COMPARATIVE ANALYSIS OF ORTHOGONAL FREQUENCY DIVISION MODULATION AND FILTER BANK-BASED MULTICARRIER MODULATION

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***Abstract* — Multicarrier modulation techniques has been one of the key systems deployed in wired and wireless communication nowadays due to its ability to share communication resources efficiently. Today Orthogonal Frequency Division Multiplexing (OFDM) has been the most implemented multicarrier scheme in recent networks such as Long Term Evolution (LTE) 4G, Digital Video Broadcasting (DVB), Digital Subscriber Line (DSL) and many others.** [1]**However, with new communication technologies coming up such as 5G, Internet of Things (IoT) and Machine to Machine (M2M), requiring higher bandwidth, greater capacity, security and lower latency. The huge number of users and devices means higher demand for data and network resources; therefore, there is the need for new multicarrier schemes that would be able to meet the requirements of these new technologies, as OFDM is not efficient in circumstances like cognitive radio systems and unsynchronized signals in uplink direction due to its high spectral leakage and bandwidth inefficiency. Filter Bank-based Multicarrier (FBMC) is one of the best contenders that addresses the shortcomings of OFDM and is favourable for the new emerging networks. This study provides a comparative evaluation of OFDM with Cyclic Prefix (CP) and FBMC with Offset Quadrature Amplitude Modulation (OQAM) processing** [1]**. The two techniques were compared using analytical expressions and simulations over MATLAB. Parameters such as power spectral density, subcarriers waveforms, prototype filters, computational complexity, delay and spectral efficiency were compared. Results of the analysis have proven that FBMC outperforms OFDM as it offers better bandwidth efficiency and spectral localization in time and frequency with low out-of-band leakage, making it more appropriate for the all-new upcoming technologies.**

Key words — OFDM, FBMC, multi-carrier modulation, Filter bank

I. INTRODUCTION

Over the past decades, Wireless communications systems have been essential in the provision of telecommunication services worldwide. From radio and TV broadcasting, satellite and cellular networks, they have really been among the major enhancers of human life. The evolution of broadband internet made wireless systems more attractive than never before because of its numerous advantages such as flexibility and mobility. Today with the modernization of countries and easier access to computers and smartphones all over the world, many people have the opportunity to use the internet[2]. The rapid development in the telecommunications sector has led to the birth of many amazing technologies like Machine to Machine communication (i.e. allowing devices to communicates between themselves), IoT (Internet of Things) where devices, things, objects such as doors, fridges, air-conditioners and many others that were not able to connect to the internet to do so and interact with each other. Making the number of users and devices rise rapidly lately while the spectrum remains the same.

Frequency spectrum is unarguably one of the most expensive and scarce resources in wireless systems, so it is very important to use it efficiently. Many methods have been developed over the years to improve the use of the frequency spectrum and one of the most promising techniques among them is multicarrier modulation technique. The principle of multicarrier modulation is to divide the serial high data rate transmit bit stream into several parallel bit stream with low data rate and send them over separate narrow band carrier signals improving bandwidth optimization, reducing fading channels and enhancing immunity to inter-symbol interference.

As of today, OFDM is the multi-carrier modulation system deployed in digital communications systems such as 4G LTE. However, it faces some challenges such as high out-of-band leakage caused by the rectangular window filer used, susceptibility of Inter Carrier Interference (ICI) and Inter Symbol Interference (ISI) due to the spectral leakage in neighbouring sidebands, reduction of bandwidth efficiency due to the use of CP to reduce ISI and ICI, high Peak-to-Average Power Ratio (PAPR), poor performance in Cognitive Radio (CR) because of the large side lobes in its filter frequency response that produces interference between primary and secondary users and difficulty to attain in practice the strict synchronization required in the uplink where the transmitters send signals from different geographic areas so additional signal processing is needed. Due to these limitations, OFDM is not appropriate for new emerging technologies where these requirements are very strict. New schemes are then needed [3] to meet those requirements and one of the best contenders is FBMC Filter Bank-based Multicarrier, which is able to overcome the numerous limitations of OFDM, offering better carrier spectral shaping than OFDM and providing bandwidth efficiency due to the omission of CP.

The aim of this article is to analyse and compare the two modulations schemes OFDM and FBMC to determine the best. The comparisons is based on empirical analysis and simulations results of the power spectral density, the carrier signals waveforms, the prototype filters parameters, the computational complexity, delay and spectral efficiency.

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II. LITERATURE REVIEW

A. OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a digital multicarrier modulation technique used in many current digital systems these days including 4G LTE, digital TV broadcasting system DVB.

The concept behind OFDM is to send data by using multiple subcarriers within the same single channel. Indeed instead of transmitting a high-rate data stream with a single carrier signal, OFDM uses a large number of closely spaced orthogonal carrier signals of different narrowband frequency that are transmitted in parallel. The carrier signals are modulated at low symbol rate with a conventional modulation schemes such as QPSK, 16QAM and 64QAM), but the combination of the multiple subcarriers provides high data rate like conventional single-carrier modulation techniques. [4]

OFDM is based on conventional Frequency Division Multiplexing technique where different data streams are mapped on separate parallel frequency channels. Frequency guard band is used to separate the different frequency channels in order to reduce interference between adjacent channels.

In OFDM, the input bit stream basically serial is divided into several parallel sub streams by the serial-to-parallel converter, this sub streams are grouped and mapped to data symbols that are complex-valued representing the modulation constellation point. The complex-valued data symbols being in frequency domain specify the phase and amplitude of the subcarrier that will be used for each data symbol. Those data symbols are the inputs of the IFFT (Inverse Fast Fourier Transform) block that transforms them in time domain where the output is the group of modulated symbols on carrier signals (sinusoids). Actually, the IFFT block modulates the data symbols onto many different orthogonal carrier signals, which pass through a parallel to serial converter, the output of this block is the summation of those modulated carrier signals on which the CP (Cyclic Prefix) is added. The cyclic prefix acts as a buffer or guard band to reduce ISI between OFDM signals. The final combination block made up from all those steps is actually the single OFDM symbol. Which is sent through the channel after some additional processing and conversion in analogue signal.

At the receiving side, the analogue signal is converted back to digital, the CP is removed, converted to parallel subcarrier signals, the FFT (Fast Fourier Transform) block performs the transformation into frequency domain where the parallel data symbols are recovered and converted into single serial bit stream as it was originally. [2] [5]

OFDM has some advantages including:

- The use of orthogonal carrier signals allowing many signals to be transmitted together with less interference between them and providing high capacity
- The use of carrier signals with narrow band frequency, making the bandwidth of the carrier signals smaller than the coherence bandwidth of the channel avoiding frequency selective fading
- Possibility of adaptive modulation scheme increasing the robustness of the system
- Compatibility with MIMO system.
- It also presents some downsides such as:
- Waste of bandwidth owing to the use of CP,
- High spectral leakage due to the use of rectangular windowing
- Strict synchronization required in uplink direction
- Non compatibility with Cognitive Radio

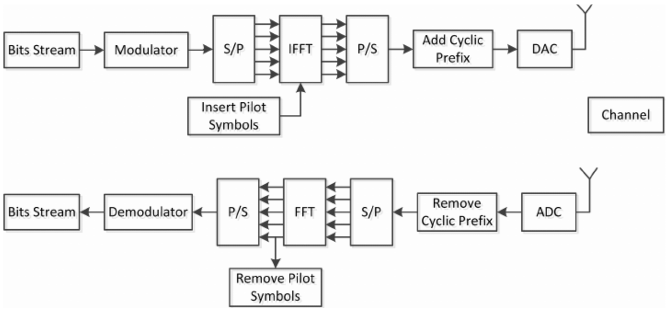

Fig 1: OFDM system block diagram

B. FBMC

Filter Bank Multicarrier (FBMC) scheme has drawn more attention lately because it provides better spectral properties compared to OFDM due to the additional use of filter banks at the transmitter and receiver. It is one of the contenders for cellular network 5G implementation as it is able to overcome the limitations of OFDM. [6] [7]

FBMC works like OFDM but consists of an additional block, which is the main processing block of FBMC; it is called Transmultiplexer (TMUX) and consists of Offset Quadrature Amplitude Modulation (OQAM) pre / post processing blocks and synthesis/ analysis filter banks, which are arrays of filters.

The transmutiplexer transmits OQAM symbols instead of QAM symbols. The OQAM pre-processing block at the transmit side, transforms QAM symbols into OQAM sysmbols where the complex-valued of the QAM symbol is divided into two real part and imaginary part, [8] providing then distinct real-valued (with one multiply by j) symbols. At the receiving side, the OQAM post-processing block performs the inverse operation of the OQAM pre-processing by converting real-valued symbols into complex-valued symbols.

OQAM processing blocks provide high capacity and orthogonality as in each sub-channel either real part or imaginary part is transmitted avoiding interference between neighboring subchannels. FFT is performed at twice the rate to maintain the bit rate high [6]

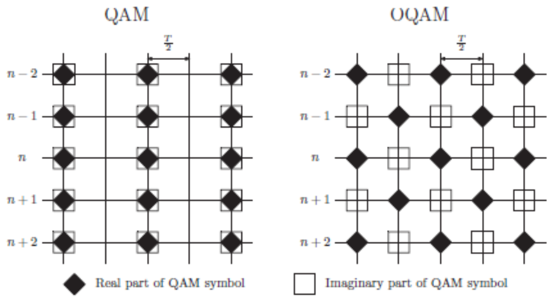

Fig 2: QAM and OQAM symbols mapping on carriers

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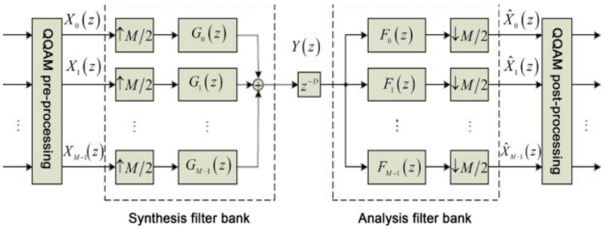

Fig 3: Transmutiplexer configuration

In FBMC, the input serial bit stream originally serial is converted into several parallel sub streams after passing through the OQAM pre-processing block. These sub streams move into the synthesis filter bank where the different data symbols pulses are shaped for transmission, the prototype filter used to design the filter bank are well localized in frequency and time avoiding ICI and ISI, also requires no CP. After summation and conversion into analogue, the signal and sent through the channel.

On the receiver side, after conversion from analogue to digital, the bit stream is converted from serial to parallel form by the serial-to-parallel converter and moves into the analysis filter bank. The output of the analysis filter bank moves into the post-processing block and later converted to serial bitstream as it was originally by the parallel-to-serial converter.

There are two ways to implement FBMC, the frequency spreading filter bank multicarrier (FS-FBMC) and the poly-phase network filter bank multicarrier (PPN-FBMC). PPN-FBMC reduces the high complexity caused by the extra filtering operations at the transmitter and receiver. [7] [8]

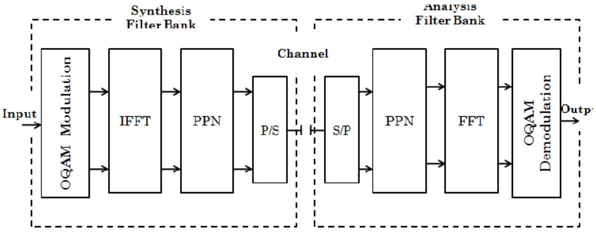

Fig 4: OFDM (QAM) and FBMC (OQAM) symbols mapping on carriers

Research on FBMC have been conducted in different ways over the years by many researchers. A comparison between the two schemes OFDM and FBMC based on filter bank architecture was first developed in 2010 by I. ESTELLA, A. ISERTE, and M.PAYARO [1] .The authors investigated the two schemes based on analytical and simulations of the sources of errors, the effect of channel coherence bandwidth and energy efficiency trade-off observed for both systems. The same idea has been expanded in [9] [10]where the authors conducts a comparative analysis of the Bit Error Probability (BEP) of FBMC and OFDM with CP under AWGN and Rayleigh channels environments.and In [10] , I. A.Sahin and H.Arslan, provide a comparative study of different FBMC prototype filters designs and OFDM modulation schemes under pratical channel environments.

In 2011, B. Farhang-Boroujeny [2] defined the advantages and disavantages of OFDM while comparing with multicarrier modulation techniques that use filter banks for signal synthesis and analysis such as FBMC.

In 2017, Parnika Kansal, Ashok Kumar Shankhwar [7]provide a comparative analysis of OFDM and FBMC schemes based on simulations over MATLAB of the power spectral density, the subchannels and the prototype filters of both schemes. Later on in [11] , the authors used the same concept to compare the Bit Error Rate (BER) and Peak-to-average power ratio (PAPR) of OFDM, F-OFDM and FBMC.

III. METHODOLOGY

The research is done using simulation and empirical formulas are used to develop algorithms to compare the two multi-carrier schemes using the same parameters. MATLAB is used as the main tool to simulate the algorithms. The following are the parameters used for the comparison in this study

A. Power Spectral Density (PSD)

The power spectral density (PSD) is the measure of the transmitted signal's power content versus frequency. Its function shows the strength of the variation of the signal's energy as function of frequency. It is used to characterize the broadband signal.

1. Power Spectral Density of OFDM

The OFDM symbols are computed using Inverse Discrete Fourier Transform (IDFT) and a set of complex input signals X_k with the addition of CP. The transmission of OFDM signal $x(n)$ will then be the sum of signals on all channels (or subcarriers). Mathematically, it is given as: [12]

$$x(n) = \sum_{k=0}^{N-1} \sum_{w=-\infty}^{+\infty} X_{k,w}\, p_T\,(n - wT) e^{j2\pi n f_k} \qquad (1)$$

When the transmitted signal is sampled at the sample rate of *N/T*, the discrete signal from (1) becomes:

$$x(n) = \sum_{k=0}^{N-1} \sum_{w=-\infty}^{+\infty} X_{k,w}\, p_T\,(n - wN) e^{j(2\pi/N)nTf_k} \qquad (2)$$

The OFDM power spectral density is then given by: [13]

$$\Phi_{OFDM}(f) = (\sigma_{x^2}/T) \sum\ P_T\,(f - k/N)^{\,2} \qquad (3)$$

2. Power Spectral Density of FBMC

In FBMC several parallel data symbols $X_{k,w}$ are transmitted through a bank of filters (synthesis filter bank). The subcarriers in FBMC QAM symbols are staggered by half symbol time allowing the real valued symbols to be transmitted instead of the complex valued symbols. The FBMC symbol is expressed mathematically as: [14]

$$x(n) = \sum_{k=0}^{N-1} \sum_{w=-\infty}^{+\infty} X_{k,w}\, p_T\,(n - wT/2) e^{j2\pi n f_k} \qquad (4)$$

The power spectral density (PSD) is expressed as : [13]

$$\Phi_{FBMC}(f) = (\sigma_{x^2}/T) \sum\ H(f - k/N)^{\,2} \qquad (5)$$

Where:

k is a set of data subcarrier indices varying from 0 to N-1;

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N , the number of subcarrier then the IDFT size

$X_{k,w}$, the data on the k^{th} carrier signal at the w$^{\text{th}}$ OFDM symbol

f_k , the carrier frequency of k^{th} carrier signal

T, the OFDM symbol period

p_T , the prototype filter at the transmitter

$p_T\,(n-wT)e^{j2\pi nf_k}$ implies that the prototype filter at the k^{th} carrier signal in the w$^{\text{th}}$ symbol is delayed in time and frequency shifted version of the low pass prototype filter $p_T\,(n)$

$P_T\,(f)$ Is the Fourier Transform of $p_T\,(n)$

σ_x^2 is the variance of zero mean and uncorrelated input symbols.

$H(f)$ is the frequency response of the prototype filter.

In this study, to easily analyse and compare the PSD, algorithms based on the transmit-sides of FBMC with frequency spreading and OFDM without CP have been modelled and simulated over MATLAB, with a overlapping factor of K=4, number of carrier signals N=512 and 1024 and 4 bits per symbols (16QAM). The PSD of the transmit signals was simulated and plotted.

B. Prototype filter

One of the main abilities of the prototype filters is to enable pulse shaping to meet the desired spectral requirements. In OFDM, the prototype filter is designed using windowing method. Rectangular window prototype filter is used. As for FBMC, the design of the prototype filter is based on the frequency sampling method. It is a key point as the filter banks are conceived from the frequency-shifted version of the frequency response of the prototype filter. Prototype filter in FBMC meets Nyquist ISI criterion for the filter to be able to mitigate interference. [15] [16]

1. Nyquist ISI Criterion

Let *h(t)* be the filter's impulse response. The condition for ISI-free can be expressed as: [17]

$$h(nT) = \begin{cases} 1; for\ n = 0 \\ 0; for\ n \neq 0 \end{cases} \tag{6}$$

Where T is the symbol duration.

According to The Nyquist criterion, it is equivalent to:

$$1/T \sum_{k=-\infty}^{+\infty} H(f-k/T) = 1; \quad \forall f \tag{7}$$

Where *H(f)* is the Fourier transform of *h(t)*

Filters like Raise-cosine, Root-Raise-Cosine, Sinc filters and PHYDYAS prototype filters are able to satisfy the Nyquist ISI criterion. [18] [15] [16]In this study, for FBMC, PHYDYAS prototype filter has been used as it is more appropriate. The simulation over MATLAB of the magnitude response, phase response, impulse response, step response and the round-off noise of the prototype filters have been performed with overlapping factor K=4, number of subchannels N=16, roll-off factor $\alpha = 1$.

C. Computational complexity evaluation

The computational complexity evaluation is based on determining the number of multiplications and additions needed to compute a new length complex-valued output sequence. However, as the adders are cheaper to implement than multipliers, the analysis is focused on the number of real multiplications.

1. OFDM

Let N be the number of subcarriers and M the size of one symbol. Assuming M symbols are transmitted, the number of real multiplications of N-point FFT/IFFT for Fourier Transform (FFT) is: [12]

$$C_{FFT} = N\,(\log_2(N) - 3) + 4. \tag{8}$$

For an OFDM transmitter with Cyclic Prefix (CP), one IFFT block, including the windowing process, the number of real valued multiplications will be given as:

$$\begin{aligned} C_{OFDM} &= C_{FFT} + 4\,(N+N_{CP}) \\ &= [N\,(\log_2(N) - 3) + 4] + 4(N + N_{CP}) \end{aligned} \tag{9}$$

2. FBMC

For an FBMC with OQAM system where the length of the prototype filter is L_P . the transmitter consists of the phase shifting process, IFFT, polyphase filtering and overlapping operation by half symbol.

The number of real-valued multiplications is given as: [12]

$$\begin{aligned} C_{FBMC} &= 2\,C_{FFT} + 4\,L_P + 4\,M \\ &= [2N\,(\log_2(N) - 3) + 8] + 4\,L_P + 4\,M \end{aligned} \tag{10}$$

Complexity of FBMC is determined by the real multiplications needed for the filter banks at the transmitter and receiver, frequency shifting and IFFT/FFT operations and overlapping processes.

D. Latency

In OFDM, the latency is caused by serial to parallel (S/P) and parallel to serial (P/S) conversions as well as the addition of the CP. Let the sample duration $T_S = T/N$, with N being the number of subcarriers and T symbol duration. The latency from S/P and P/S is $NT_S = T$. Hence, the latency in OFDM system is: [12]

$$\tau_{OFDM} = T + T_{CP} \tag{11}$$

In FBMC, latency is caused by filters with latency $(L_p\text{-}1)T_S = KT$, where L_P=KN+1, the length of the prototype filters and K the overlapping factor. Using OQAM modulation with latency T/2 and S/P and P/S conversion pair with latency T, the total latency is given by:

$$\tau_{FBMC} = KT + T/2 + T = (K+1.5)T \tag{12}$$

The latency in FBMC system is higher than that of OFDM due to the additional signal processing from the transmutiplexer (OQAM processing and filter banks).

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E. Bandwidth efficiency

Let T_{QAM} be the total time spacing to transmit one QAM symbol and F_{QAM} the total frequency spacing to transmit one QAM symbol. The bandwidth efficiency will then be given as: [12]

$$\gamma = \frac{1}{\mathrm{TQAM.FQAM}} \quad (13)$$

For OFDM with CP, let T be the symbol duration. The subcarrier spacing $F_{QAM} = 1/T$ and $T_{QAM} = T + T_{CP}$ where T_{CP} is CP duration. The bandwidth efficiency then becomes:

$$\gamma = \frac{1}{(\mathrm{T} + \mathrm{Tcp}).1/\mathrm{T}} \quad (14)$$

While in FBMC, $F_{QAM} = 1/T$ and $T_{QAM} = T$. The bandwidth efficiency is given as:

$$\gamma = \frac{1}{(\mathrm{T}).1/\mathrm{T}} \quad (15)$$

The main differences of the two schemes are summarized in the table 1

Table 1: main differences between OFDM and FBMC

PROPERTY	OFDM	FBMC
CP Extension	Use of CP reduces bandwidth efficiency	CP needlessness improves the bandwidth efficiency
Prototype filter design	Rectangular windowing	Frequency sampling
Side lobes	Large side lobes	Low side lobes
Synchronization	Required strict synchronization at the receiver for correct detection and multiple access interference (MAI) cancellation	Good frequency localization of subcarriers, MAI is eliminated
MIMO compatibility	High flexibility in MIMO techniques	Flexibility is limited
Cognitive radio performance	Poor performance	Good performance
Computational complexity	Less complex	More complex
Latency	Lower latency	Higher latency, due to extra processing
PAPR	Higher	Lower

IV. Results and Analysis

Table 2: simulations parameters

Parameters	Values
Number of carrier signals	8, 16, 32, 52
Number of FFT points	512, 1024
Overlapping factors K	2, 3, 4
Modulation	QAM, 4QAM,16QAM

A. Subcarrier waveforms

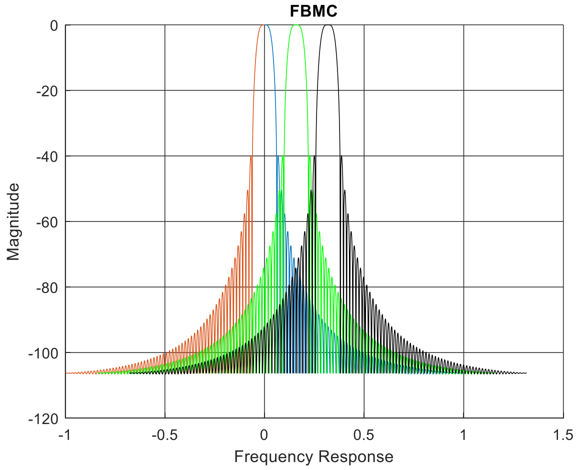

Fig 5: FBMC sub channels M=32 K=4

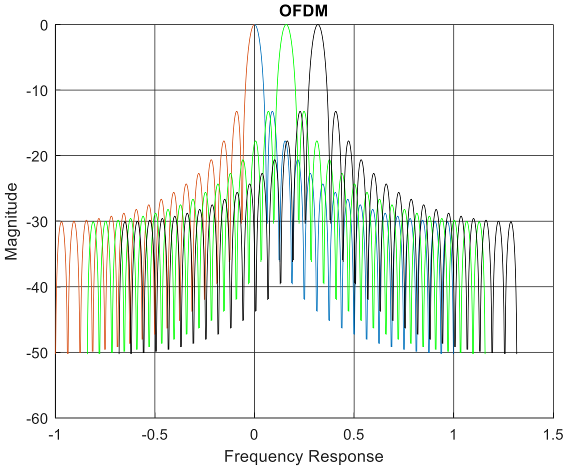

Fig 6: OFDM sub channels M=32, K=4

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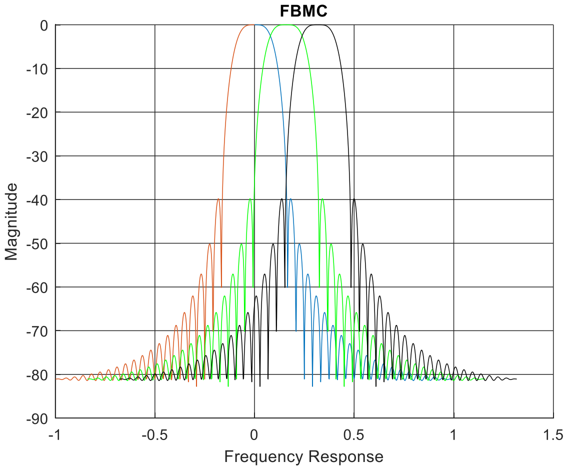

Fig 7: FBMC sub channels M=16 K=3

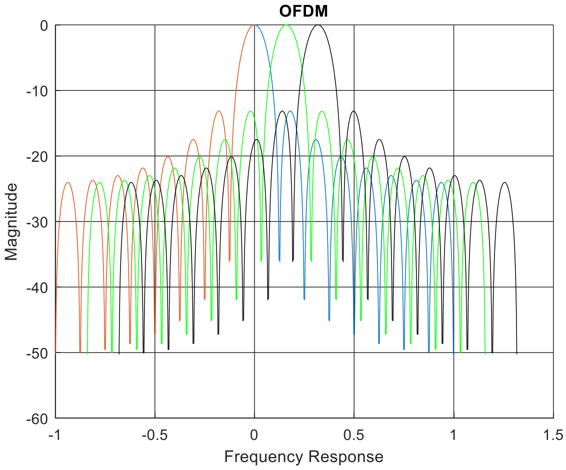

Fig 8: OFDM sub channels M=16 K=3

The Figures depict overlapping subcarriers of FBMC and OFDM with overlapping factor of K=4 and K=3

In figure5 and 7, the difference can be seen between the peak of the main lobes and that of the first side lobes with FBMC sub channels (-40 dB) greater compared to those with OFDM (-15 dB) in figure 6 and 8. Therefore, the side lobes affect more the main lobe in OFDM compare to FBMC resulting in waste of energy that decreases the spectral efficiency and increasing possibility of interferences and noise level in the receiver.

Actually, In FBMC each sub channel is filtered individually by well-shaped prototype filters. Hence, the waveforms of the subcarriers are well shaped and has very low side lobes compared to the case of OFDM where all the sub channels are filtered together through one prototype filter. The sub channels in FBMC have good spectral containment leading to resistance against the narrow band interference between them.

B. Power Spectral Density

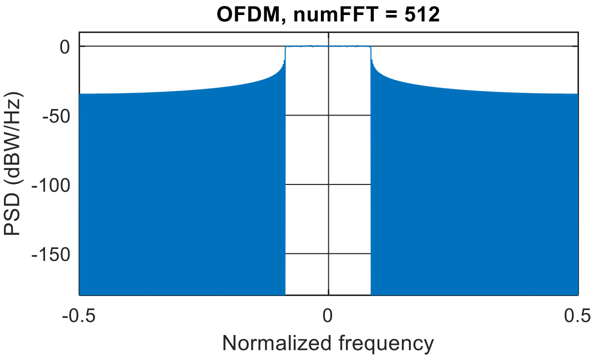

Fig 9: OFDM Power spectral density N=512, K=3

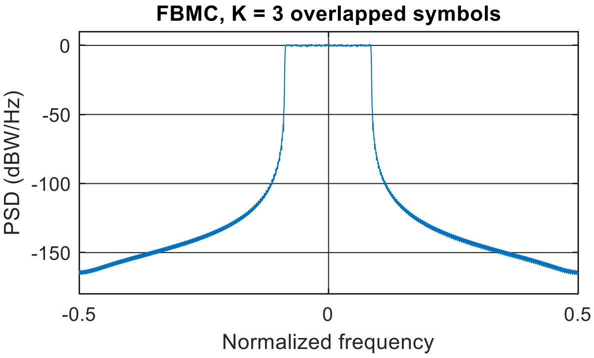

Fig 10: FBMC Power spectral density, N=512, K=3

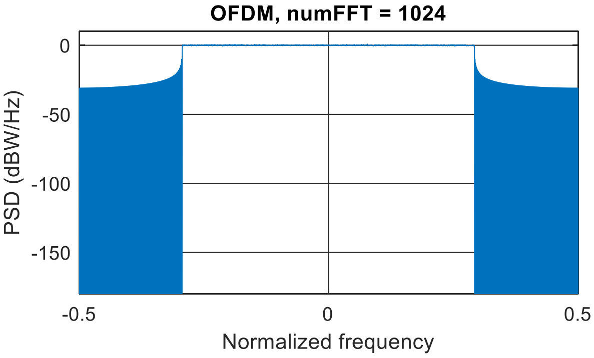

Fig 11: OFDM Power spectral density N=1024, K=4

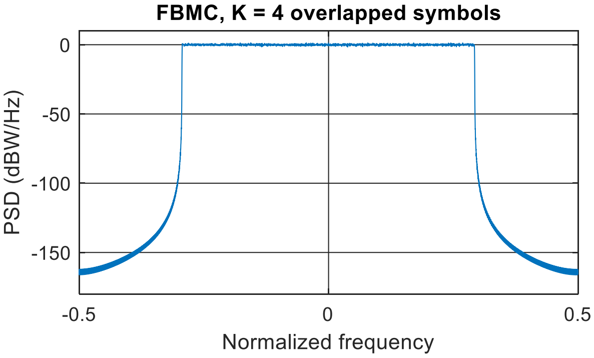

Fig 12: FBMC Power spectral density N=1024, K=4

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The figures depict the power spectral density of OFDM and FBMC respectively with the number of Fast Fourier Transform (FFT) points 512 and 1024 and the number of overlapping factor K= 4 and K=3.

In each case, the out-of-band emission (OOE) of the PSD with OFDM is higher (figure9 and 11) compared to that of FBMC (figure 10 and 12), resulting in high spectral leakage. This high spectral leakage is due to the fact that in OFDM, all the subcarriers are filtered together using a rectangular window filter, resulting in the production of high spectral leakage caused by the effect of windowing over the signal which is one of its main disadvantages. While in FBMC the subcarriers are filtered independently using a filter that satisfies the Nysquist ISI criterion, such as the Raise-cosine Filter.

Therefore, FBMC is more advantageous over OFDM by providing better spectral efficiency and energy optimization.

C. Prototype Filters

i. Magnitude response

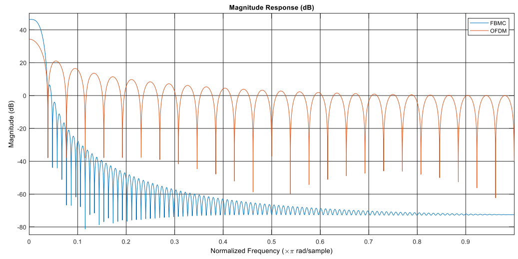

Fig 13: OFDM and FBMC magnitude response of prototype filters for M=52 K=4

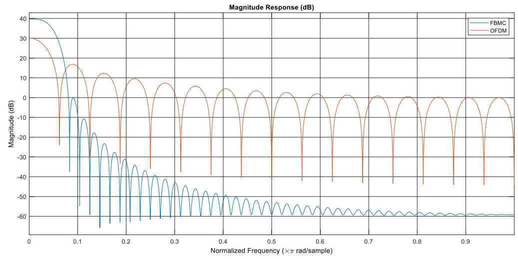

Fig 14: OFDM and FBMC magnitude response of prototype filters for M=32 K=3

The magnitude response of the prototype filters of OFDM and FBMC is plotted and compared versus the normalized frequency.

In the figure 13, the magnitude response for FBMC with k=4 denoted with the blue line decreases from a peak of 45 dB to about -38 dB at the normalized frequency of 0.05 $\pi.rad/sample$ and raises back to a peak of 5 dB to go down to about -42 dB at normalized frequency of 0.1 $\pi.rad/sample$ and follow the same process until the side lobe tail of FBMC decays completely at the normalized frequency of 0.98 $\pi.rad/sample$ while the magnitude response of OFDM denoted in red decreases from a peak of 35 dB to about -38 dB at the normalized frequency of 0.05 $\pi.rad/sample$ and raises back to a peak of 20 dB to go down to about -40 dB at normalized frequency of 0.1 $\pi.rad/sample$ and follows the same process.

In figure 14, the magnitude response for FBMC with k=3 and 32 sub channels. denoted in blue decreases from a peak of 40 dB to about -38 dB at the normalized frequency of 0.08 $\pi.rad/sample$ and raises back to a peak of 0 dB to go down to about -55 dB at normalized frequency of 0.1 $\pi.rad/sample$ and follow the same process until the side lobe tail of FBMC decays completely at the normalized frequency of 0.98 $\pi.rad/sample$. while the magnitude response of OFDM denoted in red decreases from a peak of 30 dB to about -22 dB at the normalized frequency of 0.08 $\pi.rad/sample$ and raises back to a peak of 18 dB to go down to about -30 dB at normalized frequency of 0.12 $\pi.rad/sample$ and follow the same process as in figure 13.

As seen in figures 13 and 14, the magnitude response of OFDM is lightly constant throughout the frequency, causing high Peak-Average-Power-Ratio (PAPR) while the magnitude response of FBMC reduces with the increase of frequency. In addition, there is a rapid deterioration across the sidebands or sub channels in the frequency response of FBMC system for each value of the overlapping factor K, which is not the case for that of OFDM. , meaning that there is a large isolation between the sub channels, which reduces ISI and ICI. Whilst with OFDM the isolation between sub channels is short increasing the likelihood of ICI or ISI.

The reason is that the prototype filter used in OFDM is a rectangular window filter providing waveforms shape that is more susceptible to ISI or ICI in comparison to that of OFDM using filter designed with Nyquist Pulse Shaping based on Nyquist ISI criterion, providing optimal localization in both time and frequency domain, reducing interferences between subcarriers and increasing spectral efficiency.

ii. Phase Response of the Prototype Filters

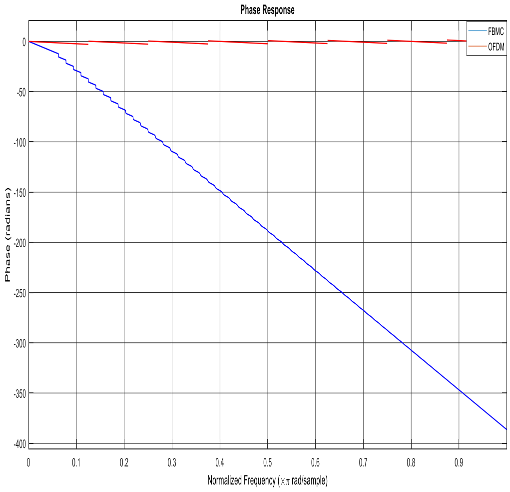

Fig 15: OFDM and FBMC Phase response of prototype filters for M=16 K=4

The figure15 shows the phase response with respect to the normalized frequency for FBMC and OFDM prototype filters.

Shown in red the phase response of OFDM prototype filter is constant throughout the normalized frequency sample range with a phase of 0 rad while the phase response of FBMC denoted in blue begins decaying at a phase of 0 rad for a normalized frequency of 0 π.rad/sample to -390 rad at a normalized frequency of 0.98 π.rad/sample.

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The phase response of the FBMC prototype filter is linear. The frequency components of the input signal are delayed to each other by the same fixed time. Resulting to no phase distortion. Then the shape of waveforms does not change or is not affected or distorted out of the filter. Making FBMC more reliable and efficient. The phase response of the OFDM prototype filter has zero phase for all frequencies.

iii. Impulse Response of Prototype Filters

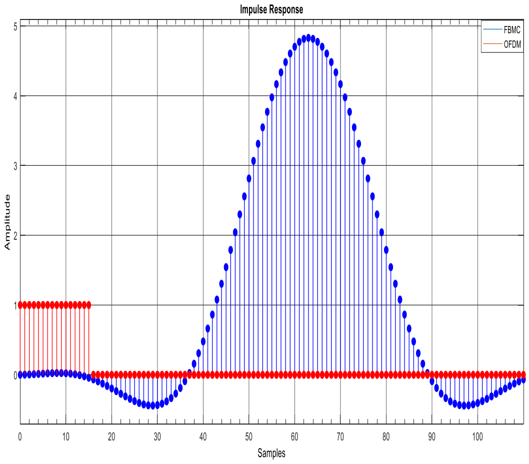

Fig 16: OFDM and FBMC Impulse response of prototype filters for M=16 K=4

The prototype filters impulse responses of FBMC and OFDM are shown in figure 16 with the number of subcarriers M=16 and overlapping factor K=4.

Depicted in blue is the impulse response of FBMC prototype filter where the amplitude varies with respect to frequency, while the one for OFDM in red is constant with respect to frequency.

The impulse response duration of the FBMC prototype filter is longer than that of OFDM and the out-of-band power leakage of FBMC is much lower than that of OFDM. Making FBMC more robust and resilient than OFDM regarding timing problems, delay spreads and frequency offset error.

iv. Step Response

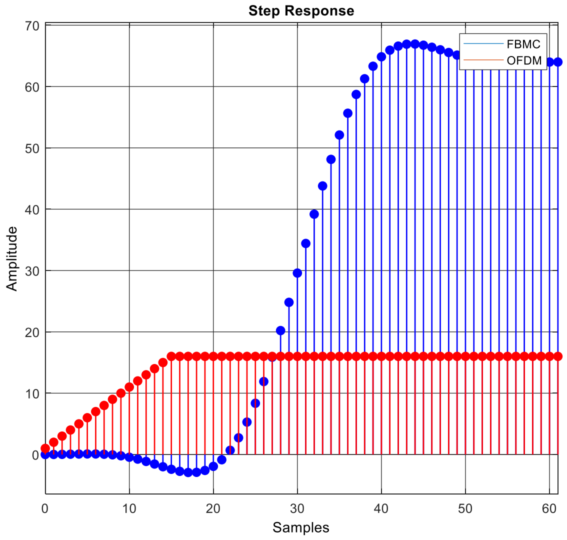

Fig 17: OFDM and FBMC Step response of prototype filters for M=16 K=4

The step response of the prototype filter of OFDM and FBMC is shown in figure 17. The amplitude of the step response of FBMC is varying with respect to frequency where that of OFDM is flat with respect to frequency.

v. Round off noise power spectrum

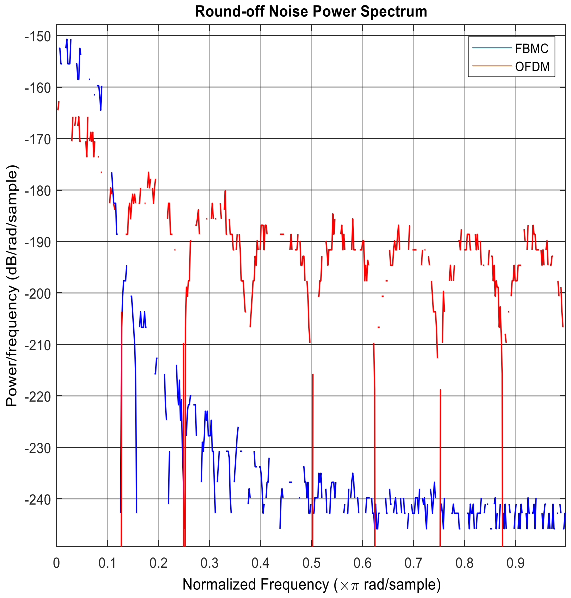

Fig 18: OFDM and FBMC Round-off Noise of prototype filters for M=16 K=4

As shown in figure 18, the Round off noise power for FBMC is high around -150 dB, -160 dB at the normalized frequency of around 0.1 π.rad/sample. It decays significantly to around -220 dB at a normalized frequency of 0.2 π.rad/sample and keep deteriorating till around -240dB at the normalized frequency of 0.98 π.rad/sample.

The round-off noise power for OFDM is around -170dB, -180dB at the normalized frequency of 0.1π.rad/sample. It begins decay to around -180 dB at frequency of 0.3 π.rad/sample and stays almost the same till normalized frequency of 0.98 π.rad/sample.

The noise power presents in the FBMC prototype filter reduces with the increase of frequency, while in OFDM it remains higher.The signals out of the FBMC prototype filter are not affected significantly by the noise making them well localized in frequency and reducing interference between them compared to those of OFDM where the noise is affecting signal more.

vi. Computational complexity

The computational complexity evaluation is based on determining the number of multiplications and additions needed to compute a new length complex-valued output sequence. However, as the adders are cheaper to implement than multipliers the analysis is focused on the number of real multiplications. Figure 19 shows the real multiplications of OFDM and FBMC. The complexity in FBMC highlighted in blue is higher than that of OFDM. The complexity increases with the increase of number of subchannels for both systems.

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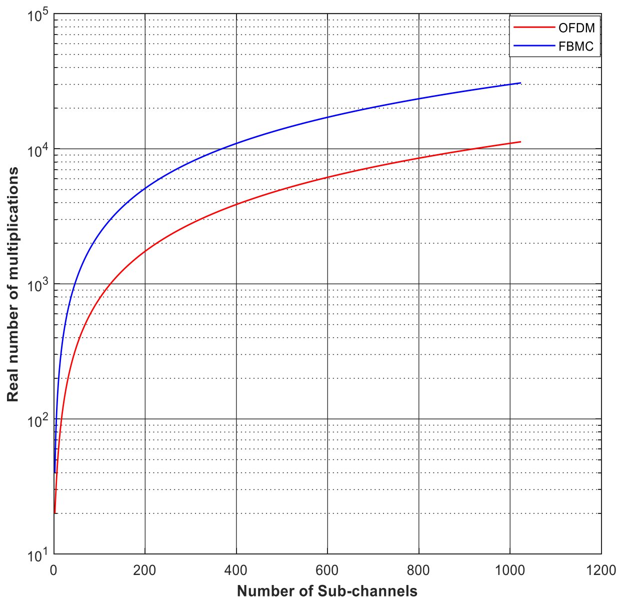

Fig 19: OFDM and FBMC Computational complexity

vii. Latency

From figure 20, the latency increases with the increase of the symbol duration for both schemes. In OFDM, the latency is caused by serial to parallel S/P and parallel to serial P/S conversions as well as the addition of the CP. The latency in FBMC system is higher compared to OFDM due to the additive signals processing such as OQAM modulation and filter banks.

It seems to be a disadvantage but this latency is able to meet the latency requirement of 5G network that is 1ms or less and many other new emerging technologies. The latency against symbol duration in OFDM and FBMC is computed below with K=4 as recommended for multicarrier systems offering better side band spectral attenuation characteristics and $T_{CP} = 5.2\ \mu s$.

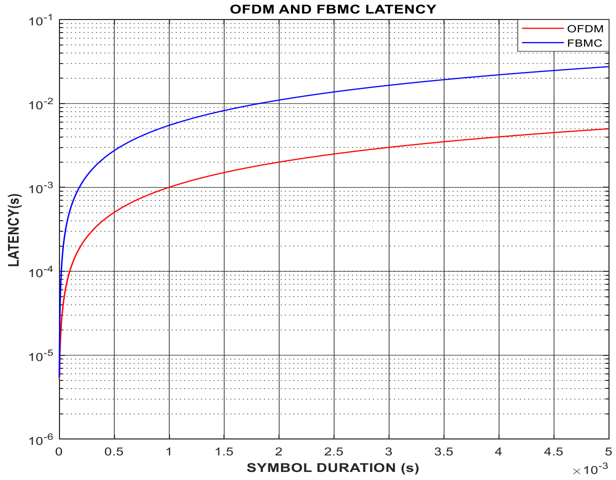

Fig 20: OFDM and FBMC Latency

V. CONCLUSION

The paper has presented the analysis and comparison of the performance of two multicarrier modulation techniques, OFDM and FBMC. The two schemes have been analyzed based on some parameters such as carrier signals waveforms, power spectral density of the transmit signal, the main characteristics of the prototype filters used, the computational complexity, latency and bandwidth efficiency. Simulations over MATLAB has been used as tools to compare some parameters and the results have proved that FBMC scheme is much better than OFDM in terms of power spectral density, showing lesser out-of-band leakage than OFDM, then bandwidth is used efficiently. In terms of carrier signals waveforms where the side lobes in FBMC decays faster than those of OFDM, reducing the likelihood of ISI or ICI. In terms of prototype filter used, the one used for FBMC is better than that of OFDM as it is well localized in frequency and time domains. The use of CP in OFDM reduces the bandwidth efficiency while in FBMC CP is needless. However, the computational complexity and latency in FBMC are higher than of OFDM systems. Though the delay is higher in FBMC, it is able to meet the round trip latency recommended in 5G network which 1 ms or less. Overall, FBMC overcomes the shortcomings of OFDM and outclasses OFDM. It is the multicarrier modulation technique for new digital communication technologies.

REFERENCES

[1] I.ESTELLA, A.ISERTE and M.PAYARO, "Ofdm and fbmc Performance Comparison for Multistream MIMO Systems," in *Future Network and Mobile-Summit 2010 Conference Proceedings Paul Cunningham and Miriam Cunningham (Eds)*, 2010.

[2] B. Farlang, "Cosine Modulated and Offset QAM Filter Bank Multicarrier Techniques: A Continuous-Time Prospect," *EUROSIP Journal Advances in Signal Processing,* vol. 2009, no. 3, pp. 1-16, 2009.

[3] H. Jamal and D. W. Matolak, "PAPR Analysis for Dual-Polarization FBMC," in *Milicom 2018 track 1 waveforms and signal processing*, 2018.

[4] M. Gopu and D. R. Khanna, "Multicarrier Modulation with OFDM for 4G Networks," *International Journal of Scientific and Research Pubkications,* vol. 2, 2012.

[5] B. Farhang-Boroujeny, "OFDM versus filter bank multicarrier," *IEEE SIGNAL PROCESSING MAGAZINE,* vol. 92, 2011.

[6] G. L. David, D. S. V.S, J. Chunkath and M. K.R, "Performance Analysis of Fast Convolution Based FBMC-OQAM System," in *International Conference on Communication Systems and Networks (ComNet)*, Trivandrum, 2016.

[7] P. Kansal and A. Shankhwar, "FBMC vs OFDM Waveforms Contenders for 5G Wireless Communication System," *Wireless Engineering and Technology,* vol. 8, no. 17, pp. 59-70, 2017.

[8] S. Kaur, K. Lavish, G. S. Gaba and N. Sarafov, "Survey of Filter Bank Multicarrier (FBMC) as an efficient waveform for 5G," *International Journal of Pure and Applied Mathematics,* vol. 118, p. 7, 2018.

[9] Q. He and A. Schmeink, "Comparison and evaluation between FBMC and OFDM systems," in *WSA 2015*, lmenau, 2015.

[10] s. A and A. H, "A Comparative Study of FBMC prototype Filters in Doubly Dispersive Channels," in *The 8th Broadband Wireless Access Workshop*, 2012.

[11] A. Bedoui and M. Et-tolba, "A Comparative Analysis of Filter Bank Multicarrier (FBMC) as 5G Multiplexing Technique," 2017.

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[12] S. Srivastava and O. Sahu, "On the Role of Overlapping Factor in FBMC-SMT Systems," *I.J. Image, Graphics and Signal Processing,* vol. 3, pp. 31-37, 2015.

[13] A. S. K. Dr, E. Sharma and P. Vig, "Performance Evaluation of oF DM and Prototype FBMC-OQAM Cognitive Radio under constraints of variable Overlapping factors," *International Journal Of Engineering Research And Development,* vol. 13, no. 9, pp. 71-91, 2017.

[14] T. Nguyen, M. Wuilpart, S. Le, P. Megret and L. V. C. Qinwei He, "Multicarrier Approaches for High-Baudrate Optical-Fiber Transmission Systems With a Single Coherent Receiver," *IEEE Photonics Journal,* vol. 9, no. 2, 2017.

[15] J. Tao, C. Da, N. Chunxing and Q. Daiming, OQAM/FBMC for Future Wireless Communications Principles, Technologies and Applications, Academic Press, 2017.

[16] M.-G. D. Benedetto, A. F. Cattoni, F. Jocelyn, B. Faouzi and L. D. Nardis, Cognitive Radio and Networking for Heterogeneous Wireless Networks, Springer International Publishing , 2014.

[17] A. Roychowdhury and P. P. Pandey, "FIR Filter Design Techniques," Bombay, 2012.

[18] A. J. Ramadhan, "Implementation of 5G FBMC PHYDYAS Prototype Filter," *International Journal of Applied Engineering Research,* vol. 12, no. 23, pp. 13476-13481, 2017.

[19] A. Kang and R. Vig, "Simulation Analysis of Prototype Filter Bank Multicarrier Cognitive Radio Under Different Performance Parameters," *Indonesian Journal of Electrical Engineering and Informatics (IJEEI),* vol. 3, no. 3, pp. 157-166, 2015.

[20] C. Kim, Y. H. Yun, K. Kim and J.-Y. Seol, "Introduction to QAM-FBMC: From Waveform Optimization to System Design," *IEEE Communications Magazine,* 2016.

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