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Optimizing Windowed Filters for Enhanced OFDM Performance in 5G Networks: A Comprehensive Analysis of PAPR, BER, and PSD

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Abstract: - Orthogonality for the frequency division multiplexing is the approach which is widely accepted for the current wireless communication, but as the technology is on the verge of moving in to the fifth generation wireless communication there are some limitations such as PAPR, PSD and BER of Orthogonal frequency division multiplexing which cannot be ignored for the fifth generation as promises the Massive machine communication, huge Reliability and minimum latency and extended mobile broadband, so to achieve above promises here in this proposed research work the filtering technique for the OFDM also in this research work specifies the importance of windowing techniques in the design of filters for Filtered Orthogonal Frequency Division Multiplexing. This is mainly by reducing Peak-to-Average Power Ratio and optimizing Bit Error Rate to minimize Out-of-Band Emissions, which contributes to enhancing spectral containment properties, thus reducing inter-system interferences in the field of communication systems. This study elucidates the principles of windowing and application in f-OFDM to offer immediate insight into how filters are designed under optimal capacity for high system efficiency. The use of windowing in simulations has proven effective in enhancing the filter design process, and demonstrates the future of the evolution of digital communications systems ,the waveform by means of various windowing methods considering the parameters Power spectral density, Bit error rate and PAPR, simulation results shows that the nuttall's blackman-harris, kaiser & root raised cosine windowed filter function are best suitable for the filtering the OFDM signal to improve the spectral efficiency, BER.

Keywords: windowed methods, fifth generation, mMTC, filtered OFDM, RRC window, eMBB, kaiser window, URLLC, Nuttall’s blackman-harris window.

I. Introduction

Upcoming next generation wireless communication systems are evolved era following the current long-term evaluation standard of 4G LTE. As there are lots of expectations such as Massive machine communication (mMTC), Ultra Reliability and low latency (URLLC) and Enhanced mobile broadband (eMBB) in almost every sector not limited to mobile communications systems, but needs to cover transportation, medical, pharmaceutical different industries, high speed vehicles, and different manufacturers these industries will require great demand for wireless services, Sending video wirelessly, real time content delivery and also ample number of wireless services. IoT-based services is prime driver of competition for fifth-generation technologies. To achieve these key goals, demands and promises next-generation technologies provide high-speed broadband, very huge reliable connectivity, and minimum latency while minimizing communication latency we need to modify the current communication system to increase data rate and spectral efficiency. To upgrade the fourth-generation mobile communication channel models, amplification devices, modulation schemes, encoding and decoding algorithm all need to be developed and designed to achieve the high standards of 5G, following that new radio waveform has been proposed to ameliorate spectral efficiency by suppressing out-of-band radiation: Filtered OFDM (F-OFDM) was suggested by the 3GGP.

Orthogonal Frequency Division Multiplexing is a fundamental technology underpinning many wireless communications that allows high rates of data to be transmitted by chopping the channel into a few equally spaced frequency bands. The OFDM filter is critical to the proper functioning of the system since it aids in upholding the signal’s accuracy and minimizing cross-talk between the channels. OFDM has received a lot of notices in current wireless space standards divisions since it can handle harsh channels without the requirement for a complicated filter of the equalizer. It is a specialized form of frequency division multiplexing FDM [1], and it has carrier frequencies separated by the spacing such that the subchannels are orthogonal to each other. The OFDM system’s orthogonality is essential to its performance because it minimizes the effect of cross-talk between the points and guarantees that no crosstalk occurs between the carriers. This property is maintained in the OFDM structure using an ideal OFDM filter, a filter that distinguishes subchannels from one other during reading and transmission [2]. There are some benefits of OFDM: Spectral efficiency is high. Frequency selective turns fading it is necessary but simpler in the frequency side, resource allocation such as power and subcarriers. The signals are shaped by the

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OFDM filter before they are transmitted, and they are received with minimal distortion because it reduces the out of band emissions by ensuring that it keeps it to his minimal level; this is significant because the out-of-band emission does not disturb the process of other channels [3].

An ideal OFDM filter should have:

(1) Sharp roll-off characteristics.

(2) The passband must be as flat as possible, with little group delay variation.

(3) High stopband attenuation.

The design of the OFDM filter is a critical parameter when considering system performance. Bad design of the filter can lead to inter-symbol interference and inter-carrier interference, both of which can cause received signal degradation to an unacceptable level. The implementation of an ideal OFDM filter requires the use of some Digital Signal Processing techniques. The primary approach involves the use of FIR and IIR filters. These filters are explicitly designed to have characteristics that closely resemble the ideal filter, some of the factors that must be considered include: 1. Transition width determines how quickly the filter moves from passband to stopband. 2. Group delay which should be uniform in the passband to prevent signal distortion. 3. Computational complexity is an integral part as it contributes to the filter's processing power and effectiveness. Nevertheless, designing the ideal OFDM filter can be a challenging [4], even with all the considerations taken into account. Some of the issues that must be considered include: 1. Spectral leakage: a condition where the energy from one subcarrier spills to the adjacent subcarriers. This phenomenon causes intercarrier interference. 2. Nonlinear effects, including resource extraction techniques: these effects can distort the quality of the signal both at the transmitter and the receiver. 3. Timing and frequency offsets represent the imperfections in the receiver, which might compromise the orthogonality of the various subcarriers [5].

Filtered Orthogonal Frequency Division Multiplexing as a waveform for 5G communication systems is investigational because of the present of numerous challenges that need to be addressed. Although F-OFDM has many different parameters that are in need of performance enhancement, the focus of this research work will be limited to three: Peak-to-Average Power Ratio, Bit Error Rate, and Out-of-Band Emission. This set of parameters was selected not randomly, but because F-OFDM is known to have a very high PAPR, which consequently leads to an increase of distortion and, as a result, an increase of BER. Although there are a lot of techniques nowadays that are used to overcome that – for instance, Partial Transmit Sequence [6], BCH codes [7], the concatenated scheme of error correction codes [8] and companding , following four have demonstrated most effective results.

Filtered Orthogonal Frequency Division Multiplexing is an accelerated technique to improve the current OFDM system by incorporating filter processes. Moreover, the Filter Bank Multicarrier systems with Offset Quadrature Amplitude Modulation to develop sharp pulse shaping filters established OOB radiation that is decreased over that of orthodox CP-OFDM [9]. The Universal Filtered Multicarrier system operation advances the filtered OFDM and FBMC performance while maintaining enhanced interference mitigation and retained spectral containment [10]. Shifting to future multicarrier systems is leading to the development of new modulation schemes beyond OFDM, including FBMC, Generalized Frequency Division Multiplexing, UFMC, and Filtered OFDM [11]. Therefore, the objective of the ident novelty is to propose the development priority of prototype filter design from it. Moreover, the attempt at developing low-complexity UFMC transmitters is also addressed [12]. Thus, filtered OFDM provides more spectral containment, interference mitigation, and network performance than traditional OFDM schemes. Furthermore, filtered OFDM, which combines filter mechanisms with current modulation, develops more resilient and effective communication systems for the wireless network of future.

II. F-OFDM/OFDM SYSTEM MODEL

Orthogonal Frequency Division Multiplexing and its modified version Orthogonal FDMA and Single Carrier FDMA are in the current 4G LTE architecture and it is a type of signal format that uses an enormous number of intently spaced carriers, each modulated by a slow data flow. However, the main limitation of this technique is that, despite some advantages, it has high sidelobes and stringent synchronization requirements that reduce spectral efficiency. Therefore, new modulation techniques for next generation communication systems are being considered to overcome some of these components. Main focus for us in terms of 5G is that the excellent spectrum localization carrying the advantages of OFDM, Filtered OFDM supports dynamic configuration, enabling mixed-service applications and a variety of deployment scenarios. Each sub band can provide its individual application or formation with significantly minimal interaction [13]. OFDM filtered waveforms can be effortlessly adjusted to support radio access network slices, providing an efficient design within the carrier band. Keeping the orthogonality of composite domains within the sub band as an Orthogonal Frequency Division Multiplexed waveform, allowing us to take over all the benefits of Orthogonal Frequency Division Multiplexing and reiterate all OFDM design component schemes. Waveform orthogonality makes MIMO and Massive MIMO significantly more compatible with succeeding high-end industries. Filtered OFDM has excellent out-of-band emission suppression, which enables extremely high spectral utilization.

An effective filter for f-OFDM must be designed using various windowing techniques. A windowing technique implies choosing the appropriate windowing function and applying it to the signal. There are various types of window functions and each has its features and areas of application. The chosen window function affects the stopbands attenuation and the main lobe size. For f-OFDM systems [14], the window function is determined by the desired trade-off between the level of side lobes and frequency localization. After selecting the windowing function, we have applied the windowing technique. This includes working with window functions that must be added to the filter's impulse response [15]. The negative consequence of windowing is the trade-off – the main lobe becomes wider and the side lobes are lower for the first case. In contrast, in the second instance, the side lobes become wider and the main lobe is lower.

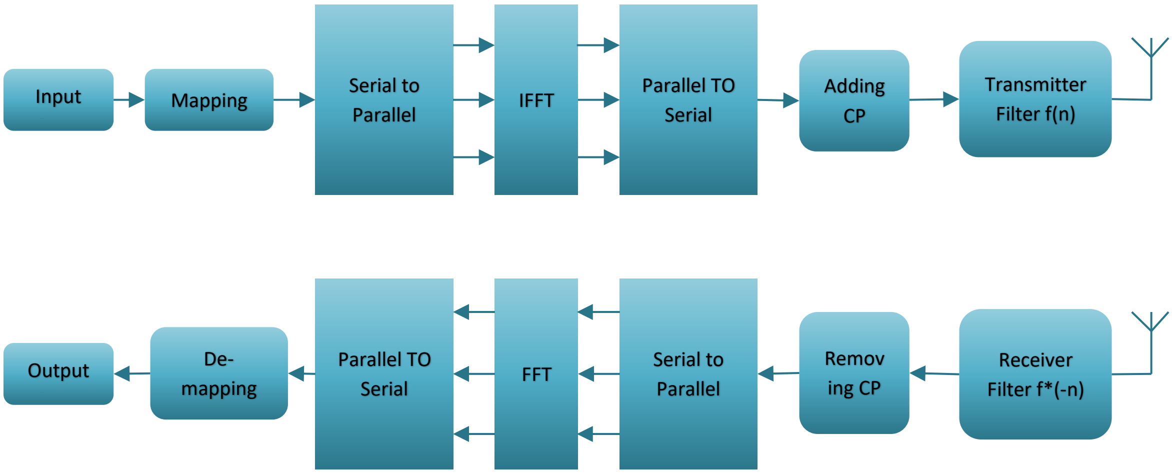

Figure 1. Filtered OFDM Simplified Block Diagram

III. OFDM IMPLEMENTATION

Considering the fourth generation LTE standard for OFDM structure as shown in above figure we have implemented for the 256 QAM modulation, 2048 Fast Fourier Transform size, with 2000 subcarriers taken as reference over the ideal AWGN channel with ideal 18 dB of Signal to Noise ratio, with those parameters consideration we implemented OFDM waveform and results are follows:

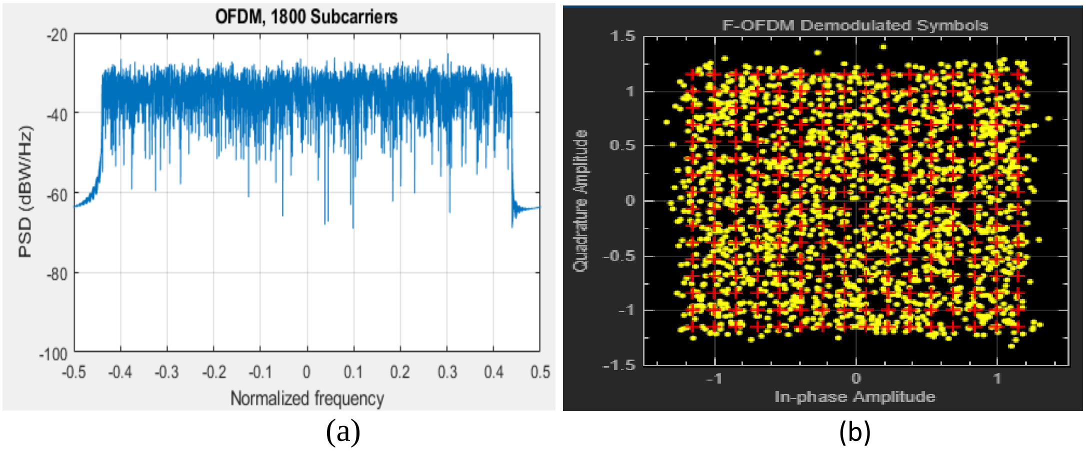

Figure 2. (a) OFDM Power Spectral Density for 1800 Subcarrier System, (b) OFDM Constellation diagram

From the above results, according to the constellation diagram in which 256 points are quietly scattered, there is a great deal of room for further improvement in removing out-of-band radiation, increasing spectral density, and also reducing BER. To meet the 5G standards in existing scheme here in this article divided the signal generated after FFT and IFFT in to number of resource blocks and these resource blocks output will be applied to windowing-based filter to achieve sharp transition, Passband flat characteristics and High out-of-band suppression. In this research work windowed sinc filtering technique is used as it is very stable and also performance of the filter can be easily changed with minor change in windowed function application, one can easily increase the computational speed by varying the FFT order. Further in the article various windowed filtering techniques have been applied to Orthogonal Frequency Division Multiplexed signal and results are compared in terms of PAPR [16], PSD and BER.

TABLE 1. Simulation Parameters

F-OFDM specifications	Values
Multi-carrier modulation schemes	OFDM, F-OFDM
F-OFDM IFFT/FFT length	2048
Sampling rate	40 MHz
Modulation	256-QAM
Frequency Band	0.45-6 GHz and 24-52.6 GHz
CP size	(1/64)* 4096 samples
Number of Active subcarriers	1156 (Total 1800 subcarrier)
Filter order	512
Subcarrier spacing	60 kHz
Channel type	multi-path channel with AWGN
F-OFDM symbol duration	16.67 µs
CP duration	1.17 µs
F-OFDM symbol duration with CP	17.84 us
fc	6 GHz
Bandwidth	120 MHz

In this research work implementation of seven windowed functions for filtering purpose and simulation results are analyzed and compared as follows:

i) Rectangle Window:

By applying Rectangular Windowed function ideally is of no window function, the results are as follows:

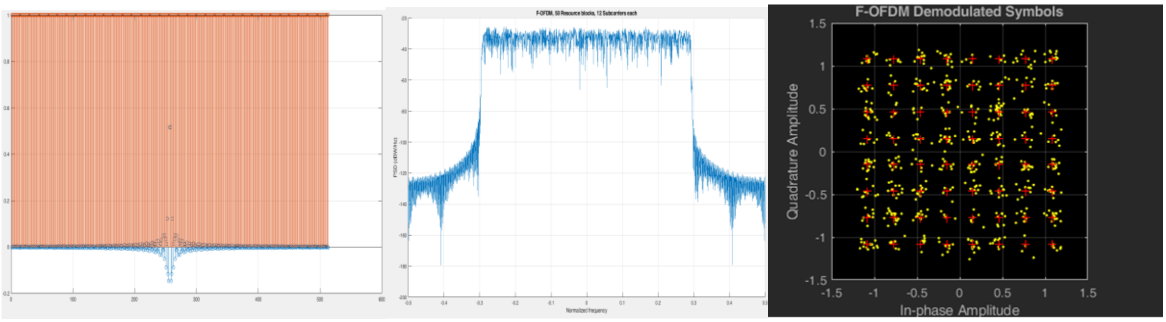

Figure 3. Windowed Filter, PSD plot and Constellation Diagram of F-OFDM by Rectangle window

ii) Triangle Window:

By applying Triangular Windowed function following results have been achieved

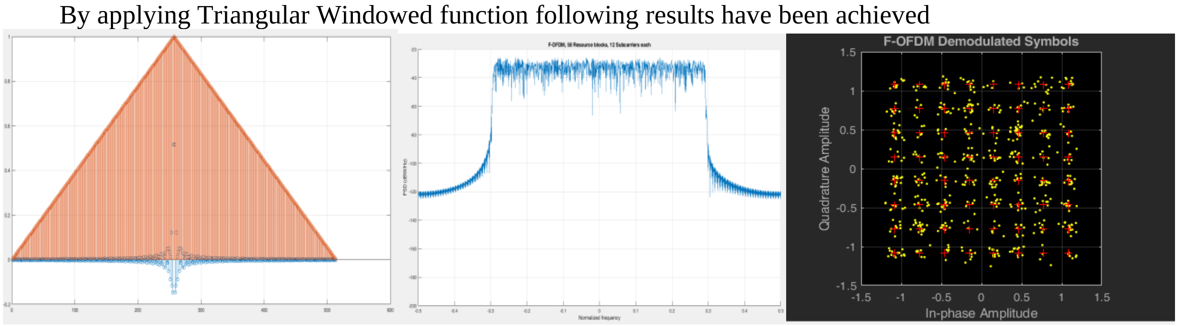

Figure 4. Windowed Filter, PSD plot and Constellation Diagram of F-OFDM by Triangle window

iii) Bartlett window:

By applying Bartlett Windowed function following results have been achieved

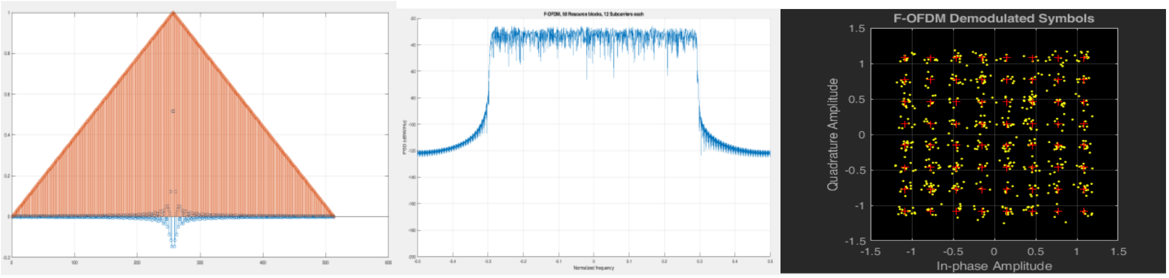

Figure 5. Windowed Filter, PSD plot and Constellation Diagram of F-OFDM by Bartlett window

iv) Hanning Window:

By applying Hanning Windowed function following results have been achieved

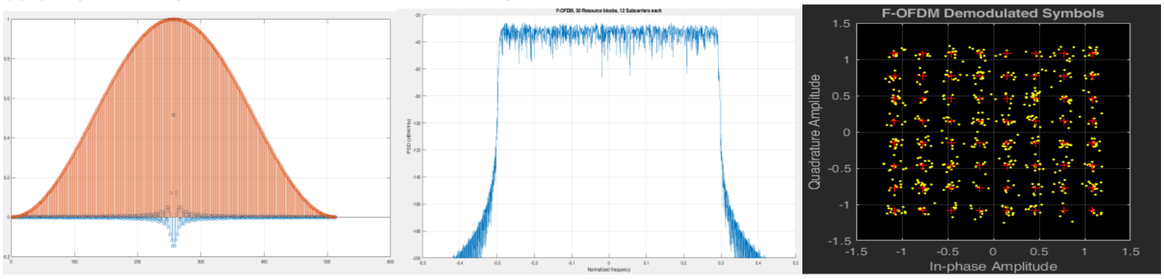

Figure 6. Windowed Filter, PSD plot and Constellation Diagram of F-OFDM by Hanning window

v) Kaiser Window:

By applying Kaiser Windowed function following results have been achieved

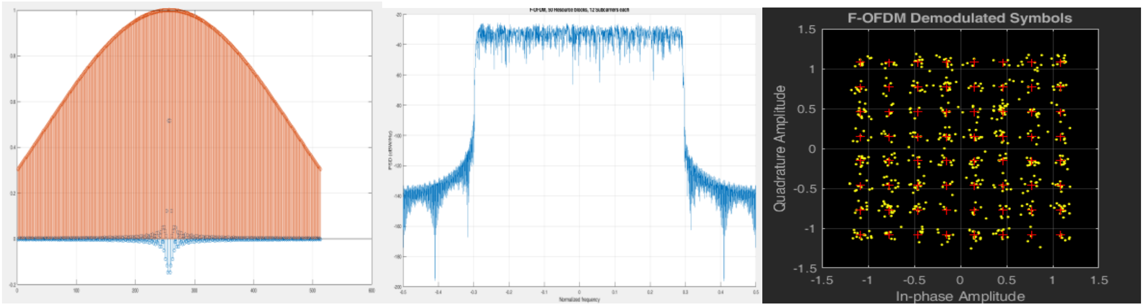

Figure 7. Windowed Filter, PSD plot and Constellation Diagram of F-OFDM by Kaiser window

vi) Nuttall's Blackman-Harris Window:

By applying Nuttall's Blackman-Harris Windowed function following results have been achieved

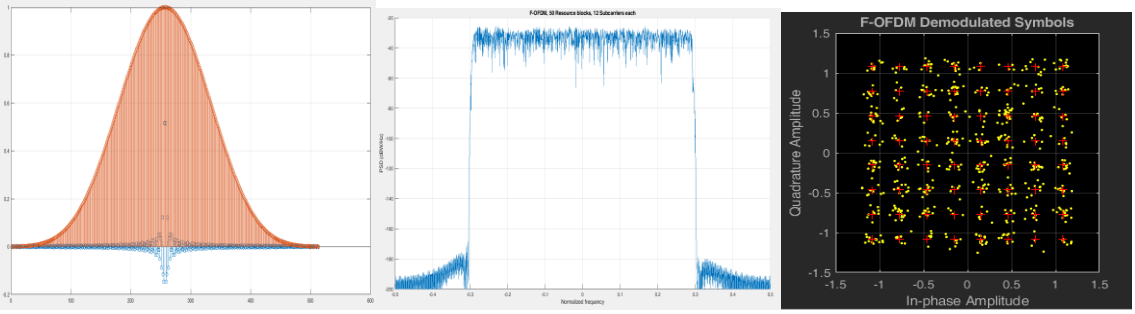

Figure 8. Windowed Filter, PSD plot and Constellation Diagram of F-OFDM by Nuttall's Blackman-Harris window

vii) RRC Window

By applying Nuttall's Blackman-Harris Windowed function following results have been achieved

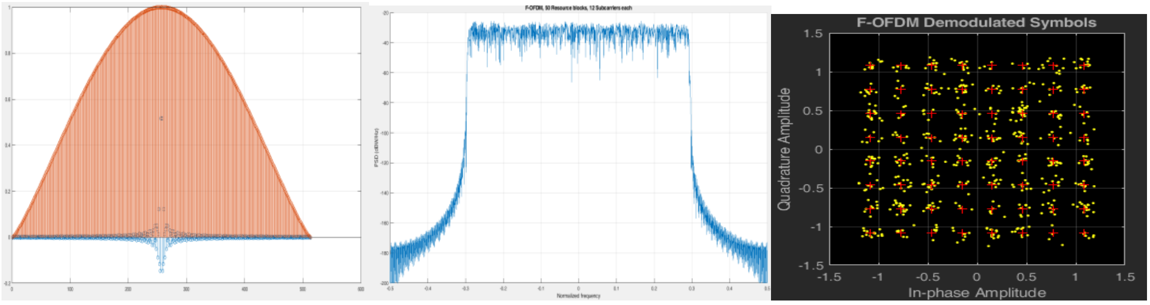

Figure 9. Windowed Filter, PSD plot and Constellation Diagram of F-OFDM by RRC window

IV. COMPARATIVE ANALYSIS OF VARIOUS FILTERS

Based on the simulation results as shown above comparing the different window functions for the various parameters like BER, PAPR and PSD individually. To find ideal filter for filtered OFDM we have analyzed the performance of those window functions, first consideration here is for the power spectral density, to design the filtered OFDM to meet the ideal characteristics filter response should have minimum leakage factor, minimum sideload attenuation and comparatively acceptable main lobe within 3dB down bandwidth, as shown in below Table:2 to achieve the required characteristics kaiser, Nuttall's Blackman Harris and RRC Window shows excellent attenuation to sidelobes compared to other windows also the leakage factor is also acceptable for those three window function, to meet the ideal characteristics kaiser, NBH, and RRC Window can be recommended for further design criteria.

Table 2. Filter Response

Sr. No.	Filter	Leakage Factor	Comparative Sidelobe attenuation	Main lobe width (-3dB)
1	Rectangle Window	9.42%	-13.3 dB	0.003418
2	Triangle Window	0.29%	-26.5 dB	0.004882
3	Bartlett Window	0.29%	-26.5 dB	0.004882
4	Hanning Window	0.14%	-30.0 dB	0.004638
5	Kaiser Window	0.05%	-31.5 dB	0.005615
6	Nuttall's Blackman Harris Window	0.03 %	-98.1dB	0.007080
7	RRC Window	0.02%	-98.1 dB	0.007080

Another comparative analysis of the window functions was also evaluated based on the transition characteristics results shown here below in the Table: 2 that NBH and RRC Window gives sharp transition, flat passband and very high out of band rejection.

Table 3: Filter Transition characteristics

Sr. No.	Filter	Transition	Pass band Characteristic	Out of Band Rejection
1	Rectangle Window	Gradual	Inflate	Very low
2	Triangle Window	Gradual	Inflate	Low
3	Bartlett Window	Gradual	Flat	Low
4	Hanning Window	Sharp	Flat	Low
5	Kaiser Window	Gradual	Flat	High
6	Nuttall's Blackman Harris Window	Very Sharp	Ext. Flat	High
7	RRC Window	Very Sharp	Ext. Flat	Very High

In this research work BER was also evaluated based on the simulation results of the seven windowed function as shown in section IV, below Table:3 shows the comparison that apart from rectangular window almost all the filter gives comparatively good Bit Error Rate at fixed SNR at 18dB, also we special mention is that Nuttall's Blackman Harris window gives very good results in terms of BER compared to other windows here further scope of research is also there by varying the SNR.

Table 4: BER Comparison

Sr. No.	Filter	BER at SNR=18dB
1	Rectangle Window	$1.2x10^{-3}$
2	Triangle Window	$8.25x10^{-4}$
3	Bartlett Window	$8.34x10^{-4}$
4	Hanning Window	$5.54x10^{-4}$
5	Kaiser Window	$5.84x10^{-4}$
6	Nuttall's Blackman Harris Window	$4.45x10^{-4}$
7	RRC Window	$5.53x10^{-4}$

Increased PAPR is a major disadvantage is a superposition of several independent orthogonal subcarriers through an IFFT process. Considering the 4G LTE standard as shown in section III, implementation of OFDM gives us the PAPR value 9.721 dB for fixed SNR now in this article implementation is done for the various window filter to analyze the performance based on PAPR as the filtering process will further increases the PAPR as shown below in Table: 4 to all the filers some techniques can be implemented to reduce the PAPR after applying the filter to OFDM.

Table 5: PAPR Comparison

Sr. No.	Filter	PAPR
1	Rectangle Window	11.3716 dB
2	Triangle Window	11.3652 dB
3	Bartlett Window	11.3649 dB
4	Hanning Window	11.3715 dB
5	Kaiser Window	11.3713 dB
6	Nuttall's Blackman Harris Window	11.3737 dB
7	RRC Window	11.3711 dB

V. CONCLUSION

Through this research work of windowing technique on the filters, f-OFDM realizes better spectral containment, which improves the interference aspect, making it suitable for next-generation networks. Notably, the windowing technique is central in the design of filters in f-OFDM because it ensures the assembly of better filters that optimize the spectrum utility aspect by minimizing out-of-band emissions. Even as technological advancements evolve communication landscapes, the application of windowing in filter design shall continue to be influential, shaping the future of digital communications. Target of this research work is to find the ideal filter for Orthogonal frequency division multiplexing so to lead towards the accomplishment for 5G standards, here in this research work based on simulation results it is very much clear that Kaiser, Nutella’s Blackman Harris window & Root Raised Cosine window function filter gives the nearly ideal results what required for further design.

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