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Filtered Orthogonal Frequency Division Multiplexing: A Waveform Candidate for 5G

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ABSTRACT: *The emerging Internet of Things will make the next generation 5G systems to support a broad range of diverse needs with greater efficiency requirements. The new class of services will need a higher data rates, to handle these demands, the lowest layer of the 5G systems must be flexible. Therefore, the waveform will have an important role in offering these new requirements. These new waveforms should enable efficient multiple access in order to handle the requirements of the future wireless communication systems which should have a variety of traffic types. This means that the corresponding required waveforms should be able to handle as much different type of traffic as possible in the same band. This paper presents the filtered orthogonal frequency division multiplexing waveform, it compares it to the original cyclic prefix OFDM applied in the 4G systems today. These new waveforms will be more robust against the time frequency synchronization problem, it has the potential for mixing different traffic specifications, and supports the scenarios of spectrum fragmentation, due to the improvement in the localization of spectrum. As a conclusion, these waveforms have a good potential in synchronicity and orthogonality and they allow us to drop some amount of signaling when supporting a large number of users. In the same time, they support all multiple input and multiple output (MIMO) scenarios and applications. for these reasons, these waveforms will be promising for 5G systems. some simulation results are shown, which demonstrate the potential of this technology.*

Keywords *–Cyclic prefix, LTE, MIMO, OFDM, Spectral efficiency*

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I. INTRODUCTION

The 4G systems, LTE, use the OFDM technique which is considered as an elegant solution to face the frequency selective problem and to improve the efficiency of the spectrum [1]. CP-OFDM is the most known and applied for multicarrier systems, where the modulation is based on the IFFT, and symbols are guarded by the use of Cyclic Prefix (CP). The 4G LTE standard arrived sometime around 2010 and offered new services worldwide, like wireless broadband data service, which is considered as an important innovation in the digital wireless communication systems. Since approximatively every ten years, a new generation is introduced to meet spectral specifications and the increasing in the data rates requirements, the industry should ask about the future applications and where LTE has fall short to meet the requirements. In the introduction of the new 5G standard, some new multicarrier schemes have gained high attraction as a potential candidate. Indeed, Filtered-OFDM is a promising contender since it has some advantageous characteristics, where the complete band is filtered as a whole. The subcarriers are shaped by a sinc-filter in frequency domain or instead of sinc-shapes they have a more suitable form according to the filter design with reduced side-lobe levels [2].

Recently, it becomes clear that the waveform of 5G should offer but not only the following: 1. Dedicated services for different needs and characteristics of channel, 2. Emission with reduced out of band, 3. tolerance to misalignment in the time-frequency [3, 4].

For 5G the objectives targeted by the European Union METIS project are to provide, at the 2020 horizon, 1000 times more mobile data volume per area, 10–100 times more connected devices, 10–100 times higher user data rates, 10 times longer battery life for low-power massive machine communication, and 5 times reduced end-to-end latency [5]. All these increases will be possible only by combining several factors: better usage of the available spectrum, use a new spectrum (above 6GHz), small cells generalization, introduction of massive MIMO, ... In addition to that the 4G LTE scheme is not suited to meet these essential requirements of 5G, so, consequently there is a need to define a new air interface. The 4G system is based on CP-OFDM modulation and any alternative multicarrier modulation can improve it only by removing the cyclic prefix in time and by reducing the bands of guard in frequency, which is marginal for the expectations of 5G. The CP-OFDM has two main drawbacks - a bad spectral confinement and a flexibility lack in the waveform - which are serious in the perspective of multi-services offered by the future 5G communication system. Dynamic spectrum aggregation is necessary to get an optimum usage of the available bandwidths below 6 GHz [6], the CP-OFDM based approach suffers from a high emission in the Out Of Band (OOB) and also from the granularity of the resource block which affects the allocation of a single subcarrier to low data rate communication services. And there are other problems which may also occur with frequency shifts due to Doppler effects in the case of the high mobility applications. As mentioned by Wunder et al. [7], obtain a significant reduction in the latency is a problematic in CP-OFDM. In addition, to the spectral efficiency reduction when the cyclic prefix is used to avoid interference problems.

For all these reasons, if is urgent to design a new system based on good flexibility of the waveform which can solve the challenges of 5G in its physical layer. This paper compares the filtered OFDM and the Filter Bank Multicarrier (FBMC) to OFDM with respect to their probability of error when changing some parameters mentioned later on.

The remainder of this paper is organized as follows. In Section II, we introduce the three waveforms to be compared – CP-OFDM, filtered OFDM (F-OFDM), and the Filter Bank Multi-Carrier (FBMC). Section III presents the block diagrams of these three systems. The comparison metrics, like the time frequency efficiency, are also presented in Section IV. The system performance is investigated in Section V through extensive trace-driven simulation. Finally, conclusions are given in Section VI along with the suggestions for future work.

II. THEORETICAL BACKGROUND

Without any discussion, CP-OFDM became the reference Multi Carrier Modulation (MCM). In the same time, two variants with a lower degree of maturity was available, the filtered multi-tone (FMT) and the filter bank multi-carrier (FBMC). More recently, a new scheme named FOFDM is also entering the debate for the fifth generation. Instead to be filtered subcarrier by subcarrier the new one correspond to be sub-band filtered. In this section, we briefly go through this list of waveforms and to be complete we will present the basic CP-OFDM. But before, we will define some parameters used in the formulation below:

M: Maximum number of subcarriers = Size of the (I)FFT
K: Number of sub-symbols in the case of block transmission
T_s: Sampling period which is considered here as unity
T: Duration of each single OFDM symbol
c: Symbol transmitted over each carrier in complex constellation
a: Symbol transmitted over each carrier in real valued constellation.

2.1 Orthogonal Frequency Division Multiplexing

The fundamental advantage of OFDM is the usage of subcarriers overlapped to modulate parallel data streams, which makes it more efficient in bandwidth efficient than the conventional technique. These subcarriers need to be orthogonal, to avoid the inter-carrier interference. The fast Fourier transform (FFT) is used to derive this set of orthogonal subcarriers. By modulating low rate data streams onto these subcarriers, OFDM system can ensure flat fading condition on each subcarrier. OFDM is a simple MCM technique which is widely used in many applications, in a single carrier modulation the transmitted data occupies the entire available bandwidth, the OFDM data are modulated over a number of narrow subcarriers each of them has a bandwidth smaller than the coherent bandwidth of the channel, giving an approximately flat fading channel at each subcarrier. In addition, a cyclic prefix is inserted after each symbol, which is a copy of a certain number of samples from the tail, with L_{cp} is its length. This further improves the flatness of the channel at each subcarrier, which enhances the robustness against the frequency selectivity of the channel. In OFDM, the transmission is done symbol-by-symbol which means that $K=1$, so the baseband symbol of CP-OFDM is expressed, for $k \in [-Lcp, M-1]$, as

$$s_{CP-OFDM}(k) = \sum_{m=0}^{M-1} c_m e^{\frac{j2\pi mk}{M}} \tag{1}$$

where c_m are the transmitted complex symbols at each subcarrier m, like QAM constellations. The overall operation can be realized by FFT and IFFT. One of the advantage of CP-OFDM is maintaining the orthogonality for the transmission over channel which is dispersive in time. Consequently, a simple method for channel estimation and equalization is used to recover orthogonality at the receiver. However, the rectangular pulse used in CP-OFDM has several disadvantages, so, implicitly the pulse shaping will be realized by the Fourier transform.

2.2 Filter Bank Multi-Carrier

The introduction of structured transmission is the remarkable contribution of FBMC, which allow the system to escape the Balian-Low theorem requirements [8]. The FBMC technique employ a better pulse shape, keeping the orthogonality, and transmitting at the Nyquist rate. In OFDM technique we transmit complex symbols at subcarriers, but in the structured technique we transmit the real and imaginary parts of the complex symbols separately with a half symbol duration delay, $T/2$. Better details of FBMC concept is in Le Floch et al. and [9]. The baseband signal in FBMC can be presented, for any integer k, as in [10]:

$$s_{FBMC}(k) = \sum_{n \in Z} \sum_{m=0}^{M-1} a_{m,n} \underbrace{g(k - nN_1) e^{j\frac{2\pi}{M}mk} e^{j\phi_{m,n}}}_{g_{m,n}(k)} \tag{2}$$

with g the filter, $N_1 = M/2$ the offset of the discrete-time, $\varphi_{m,n}$ an additional phase term at subcarrier m and symbol index n, which can be expressed as $\pi/2(n + m)$. $a_{m,n}$ the real value of the transmitted symbols, and obtained from the real and imaginary parts of a QAM constellation. For perfect reconstruction, the filter g must satisfy the orthogonality condition:

$$\Re\left\{ \sum_{k \in Z} g_{m,n}(k).g^{*}_{p,q}(k) \right\} = \delta_{m,p}\delta_{n,q} \tag{3}$$

where $*$ is the complex conjugation, $\delta_{m,p} = 1$ if $m = p$ and $\delta_{m,p} = 0$ if $m \neq p$.

As plain OFDM, FBMC takes advantage of fast IFFT/FFT algorithms. But, it has an extra complexity compared to OFDM. This complexity comes from the fact of working with half duration real symbols which means performing the IFFT/FFT at twice rate, and from the additional blocks of filters. This additional complexity depends on the selected scheme in the implementation.

2.3 Filtered-OFDM

Filtered OFDM (FOFDM) is also a new proposed multicarrier modulation scheme. it also introduces the filtering process in the time domain. The filter bandwidth is designed for a certain sub-band but it is not necessarily equal to 1 PRB; each sub-band is separately modulated using classical OFDM modulation. The FOFDM does not fix the filter length to the CP length which gives more freedom for the design of filter, implying a small filter transition bandwidth. The signal FOFDM is formed by K CP-OFDM sub-symbols of length $M + L_{cp}$. After applying the L-length time-domain filter f_i on each sub-band i, the FOFDM signal is produced and can be written for $k \in [-L_{cp}, KM + (K-1)L_{cp} + L - 2]$ as

$$s_{FOFDM}(k) = \sum_{i=1}^{B} \sum_{n=0}^{K-1} \sum_{l=0}^{L-1} \sum_{m=0}^{M-1} c^{i}_{m,n}.e^{j\frac{2\pi(k-l-nL_{cp})m}{M}} f_i(l) \tag{4}$$

where $c^{i}_{m,n}$ are the complex symbols for subcarrier m, the sub-symbol n and sub-band i. Only a fraction of the M subcarriers may need to be activated, depending on the schemes of the different modulation. The FOFDM targets the uplink with narrow sub-bands corresponding to few tens of subcarriers, should be considered in the implementation.

III. SYSTEMS MODELS

3.1 CP-OFDM

In a digital domain, binary input data (bits) are collected and coded with a channel coding schemes such as convolutional codes. After that the coded bit stream is interleaved to obtain diversity gain. Afterwards, a group of interleaved bits are grouped together (1 for BPSK, 2 for QPSK, 4 for 16QAM, ...) and mapped with the corresponding points in the constellation. At this instant, the data in complex numbers representation and they are in serial. So, the known pilot symbols mapped with known mapping schemes can be inserted at this time, and we obtained the modulated data stream mentioned in the Fig. 1. After applying a serial to parallel converter, the IFFT operator is performed on this parallel complex data. The transformed data is grouped together again, as per the number of required transmission subcarriers. Cyclic prefix is inserted in every block of data according to the system specification and the data is multiplexed to a serial order. Here, the data can be considered OFDM modulated and ready to be transmitted. A Digital/Analog Converter (DAC) is used to transform the digital data to time domain analog data. RF modulation is performed and the signal is up-converted to transmission frequency. When transmitted by the antenna, the OFDM signals go through all the impairments of the wireless channel.

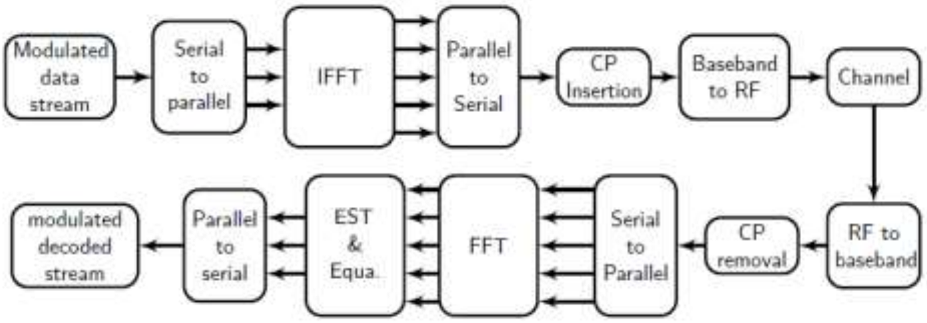

Fig. 1: CP-OFDM transceiver scheme

At the receiver, they will be down-converted and reconverted to digital using an Analog/Digital converter (ADC). We should make attention to frequency offset due to channel and mobility, so a carrier frequency recovery should be performed when the down-conversion operation is working. After the digitization process, the symbol timing synchronization is achieved. Then the FFT operator is used to demodulate the OFDM signal. After that, channel estimation is performed using the demodulated pilots. Using the estimations, the complex received data is obtained which are de-mapped according to the transmission constellation diagram. At this moment, FEC decoding and de-interleaving are used to recover the originally transmitted bit stream. The CP-OFDM is the most commonly known and applied multicarrier format (in 3GPP LTE and IEEE 802.11).

3.2 FBMC

The simple block diagram shown in Fig.1 can be adapted to implement the filter bank, it is just sufficient to extend the IFFT and the FFT. In section III.1, a data stream is applied to one input of the IFFT and it modulates one carrier. In a filter bank with overlapping factor K, as shown in Fig. 3, a data stream modulates $2K$-1 carriers. Thus, the filter bank in the transmitter can be implemented with an extended IFFT of size KM, to generate all the necessary carriers; and each data element, after multiplication by the filter frequency coefficients, is sent to the $(2K\text{-}1)$ inputs of the IFFT from $(i-1)K+1$ to $(i+1)K-1$. So, the data element is spread over several IFFT inputs, as shown in Fig. 2. 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. Therefore, the filter bank output is provided by an overlap and sum operation, as shown in Fig. 3.

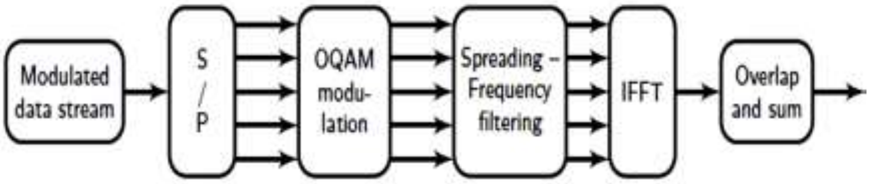

Fig. 2: FBMC transmitter scheme

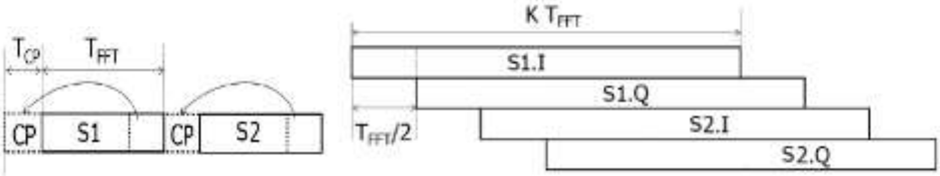

Fig. 3: CP-OFDM vs FBMC frames

The implementation of the receiver is also based on an extended FFT, of size KM. In that case, the FFT input blocks overlap, it is the classical sliding window situation. At the output of the FFT, the data elements are recovered with the help of a weighted de-spreading operation. In fact, the data recovery rests on the property of the frequency coefficients of the Nyquist filter. The delay of the whole system, when the transmitter and the receiver are connected, is KM samples, or K multicarrier symbols.A remarkable feature of the scheme presented in Fig. 2 is its simplicity: it is just the scheme shown in Fig. 1 completed by minor operations before and after the IFFT/FFT. In fact, the key difference is the complexity, due to the increasing of the FFT size from M to KM. Due to the overlapping in the time domain of the IFFT outputs and FFT inputs, a lot of redundancy is present in the computations which can be reduced by using certain scheme or idea.

3.3 F-OFDM

The transmitter scheme is depicted in Fig. 4. We denote M the number of carriers, and N_i the number of subcarriers. There are N_i subcarriers per carrier. For each F-OFDM symbol, N_i data are mapped in frequency domain, an IFFT of size N_i is applied to each carrier, and a CP is appended. It ensures the circularity of the received signal. The output of each stage are then fed to a filter parametrized by a prototype filter. After that the summation of the M stages is done and symbols are then transmitted. In terms of complexity, one can see a slightly increase compared to OFDM. A small complexity analysis will be done in the next section. The receiver scheme consists on selecting a window of size MN. It is followed by a MN FFT stage. The receiver is thus with low complexity, similar to the one of CP-OFDM. The key differences with respect to conventional system are:

1. Sub-band filter is added to CP-OFDM, No change on existing CP-OFDM
2. Filtering for each sub-band (sub-band BW >= 1RB)
3. Independent Subcarrier spacing/ CP length/ TTI for each sub-band
4. Rather low guard tone overhead between neighboring sub-band
5. Asynchronous inter-band transmission due to perfect OOB performance

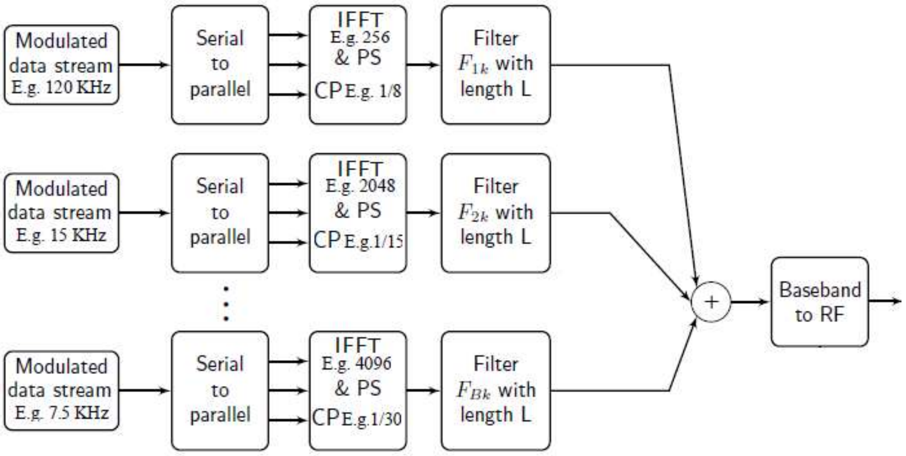

Fig. 4: FOFDM transmitter scheme

IV. COMPARISON METRICS

In this section, we provide a comparison of the different waveform presented in this paper. The comparison includes several metrics: the spectral efficiency, the tail issue, the spectrum confinement, the mobility, the latency, the complexity, and the compatibility with 4G (LTE). This comparison is necessary to provide a global view of the advantages/drawbacks of schemes.

4.1 The Spectral Efficiency

The spectral efficiency analysis for part of the 5G waveforms is done by Lin and Siohan. CP-OFDM cannot achieve this maximum value due to the addition of a CP of length T_{CP}. So, the efficiency reduction is:

$$\eta_{CP-OFDM} = \frac{T}{T+T_{CP}} < 1 \tag{5}$$

In contrast, the FBMC scheme respects the Nyquist rate and no CP is used. Hence it is possible to achieve the maximum efficiency:

$$\eta_{FBMC} = \frac{1}{T.F} = 1 \tag{6}$$

Where F is the spacing between subcarriers, the maximum efficiency for the system is reached when: $T.F = 1$. Finally, F-OFDM retains the CP-OFDM process and employs a FIR filtering on top. The filtering does not reduce spectral efficiency. Therefore, the spectral efficiency of F-OFDM is also equal to CP-OFDM.

4.2 The Tail Issue

In a burst transmission, the tail issue mainly reflects the potential overlap between two bursts, which means symbols are not completely isolated in the time domain but instead part of the symbols is overlapped. This issue has been identified for the FBMC scheme. In CP-OFDM, each symbol is completely isolated in the time domain so that it does not have any tail issue. In contrast to CP-OFDM, F-OFDM uses a filter length is longer than the CP length, therefore, the additional filtering will cause the tail issue.

4.3 The Spectrum Confinement

Two main problems with CP-OFDM lead to bad spectrum confinement: Spectral leakage due to the waveform discontinuity, and the rectangular pulse shape for CP-OFDM. The first problem can be solved when the envelope of the symbol edges is smoothly decreasing to zero. To solve the second one in FBMC, the rectangular filter is replaced with a prototype filter that has good frequency localization and a length longer than the FFT size. For F-OFDM, the discontinuity issue can be overcome by FIR filtering. However, the improvement in spectrum confinement is less than for FBMC.

4.4 The Mobility

Mobility robustness is also a very important criterion for 5G, the FBMC schemes have, in general, better robustness against the Doppler effect due to the subcarrier filtering process. On the other hand, the F-OFDM scheme handle the Doppler effect in the same manner as CP-OFDM, the claimed advantage is that the subcarrier spacing can be made wider for a particular sub-band in order to serve high-mobility users.

4.5 The Latency

Latency is another important consideration for 5G networks, CP-OFDM is advantageous because of its short transceiver latency, which is mainly due to the FFT transform and CP, in other words $T + T_{CP}$. Any additional filtering will naturally increase the latency. Moreover, latency and spectrum confinement are two competing factors. FBMC has the highest latency, F-OFDM needs additional buffers to absorb the filter transition period, which naturally slightly increases the latency.

4.6 The Complexity

One important advantage of the CP-OFDM is its low modem complexity. It is obvious that when working on some new advanced modulation simplicity might need to be sacrificed. It is important to compare the new candidates to CP-OFDM. In the FBMC scheme, the complexity is more than double. For the F-OFDM modulation, a FIR filtering is employed on the top of CP-OFDM modulation, the authors have not reported concrete complexity, we could infer that its complexity should be between of those of FBMC and CP-OFDM.

4.7 The Compatibility with 4G

Another consideration, but it does not mean that the new receiver is able to decode LTE signals; it rather means that the new system should preferably be able to reuse existing LTE techniques, like reference signal (RS) design and MIMO coding, in a straightforward manner. However, for FBMC systems, only real-valued symbols are transmitted due to offset QAM signaling. It thus cannot directly reuse the LTE techniques. For the F-OFDM scheme, it is claimed that the signal within the sub-band has the same character as the OFDM signal, the system can maintain a good compatibility with LTE.

V. SIMULATION RESULTS AND ANALYSIS

A key performance index to evaluate the capacity-approaching is the BER given a received SNR over an AWGN channel. We consider the parameters mentioned in Tab. 1 (most used in the literature). In this section, we examine the performance of the FBMC and FOFDM waveforms and compare the results with that of CP-OFDM. Our simulations have been carried out with parameters that are shown in Tab. 1. Monte Carlo simulation by MatLab is used to obtain the results shown in the following figures. For the evaluation, three performance metrics are considered the Power Spectral Density (PSD), the Probability of Error (BER: Bit Error Rate), and the Peak to Average Power Ratio (PAPR). We can predict before simulations that in the first two metrics we will obtain some gain but in the PAPR metric the CP-OFDM will be better because of the filtering effect in both FBMC and F-OFDM which improves slightly the PAPR with respect to FBMC.

Overall Parameters		
FFT size	N_{FFT}	1024
Bit Per Symbol	m	2, 4, 6, 8
Resource block size	N_{SC}	12, 16
Number of active RBs	N_{RB}	50, 60
CP-OFDM Parameters		
Cyclic Prefix	N_{CP}	72 samples
F-OFDM Parameters		
Filter Length	L	513
FBMC Parameters		
Overlapping Factor	K	2, 3, 4

Tab. 1: Simulation Parameters

5.1 Power Spectral Density – PSD

A comparison of the theoretical power spectrum density of CP-OFDM and F-OFDM for two different values of Resource blocks (NRB) and Number of subcarriers in each RB (NSC) is shown in Fig. 5, where the PSD is represented in dBW/Hz and function of the normalized frequency. We can simply remark that the reduction of PSD in the Out of Band (OOB) region due to the filtering process used in F-OFDM, this reduction makes this new waveform more robust to the Inter-Carrier Interference.

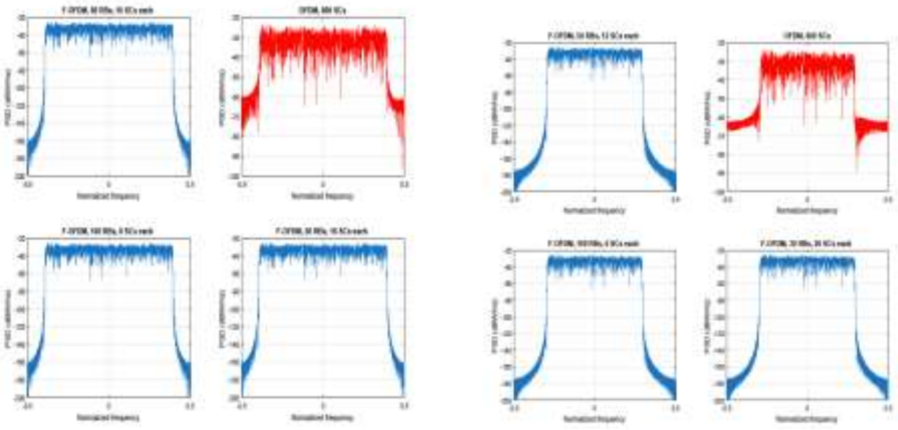

Fig. 5: PSD Comparison between CP-OFDM and FOFDM

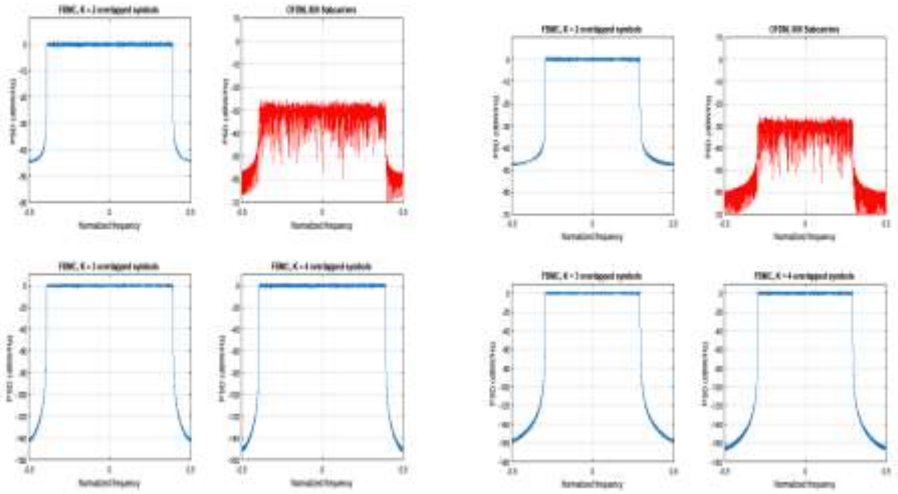

Fig. 6: PSD Comparison between CP-OFDM and FBMC

In Fig. 6 the comparison of PSD between CP-OFDM with FBMC for various values of overlapping factor K is shown. Here, we should focus on two things: The first one is the difference in the power level in the corresponding band where this difference is due to the power transmitted in the CP-OFDM system and in the FBMC system used in the simulation which they are not the same. The second one, it is obviously shown that in FBMC the power in the OOB is very small compared to the power in the corresponding band. So, we can say that the FBMC has the best PSD when compared to the CP-OFDM and F-OFDM.

5.2 Bit Error Rate - BER

A comparison of the probability of error, which is presented by the BER, of F-OFDM and FBMC with respect to the different modulation levels from QPSK to 256QAM modulation is presented in Fig. 7. This figure demonstrates what it was proved theoretically that when the modulation level increase the BER increase also, we should make attention the error floor obtained in F-OFDM when 256QAM modulation is used.

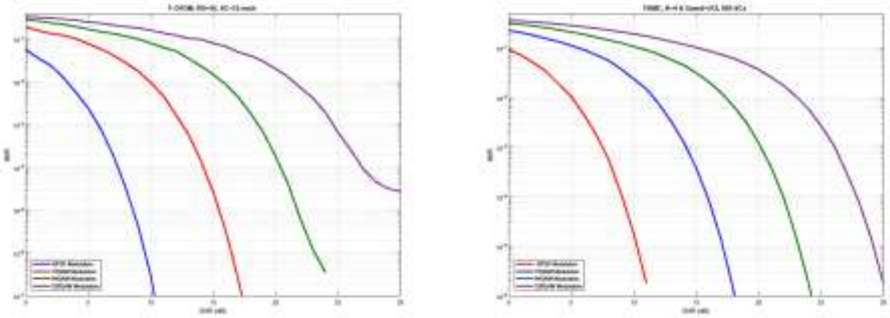

Fig. 7: F-OFDM and FBMC performances with respect to modulation levels

When compared to the CP-OFDM system the F-OFDM presents a net gain in all cases simulated in our work. Fig. 8 shows that the F-OFDM using QPSK or 16QAM and different number of subcarriers has better BER from the CP-OFDM with approximately 2 dB at BER=10^{-5} for QPSK modulation and 1.75 dB at the same BER for 16QAM modulation. In Fig. 9, the comparison between FBMC and CP-OFDM for both modulation QPSK and 16QAM is presented. The simulation results show that the CP-OFDM and the FBMC waveforms have the same performance with respect to the BER whatever is the modulation or the number of subcarriers. So, we can say that F-OFDM has the best BER when compared to the CP-OFDM and FBMC.

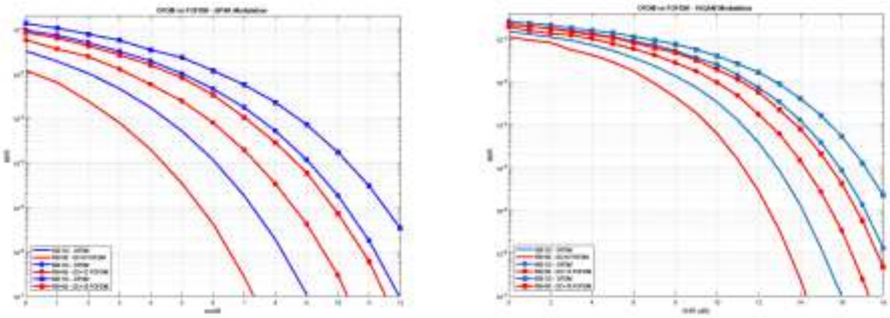

Fig. 8: BER Comparison between F-OFDM and CP-OFDM

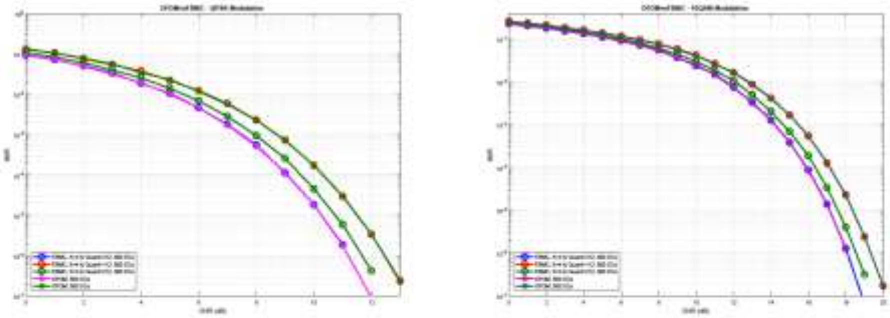

Fig. 9: BER Comparison between FBMC and CP-OFDM

5.3 Peak-to-Average Power Ratio - PAPR

Theoretically, A CP provides a more constant amplitude, which reduces the peak to average power ratio (PAPR) and makes it appealing for power amplifiers. Furthermore, the CP allows for slightly smaller receive FFT sizes and potentially better coexistence with CP-OFDM. In the same time the filtering process increase the PAPR problem. So, we can expect that CP-OFDM will has the best PAPR ratio when comparing to the F-OFDM and FBMC, moreover, FBMC will have the worst PAPR ratio since it uses the filtering process and does not add a cyclic prefix to the symbols. The Fig. 10 confirms our theoretical conclusion, where the PAPR ratio is presented in dB for different modulations used and different number of subcarriers. In all these cases the PAPR of CP-OFDM is between 8.4 and 8.8 dB where the PAPR of F-OFDM and FBMC is larger than 10 dB. We can remark also that the difference between F-OFDM and FBMC varies but the one for F-OFDM is always smaller than that for FBMC. So, when we use any waveform different that the CP-OFDM, we will lose approximately 2 dB in the PAPR.

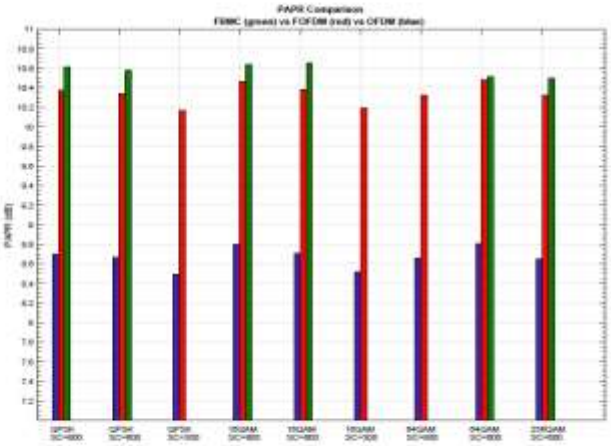

Fig. 10: PAPR Comparison between CP-OFDM, F-OFDM, and FBMC

VI. CONCLUSION

In this paper, the implementation of two different candidates for the fifth generation, Filtered OFDM (F-OFDM, FBMC), is studied and presented. The first objective was to compare them with the conventional CP-OFDM but during our work, we have been capable to compare them between themselves. The simulation results show that each of the waveforms presented in this paper improves some parameters and deteriorates other parameters, so we need to take other criteria to choose the waveform for the next generation, like the tail issue, the complexity, the latency, and others. The FBMC and F-OFDM improve the PSD but deteriorate the PAPR ratio, in the same time the F-OFDM improve the BER rate, which push us to say that the F-OFDM represents a good candidate to the 5G system with respect to other metrics presented in this paper.

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