obviously these three cases will have different requirements. In a scenario where there are lots of users, like spectators at an event, there will be a requirement for very high traffic capacity to meet the needs of all the users, but those users will be either static or moving slowly so the requirement for mobility will be low. In contrast, providing eMBB services to passengers in a high-speed train will require a high degree of mobility. On the other hand the traffic capacity will be lower than the previous case [6]. eMBB is expected to support a traffic capacity of 10 Mbps per square metre in hotspot areas, data rates up to 1 Gbps with very high peaks in tens of Gbps, very low latency, connection density of up to one million connections per square kilometre and high mobility.

2.4.2 Ultra-Reliable Low-Latency Communications

URLLC is a service category introduced in 5G. It will be supported in the New Radio of 5G. It's targets have to deal with data messages which are time-sensitive and must be delivered end-to-end with maximum security, high reliability and very low latency. The requirement of low latency means that transmission of data has to be decoded at the receiver before a deadline, otherwise it's of no use and has to be dropped from the system. This clearly implies a loss in reliability. As an example, the current 3GPP requirement for URLLC includes the hard latency of one millisecond over the air interface and the system reliability of 99.999% [2]. This means that the QoS (Quality of Service) of URLLC is not satisfied if more than a packet out of 100000 packets is not delivered successfully in one millisecond over the wireless medium. The particular QoS requirements of URLLC introduces new challenges in the wireless system design. Hybrid automatic repeat request (HARQ) is the mechanism allowing high reliability, thanks to which it is possible to do a high number of retransmissions. Unfortunately this is not enough when we have to deal with very restricted latency requirements. In order to minimize the number of retransmissions a sufficient number of resources could be allocated, minimizing the block error rate (BLER) of HARQ, although this could lead to a low spectral efficiency and system capacity. All URLLC users connected to the radio access network are expected to satisfy the QoS and receive equal grade of service (EGOS) [2].

Let's take as an example LTE networks. In LTE we have several latency components. In Figure 2.2 the various components of the latency the user experiences are listed.

According to that table, if we consider an uplink transmission, after a user is alligned with the base station, its total average radio access delay accounts for the following steps: UE waits for a Physical Uplink Control Channel; UE sends a scheduling request; BS decodes the scheduling request and generates the scheduling grant; BS sends the scheduling grant; UE decodes the scheduling grant; UE sends uplink data; BS decodes the data [4].

The explained steps are resumed in Figure 2.3, where we have the figurative representation of the connection establishment depending on time (which is represented vertically down forward).

URLLC services will use a grant free uplink resource to transmit data. Figure 2.4 shows how the transmsission establishment should take place. Here the UE just transmits on receiving new data and does not need to wait for the base station to assign resources [3].

Moreover, latency in URLLC services can be further reduced by preempting eMBB transmissions. Resources can be stolen from pre-scheduled eMBB resources

VARIOUS DELAY SOURCES OF AN LTE SYSTEM (RELEASE 8) IN THE UPLINK AND DOWNLINK

Delay Component	Description	Time (ms)
Grant acquisition	A user connected and aligned to a base station will send a Scheduling Request (SR) when it has data to transmit. The SR can only be sent in an SR-valid Physical Uplink Control Channel (PRCCH). This component characterizes the average waiting time for a PRCCH.	5ms
Random Access	This procedure applies to the users not aligned with the base station. To establish a link, the user initiates an uplink grant acquisition process over the random access channel. This process includes preamble transmissions and detection, scheduling, and processing at both the user and the base station.	9.5ms
Transmit time interval	The minimum time to transmit each packet of request, grant or data	1ms
Signal processing	The time used for the processing (e.g., encoding and decoding) data and control	3ms
Packet retransmission in access network	The (uplink) hybrid automatic repeat request process delay for each retransmission	8ms
Core network/Internet	Queueing delay due to congestion, propagation delay, packet retransmission delay caused by upper layer (e.g., TCP)	Vary widely

Figure 2.2: Table resuming LTE latency components [4].

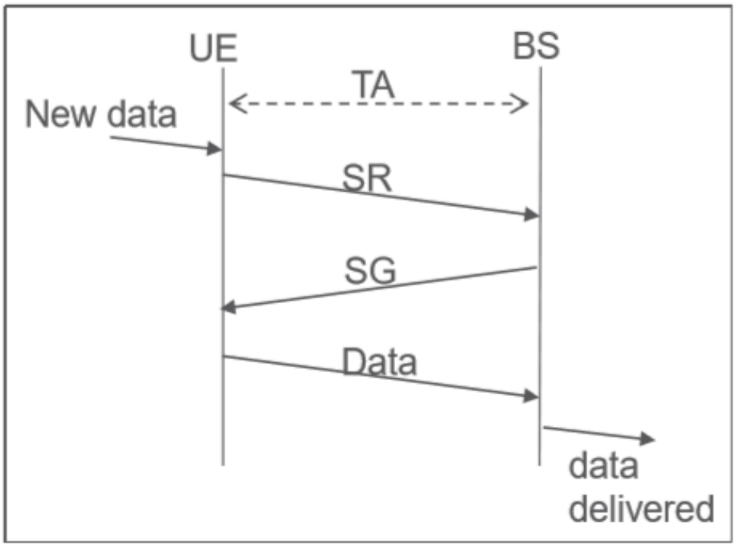

Figure 2.3: Conventional Grant Based Access [3].

by the MAC scheduler to transmit URLLC data, as shown in Figure 2.5.

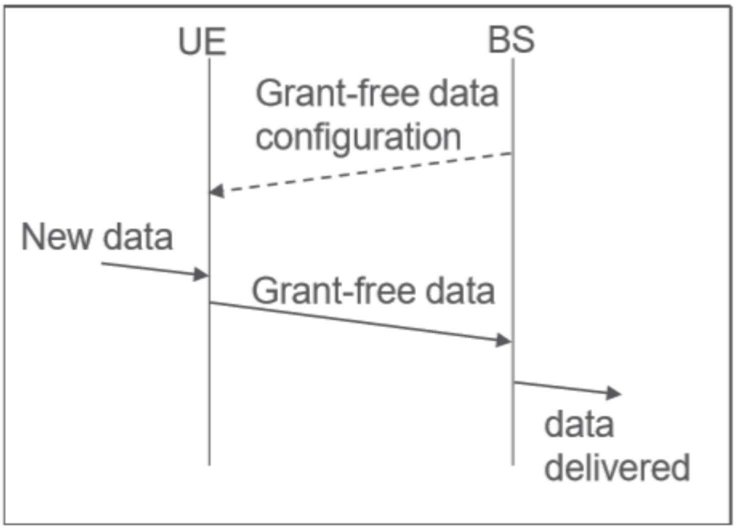

Figure 2.4: Latency reduction with grant free access [3].

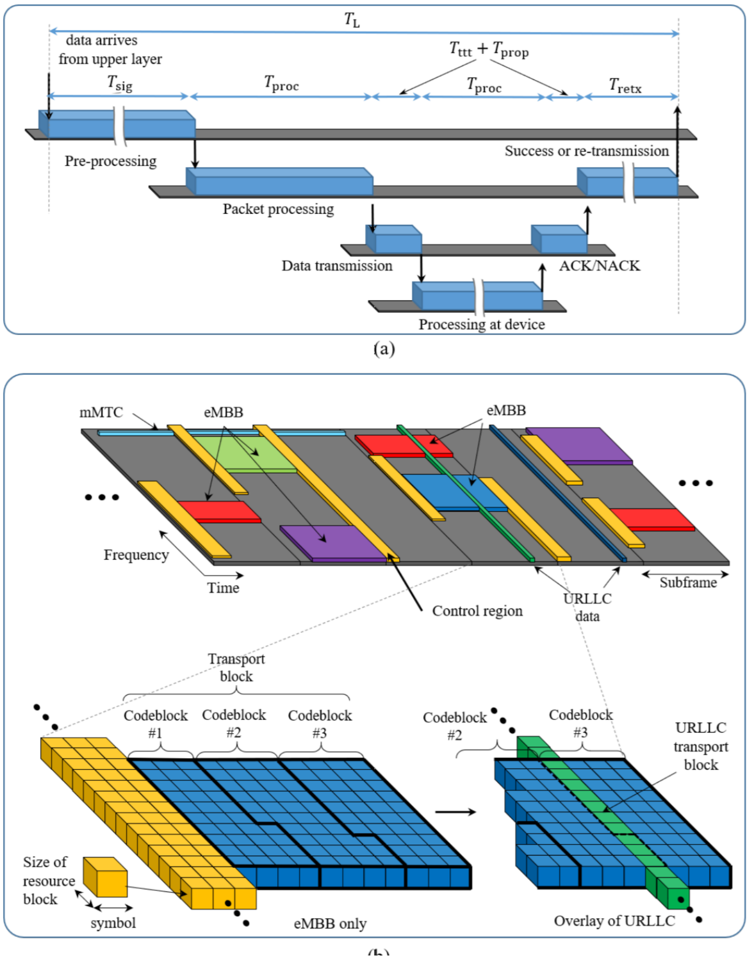

Figure 2.5: Physical layer downlink scenario in URLLC service: a) illustration of latency components; b) transmission of eMBB, mMTC, and URLLC packet in subframe level, and scheduling of URLLC packet into eMBB packet in symbol level [5]

2.4.3 Massive Machine Type Comunication

Another important service that 5G is going to deploy, which makes the future mobile networks face several important challenges is Massive Machine Type Communications (mMTC), often called Machine-to-Machine (M2M). mMTC introduces hard technical challenges such us increased oeverhead and control signaling as well as diverse application-specific constraints like ultra-low complexity, high energy efficiency, critical timing and continuous data intensive uploading [18]. Massive means that a very large number of devices, at least 10 times greater than the current number of cellular subscribers, with varying QoS requirements must connect to the cellular network.

Clearly, mMTC carries different requirements than normal Human Type Communications (HTC), adding new constraints in cellular networks. If we take a look at Figure 2.6, we can see the various difference in terms of requirements between normal HTC and MTC in the context of cellular networks.

Requirements	HTC over cellular	MTC over cellular
Uplink	Uplink is usually more lightly loaded and power-constrained	For many MTC applications, the main bottleneck; high signaling overhead and extreme power constraints
Downlink	The main bottleneck for high data rate services, since most traffic comes from the core network	Needs to be able to deep sleep, but wake up on command for network-initiated communication
Subscriber load	Relatively few (< 100) simultaneous devices per cell	Many (>> 100) simultaneous devices per cell with traffic uploading that can be event-triggered, periodic, or continuous
Device types	Relatively homogeneous, smart phones and data consumption devices like tablets	Extremely heterogeneous device landscape that includes environmental sensors, utility meters, wearable devices, and many unforeseen applications
Delay requirements	Defined service classes by 3GPP, vary between real-time conversational and best effort data	Very diverse delay requirements, ranging from emergency/time critical to very delay tolerant applications
Energy requirements	Flexible energy requirements due to the ability to recharge daily	Many ultra-low energy applications that require extreme power consumption measures
Signaling requirements	Signaling protocol overhead is not a concern and the design provides reliable mobility and connection management mechanisms	Application-dependent signaling protocols, with extremely efficient overhead signaling and contention resolution
Architectural requirements	Well-understood hierarchical cellular architecture with standardized interfaces between access and core network elements	Wide area coverage may require integration of data aggregators with multihop relaying; relaxed requirements for handover and roaming support

Figure 2.6: MTC versus HTC requirements in the context of cellular networks [18]

2.5 Key Technologies

In order to completely fullfill all the requirements needed in the next 5G mobile networks it is obvious that new techniques and technologies have to be implemented. The following sections cover some of the key factors that are going to play an important role in 5G which will enable stronger definitely performances.

2.5.1 Network Densification

Network densification is a frequently discussed topic. Thanks to smartphones and tablets, wireless subscribers are using more and more network resources than ever before. Operators need to add more capacity to their networks to manage all the traffic while providing the expected network speeds to their clients. Network densification basically means adding more cell sites to increase the amount of available capacity. Cell sites, strategically placed in capacity-strained areas, add more capacity where it is most needed and also help offload traffic from surrounding sites. Clearly, the areas where more capacity is needed are urban areas. They need more focus.

Instead of the enhancement of radio access networks (RANs), the future wireless networks are more likely to act as a mixture of various types of RANs, like: macrocell BSs, femto-cell BSs, pico-cell BSs and WiFi access points (APs) and so on. The logic is to put smaller cells like pico or femto size in places where subscriber density is bigger and bigger cell sizes where it is smaller.

2.5.2 Massive MIMO

MIMO stands for Multiple-input multiple-output, which can essentially be described by this single principle: a wireless network that allows the transmitting and receiving of more than one data signal simultaneously over the same radio channel, typically using a separate antenna for the transmitting and receiving of each data signal.

Standard MIMO networks usually use two or four antennas to transmit data and the same number to receive it. Massive MIMO, instead, is a MIMO system with an particularly high number of antennas at the base station. System's trend will be about tens or even hundreds of antennas.

As [8] says, the use of higher frequencies makes it possible to deploy large scale antenna arrays at the base station, which are used to provide array gain to overcome higher path loss and provide spatial multiplexing gain. Typical antenna numbers under consideration for the base station vary from 256 to 1024 for the mm-wave bands. The antennas consist of cross polarized elements arranged in a two dimensional array (2D). The array may also consist of constituent sub-arrays. The antenna elements may further consist of groups of dipoles or patch antennas in order to achieve the desired gain. (For example, two dipoles per element are required to offer a gain of 5.2 dBi/element).

3D MIMO

The real-world channel has three-dimensional (3D) characteristics, rendering two-dimensional (2D) MIMO techniques not good enough. The possibility of tilting the transmit beam angle in the full 3D space will intuitively improve the overall system throughput and interference management, particularly for scenarios where mobile users are distributed in a 3D space with different elevation such as modern urban environments. This is becoming more and more important as smaller cells have been introduced. One core enabling technology for 3D MIMO is the so called active antenna system (AAS). AAS technology integrates radio frequency components (power amplifiers and transceivers) with the antenna elements. In this manner the phase and amplitude of the signals from each antenna element can be electronically controlled, thus facilitating more flexible and intelligent beamforming, resulting in increased capacity and coverage [17].

2.5.3 Mm-Wave

Millimeter-wave (mm-wave) channels are characterized by some remarkably different propagation effects. [8] list effects such as: noticeable atmospheric absorption for longer links, reflection on surfaces with a roughness that is comparable to the wavelength, and poor diffraction. Attenuation and dispersion characteristics, which determine system performance, will also be significantly different.

Chapter 3

Multi-carrier Modulation

3.1 What is a multi-carrier system

So far we have dealt with the background of future 5G mobile networks, talking about the potentialities it could give in order to increase the QoS of currently 4G mobile networks. What this elaborate treats more specifically is the physical layer of 5G and in particular the multi-carrier systems which are the key techniques nowadays enabling the transmissions in the wireless environment.

When we want to transmit a signal it is affected by the channel. We would like the channel having a flat behaviour, meaning that the frequency response of the channel should be flat (or at least approximately flat) over the signal spectrum. Unfortunately, in the wireless medium we don't have a flat behaviour. This is because when we establish a connection between source and destination, what we will have is a direct path between the two, but also several reflected paths (which can be thought of delayed versions of the original signal that reach the destination). The problem is that it is sufficient to have just one reflected path to change the behaviour of the channel. More specifically, one reflected path is enough to make the channel have a sinusoidal frequency response. It is obvious that if we wanted to transmit a signal occupying a considerable amount of bandwidth we would encounter certainly lot of problems.

The best solution is to adopt a multicarrier signal. The first multicarrier signal has been Orthogonal Frequency Division Multiplexing (OFDM). Thanks to OFDM we can divide our signal spectrum into several sub-carriers. The excellent property in multicarrier systems is that in each sub-carrier we are able to approximate the channel behaviour as flat. Furthermore we have the property of orthogonality. This means that in each sub-carrier, transmitting our symbol, the interference of adjacent sub-carriers is zero. This implies no interference between adjacent sub-carriers. As we will see, in order to avoid ICI (Inter-Carrier Interference) and ISI (Inter-Symbol Interference) completely, other methods have to be adopted. In the case of using OFDM, the problem for what concerns the wireless medium is solved and we can transmit our symbol. The principle of OFDM can be further developed and taken on other multicarrier systems. As we will see, Filtered Bank Multicarrier (FBMC) and Universal Filtered Multicarrier (UFMC) are variants of OFDM, having some characteristics that in certain aspects make them better alternatives than OFDM.

What this chapter wants to talk about is a brief explanation of what is a multicarrier system and then wants to deal with the three systems which are taken in consideration in this elaborate and briefly explain how they work, their advantages and disadvantages.

3.2 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a frequency-division multiplexing (FDM) scheme used as a digital multi-carrier modulation method. OFDM was introduced by Chang of Bell Labs in 1966 [16].

3.2.1 Key principles of OFDM

The success of OFDM is that it satisfies the flat fading condition, as well as the limited ISI condition, respectively (3.1) and (3.2):

$$B_{\mathrm{A}} << \frac{1}{D} \tag{3.1}$$

$$D << T \tag{3.2}$$

Where B_{A} is the available bandwidth, D is the Delay Spread experienced by the transmitted symbol and T is the symbol duration. Whenever this condition is satisfied we can approximate the channel as flat, implying that we have a flat fading condition.

Clearly, since the medium is wireless, the total delay contribution is not given only by the direct path, that is the Line of Sight, but also by the other reflected paths. By considering just the total available bandwidth, the flat fading condition is not satisfied.

The solution given by OFDM is to take the available band and divide it into small sub-bands. On each of them an independent signal is transmitted. More specifically, the available band is divided in small frequency slots Δ. On each frequency slot a symbol is transmitted. The flat fading condition is satisfied if:

$$\Delta << \frac{1}{D} \tag{3.3}$$

The number of sub-bands N is given by:

$$N = \frac{B_{\mathrm{A}}}{\Delta} \tag{3.4}$$

Eventually we can transmit the same constellation, that would be transmitted on a single carrier scheme, in each sub-carrier.

For what concerns the choice of the sub-carriers, each sub-carrier is placed at the center of each sub-band, with the addition that each sub-carrier is equally spaced, since the sub-band amplitudes are the same. Above all, the most important characteristic of OFDM, which is given by its name, is the property of orthogonality of each sub-carrier, that is at each sub-carrier the interference of adjacent sub-carriers is zero. This feature is made possible by the utilization of a DFT (Discrete Fourier Transform).

What is a OFDM transmitted waveform? It is simply the sum of all the waveforms transmitted in each sub-carrier:

$$s(t) = \sum_{i=0}^{N-1} s_{\mathrm{i}}(t) \tag{3.5}$$

Where s(t) is the OFDM symbol and $s_i(t)$ is the i-th sub-carrier symbol. A sub-carrier signal is a sinusoidal signal whose period changes depending on the transmitting sub-carrier: the number of periods of the sinusoidal signal will be different in each sub-carrier.

Spectrum

Regarding the spectrum, the logic is similar to that of the waveform. The total spectrum of OFDM is the sum of all the spectrums at each sub-carrier. Basically it's a summation of multiple sinc. When we sum lots of sinc (since N is expected to be a large number) we obtain an approximate flat spectrum. A generic OFDM spectrum with 600 carriers is shown in Figure 3.1.

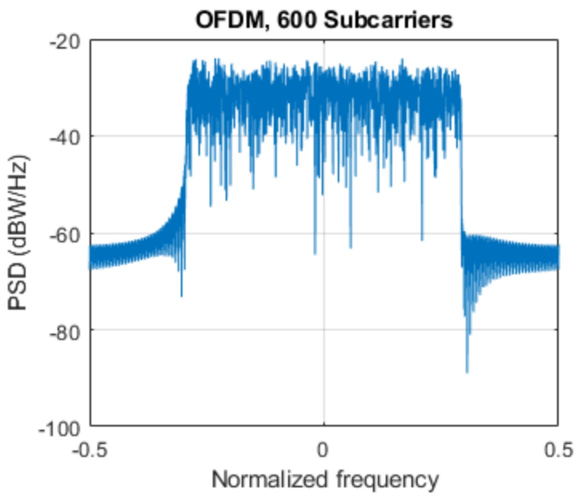

Figure 3.1: Generic OFDM Spectrum with 600 sub-carriers [10].

Due to bad frequency behaviour, where secondary lobes contain lot of power, if we use all the carriers, there is a lot of power exiting our available band and producing interference on adjacent channels. This is clearly not acceptable. A solution could be to turn off external sub-bands and do not transmit at the beginning and at the end, in order to reduce interference and to reduce the amount of power exiting our available bandwidth. Obviously this is a loss in terms of bit rate.

Digital implementation

Which is the technique enabling the orthogonality feature between the sub-carriers in a OFDM digital implementation? The answer to that is given by the Discrete Fourier Transform (DFT). Actually, the Fast Fourier Transform (FFT) is more often used when the number of samples are a power of 2, since it facilitates the calculations. What we want to use in the transmitter is the Inverse Discrete Fourier Transform (IDFT), or better the Inverse Fast Fourier Transform (IFFT), because DFT is a transformation from the time domain to the frequency domain. Since we want to transmit a signal in the time domain, we have to perform the inverse operation (the IDFT) from the frequency domain to the time domain. DFT and IDFT formulas are given respectively by (3.5) and (3.6) below:

$$x_{\mathrm{i}} = \sum_{m=0}^{N-1} s_{\mathrm{m}} e^{-j\frac{2\pi}{N}mi} \tag{3.6}$$

$$s_{\mathrm{m}} = \sum_{i=0}^{N-1} x_{\mathrm{i}} e^{+j\frac{2\pi}{N}mi} \tag{3.7}$$

Where $\mathrm{x_i}$ and $\mathrm{s_m}$ are the i-th time sample and m-th frequency sample respectively. At the transmitter, the signal is defined in the frequency domain. It is a sampled digital signal, and it is defined such that the discrete Fourier spectrum exists only at discrete frequencies. Each OFDM carrier corresponds to one element of this discrete Fourier spectrum.

The implementation of OFDM transceiver is given by Figure 3.2.

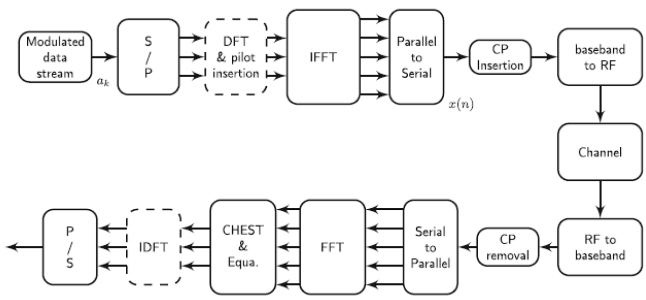

Fig. 1 CP-OFDM transceiver (additional SC-FDMA stages in dash). S/P and P/S, respectively, denote parallel to serial and serial to parallel

Figure 3.2: OFDM scheme [13]. The dashed blocks are not taken in consideration.

It is an obvious consequence that at the receiver stage, in order to recover each sub-carrier, a DFT or FFT operation has to be performed.

3.2.2 Cyclic Prefix

Since the medium is wireless we have multiple reflected paths. If we consider just one reflected channel we have that in the first portion of the direct symbol (Line of Sight) the delayed received symbol produces ISI. Even if (3.2) is satisfied, there is still some ISI. In a single carrier system, (3.2) is not satisfied and this implies: ISI produced on the entire symbol and many previous symbols to be involved.

Even if OFDM satisfies (3.2), still the problem has to be solved. A solution is to introduce some guard times to separate consecutive symbols. If:

$$T_{\mathrm{G}} > D \tag{3.8}$$

where $\mathrm{T_G}$ is the guard time duration, We have completely solved the problem. A straightforward price to pay is the reduction of the effective symbol time: the nominal symbol time is T, but the true symbol time is $\mathrm{T+T_G}$, leading to a reduction of the bit rate.

Even though ISI is removed, we still have a problem of Inter-Carrier Interference (ICI). The problem turns up when the convolution between the transmitted signal and the channel has to be performed. Since we have time instants in which nothing is transmitted, we introduce synchronization problems at the receiver which leads to sub-carrier dependency issues. To be more specific we could take the following logic: at the beginning of the symbol, there's an abrupt change from no signal to signal (the signal is in part sinusoidal and in part zero), thus it's not a pure sinusoidal signal in that fragment

The solution to this problem is simple: a part of the symbol's tail is copied and put before it's beginning. Consequently, all the sinusoidal signals are continuous, because the starting phase and the final phase are the same. This redundancy is most commonly called ad Cyclic Prefix (CP). CP completely eliminates ICI.

3.2.3 Disadvantages

OFDM has lots of advantages, which unfortunately leads to some disadvantages in terms of performance. Which are the main prices we have to pay? We have already mentioned the reduction of effective symbol time and bit rate introduced by the guard time.

Now we want to analyze the problems created by the CP. A first intuitive answer is that a further power loss is introduced, because now something inside the guard interval is transmitted, but it's a redundant information. Thus, more power is utilized to transmit something again. Another issue is the latency: the end of the symbol is needed to wait in order to copy the CP must be at least the delay spread.

PAPR

There is another fundamental problem to be considered, which is the high PAPR that OFDM carries. The OFDM signal is the sum of N independent signals modulated onto sub-channels of equal bandwidth, which can be efficiently implemented by an Inverse Discrete Fourier Transform (IDFT), as we have seen. The frequency-domain data sequence are independent, identically distributed (i.i.d.) random variables and due to the central limit theorem[1], a small percentage of output samples will take very large magnitudes. This results in the PAPR problem of OFDM systems.

In general, the PAPR (χ) of the time-domain sequence is defined as the ratio between the maximum instantaneous power and the average power, that is:

$$\chi = PAPR = \frac{max(|s|^2)}{E\{|s|^2\}} \tag{3.9}$$

[1]In probability theory, the central limit theorem (CLT) establishes that, in some situations, when independent random variables are added, their properly normalized sum tends toward a normal distribution (informally a "bell curve") even if the original variables themselves are not normally distributed [15].

3.3 Filter Bank Multi-Carrier (FBMC)

5G is searching for an alternative to OFDM. One possible solution to completely eliminate the CP insertion block is, instead, to do some filtering operation before the IFFT block, applying a bank of filters to the data stream.

Like OFDM, also FBMC divides the bandwidth into a number of sub-channels. A OQAM (Offset Quadrature Amplitude Modulation) is used. As we will see, this combination of filter banks and OQAM leads to avoid CP and to obtain the maximum bit rate. [7].

3.3.1 Digital implementation

In this section the implementation of the FBMC transmitter and receiver is going to be discussed. Figure 3.3 shows the implementation scheme of the FBMC transceiver.

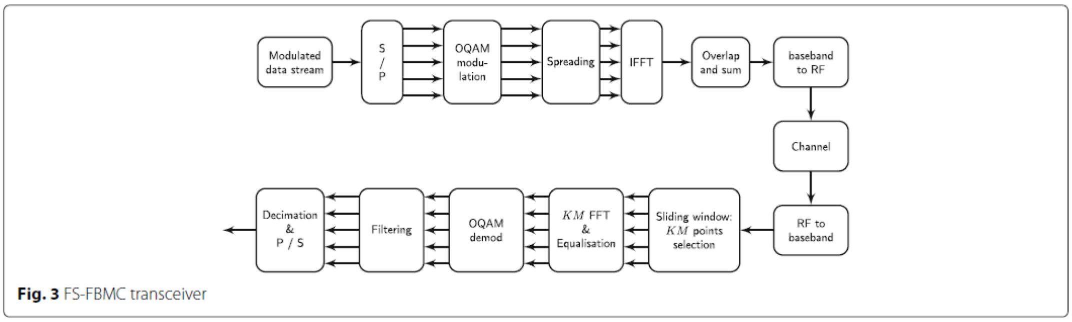

Figure 3.3: FBMC scheme [13].

Since it is a multicarrier system, the same logic of OFDM can be applied here: in order to modulate the various carriers we take advantage of the IFFT, though this time, as said before, some other steps have to be done.

For the proper functioning of the system, the receiver must be perfectly synchronized with the transmitter. In addition, due to the channel carrying multipath propagation and due to its impulse response, the multicarrier symbols overlap at the receiver input and it is no more possible to demodulate with just the FFT, because the orthogonality property has been lost due to ISI. We have seen that OFDM remedy to this problem is the insertion of CP. Instead, another solution can be taken: keeping the timing and the symbol duration as they are, but adding some processing to the IFFT/FFT, as said in [7].

Design of the prototype filter

Figure 3.4 represents the frequency response of a bank of FFT filters, in which the unit of the frequency axis is 1/M, the sub-carrier spacing.

At the frequencies which are integer multiples of 1/M, only one filter frequency response is non-zero. In the terminology of filter banks, the first filter in the bank, the filter associated with the zero frequency carrier, is called the prototype filter, weather the other filters are derived from it by shifting in frequency. The problem of this filter is the out-of-band ripples, which is too high. In order to improve the performance, it is necessary to increase the number of coefficients in the time

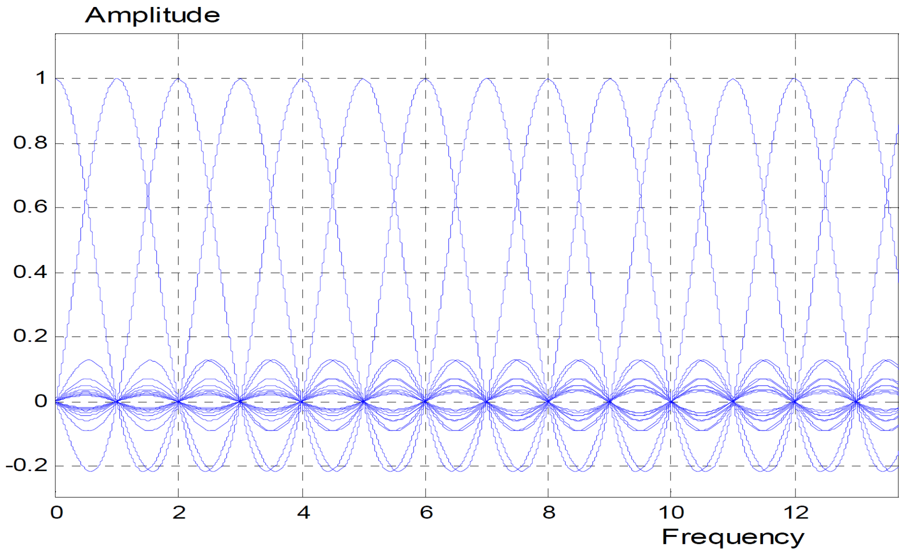

Figure 3.4: The FFT filter bank frequency response (frequency unit: sub-carrier spacing) [7].

domain and in the frequency domain. As said in [7], in the frequency domain additional coefficients are inserted between the existing coefficients, allowing for a better control of the filter frequency response.

Furthermore, there is another thing to consider: prototype filters are characterized by the overlapping factor K, which is the ratio of the filter impulse response duration Θ and the symbol time period:

$$K = \frac{\Theta}{T} \tag{3.10}$$

But it is also the number of multicarrier symbols which overlap in the time domain. In the frequency domain, thus, it is the number of frequency coefficients which are introduced between the FFT filter coefficients [7]. Once this new factor is introduced, an implementation of the prototype filter which improves the performance of the system can be set.

By always taking [7], Table 3.1 represents the frequency coefficients of the half-Nyquist filter for K = 2, 3 and 4.

Value of K	**H0**	**H1**	**H2**	**H3**
2	1	$\sqrt{2}/2$	**-**	**-**
3	1	0.911438	0.411428	**-**
4	1	0.971960	$\sqrt{2}/2$	0.235147

Table 3.1: Values of prototype filter coefficients for each K.

In the frequency domain, the filter response consists of 2K-1 coefficients. Figure 3.5 shows the prototype filter frequency coefficients and frequency response.

Consequently, the filter bank is obtained by the frequency shifts k/M, just like the FFT case aforementioned, where the filter with index k is obtained by multiplying the prototype filter coefficients by $e^{j2\pi\frac{k}{M}}$, where M is the number of samples.

Figure 3.6 shows a section of the filter bank.

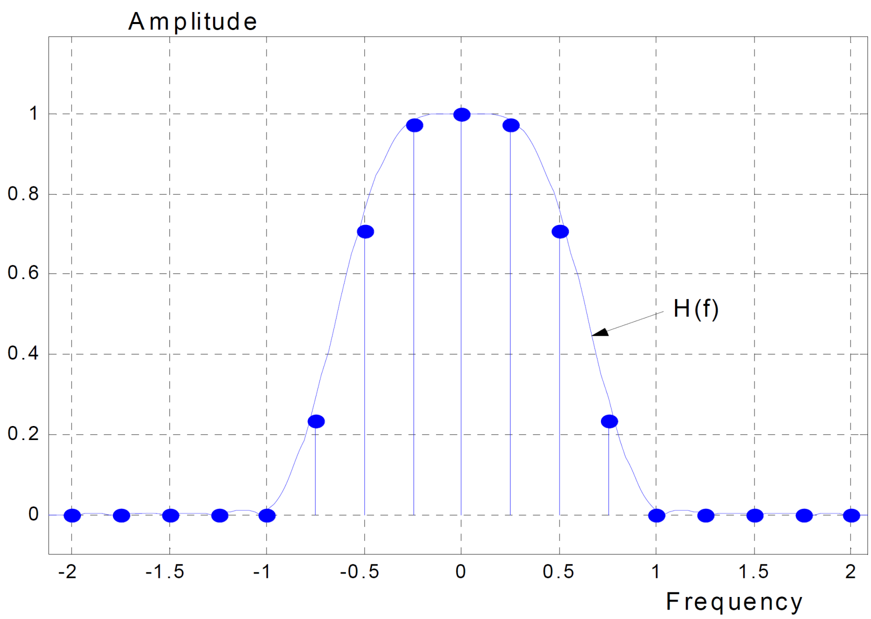

Figure 3.5: Prototype filter frequency coefficients and frequency response for K = 4 [7].

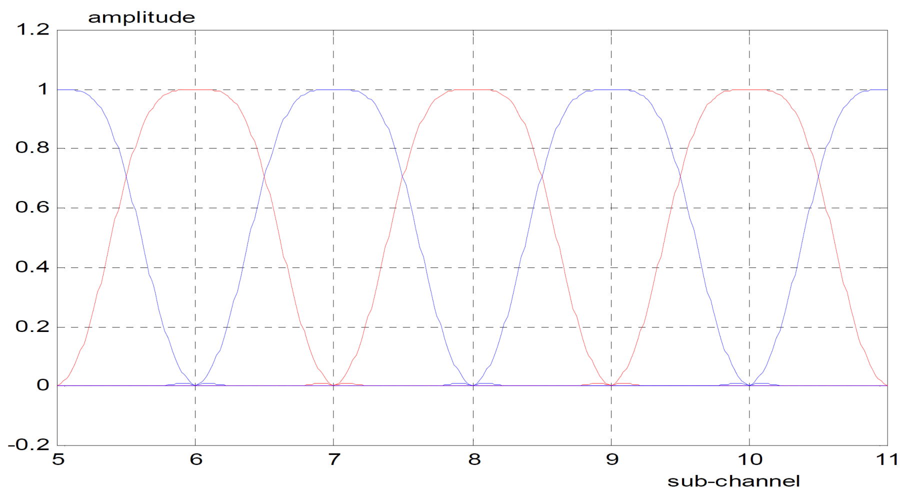

Figure 3.6: Section of a filter bank based on the prototype filter with K = 4 [7].

A key observation is that the sub-channels with even index/odd index do not overlap. This characteristic will be discussed later. A particular sub-channel overlaps in frequency with its neighbours only. The number of coefficients which overlap is equal to K-1 and the frequency coefficients of the interference filter are:

$$G_{\mathrm{k}} = H_{\mathrm{k}} H_{\mathrm{K\text{-}k}}; k = 1, ..., K - 1 \tag{3.11}$$

The set of coefficients is symmetrical and for K = 4:

$$G_1 = 0,228553 = G_3; G_2 = 0,5 \tag{3.12}$$

In Figure 3.7 the frequency response of the interference filter (K = 4) is represented.

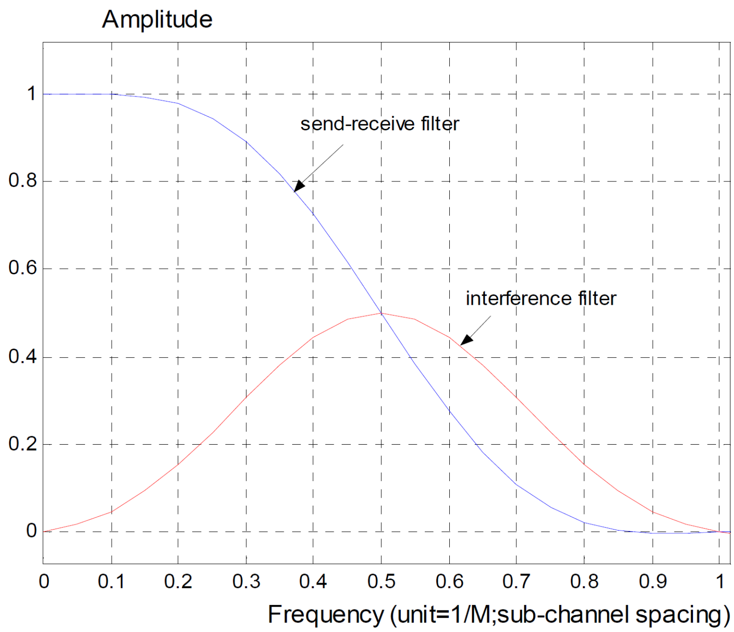

Figure 3.7: Frequency responses of the sub-channel filter and interference filter [7].

In the time domain, the interference filter impulse response is given by:

$$g(t) = [G_2 + 2G_1 cos(2\pi \frac{t}{2K})]e^{j2\pi \frac{t}{2T}} \tag{3.13}$$

By looking at g(t) expression a very important result can be obtained, which determines the modulation to be used in order to deal with interference: the factor $e^{j2\pi \frac{t}{2T}} = cos(\pi t/T) + jsin(\pi t/T)$ reflects the symmetry of the frequency coefficients and, due to this factor, the imaginary part of g(t) crosses the zero axis at the integer multiples of the symbol period T while the real part crosses the zero axis at the odd multiples of T/2. The zero crossings are interleaved and it is the basis for the OQAM which will be discussed later.

Transmitter and receiver

After having developed the prototype filter and the filter bank, it is now possible to build the transmitter and the receiver. Figure 3.8 shows the FBMC transmitter scheme.

The operation done by the filter is called frequency spreading, since as the name says, the frequency samples are spread along the frequency in various sub-channels. Basically, in a filter bank with overlapping factor K, a data element modulates 2K-1 carriers. The filter bank in the transmitter is implemented as follows: an IFFT of size KM is used, to generate all necessary carriers, then a particular data element $d_i(mM)$, after being multiplied by the filter frequency coefficients, goes to the 2K-1 inputs of the IFFT with indices $(i-1)K+1, ..., (i+1)K-1$. With this method, the data element is spread over various IFFT inputs. For each set of input data, the output of the IFFT is a block of KM samples and, since the symbol rate is 1/M, K consecutive IFFT outputs overlap in the time domain. The figure shows that the sub-channels with indices i and i+2 are separated and do not overlap. On the contrary, sub-channel i+1 overlaps with both and orthogonality is necessary. That

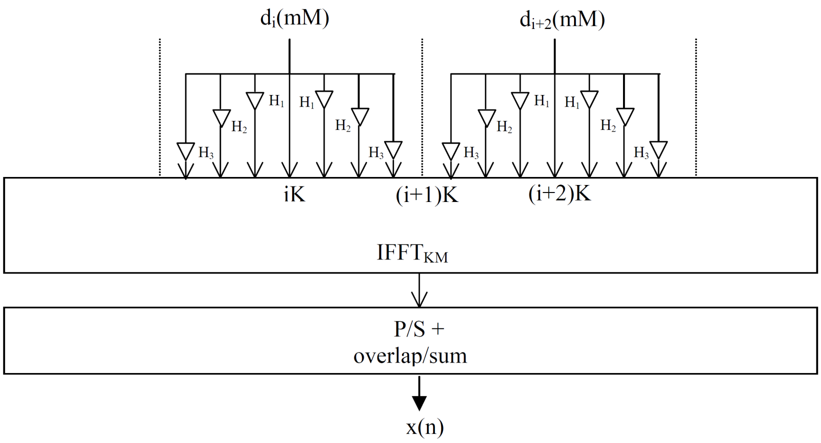

Figure 3.8: FBMC transmitter scheme (frequency spreading, IFFT and P/S + overlap/sum) [7].

is provided by using real inputs of the IFFT for i and i+2, and imaginary inputs for i+1, or the inverse.

Figure 3.9, instead, shows the receiver schemes. the same inverse logic can be applied. Instead of a spreading operation, this time a despreading operation is done.

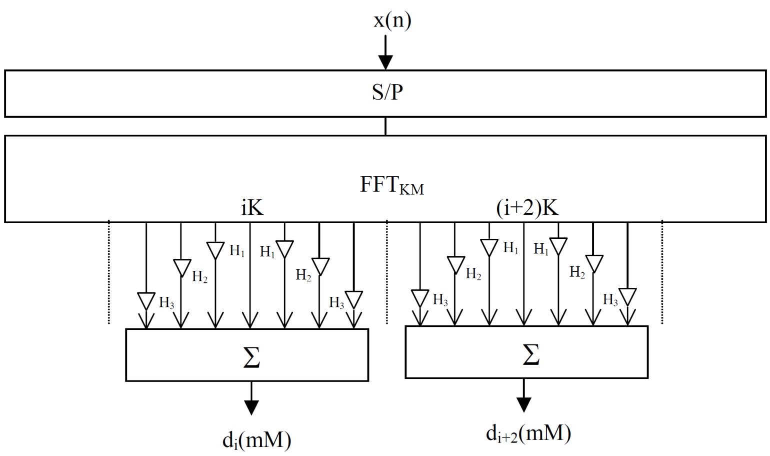

Figure 3.9: FBMC receiver scheme [7].

3.3.2 OQAM

In FBMC systems, if the sub-channels are separated, any kind of modulation can be used . If only the sub-channels with even (odd) index are exploited, there is no overlap and QAM modulation can be applied. However, this would imply no full speed. If this was the target, all the sub-channels must be exploited and a specific modulation is needed to deal with the frequency domain overlapping of the neighbouring sub-channels.

Two very important features have to be pointed out: firstly, orthogonality is needed because of the overlapping issue between neighboring sub-channels. As we saw, the IFFT block can make up for it by using the real part of its inputs with even index and the imaginary part of its inputs with odd index. This creates a problem, that is the decrease of system capacity by a factor two. To compensate to this problem, the second feature, suggested by the symmetry of the transmitter and receiver and the fact that they are identical, is that the imaginary part of the impulse response of the sub-channel interference filter crosses the time axis at the odd multiples of half the symbol period.

We can achieve full capacity by doubling the symbol rate and, for each sub-channel, use alternatively the real and the imaginary part of the IFFT. This way, the real and the imaginary part of a complex data symbol are not transmitted simultaneously, with the addition that the imaginary part is delayed by half the symbol duration [7].

3.3.3 Advantages and issues

The channel is inserted between the transmitter and the receiver and it introduces a number of impairments, such as amplitude and phase distortion, timing offset, frequency offset and noise. The impact of these impairments and the way to counter them depend on how the multi-carrier system is exploited. A feature of FBMC is that independent groups of sub-channels can be allocated to different users and user synchronization is not mandatory, although beneficial if realized [7].

FBMC introduces some disadvantages. One of the disadvantages which might be notice is the greater complexity of FBMC implementation with respect to OFDM. It is brought by the filter bank in the receiver. It depends on the number of M sub-channels in the system and also on the overlapping factor K. One of the most important advantages is the avoidance of inserting the CP. This leads to a full bit rate and a better spectral efficiency.

3.4 Universal Filtered Multi-Carrier (UFMC)

With FBMC we have seen that it's possibile to obtain a full bit rate by avoiding to insert the cyclic prefix and performing some filtering operations to the frequency coefficients. This also would improve the side-lobe attenuation by using a proper prototype filter.

Universal Filtering Multi-Carrier also use the logic of dividing the available band into sub-channels as FBMC does. This time though the transmitter/receiver scheme is different as we are going to see. Referring to [12], a group of sub-carrier modulation is performed in UFMC. The sub-carrier grouping reduces the length of the filter compared with FBMC and also reduces time to perform modulation.

3.4.1 Digital Implementation

Figure 3.10 shows the UFMC architecture.

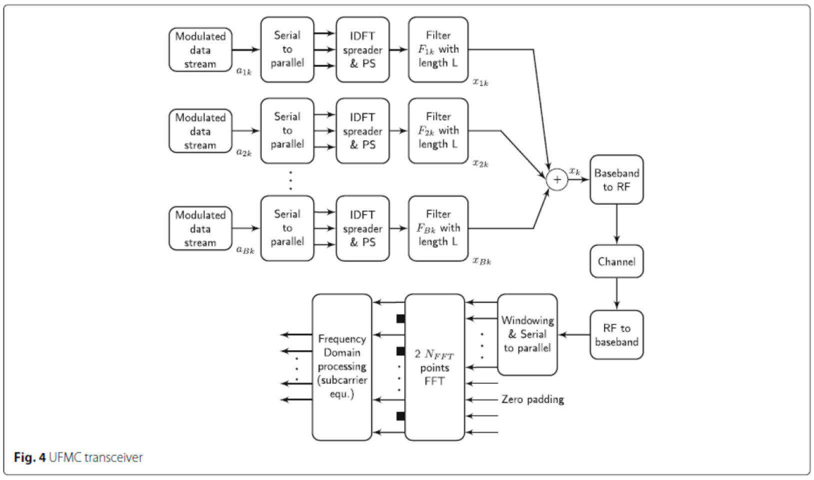

Figure 3.10: UFMC scheme [13].

UFMC is a combination of the features of OFDM and FBMC. It is based on frequency division multiplexing FDM. The incoming data stream is divided into different sub-streams. Some of the greatest advantages UFMC introduces are a reduced out of band emission and better time frequency synchronization.

The total bandwidth is split into a number of B sub-bands. Each sub-band can be further divided into several sub-carriers. There are a total of N sub-carriers. A N-point inverse discrete Fourier transform is taken in order to convert from frequency to time domain. [1]. The output signal is then filtered using an FIR filter with length L. The output signal can be represented by using the equation:

$$y_{\mathrm{i}}(k) = x_{\mathrm{i}} * f_{\mathrm{i}} = \sum_{l=0}^{L-1} f_{\mathrm{i}}(l)x_{\mathrm{i}}(k-l); k = 0, ..., N+L-1 \tag{3.14}$$

Due to the linear convolution of x_{i} and f_{i}, the resultant symbol length becomes N+L-1. The FIR filter used here is a Dolph-Chebyshev filter. As [1] says, the reason why this filter is being used to filter each sub-band is because it reduces the out of band radiation. The rectangular filter used in OFDM is not well center in time or in frequency domain. The sinc function which comes from the Fourier transformation of the rectangular symbol shape cause high spectral side lobe levels. Due to these high spectral side lobe levels, the out of band radiation to the neighboring sub-bands is significantly increased.

3.4.2 Pros and Cons

Since UFMC is a derivative of OFDM, there are a lot of similarities in their properties. OFDM, being already used for LTE and LTE-A systems, is taken into consideration for future 5G networks too. But UFMC has several advantages over it. The foremost and obvious difference between the two candidates is the absence of Cyclic prefix CP. UFMC uses additional per sub-band filters which reduce the spectral side lobe levels outside the sub-band. This increases robustness beside any sources of inter carrier interference. OFDM has efficient implementation of (FFT/IFFT) and has simple equalization schemes but spectral efficiency is lost due to cyclic prefixes. The main advantage of UFMC over OFDM is the use of Dolph-Chebyshev filter. According to its filter properties the effect of side lobe interference with the adjacent sub-carrier can be significantly reduced [1].

By using this filter, UFMC is more robust to inter-carrier interference and loss of orthogonality would not be a problem. PAPR is also reduced.

Chapter 4

Lab Simulation

4.1 Development Environment

4.1.1 LabVIEW

LabVIEW (standing for Laboratory Virtual Instrument Engineering Workbench) is a platform for system-design, as well as a development environment for a visual programming language, developed by National Instruments. It uses a graphical language whose name is "G", and it is used mainly for data acquisition, instrument control and industrial automation.

What LabVIEW does is executing source-codes, that are programs called Virtual Instrument (VI), with the extension ".vi". The execution follows the structure of a graphical block diagram, which can be programmed by connecting different function-nodes and by drawing wires. The variables are propagated by the wires and nodes can be executed as soon as all its inputs data are available.

In addition to the block diagram, each VI is further composed of a front panel, which is a user interface where one can insert values at each input, visualize charts and graphs, and other similar actions. Eventually, each VI has also a connector panel, used to represent the VI in the block diagrams of other, calling VIs.

The front panel is built using controls and indicators. Controls are basically the inputs: by means of the controls we can provide information to the VI. On the other hand, indicators are the outputs: they indicate, or display, the results based on the given inputs. The block diagram contains the graphical source code. If the user put an object in the block diagram, that object appears in the front panel as well. The block diagram contains the structures and functions performing operations on controls and supplying data to indicators. Here we can find well-known structures such as if, while loop, for loop and so on. Structures and functions can be found in the apposite Functions Palette and can be placed directly in the block diagram. Controls, indicators, structures and functions are referred to as nodes. Nodes are connected to each other by wires. Each VI can be run as a program by itself or can be dropped and used in another VI (in this case it is used as a subVI), and the inputs and outputs are given by the connector panel.

LabVIEW has certainly an user-friendly characteristic of a graphical approach of dragging and dropping virtual representations of lab equipment, allowing simple creations of small applications. Nonetheless, the potential of the software is remarkable.

Some useful functions

Functions, as we said, can be found in the function palette. In particular, in this work the most common array functions has been extensively used:

- Array Size: Returns the number of elements in each dimension of array.
- Array Subset: Returns a portion of array starting at index and containing length elements.
- Build Array: Concatenates multiple arrays or appends elements to an n-dimensional array.
- Index Array: Returns the element or sub-array of n-dimension array at index.
- Initialize Array: Creates an n-dimensional array in which every element is initialized to the value of element.
- Reshape Array: Changes the dimensions of an array according to the values of dimension size 0..m-1.
- Split 1D Array: Divides array at index and returns the two portions with the element of index at the beginning of second subarray.

4.1.2 USRP

Universal Software Radio Peripheral (USRP) is a range of software-defined radios developed by National Instruments. It is intended to be an inexpensive harware platform for software radio, commonly used by research labs and universities.

4.2 Project Implementation

In this project I implemented, by means of the software LabVIEW, the transmitter and receiver modulation schemes of three of the possible techniques that are going to be used in the 5G mobile networks. I used the National Instrument hardware NI-USRP to transmit the waveforms. With the help of a spectrum analyzer, I compared their spectrum and collected results. These are OFDM (Orthogonal Frequency Division Multiplexing), FBMC (Filter Bank Multi Carrier) and UFMC (Universal Filtered Multicarrier).

In order to have a guideline of how to build the structure of the Transmitter/Receiver, I took advantage of some useful Matlab scripts I found on the Internet where the modulation schemes were implemented, which are [9] and [11]. I followed the logic of those scripts to implement the project in LabVIEW. Firstly, I needed to study how to use LabVIEW, since it was the first time I had to handle with this software and thus I learned its basic knowledge to work with it.

The main target of my work was to simulate the implemented waveforms in the laboratory and compare their PDSs and PAPRs. PAPR, as we said, is an important issue, since one of 5G's main topic is to possibly find a better competitor than OFDM, and one of the most important problems of OFDM is the considerably high PAPR. In addition, I took other measures such as bandwidth and power.

4.2.1 OFDM

I started by implementing the OFDM transmitter. The OFDM transmission scheme is represented in figure 4.1 and is the following:

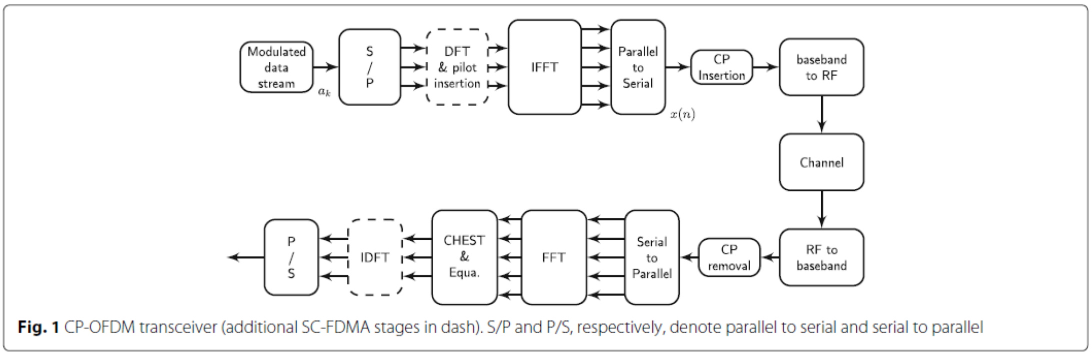

Figure 4.1: OFDM scheme [13].

The "DFT and pilot insertion" and "IDFT" blocks are built in the SC-FDMA scheme, which I didn't implement.

Transmitter

Front panel and the block diagram of the OFDM transmitter are represented by Figure 4.2 and Figure 4.3:

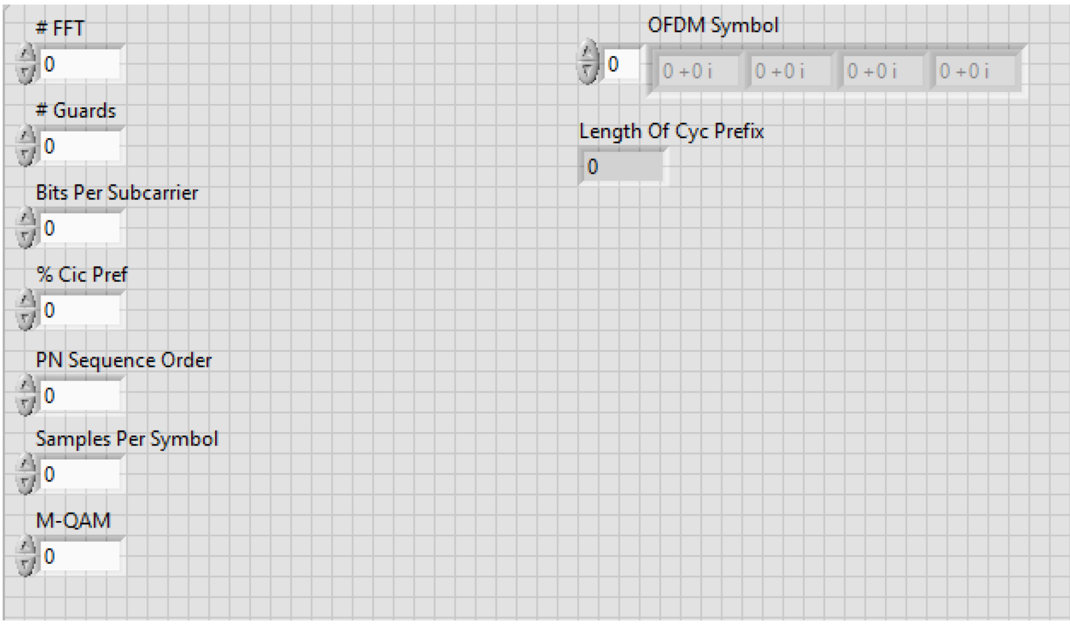

Figure 4.2: Front Panel of the OFDM Transmitter.

Several variables are defined: #FFT is the number of FFT points. #Guards is the number of guard symbols to be added. Bit Per Subcarrier is the number of bits which form a symbol (if a 4-QAM modulation scheme is used, the number of bits is 2). PN Sequence Order is the sequence to generate the random bits. The Modulation Toolkit provided by National Instruments is used in this project,

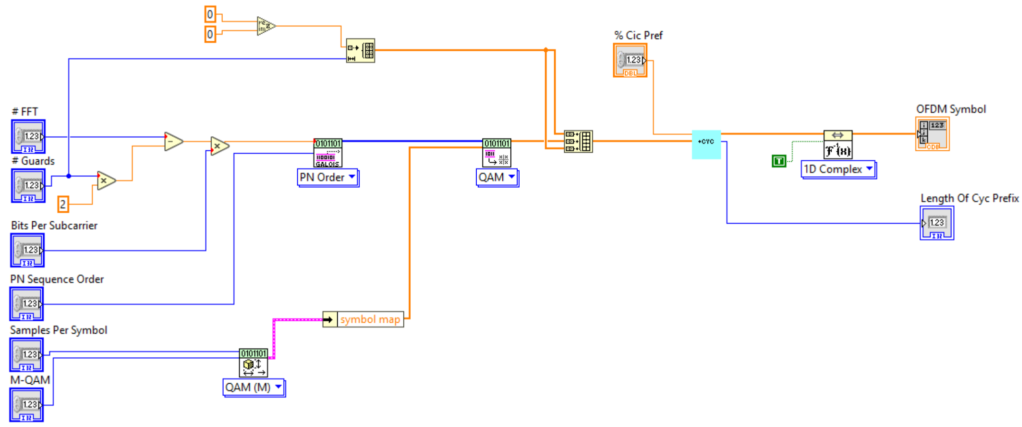

Figure 4.3: Block Diagram of the OFDM Transmitter.

which contains lots of useful functions such as MT Generate Bits (which generates the random bit sequence), MT Bits To Symbols (which maps the input bits to output symbols, according to the the given constellation), and so on. Samples Per Symbol and M-QAM are parameters to pass to the function MT Generate System Parameters, which creates the symbol map to provide when bits have to turn into symbols.

Figure 4.3 shows that a number of bits equal to: BitsPerSubcarrier* #FFT - #Guards*2 is generated. After modulating the bits into symbols, guard symbols are added to left and right side and the output is passed to the Add Cyclic Prefix function. The Add Cyclic Prefix function has been implemented by me, and its front panel and block diagram are shown in figure 4.4 and 4.5

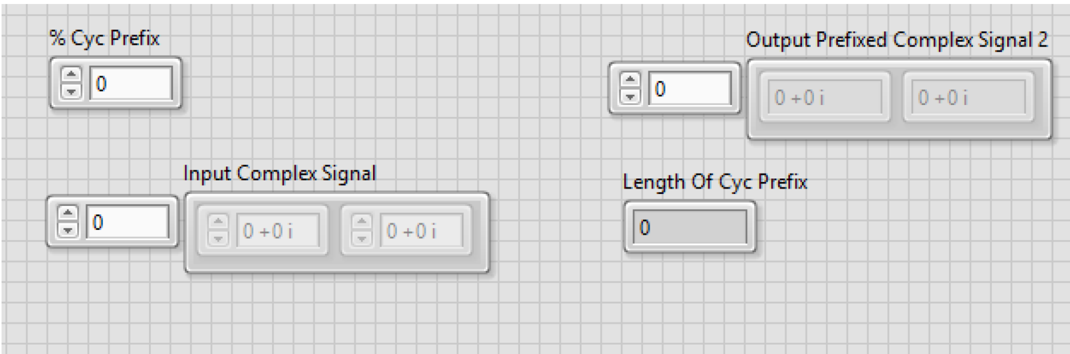

Figure 4.4: Front Panel of the Add Cyclic Prefix function.

In this VI, the % of the Cyclic Prefix needs to be provided as input. It has to be a number between 0 and 1. At the beginning the input signal is doubled. One part goes directly to the "Build Array" function, the other is cut with the usage of the "Split 1D Array", whose split point is given by the position calculated as follows: (1-%CycPrefix)*SymbolLength. The portion of the signal will be copied and put at the beginning of the original signal. Then the outputs of the node will be the prefixed signal plus the length of the cyclic prefix (an integer number), which it's a parameter needed in the receiver when it'll come to remove the Cyclic Prefix.

As a last step, the IFFT block is fed with the stream to obtain the OFDM

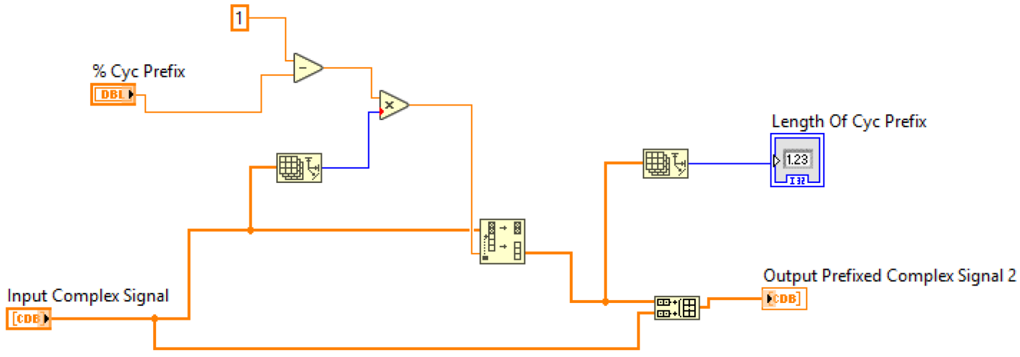

Figure 4.5: Block diagram of the Add Cyclic Prefix function.

symbol to be transmitted. It was already discuss that the IFFT block is actually the block which modulates each symbol to the different sub-carriers. This means that if a number of 1024 symbols is passed to the IFFT block (which is exactly the case taken in consideration here), a number of 1024 carriers is created.

4.2.2 FBMC

Filter Bank Multi-Carrier is thought as one of the main competitors of OFDM, since it can achieve lower values of PAPR. A reason for that good characteristic is because in FBMC there is no addition of the cyclic prefix like in the OFDM modulator, which is definitely an advantage. The FBMC architecture is given by figure 4.6.

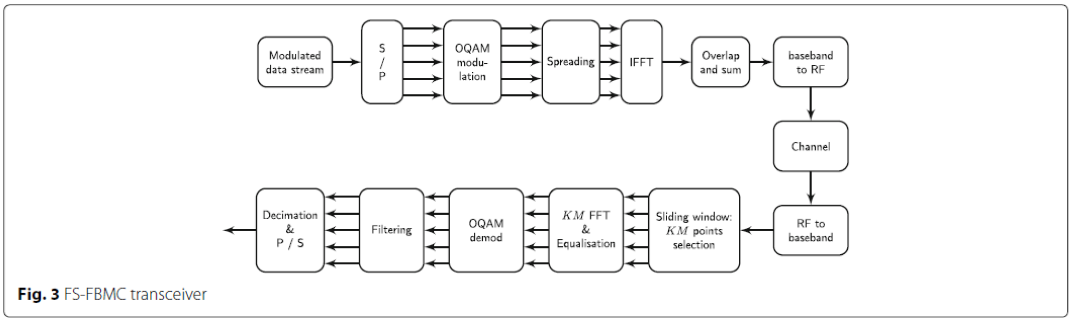

Figure 4.6: FBMC scheme [13].

FBMC filters each sub-carrier modulated signal in a multicarrier system. The filters are characterized by the overlapping factor K, which is the number of multicarrier symbols that overlap in the time domain. K can be equal to 2, 3 or 4. Symbols are overlapped with a delay of N/2, where N is the number of sub-carriers. In order to achieve full capacity, OQAM (Offset QAM) modulation is used, in which the real and imaginary parts of a complex data symbol are not transmitted simultaneously, as the imaginary part is delayed by half of the symbol duration.

Transmitter

The front panel of the FBMC transmitter is shown in figure 4.7.

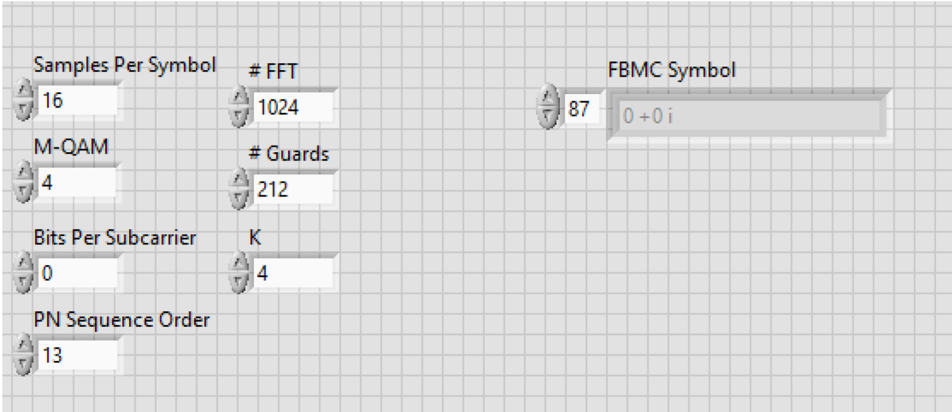

Figure 4.7: Front Panel of the FBMC Transmitter.

As we can see, the same variables of the OFDM transmitter, which are #FFT, #Guards, Bits Per Subcarrier, PN Sequence Order, Samples Per Symbols and M-QAM, are used. A number of data bits equal to: #FFT – 2*#Guards * BitsPer-Subcarrier/2 is generated (if #FFT = 1024, #Guards = 212 and BitPerSubcarrier = 2, then the bit stream length is equal to 600. after the modulation step, a number of 300 symbols will be generated and subsequently the guard symbols will be added in order to obtain a number of 1024 symbols).

Following [9], at the beginning an empty array is initialized, with the function "Initialize Array", whose dimension is equal to #FFT*K*2. Later an explanation for this reason will be given. Basically, this array is fed to the for loop, transformed to a shift register and filled with the current symbol. Therefore, in the next for iteration, the filled array will still be in memory and will be shifted by half the symbol duration. Eventually, the new symbol will be summed with the overlapping part of the previous symbol.

In Figure 4.8 it is shown how the array is initialized, with the proper "Array Initialize" function. Figure 4.8 is a portion of the FBMC block digram implemented in this work. Since the overall block diagram was too big, It was split it in different portions.

In Figure 4.9 the coefficients of the prototype filter are set. They depend on the value of K.

In table 4.1 all the values of the filter coefficients for K=2, K=3 and K=4 are given.

Value of K	**H0**	**H1**	**H2**	**H3**
2	1	$\sqrt{2}/2$	-	-
3	1	0.911438	0.411428	-
4	1	0.971960	$\sqrt{2}/2$	0.235147

Table 4.1: Values of K.

Next step is shown in Figure 4.10. In Figure 4.10 it is shown that in the upper part the random bits are generated and the OQAM modulation is performed. It is done inside the inner for loop, whose number of iterations is equal to the length of the stream divided by the number of bits per symbol. Thanks to the "Reshape Array" function it is possible to feed the for loop with two bits at each iteration for a number

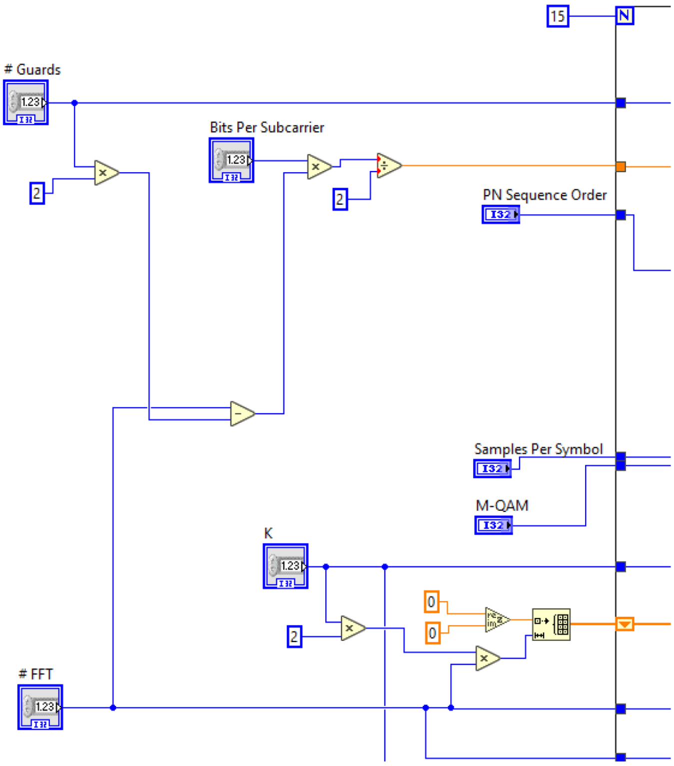

Figure 4.8: Block Diagram (1) of the FBMC Transmitter. Here an array whose dimension is equal to #FFT*K*2 is initialized.

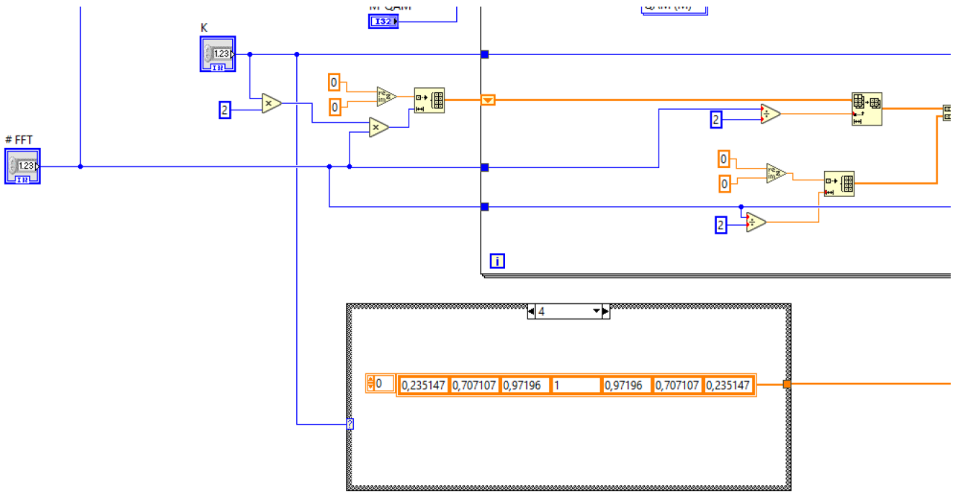

Figure 4.9: Block Diagram (2) of the FBMC Transmitter.

of iterations equal to BitStreamLength/BitsPerSymbol (with this function, the bit stream, which is a 1x600 array in this case, is turn to a 2x300). Each iteration of the for loop will take in a symbol which will have to be modulated. Then, after performing the MT Map Bits to Symbols, the real part and the imaginary part are simply split and put sequentially one after another. This thanks firstly to the "Re/Im" function which gives the real and the imaginary part separately and secondly to "Build Array" function, which concatenates the values. Outside the for loop, an array with double of the length will be created, in which the real part and the imaginary part will be alternated. The array is the passed to the upsampler (The upsampling value will depend on the value of K). Therefore, the guard symbols are added.

What happens in the lower part, taking [9] as reference point, is the following: firstly, the array initialized outside (which the first time will be empty), whose elements are complex values, is passed to the for loop as a shift register. Its length is equal to K*2*1024. This means that if K = 4, the upsampling value is 4 too, then the final length of FBMC symbol is going to be 4096. The array length, then is going to be the double, 8192. After being passed into the for loop, its first #FFT/2 elements are cut of, by using the "Array Sub-set" function, and instead of them, zero values are appended. The constructed array is then passed to a "Split 1D array" function: the splitting point is the point at position K*#FFT, which means that the upper output array is an array going from position 0 to K*#FFT - 1 (4095 if K = 4), and the lower output array is going from K*#FFT to K*2*#FFT.

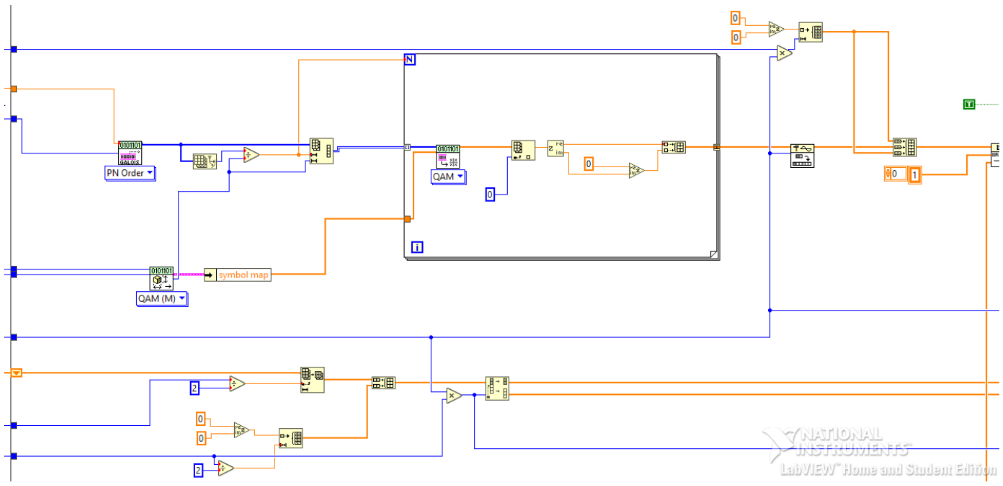

Figure 4.10: Block Diagram (3) of the FBMC Transmitter.

The final step is represented in Figure 4.11.

After the upsampler, the array is passed to the prototype filter with the chosen coefficients. After that, the first K values are cut and replaced with a number K of zero values. This is done for filter transient issues. What comes next is the Inverse FFT operation, which will modulate each sub-carrier. The IFFT output is then summed with the lower output of the "Split 1D array" function discussed before: this represents the overlapping section of the previous symbol which is summed with the current symbol. Instead, the upper part is appended before the FBMC symbol. The outcoming overall symbol exiting the big for loop is then cut of in order to have a length going from 0 to K*#FFT - 1. A certain amount of loop iterations have to be waited so that the array is completely filled (I put for example 15 iterations).

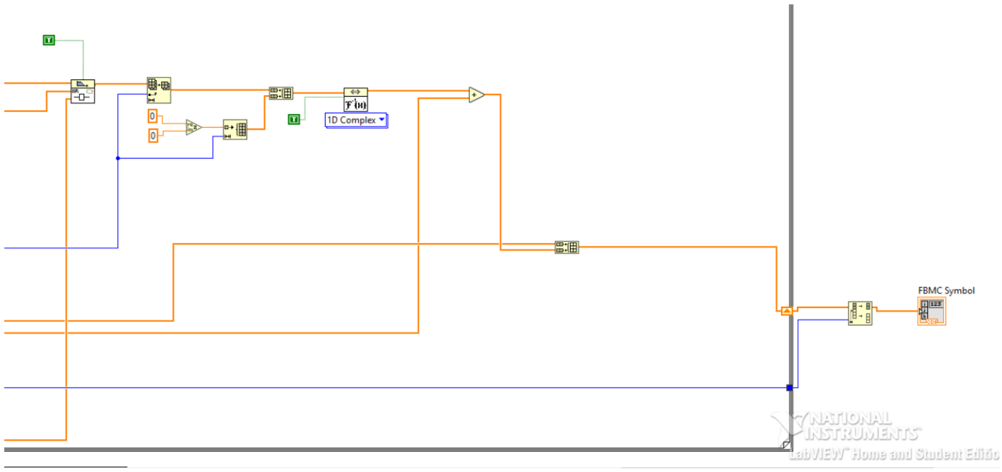

Figure 4.11: Block Diagram (4) of the FBMC Transmitter.

4.2.3 UFMC

Universal Filtered Multicarrier is another contender for 5G mobile networks. In UFMC each sub-carrier is further divided in smaller sub-bands. All the filtering operations are performed in each sub-band.

Figure 4.12 shows the block diagram of the UFMC transceiver.

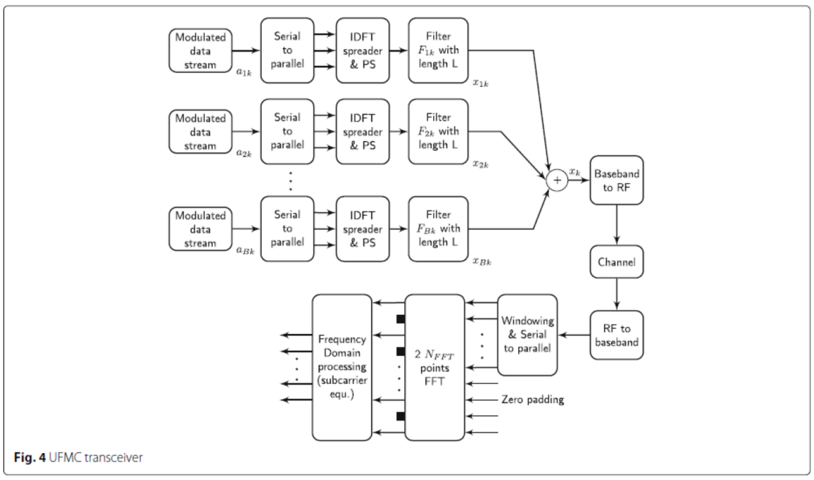

Figure 4.12: UFMC scheme [13].

In UFMC waveform a group of carriers is filtered with a Dolph-Chebyshev window. The filtering operation leads to a lower out-of-band leakage than OFDM. The transmitted signal uses no CP.

Transmitter

Figure 4.13 shows the front panel of the UFMC transmitter.

Two new variables are introduced: the number of subbands (#Subband) and the Subband Size, which will determine the characteristics of each sub-band. In order to get the coefficients of the Chebyshev filter (since I didn't know how to properly use the Chebyshev function in LabVIEW) I used the coefficients found in

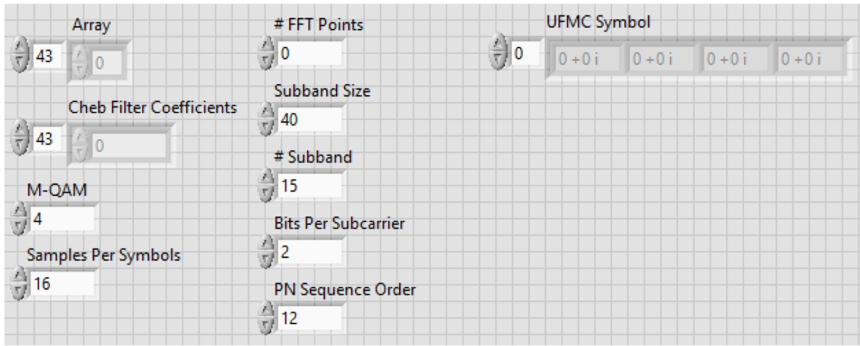

Figure 4.13: Front Panel of the UFMC Transmitter.

the Matlab code [11]. Basically, it is a Chebishev filter with: Filter length = 43 and Sidelobe attenuation = 40. The fiter coefficients are put in the variable Cheb Fiter Coefficients. The variable Array is an array of the same length of the Cheb filter, which each position is the number of the array n-th position (the value in position 0 is euqal to 0; the value in position 1, is equal to 1, and so on). This is needed to perform the shift in frequency for each sub-band, which will be explained later on. Since the block diagram was too great to be completely shown in one picture, It has been split in three parts.

The first part is illustrated in Figure 4.14.

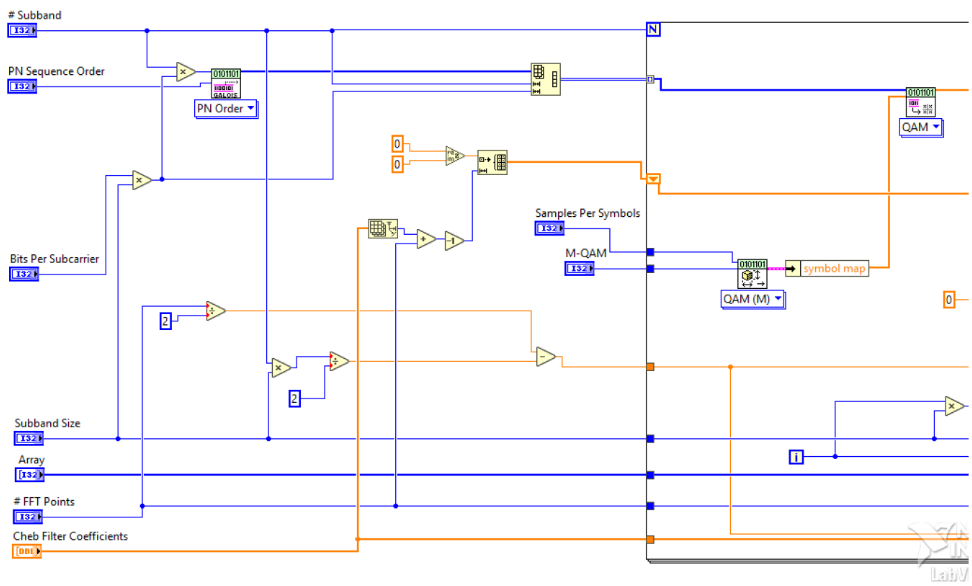

Figure 4.14: Block Diagram (1) of the UFMC Transmitter.

Since all the sub-bands have to be summed up at the end, it is necessary to build an empty array of size #FFT + Filter Length and put in a shift register to the for loop. The function MT Generate Bits generates a bit stream of length equal to SubbandSize*BitPerSubcarrier*#Subbands. The bit stream needs to be divided by the number of sub-bands. Basically, with the usage of the function Shape Array, the 1D array has turn to a 2D array with the number of rows equal to #Subbands and the number of columns equal to Subband Size. Each for iteration will take as input a row of the matrix.

Let's have a look at Figure 4.15.

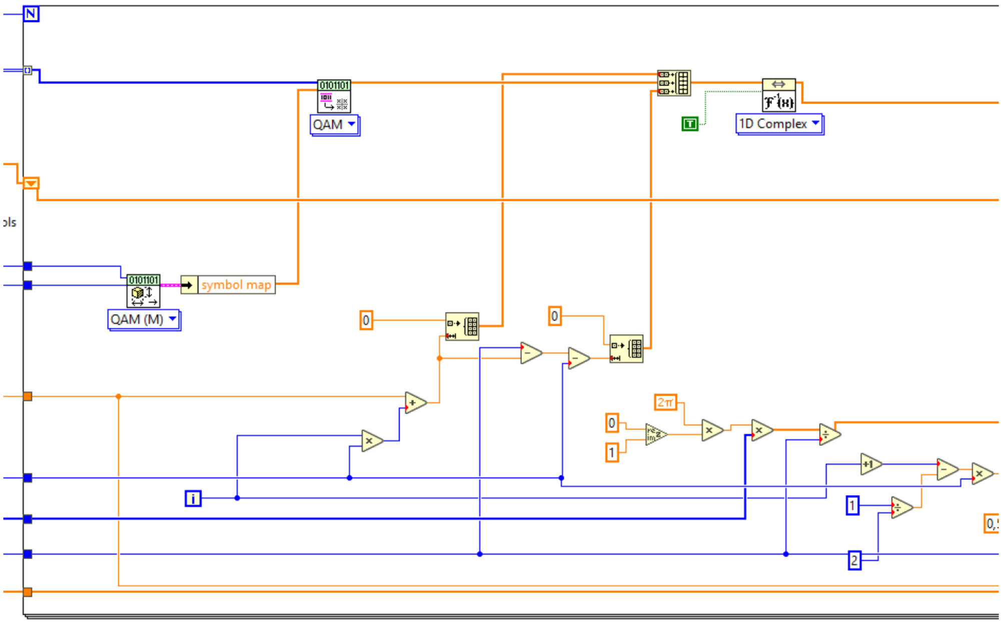

Figure 4.15: Block Diagram (2) of the UFMC Transmitter.

Each sub-band bit stream is send to the QAM modulator. Then, guard symbols has to be added. This time the number of guard symbols is not given as input as in OFDM and FBMC implementations. Instead, the number of guard symbols will be added in this way: on the left side a number of guard symbols equal to $(\#FFT/2) - (\#Subbands * SubbandSize/2) + (i * SubbandSize)$ will be appended (i is the number of for loop iterations), whereas a number of guard symbols equal to $\#FFT - [(\#FFT/2) - (\#Subbands * SubbandSize/2) + (i * SubbandSize)] - SubbandSize$ will be put at the right end. After that, the IFFT operation is done.

The next important step is shown in Figure 4.16.

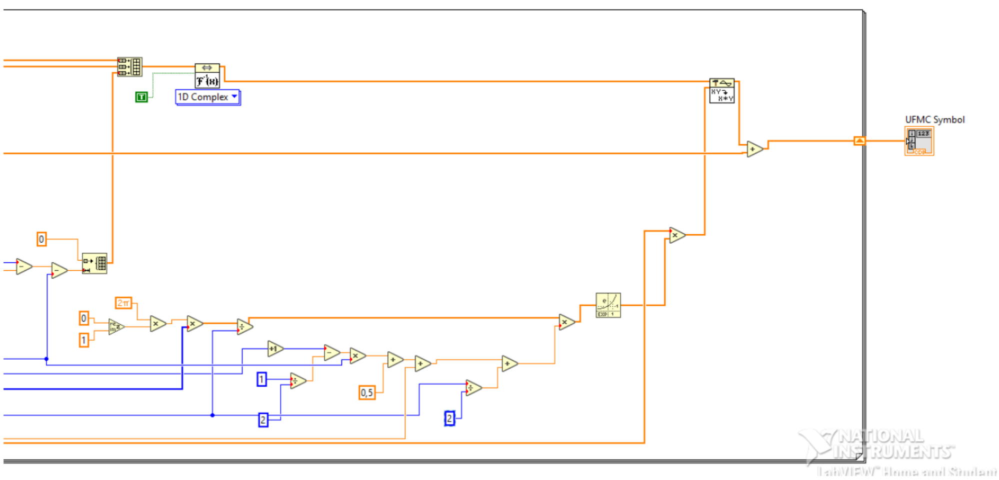

Figure 4.16: Block Diagram (3) of the UFMC Transmitter.

After the IFFT, the convolution with the Dolph-Chebyshev Filter Coefficients is done: clearly, each sub-band has to be shifted in frequency at each for step: to follow the Matlab expression in [11], the frequency shift is done by multiplying the Chebyshev filter coefficients by $exp(j*2*\pi*[0:FilterLength-1]'/\#FFT*((i-0.5)*subbandSize+0.5+SubbandOffset+\#FFT/2))$. Where [0:FilterLength-1]' is the transpose of the array [1 2 3 ..... FilterLength-1] and SubbandOffset = #FFT/2 - #Subbands*SubbandSize/2.

Eventually, all the sub-bands are summed up and the UFMC symbol is transmitted.

4.3 Simulation with USRP

Once the transmitters are implemented, it's time to proceed with the simulation of the waveforms. In order to transmit the signals I took advantage of the NI-USRP SDR (Software Defined Radio) and the spectrum analyzer provided by the laboratory situated in "Universidad Carlos III" of Leganés, Madrid.

The Modulation Toolkit provided by National Instruments supplies some examples of how to establish a connection with USRP. These examples are VIs with their front panel and block diagram. I took advantage of their implementations and by further modifying them I connected the VIs containing the OFDM, FBMC and UFMC transmitters.

The original idea was also to simulate a connection between transmitter and receiver by the means of two USRP, one for the transmission and one for the reception. For time limitation problems related to my stay in Madrid it hasn't been possible to realize it. Despite that, it has been possible to simulate the transmission of the waveform.

There are three main input parameters to USRP, which are the I/Q Sampling Rate (bps), the Frequency Carrier (Hz) and the Transmission Gain (dB).

4.3.1 OFDM Waveform

The first simulation is Orthogonal Frequency Division Multiplexing. Here the attention is posed on the Cyclic Prefix. The greater is the CP, the worse is the Spectral Efficiency and the higher is the PAPR. The usual value of the CP percentage (with respect to the entire symbol) is about 0,1 (10%).

Transmission

Figure 4.17 represents the front panel of the Virtual Instrument in which the simulation is executed. The chart of the constellation is not taken in consideration. Figure 4.18 represents the block diagram of the VI. In the upper the set up of the connection with USRP is implemented by connecting some specific nodes. In the lower part the OFDM transmitter VI is connected. Table 4.2 resumes the values of the parameters given as input in the front panel.

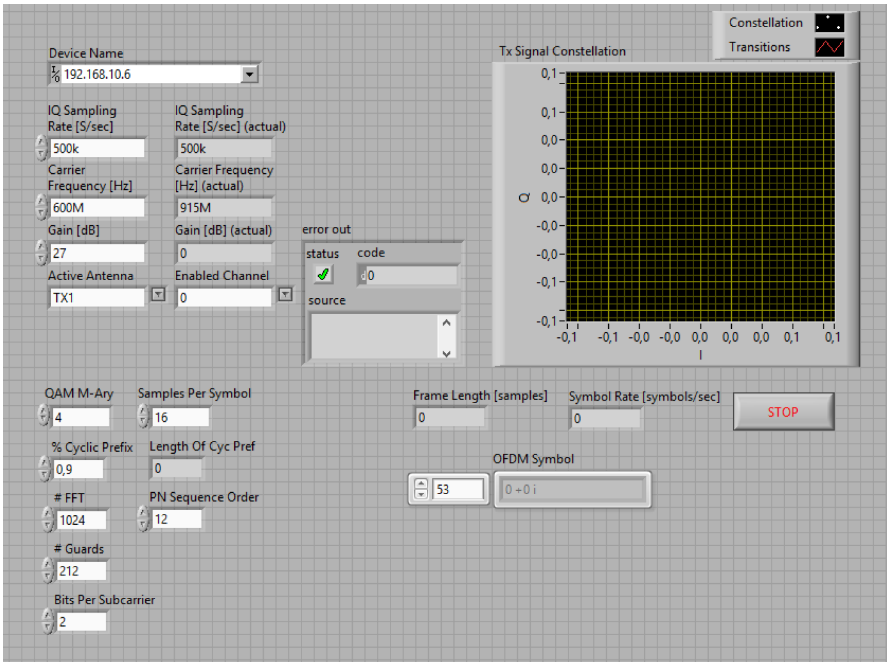

Figure 4.17: Front Panel of OFDM Transmission.

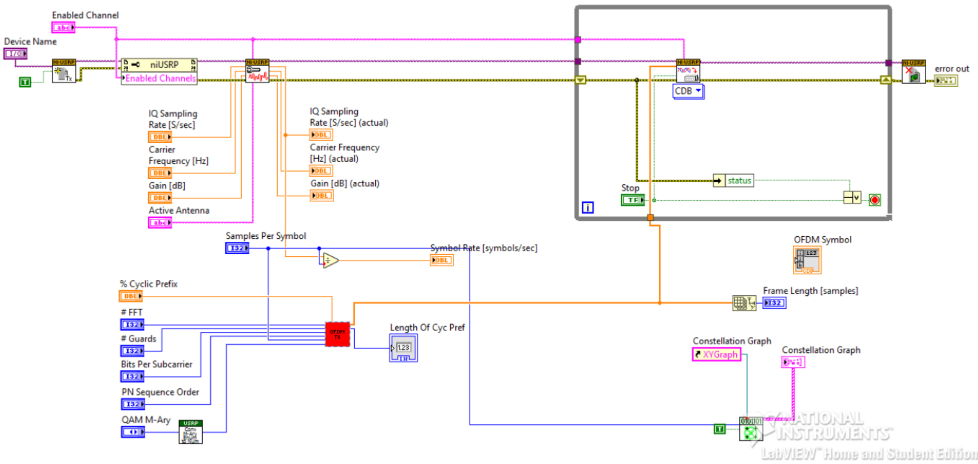

Figure 4.18: Block Diagram of OFDM Transmission.

Results

With the usage of the spectrum analyzer provided by the university's lab, it was possible to obtain the PDS of the transmitted waveform. Thanks to the tools given by the spectrum analyzer software, it was possible to evaluate the bandwidth, power, and power outside the bandwidth from the PDS. In addition, it was possible to obtain the Complementary Commulative Distribution Function (CCDF), from which the PAPR can be evaluated.

Figure 4.19 shows the spectrum of the OFDM waveform. The y-axis represents the amplitude values, expressed in dBm, of the PDS, while the x-axis represents the values of the frequencies. The center frequency is 600 MHz, which is the value given to USRP.

By looking at the spectrum, the different sub-carriers can be clearly seen. The

Parameters	Values
#FFT	1024
#Guards	212
Bits Per Subcarrier	2
PN Sequence Order	12
M-QAM	4
%Cyclic Prefix	0,1
I/Q Sampling Rate	1 Mbps
Carrier Frequency	600 Mhz
Tx Gain	0 dB

Table 4.2: OFDM Simulation Parameters. I/Q Sampling Rate, Carrier Frequency and Tx Gain are specific value to be provided to the USRP hardware.

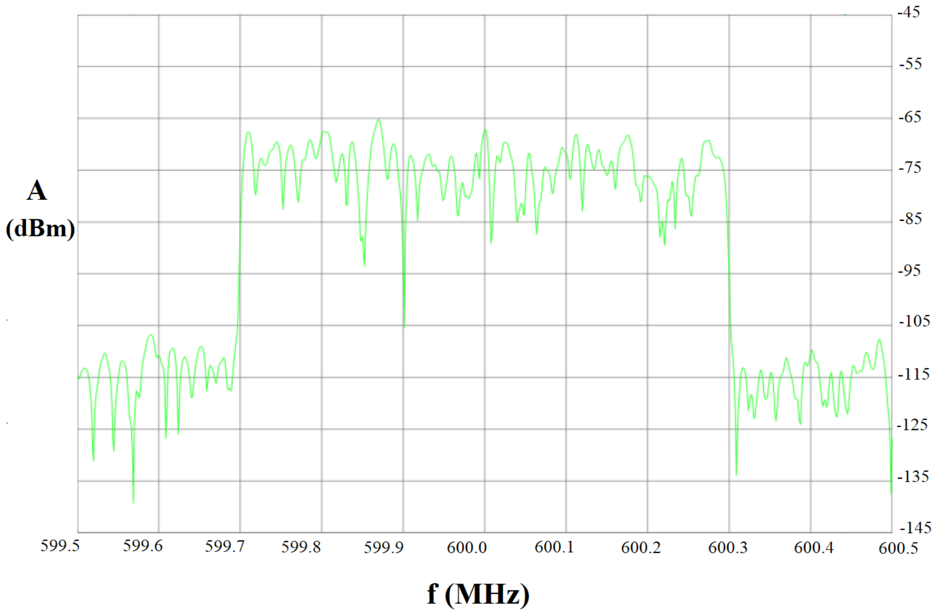

Figure 4.19: Spectrum of the OFDM Symbol. Center Frequency = 600 MHz; RBW = 10 KHz; Frequency Range = 1 MHz.

value of the Bandwidth is B = 607500 Hz roughly.

Eventually, Figure 4.20 shows the OFDM CCDF, represented by the green curve. The y-axis represents the probability with which the signal power is at or above the power value specified by the x-axis. Therefore, the x-axis represents the dB above the average power. The grey curve is the Gaussian curve. The Peak to Average Power Ratio of the OFDM waveform is value is around 11 dB.

All the measured values of OFDM waveform are reported in Table 4.3.

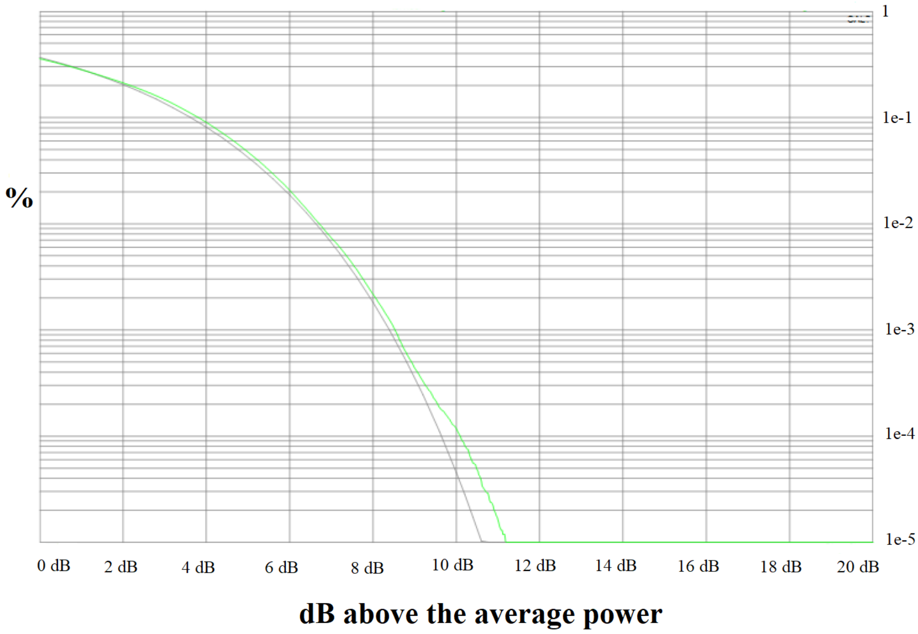

Figure 4.20: OFDM CCDF.

Parameters	OFDM Values
PAPR	11 dB
Bandwidth	607500 Hz
Power	-55,054 dBm
Power left out of band	-92,485 dBm
Power right out of band	-101,462 dBm

Table 4.3: Values of the collected OFDM results..

4.3.2 FBMC Waveform

The second simulation is with FBMC modulation. We expect a better spectrum characteristic than OFDM for the reason explained in the previous chapters. More importantly, we expect a lower value of the PAPR, which is one of the best qualities of Filter Bank Muticarrier.

Transmission

Figure 4.21 and 4.22 represent the front panel and block diagram of the VI containing the simulation implementation.

Table 4.4 contains the parameter passed to the VI. They are basically the same as OFDM, since no new variables have been added, with the only exception that this time there is no CP.

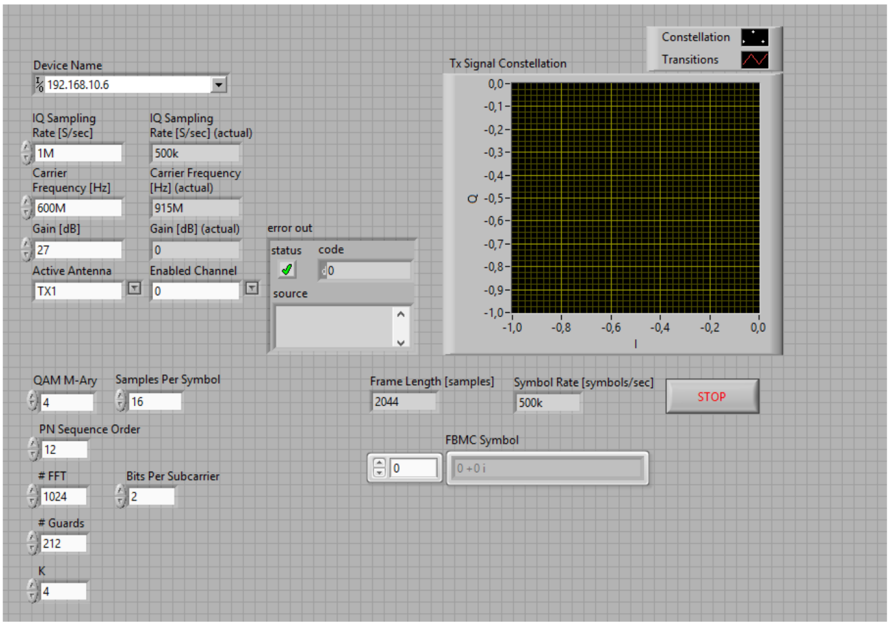

Figure 4.21: Front Panel of FBMC Transmission.

Parameters	Values
#FFT	1024
#Guards	212
Bits Per Subcarrier	2
PN Sequence Order	12
M-QAM	4
I/Q Sampling Rate	1 Mbps
Carrier Frequency	600 Mhz
Tx Gain	0 dB

Table 4.4: FBMC Simulation Parameters. I/Q Sampling Rate, Carrier Frequency and Tx Gain are specific value to be provided to the USRP hardware. There is no Cyclic Prefix.

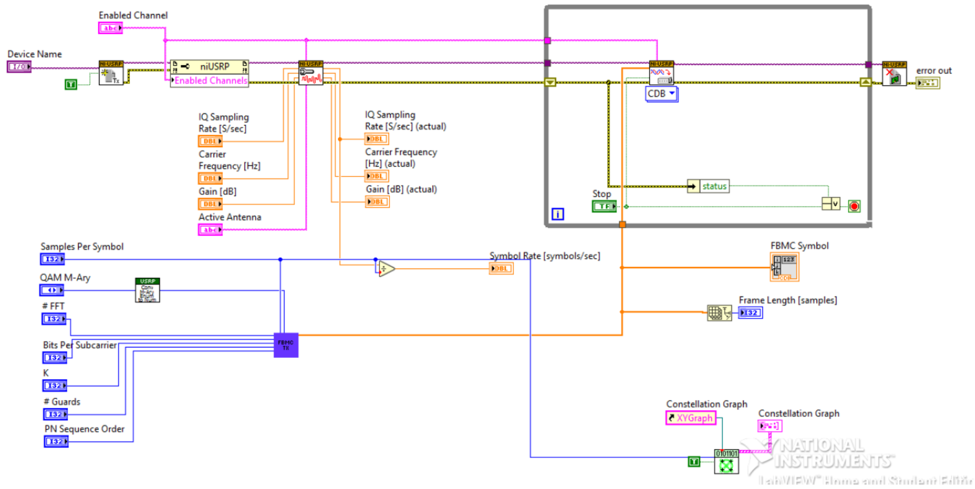

Figure 4.22: Block Diagram of FBMC Transmission.

Results

The FBMC PDS is shown in Figure 4.23. It is centered at 600 Mhz. The value of the Bandwidth is around 600 KHz. As we will see later, it has a better characteristic, since the PAPR is lower than OFDM's one.

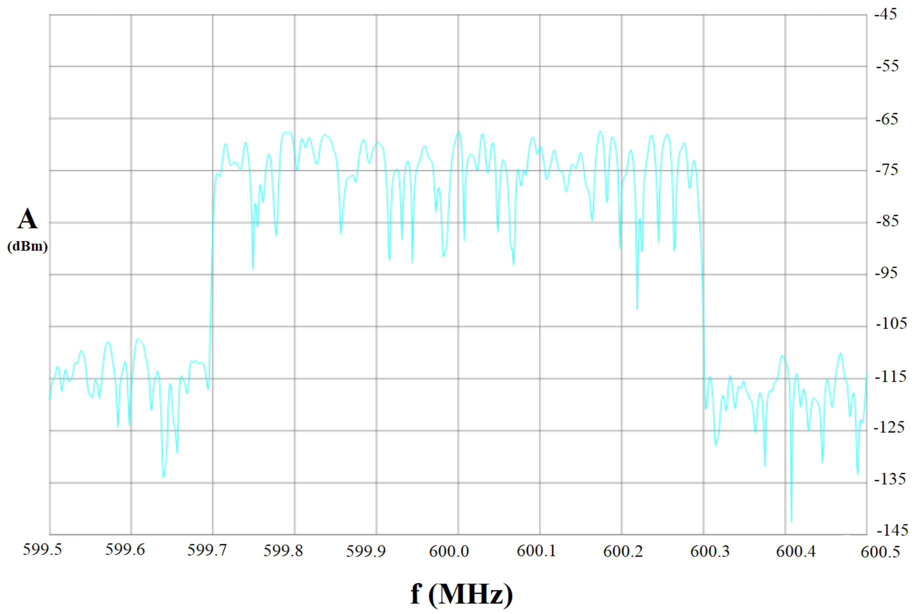

Figure 4.23: Spectrum of the FBMC Symbol. Center Frequency = 600 MHz; RBW = 10 KHz; Frequency Range = 1 MHz.

Figure 4.24 shows the CCDF of FBMC. The value of the PAPR is around 10 dB, which is lower than OFDM, as expected.

The measured values of FBMC waveform are all reported in Table 4.5.

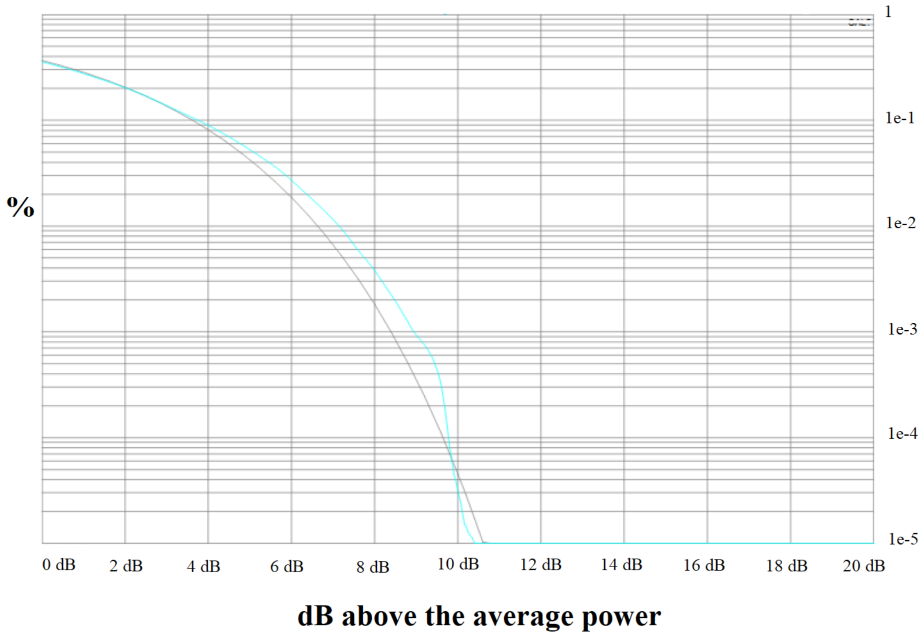

Figure 4.24: FBMC CCDF.

Parameters	**FBMC**
PAPR	10 dB
Bandwidth	600000 Hz
Power	-54.86 dBm
Power left out of band	-100,15 dBm
Power right out of band	-103,908 dBm

Table 4.5: Values of the collected FBMC results. As expected, the value of the FBMC PAPR is lower.

4.3.3 UFMC Waveform

The last simulation is the UFMC waveform.

Transmission

Figure 4.25 and 4.26 represent respectively the front panel and the block diagram of the VI containing the USRP simulation implementation.

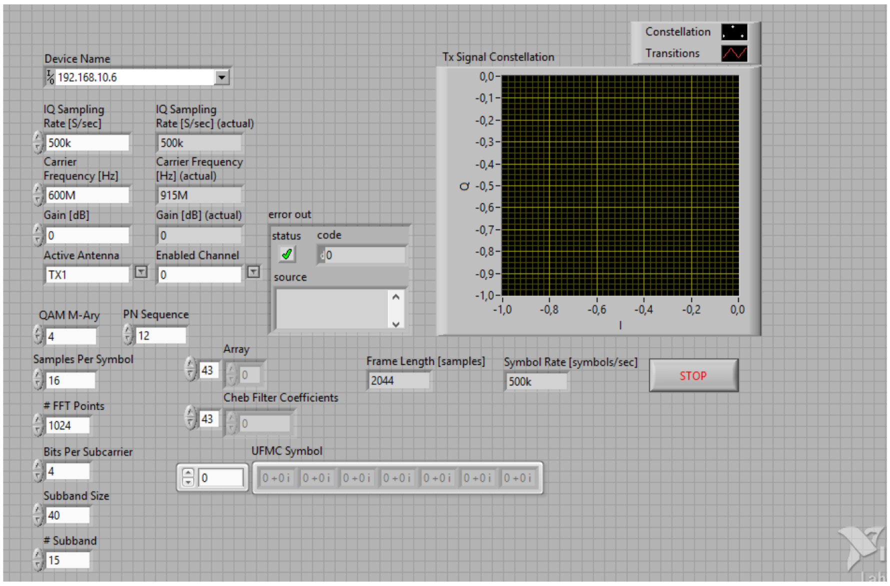

Figure 4.25: Front Panel of UFMC Transmission.

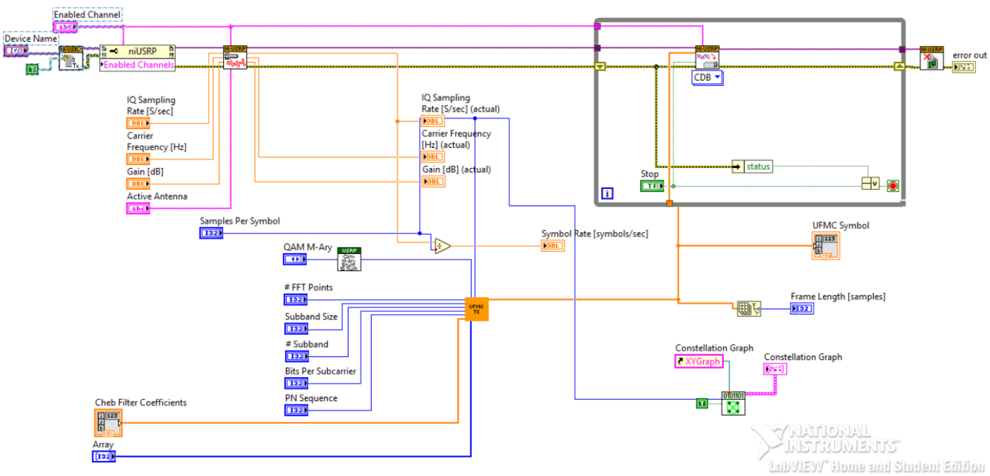

Figure 4.26: Block Diagram of UFMC Transmission.

The values of the parameters given as input are reported in Table 4.6.

The number of sub-bands and the sub-band size are chosen in order to make the comparison with the other PDSs reasonable. A number of sub-bands equal to 15 and a sub-band size equal to 40 is an appropriate choice for our purpose. The number of guard bits are not give as input, since they are added directly inside the UFMC Transmitter VI.

Parameters	Values
#FFT	1024
Bits Per Subcarrier	2
PN Sequence Order	12
M-QAM	4
#Subbands	15
Subband Size	40
I/Q Sampling Rate	1 Mbps
Carrier Frequency	600 Mhz
Tx Gain	0 dB

Table 4.6: UFMC Simulation Parameters. I/Q Sampling Rate, Carrier Frequency and Tx Gain are specific value to be provided to the USRP hardware.

Results

Figure 4.27 shows the spectrum of the UFMC waveform.

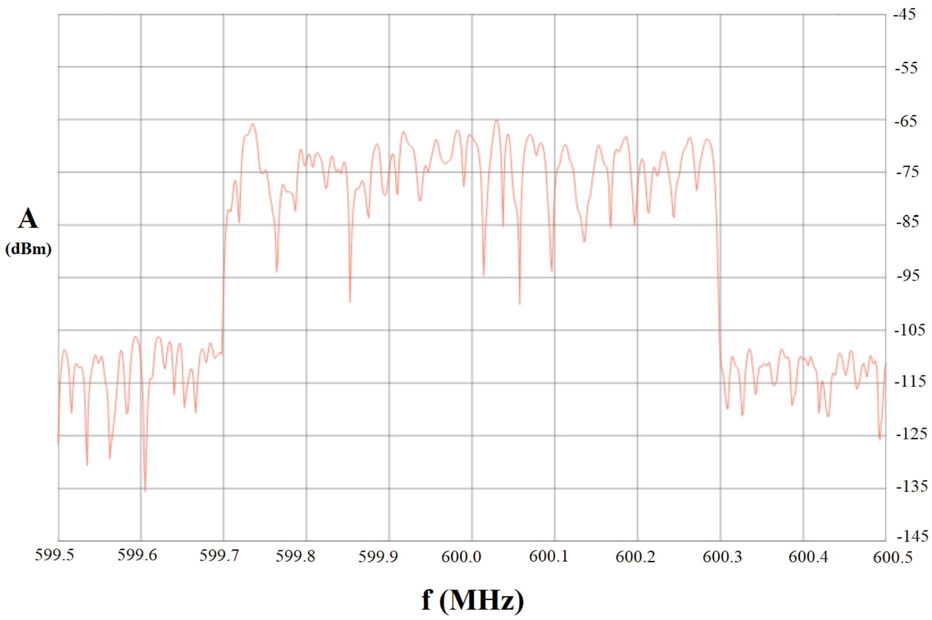

Figure 4.27: Spectrum of the UFMC Symbol. Center Frequency = 600 MHz; RBW = 10 KHz; Frequency Range = 1 MHz.

Figure 4.28 shows the CCDF of UFMC. The value of the PAPR is around 11 dB. There is no much difference with respect to OFDM. Theoretically UFCM PAPR should be a little bit lower than OFDM. Here we can't affirm that for sure, since the tools of the spectrum analyzer are not too precised.

All the measured values of UFMC waveform are reported in Table 4.7

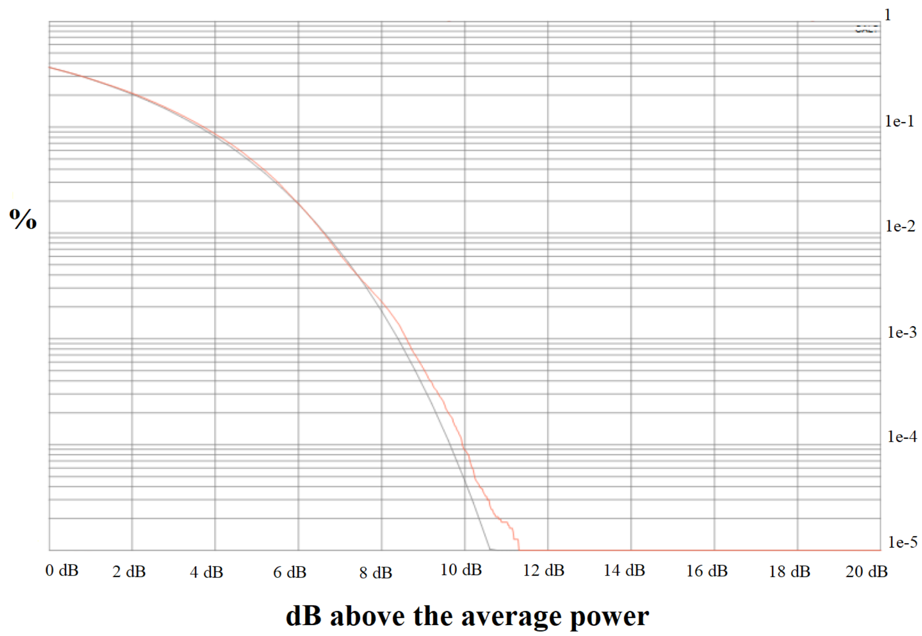

Figure 4.28: UFMC CCDF.

Parameters	UFMC
PAPR	11 dB
Bandwidth	600000 Hz
Power	-55.345 dBm
Power left out of band	-97,94 dBm
Power right out of band	-99,302 dBm

Table 4.7: Values of the collected UFMC results. UFMC PAPR should be a little bit lower than OFDM.

4.4 Comparison

After implementing the transmitters and running the waveform simulations all the results have been collected and as a final step a comparison between OFDM, FBMC and UFMC has to be done.

In Figure 4.29 the PSD of the three waveforms are compared by putting them one on another. The differences are quite subtle, but we can see actually that the side lobes of FBMC are lower than the other ones.

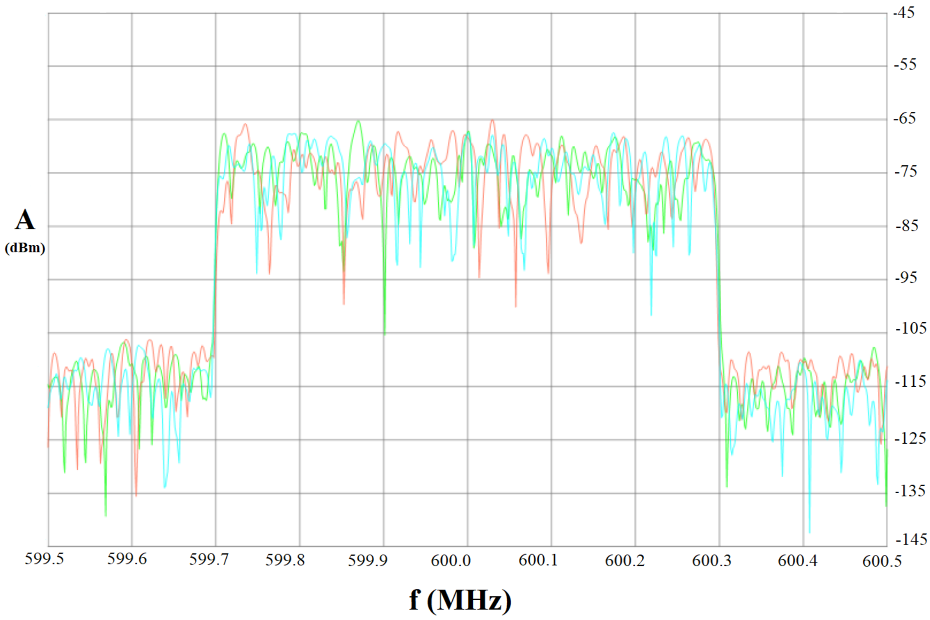

Figure 4.29: Comparison between OFDM, FBMC and UFMC Spectrums. The green one represents OFDM, the blue one FBMC and the red one UFMC. Center Frequency = 600 MHz; RBW = 10 KHz; Frequency Range = 1 MHz.

To have a clearer and more ordered view, Table 4.8 resumes all the obtained results.

Parameters	OFDM	FBMC	UFMC
PAPR	11 dB	10 dB	11 dB
Bandwidth	607500 Hz	600000 Hz	600000 Hz
Power	-55,054 dBm	-54.86 dBm	-55.345 dBm
Power left out of band	-92,485 dBm	-100,15 dBm	-97,94 dBm
Power right out of band	-101,462 dBm	-103,908 dBm	-99,302 dBm

Table 4.8: Values of the collected results. As expected, the value of the FBMC PAPR is quite lower. The values of the PAPRs are approximated. The UFMC one should be a little bit lower than OFDM. The bigger difference is obviously with respect to FBMC.

4.5 OFDM and FBMC Receivers

As mentioned before, also the receiver schemes of OFDM and FBMC have been implemented in this work. Since time wasn't enough to complete the full original task, it was impossible to implement the UFMC receiver.

OFDM and FBMC reveiver schemes will be shown in the following sections.

OFDM Receiver

Figure 4.30 and 4.31 respectively show the front panel and the block diagram of the OFDM receiver VI. We basically have the same parameters of the receiver, except we have to give as input the transmitted OFDM symbol. In addition, as we mentioned in the Add Cyclic Prefix function, another parameter to be given is the length of the Cyclic Prefix, which determines the percentage of the signal we have to remove in order to properly obtain the original signal.

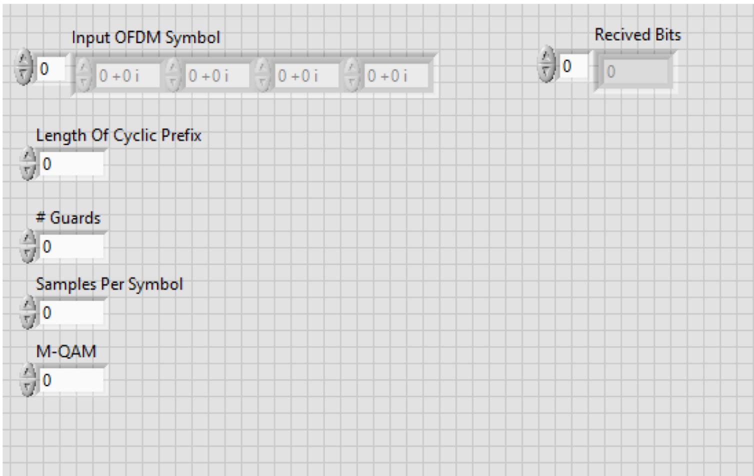

Figure 4.30: Front Panel of the OFDM Receiver.

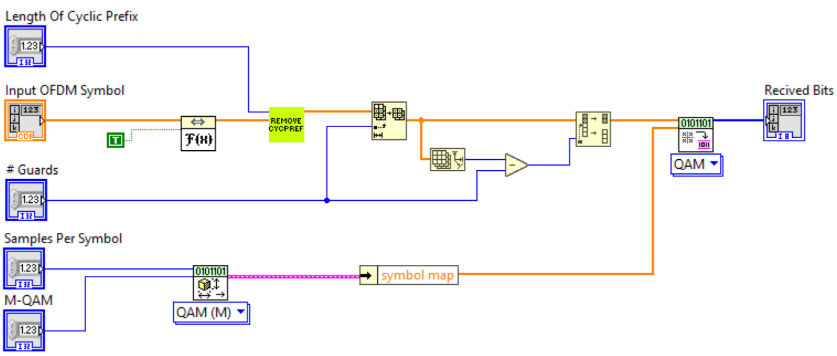

Figure 4.31: Block Diagram of the OFDM Receiver.

The block removing the CP has been implemented separately. Figure 4.32 and 4.33 represents the front panel and the block diagram of the Remove Cyclic Prefix VI. The logic here is very simple: by using the "Array Sub-set" function, we basically split the input array and take the sub-array starting at the end of the Cyclic Prefix.

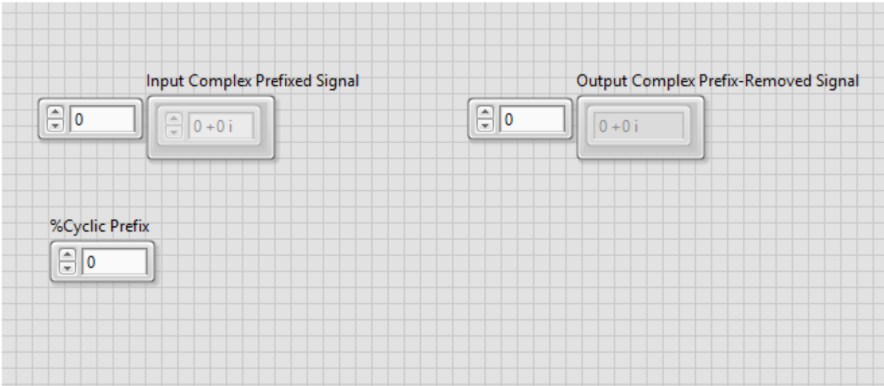

Figure 4.32: Front Panel of the Remove Cyclic Prefix VI.

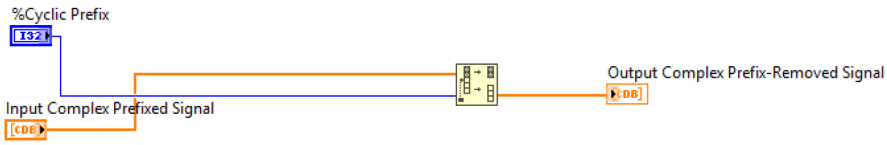

Figure 4.33: Block Diagram of the Remove Cyclic Prefix VI.

The OFDM receiver contains the inverse operations of the OFDM transmitter: firstly, we have to perform the Fast Fourier Transform (FFT) in order to bring us back to the QAM symbol coefficients. Right after that, we remove the CP with our proper function. Then, the guard symbols. What it's essentially done here is, with the advantage of the array functions (array subset, array size and split 1D array), the guards symbols are cut off on the left at first, and then on the right. Eventually, the last step is the demodulation in order to obtain the original bit sequence.

FBMC Receiver

The front panel of the FBMC receiver is represented in Figure 4.34. The parameters are the same of the FBMC transmitter, plus the input FBMC symbol we have to pass to the VI.

Since the block diagram too big, I had to split it in three parts. The steps are basically the inverse of the steps found in the FBMC receiver.

In the first part, represented in Figure 4.35, the input FBMC symbol firstly passes through the FFT block. After that, the convolution with the filter coefficients has to be done. The values of the filter depend on the value of K. We take the already seen Table 4.1 as a point of reference. Next step is removing the first K values and fill with K zero values.

Then, as shown in Figure 4.36, it comes the removal of guard symbols. A particular attention has to be put on the downsampling step. It basically works in this way: usign the "Reshape Array" function, the for loop is fed with an array of size K (if K=4 then the upsampling was done by a factor 4, so we have to downsample by a factor 4). Inside the for loop, each iteration takes the first position of the array which enters the loop, which is passed to a switch case. If the position is even, then the value is real. If it's odd, then the value is imaginary.

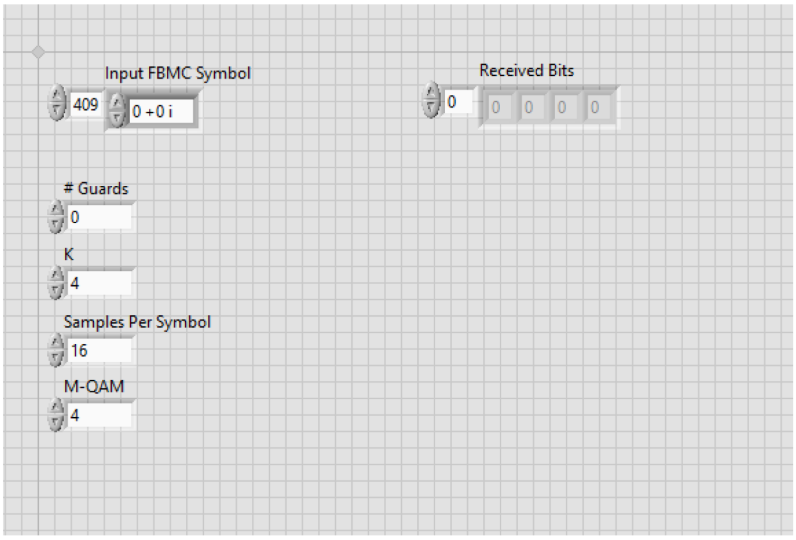

Figure 4.34: Front Panel of the FBMC Receiver.

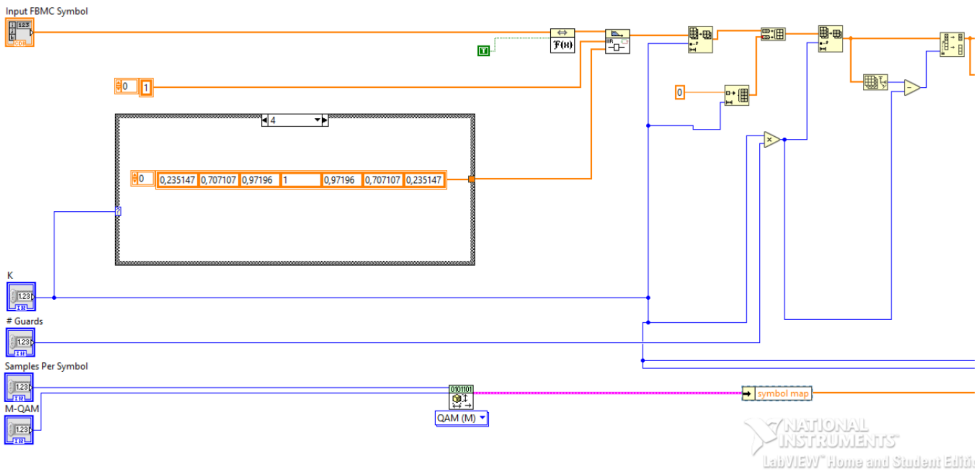

Figure 4.35: Block Diagram (1) of the FBMC Receiver.

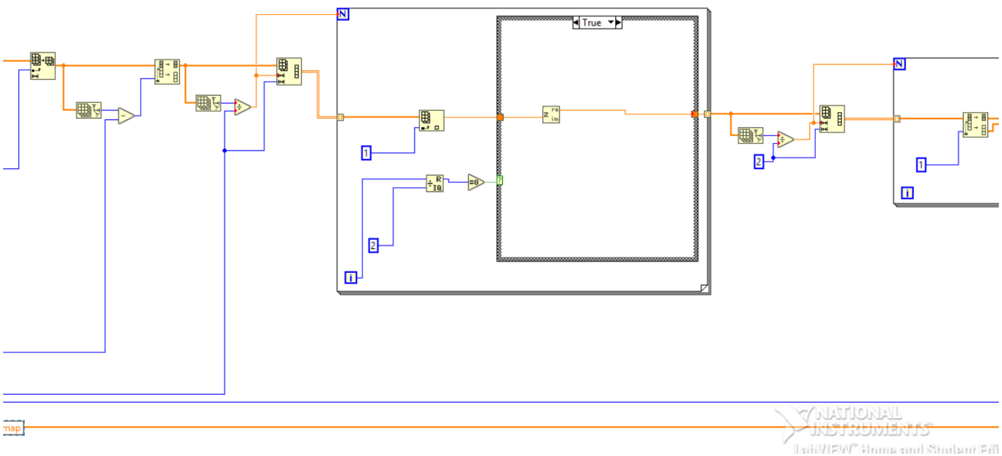

Figure 4.36: Block Diagram (2) of the FBMC Receiver.

Now let's take a look at Figure 4.37. After the downsampling step it's time to rebuild the array in order to put together each real and imaginary value into a single one (because then we have to demodulate). This is done with a "Split 1D Array", and then with a sum function in which we sum up real and imaginary part: basically, before the for loop, by usiing the "Reshape Array" function, each for loop is feed with 2 inputs (a real part and a imaginary part) at each time; inside the for loop, therefore, we split the two parts and sum them up in order to obtain a single value (real + imaginary).

Eventually, demodulation has to be done in order to obtain the original bit sequence.

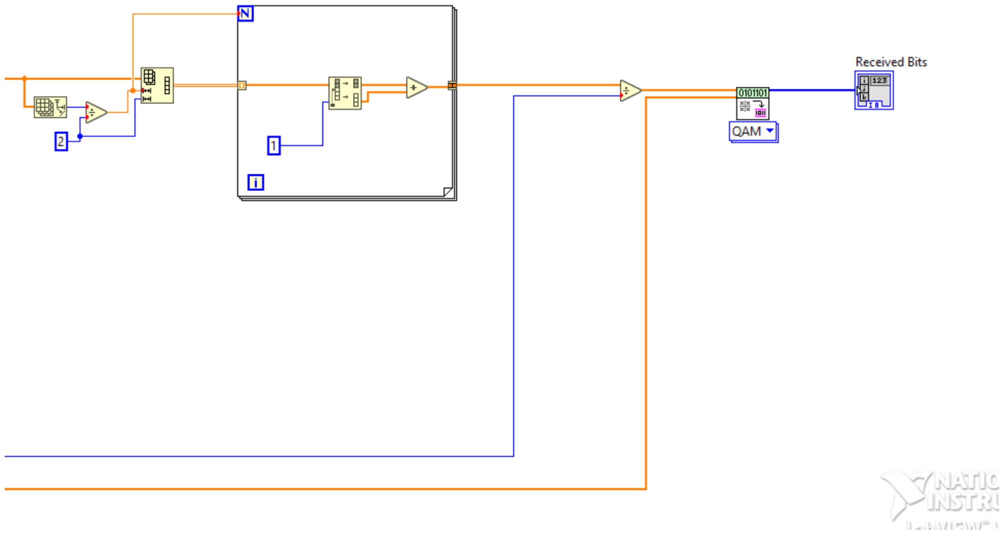

Figure 4.37: Block Diagram (3) of the FBMC Receiver.

Chapter 5

Conclusions

This work treated one of the most important topics of 5G mobile networks, which is the choice of the multi-carrier modulation technique that is going to be used. 5G requirements are considerably challenging and in order to satisfy them, lots of techniques and schemes are in development. As we have seen, a new Radio Spectrum, in which there are very high frequencies, is going to be used for very high speed requirements. Moreover, the number of cells is going to increase, using smaller and smaller cells. MIMO technology, already firmly used in 4G, is going to be enlarged to increase capacity. As OFDM has been the choice of LTE, with the next generation of mobile networks lots of other alternatives are taken in consideration to improve the already mentioned problems of OFDM, which telecommunication companies want to overcome. The architecture of Filter Bank Multi-Carrier has been discussed, highlighting that the CP is not used, and thus that the spectral efficiency is increased. Problems certainly turn up in terms of complexity. On the other hand, another alternative, Universal Filtered Multi-Carrier has been introduced, whose logic is similar to FBMC, that is not using the CP and instead doing some filtering operation in the main chain, more specifically with the usage of Dolph-Chebishev filters. After having talked about the main characteristics of the three multi-carrier schemes, an implementation in LabVIEW of OFDM, FBMC and UFMC transmitters has been shown, together with OFDM and FBMC receivers (unfortunately, as already said, the time to implement the UFMC receiver wasn't enough). Consequently, in order to verify the validity of the work, a laboratory simulation, using a Software Defined Radio, more precisely a USRP by National Instruments, and a spectrum analyzer has been done to test the transmitters and to collect some results. These results would serve for another project, which wasn't my commission, consisting in the connection of transmitters and receivers of the three schemes by using two USRP (one for the transmitter and one for the receiver). In Addition, by visualizing the results, it has been shown that better performances in terms of PAPR can be reached with FBMC and UFMC (unfortunately, the accuracy of the measurements wasn't the best), and that actually FBMC has the advantage of having lower side-lobes power.

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