Optimal Filter Selection for MIMO F-OFDM Systems in 5G Wireless Communication

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Abstract — Strong demand for mobile broadband cellular systems has boosted the popularity of emerging high-speed modulation technologies such as multiple input multiple output (MIMO) and cyclic prefix orthogonal frequency division multiplexing (CP-OFDM). However, CP-OFDM suffers from some significant drawbacks in 5G networks, including severe out-of-band emissions (OOBE) and poor spectral efficiency. Filtered orthogonal frequency division multiplexing (F-OFDM) has therefore been found to be a good alternative, as it allows to address these shortcomings by relying on digital filtering to eliminate OOBE and improve spectral efficiency. This study focuses on evaluating the performance of MIMO F-OFDM systems and comparing it with the results achieved by MIMO CP-OFDM, with a particular emphasis placed on reducing spectral leakage and improving overall system performance by using various window functions. Six window types, including Hanning, Hamming, Blackman, root raised cosine (RRC), Nuttall, and Blackman-Harris, are investigated. The research aimed to assess the performance of the system in terms of power spectral density (PSD), peak-to-average power ratio (PAPR), and bit error rate (BER), while using different modulation schemes, i.e. QPSK, 16QAM, 64QAM, and 256QAM, over Rayleigh fading and AWGN channels. Simulation results show that the proposed window filter (Nuttall-Blackman-Hanning) significantly reduces OOBE while maintaining efficient spectral performance. The findings demonstrate that MIMO F-OFDM with the proposed filters achieves better spectral efficiency and reliability, making it a promising candidate for 5G applications requiring high data rates, low latency, and robust signal integrity.

Keywords — 5G, BER, CP-OFDM, F-OFDM, MIMO, PAPR, PSD

1. Introduction

Rapid development of 5G wireless communication systems has resulted in a pressing need for higher data rates, enhanced spectral efficiency, and low latency to support a wide range of applications. These applications include enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC) [1], [2]. As demand for reliable and high-speed communication continues to increase, existing technologies used in previous generation solutions, such as cyclic prefix orthogonal frequency division multiplexing (CP-OFDM), face significant challenges in meeting the stringent requirements of 5G networks.

CP-OFDM, which has been successfully utilized in 4G LTE systems, is well known for its simplicity and effectiveness in managing channel properties [3], [4]. However, its limitations, such as high OOBE and inefficient spectral utilization, hinder its suitability for the demanding environment of 5G. These drawbacks result in interference with adjacent frequency bands, reducing overall system performance and spectral efficiency [5]–[8]. To address these challenges, various alternative waveform techniques have been proposed for 5G, including filter bank multi-carrier (FBMC) and generalized frequency division multiplexing (GFDM), each aiming to optimize spectral efficiency and reduce OOBE [9]–[12]. However, these techniques often suffer from increased system complexity and additional computational overhead.

One promising alternative to CP-OFDM is filtered orthogonal frequency division multiplexing (F-OFDM), which improves spectral efficiency by applying digital filters to reduce OOBE while maintaining the core advantages of CP-OFDM, such as its robustness against multipath fading and ability to manage high data rates. F-OFDM has emerged as a practical solution, particularly for asynchronous transmission scenarios, making it highly compatible with 5G requirements [13]–[15].

Despite their advantages, performance of F-OFDM systems depends heavily on the design of the filter applied. Specifically, the selection of window functions plays a critical role in reducing OOBE and optimizing system efficiency. Previous studies have typically focused on individual window functions such as Hanning, Hamming, and root raised cosine (RRC). However, there is a need for a more systematic evaluation of different window designs to identify the most effective filter for F-OFDM in 5G applications.

1.1. Research Problem and Objective

This study addresses the gap that exists in current research by systematically evaluating the performance of F-OFDM systems in multiple input multiple output (MIMO) setups, using six different window functions: Hanning, Hamming, Blackman, RRC, Nuttall, and Blackman-Harris. The primary aim of the research is to identify the optimal window function or combination of window functions that minimizes OOBE and enhances overall spectral efficiency, while also analyzing the impact on key performance metrics such as power spectral density (PSD), peak-to-average power ratio (PAPR) and bit error rate (BER). The study further explores how these filters perform under different modulation schemes and channel conditions, specifically in additive white Gaussian noise (AWGN) and Rayleigh fading environments.

By addressing these issues, the research seeks to provide a comprehensive solution to improve spectral efficiency and reliability of F-OFDM systems – properties which are critical for the successful deployment of 5G networks in real-world scenarios such as urban environments, Internet of Things (IoT) applications and high-speed vehicular communications.

Additionally, this study aims to contribute to the ongoing development of filtering techniques that could be essential not only for 5G, but also for future 6G networks.

Compared to traditional MIMO CP-OFDM systems, the proposed MIMO F-OFDM architecture with optimized window filters demonstrates superior performance in terms of OOBE reduction and BER, under various channel conditions. This validates its potential as a robust solution for advanced wireless communication scenarios.

The subsequent sections of this work are organized as follows. Section 2 examines the relevant literature that specifically addresses F-OFDM solutions used in wireless communication systems. Section 3 introduces the F-OFDM-MIMO system model and delineates the process of shaping the symbol spectrum. Within the F-OFDM system, the window function is used to truncate the sinc function for the purpose of constructing the filter. The analysis and discussion of the simulation findings are presented in Section 4. Finally, the document is concluded in Section 5 which summarizes key results and provides insights into future research directions.

2. Related Work

Taking into account previous discussions, the design of the filter needs to be approached in a way that avoids adding unnecessary complexity or delays to the system. Furthermore, the filter-based waveform must meet the requirements of 5G solutions. CP-OFDM utilizes a sinc function-based filter in the frequency domain, which tends to exhibit high side lobes, and thus negatively affects system performance. A feasible filter that can be directly implemented within the system is the truncated-sinc filter, which is created by windowing the sinc function with a suitably selected window [16]. Consequently, F-OFDM based on the windowed-sinc filter has been shown to surpass CP-OFDM in terms of performance.

The authors of [17] performed a benchmark study to compare the performance of windowed orthogonal frequency division multiplexing (W-OFDM) and F-OFDM. Their findings concluded that F-OFDM offers a better reduction of OOBE and is suitable for asynchronous communication, particularly when using higher-order modulation methods. Furthermore, [18] provide a concise overview of the performance of F-OFDM while employing MIMO setups, such as SIMO and MISO, together with several digital modulation methods. Across various settings, the results showed that MIMO F-OFDM improves system performance.

In [15], the effect of neighboring signal interference on MIMO systems was evaluated by employing F-OFDM and CP-OFDM modulation techniques. Using different detection strategies and BER calculations, the simulations conducted in the course of the study revealed that F-OFDM outperforms CP-OFDM as far as the management of interference is concerned.

Paper [19] extended this work by comparing the performance of CP-OFDM, W-OFDM, and F-OFDM under Rayleigh fading conditions. Its results confirmed that F-OFDM offers better spectral efficiency and overall performance than its counterparts.

The authors of [20] proposed a generic function model to design window functions with high energy concentration and rapid attenuation of the side lobes. Their analysis suggested that optimized window functions reduce OOBE while maintaining nearly the same BER as achieved by traditional window filters. The effectiveness of MIMO systems combined with CP-OFDM and F-OFDM was further explored in [21], where performance was analyzed while using various digital modulation techniques and windowed filters (Hanning, Hamming, Blackman, RRC). The simulations showed that the Hanning filter was robust and efficient in signal recovery.

Paper [22] provides an experimental study on F-OFDM using different windowed-sinc filters, both equal and unequal in sub-band sizes. Its results indicated that F-OFDM, compared to traditional CP-OFDM, not only achieves a lower OOBE but also improves spectrum efficiency by 5–6%.

The authors of [23] investigated the performance of MIMO-OFDM systems within 5G networks, incorporating advanced modulation schemes. They evaluated critical performance metrics including throughput, BER, and spectral efficiency. The findings revealed that while higher-order modulation schemes substantially enhance throughput and spectral efficiency, they also lead to increased BER, especially at lower SNR levels.

In essence, while previous studies have focused on optimizing individual window functions or exploring specific modulation techniques, the present study contributes by systematically evaluating six different window designs and analyzing their effects across key performance metrics, offering a comprehensive solution for 5G communication systems.

A closely related study [24] titled "Optimal filter choice for filtered OFDM" compared six window functions for F-OFDM systems and identified the Kaiser window as the most effective in its evaluation settings. While the authors focused primarily on SISO configurations and evaluated filters such as Hamming, Hanning, Blackman, and Kaiser, this study extends the investigation to MIMO scenarios using a broader set of six window functions, including their combinations, such as Nuttall-Blackman-Hanning. These combinations demonstrated an improved performance in minimizing OOBE and reducing BER. This distinction highlights that the term *optimal* is context-dependent and subject to the system's configuration, channel model, and performance objectives.

In order to enhance filter performance by narrowing the main lobe, lowering side lobe power, and minimizing latency, the main goal of this work is to develop an ideal window function for an F-OFDM system. For filter development, the one that meets the least OOBE requirement among the six suggested window function types has been chosen.

Additionally, we investigate the concept of integrating two or three window functions to further decrease OOBE and improve speed. The MIMO technology is integrated with F-OFDM to improve channel reliability and capacity. Consequently, this combination enhances spectrum utilization and reduces BER.

3. F-OFDM System Model

Despite the advantages offered by CP-OFDM, such as optimizing spectrum usage through the orthogonality of subcarriers and its resilience to inter-symbol interference (ISI) in dispersive channels, it is not ideally suited for 5G networks due to the presence of side lobes that result in increased OOBE. These emissions lead to inefficiencies in spectrum utilization and cause interference with adjacent users in neighboring frequency bands, posing a significant challenge for high-capacity communication systems.

One of the primary objectives of 5G is to improve spectral efficiency by reducing the guard band to less than 10% of the allocation used in 4G systems. F-OFDM addresses the limitations of CP-OFDM by combining its advantages with additional features designed specifically to meet the requirements of 5G. In particular, F-OFDM integrates digital filtering techniques, enabling asynchronous transmission and guaranteeing increased throughput. These enhancements make F-OFDM more efficient in spectrum utilization and more effective in mitigating interference [22].

A key strength of F-OFDM lies in its superior performance in time and frequency localization, ensuring accurate signal processing in both critical domains for applications requiring low latency and high spectral efficiency, such as real-time communications and high-capacity mobile networks. Moreover, F-OFDM requires only a simplified equalizer to manage channel effects, making it flexible and efficient in various communication environments. Its structural design allows it to coexist with other waveforms in different sub-bands, thus offering significant flexibility in filter design across sub-bands and thereby minimizing interference between different frequency ranges [25].

F-OFDM, also known as full-band filtered OFDM, provides a robust solution to the challenges faced by traditional CP-OFDM systems in 5G.

In this study, the focus is on analyzing the branch structure of an F-OFDM system, with its architecture illustrated in Fig. 1.

Following the sampling process of the F-OFDM signal illustrated in Fig. 1 [26], the total length of an F-OFDM symbol,

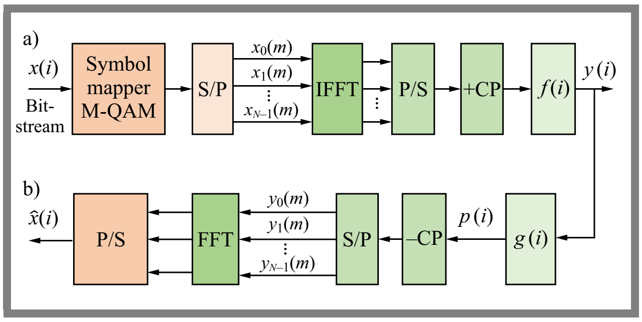

Fig. 1. F-OFDM transceiver scheme: a) upper section of the transmitter and b) lower section of the receiver.

including the cyclic prefix (CP), is denoted as:

$$N_{F-OFDM} = N + N_{cp} \,,$$

where N represents the length of the useful data symbol and N_{cp} denotes the CP length.

The discrete baseband signal $s(i)$ of F-OFDM is defined in the following way:

$$s(i) = \frac{1}{N} \sum_{k=0}^{N-1} x_k(m)\, e^{\frac{j2\pi k(i-N_{cp})}{N}} \,, \quad (1)$$

where $0 \leqslant i \leqslant N_{F-OFDM} - 1$, $x_k(m)$ is the k-th data symbol of the F-OFDM signal of the m-th frame.

Filtering $s(i)$, actually represents a convolution of $s(i)$ and filter $f(i)$, which can be formulated as:

$$y(i) = \frac{1}{N} \sum_{l=-\infty}^{l=\infty} f(i-l) \sum_{k=0}^{N-1} x_k(m)\, e^{\frac{j2\pi k(i-N_{cp})}{N}} \,. \quad (2)$$

Filter design is the primary challenge in F-OFDM systems. Generally, the Hanning window is used to truncate the sinc function and obtain the commonly used filter $f(i)$ [20]. In this work, six types of window functions most commonly used in recent years have been proposed for filter design: Hanning, Hamming, Blackman, RRC, Nuttall, and Blackman-Harris. The window functions are listed bellow [27]:

Hanning window:

$$W_{hn}(i) = 0.5\left[1+\cos\frac{2\pi i}{N-1}\right], \quad -\frac{N-1}{2} \leqslant i \leqslant \frac{N-1}{2} \,. \quad (3)$$

Hamming window:

$$W_{hm}(i) = 0.54 + 0.46\cos\frac{2\pi i}{N-1}\,, \quad -\frac{N-1}{2} \leqslant i \leqslant \frac{N-1}{2} \,. \quad (4)$$

Blackman window:

$$W_{bl}(i) = 0.42 + 0.5\cos\frac{2\pi i}{N-1} + 0.08\cos\frac{4\pi i}{N-1}\,, \quad -\frac{N-1}{2} \leqslant i \leqslant \frac{N-1}{2} \,. \quad (5)$$

RRC window:

$$W_{rrc}(i) = \left[0.5\left(1+\cos\frac{2\pi i}{N-1}\right)\right]^{0.6}\,, \quad -\frac{N-1}{2} \leqslant i \leqslant \frac{N-1}{2} \,. \quad (6)$$

Tab. 1. Comparative analysis of this study and previous works.

Ref.	Main focus of previous works	Limitation of previous works	Proposed objectives
[17]	Multirate 5G downlink performance comparison between F-OFDM and W-OFDM schemes using various methods	– Study the performance of F-OFDM only, – Study using RRC and Blackman windows only for F-OFDM, – Uses AWGN only, – Includes effect of QPSK and 256QAM only, – Analyzes PSD and BER vs. SNR	– Investigation of MIMO technology integrated with F-OFDM, – Analysis of different windowing techniques for F-OFDM, – Evaluation using both AWGN and Rayleigh channels, – Examination of the impact of modulation order, – Study includes PSD, PAPR and BER vs. SNR
[18]	Implementing enhanced MIMO with F-OFDM to boost system efficiency in future 5G cellular networks	– Analyzes the performance of MIMO F-OFDM system-based RRC window filter, – Study includes PSD and BER vs. SNR	– Study the performance of MIMO combined with F-OFDM, – Six different window functions have been suggested for the filter design, – Includes PSD, PAPR and BER vs. SNR
[15]	Performance comparison of F-OFDM and OFDM for MIMO systems in a 5G scenario	– Analyzes the performance of a MIMO F-OFDM system using an RRC window filter, – Study uses QPSK modulation only	– Performance analysis of MIMO combined with F-OFDM, – Six different window functions have been suggested for the filter design. – Work includes effect of modulation order
[19]	Performance evaluation of OFDM, W-OFDM, and F-OFDM over Rayleigh fading channels for 5G systems	– Study the performance of the MIMO F-OFDM system-based RRC window filter, – Work includes PSD and BER vs. SNR	– Performance evaluation of MIMO combined with F-OFDM system-based six types of window filters for filter design, – Work includes PSD, PAPR and BER vs. SNR
[20]	Filter design based on a generic function model for reducing OOBE in F-OFDM	– Evaluation of the performance of F-OFDM only with different window filters using the effect of single, combination, and squared window filters, – Study uses AWGN and 64QAM only	– Analysis of the performance of MIMO combined with F-OFDM, – Six different window functions have been proposed for the filter design, – Using the effect of single, combination, and squared window filters, – Study using the AWGN and Rayleigh channel and includes the effect of modulation order
[21]	Design and performance evaluation of MIMO F-OFDM systems for 5G and beyond	– Four different types of window functions have been proposed for the filter design, – Study includes PSD and BER vs. SNR	– Six different window functions have been introduced for the filter design, – Work includes PSD, PAPR and BER vs. SNR
[22]	An experimental investigation of F-OFDM spectrum efficiency for 5G applications	– Analysis of F-OFDM only, – Study using AWGN only, – Five types of window functions have been proposed for the filter design. – Work includes PSD and BER vs. SNR	– Study the performance of MIMO combined with F-OFDM, – Two cases: AWGN and Rayleigh channel, – Six types of window function have been proposed for the filter design, – Includes PSD, PAPR and BER vs. SNR comparison
[23]	Performance analysis of MIMO-OFDM systems	– Performance analysis of MIMO-OFDM, – Study includes PSD and BER vs. SNR	– Study the performance of MIMO F-OFDM, – Research includes PSD, PAPR and BER vs. SNR

Nuttall window:

$$\begin{aligned} W_{nutt}(i) = a_0 + a_1 \cos\frac{2\,\pi\,i}{N-1} \\ + a_2 \cos\frac{4\,\pi\,i}{N-1} + a_3 \cos\frac{6\,\pi\,i}{N-1}\,, \\ -\frac{N-1}{2} \leqslant i \leqslant \frac{N-1}{2}\,. \end{aligned} \tag{7}$$

with: $a_0 = 0.355768$, $a_1 = 0.487396$, $a_2 = 0.144232$, $a_3 = 0.012604$.

Blackman–Harris window:

$$\begin{aligned} W_{bl_{harris}}(i) = a_0 + a_1 \cos\frac{2\,\pi\,i}{N-1} \\ + a_2 \cos\frac{4\,\pi\,i}{N-1} + a_3 \cos\frac{6\,\pi\,i}{N-1}\,, \\ -\frac{N-1}{2} \leqslant i \leqslant \frac{N-1}{2}\,. \end{aligned} \tag{8}$$

with: $a_0 = 0.35875$, $a_1 = 0.48829$, $a_2 = 0.14128$, $a_3 = 0.01168$.

In Eq. (8), N is the signal length after sampling and N is an odd number.

The definition of the discredited sinc function is as follows:

$$\mathrm{sinc}(i) = \frac{\sin(w_c\, i)}{w_c\, i}, \quad -\frac{N-1}{2} \leqslant i \leqslant \frac{N-1}{2} \,. \tag{9}$$

w_c is the cutoff frequency of an ideal low pass filter (LPF).

Therefore, a windowed-sinc filter can be formulated as follows:

$$f(i) = \mathrm{sinc}(i).W(i) \,, \tag{10}$$

where $\mathrm{sinc}(i)$ represents the time domain sinc response of LPF and i is the time domain window function.

Based on Fig. 1 and the matched filtering method from signal detection theory [28], the transmitter applies a filter $f(i)$ to filter signal symbols in the time domain, while the receiver uses a matched filter $g(i)$. In accordance with the signal detection theory, at the receiver side, the matched filter satisfies $g(i) = f(-i)$; if $f(i)$ is set as a real-valued even function, then $f(i) = f(-i)$, implying $g(i) = f(i)$.

Consequently, after passing through the matched filter, signal $p(i)$ is obtained as $p(i) = y(i) * g(i)$, where $*$ denotes the convolution operation. After eliminating the cyclic prefix (CP), performing serial-to-parallel conversions, fast Fourier transform (FFT), and parallel-to-serial conversion, $\hat{x}(i)$ can be derived as follows:

$$\hat{x}(i) = \frac{1}{N} \sum_{l=-\infty}^{l=\infty} p(i-l) \sum_{k=0}^{N-1} y_k(i)\, e^{\frac{j2\pi k(i-N_{cp})}{N}} \,, \tag{11}$$

While the types of window functions and simulation parameters have been outlined, this section aims to provide a more comprehensive explanation of the specific procedures followed throughout the simulations by applying them to the time-domain signal by truncating the sinc function, in line with the filter design methodology. For each window type, the corresponding filter coefficients were derived and integrated into the F-OFDM.

Regarding modulation schemes, we employed quadrature phase shift keying (QPSK) as well as m-ary quadrature amplitude modulation (M-QAM) with M= 16, 64 and 256. The system's performance was evaluated in terms of key metrics, including PSD, PAPR, and BER, using varying modulation schemes. The simulations were conducted under both AWGN and Rayleigh fading channel conditions to ensure a thorough and representative assessment of filter performance across different channel environments.

This approach ensures the accuracy and reliability of the results, establishing a foundation for comparing the performance of MIMO F-OFDM and MIMO CP-OFDM systems.

4. Results and Discussion

As noted in [29], the filter length in an F-OFDM system typically follows the inequality:

$$N \leqslant \frac{N_{F-OFDM}}{2} \,,$$

where N represents the filter length and N_{F-OFDM} refers to the length of the F-OFDM symbol. In this case, the symbol length is set to 1024, which makes the FFT/IFFT length 1024 as well. Since the filter length N is usually chosen as an odd number, this study uses a filter length of 513. The modulation techniques used are QPSK and M-QAM, with M =16, 64, 256 representing 16QAM, 64QAM and 256QAM, respectively. A total of 600 subcarriers have been utilized.

In this study, the MIMO technology, known for improving capacity and enhancing channel reliability, is combined with F-OFDM. Specifically, the paper explores the integration of MIMO 4 × 4 with F-OFDM using an optimal window function to maximize system performance.

The filters exhibited varying performance, and a comparative analysis is necessary for clarity. For example, the Nuttall window provided the best overall performance in reducing OOBE. Although the two proposed window filters 1 and 2 performed well in terms of spectral efficiency and signal recovery, the proposed window filter 2 was effective in minimizing BER but less successful in reducing OOBE. This comparison highlights the need to select the appropriate window filter according to the specific performance criteria, such as spectral efficiency, BER, or PAPR.

To gain further insight into the OOBE characteristics, PSD of the F-OFDM system is calculated. This analysis offers a deeper understanding of how OOBE is affected by different filter designs.

Let us rewrite Eq. (1) in a continuous form:

$$s(t) = \frac{1}{N} \sum_{k=0}^{N-1} x_k(m)\, e^{j2\pi k \Delta f t}, \quad -\frac{T_s}{2} \leqslant t \leqslant \frac{T_s}{2} \,, \tag{12}$$

where: $T_s = \frac{1}{\Delta f} + T_{cp}$ and T_{cp} is the time length of the CP.

Upon completion of the filter $f(t)$:

$$y(t) = s(t) * f(t) \,. \tag{13}$$

The signal at the transmitter end of the F-OFDM system is known as $y(t)$, $f(t) = w(t).\mathrm{sinc}(t)$.

The Fourier transformation is used to transform the transmitted signal:

$$Y(f) = S(f).F(f) \,. \tag{14}$$

where $Y(f)$ is the Fourier transform of the transmitted signal $y(t)$, $S(f)$ is the Fourier transform of $s(t)$, $F(f)$ is the Fourier transform of the filter $f(t)$.

$$S(f) = \frac{1}{N} \sum_{k=0}^{N-1} x_k(m)\, T_s\, \mathrm{sinc}\Big[\pi(f - k\,\Delta f)T_s\Big] \,, \tag{15}$$

$$\begin{aligned} F(f) = \mathcal{F}\Big[w(t).\mathrm{sinc}(t)\Big] &= \mathcal{F}\Big[w(t)\Big] * \mathcal{F}\Big[\mathrm{sinc}(t)\Big] \\ &= W(f) * \mathcal{F}\Big[\mathrm{sinc}(t)\Big] \,, \end{aligned} \tag{16}$$

where $\mathcal{F}[.]$ is the Fourier transform symbol and $W(f)$ represents the Fourier transform of the window function. The degree of OOBE of $S(f)$ is determined by the degree of OOBE of the system and $W(f)$ is responsible for the PSD of $S(f)$.

Tab. 2. Overview of the parameters of the simulated model.

Parameters	Considerations for simulation
Message type	Binary bits
Channel	AWGN and Rayleigh
SNR	0 to 22 dB
Filters used for F-OFDM	Hanning, Hamming, Blackman, RRC, Nuttall, and Blackman-Harris
Number of subcarriers	600
CP length	74 for CP-OFDM and 72 for F-OFDM
Filter order	512
Tone offset	5 subcarriers
IFFT / FFT size	1024
Digital modulation	QPSK, 16QAM, 64QAM, and 256QAM
Antenna configuration	T4 × R4

PSD for the F-OFDM system is:

$$10\log_{10}\left|Y(f)\right|^2 = 10\log_{10}\left|S(f).\left\{W(f)*\mathcal{F}[\text{sinc}(t)]\right\}\right|^2. \tag{17}$$

PAPR of the F-OFDM system is as follows:

$$PAPR_{F\_OFDM} = \frac{\max(|y(t)|^2)}{E(|y(t)|^2)}, \tag{18}$$

in which $\max(.)$ is the F-OFDM signal's maximum value and $E(.)$ is its average value.

Table 2 provides a summary of the performance characteristics of the simulated model, namely PSD, PAPR, and BER.

4.1. Power Spectral Density

This subsection compares the performance of several window-based filters, including RRC, Hanning, Blackman, Hamming, Blackman-Harris, and Nuttall, in terms of their impact on the power spectrum.

As illustrated in Fig. 2, the filters significantly reduce OOBE when compared to traditional OFDM. Specifically, greater attenuation is achieved in the stopband region with the application of these filters, leading to a marked improvement in spectral containment.

Table 3 highlights the difference in OOBE between the CP-OFDM and F-OFDM systems using various window filters. In CP-OFDM, an attenuation of 66 dB is achieved, with the highest spectral leakage (out-of-band emission). Windows such as RRC, Hanning, Blackman, Hamming, Blackman-Harris, and Nuttall show a clear improvement in reducing spectral leakage compared to CP-OFDM. Among the window functions tested, the proposed windows 1 and 2 offer a sharp and rapid reduction in out-of-beam PSD, which means that they are more effective in reducing spectral interference.

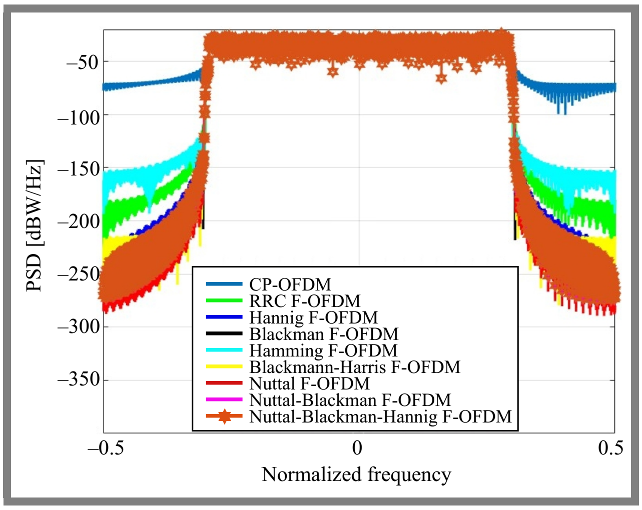

Fig. 2. PSDs of different windows-based F-OFDM systems (50 resource blocks, 12 subcarriers each) compared to CP-OFDM.

Tab. 3. Comparison of F-OFDM OOBE with CP-OFDM.

Window filter	OOBE difference [dB]
Hamming	–152
RRC	–175
Blackman-Harris	–207
Hanning	–233
Blackman	–250
Nuttall	–256
Proposed window 1 (Nuttall-Blackman)	–253
Proposed window 2 (Nuttall-Blackman-Hanning)	–252

The comparison reveals that windows-based filtering, particularly with the Nuttall window and the two proposed windows, offers superior OOBE suppression. We also notice that the PSD values are very close, which makes it a highly effective solution for enhancing spectral efficiency of F-OFDM systems in 5G networks. Although the performance curves (e.g., PAPR and BER) exhibit very close numerical values, even slight improvements can lead to noticeable enhancements in real-time 5G applications, particularly in ultra-reliable low-latency communications (URLLC), where every decibel counts.

4.2. Peak to Average Power Ratio

Next, we assess PAPR for a CP-OFDM system, both with and without the application of a windowed sinc filter, across various modulation schemes. The evaluation is based on the complementary cumulative distribution function (CCDF), which illustrates the probability that the instantaneous power of a signal exceeds a specified threshold relative to its average power level. Figures 3–6 show CCDF comparisons for

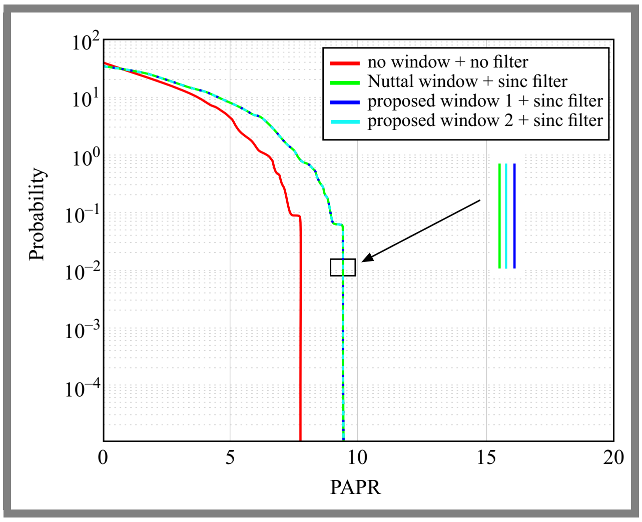

Fig. 3. Comparison of CCDF for CP-OFDM and F-OFDM systems with QPSK modulation.

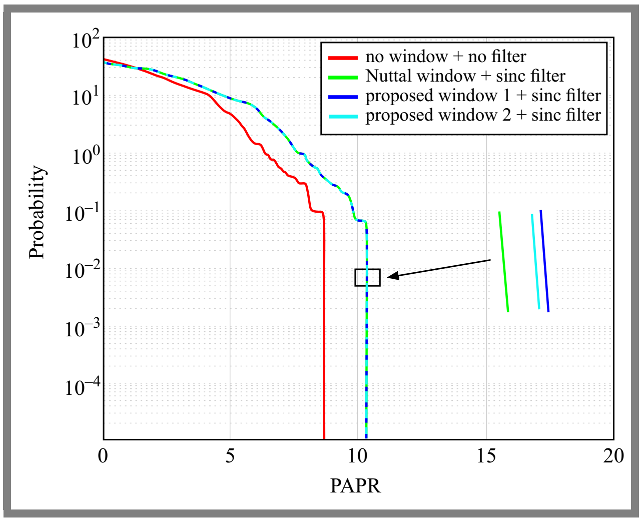

Fig. 4. Comparison of CCDF for CP-OFDM and F-OFDM systems with 16QAM modulation.

different modulation schemes: QPSK, 16QAM, 64QAM and 256QAM.

The results indicate that CP-OFDM systems across all modulation orders exhibit lower PAPR values compared to their F-OFDM counterpart. This suggests that CP-OFDM systems are less prone to high instantaneous power peaks. However, it is important to note that F-OFDM systems, particularly when using single and combination window filters, follow similar PAPR trends. These trends reflect that while F-OFDM achieves superior spectral efficiency, it may lead to slightly higher PAPR values, which could affect energy efficiency in selected applications.

Table 4 provides a detailed comparison of PAPR values between CP-OFDM and F-OFDM systems using the Nuttall window filter and the proposed window filters 1 and 2, for different modulation orders. The two proposed window filters 1 and 2 demonstrate a match in PAPR values with the Nuttall filter, indicating that filter design does not have a significant impact on power efficiency in F-OFDM systems.

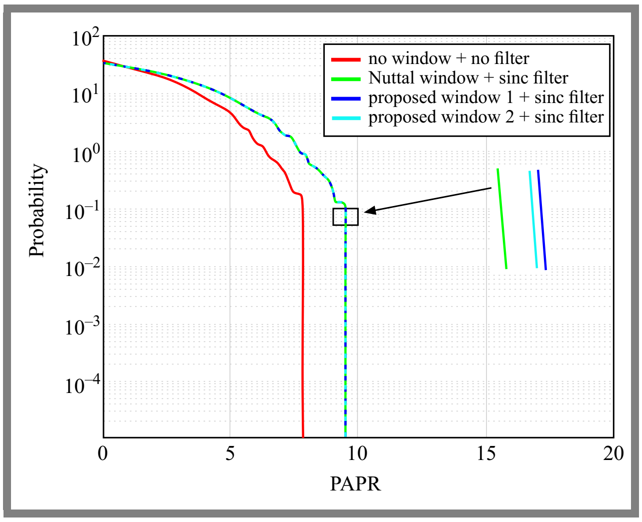

Fig. 5. Comparison of CCDF for CP-OFDM and F-OFDM systems with 64QAM modulation.

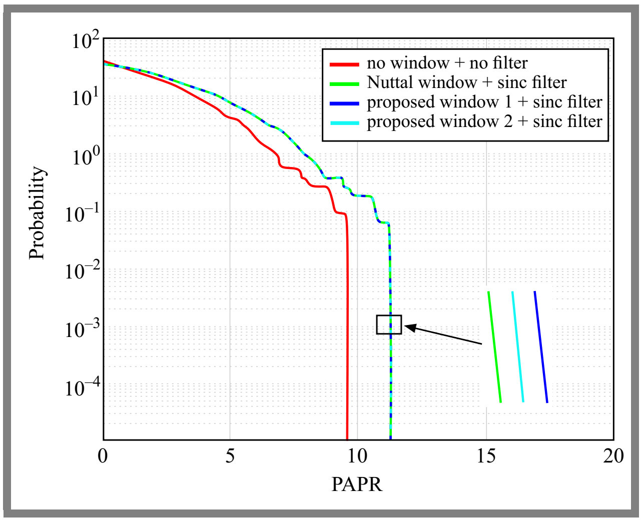

Fig. 6. Comparison of CCDF for CP-OFDM and F-OFDM systems with 256QAM modulation.

The data show that as the modulation order increases, PAPR values tend to rise, which is a common characteristic of higher-order modulation schemes. When QPSK modulation is employed, we see an improvement in PAPR performance compared to all modulation orders, but F-OFDM systems generally present higher PAPR values compared to CP-OFDM, suggesting a trade-off between spectral efficiency and power efficiency.

4.3. Bit Error Rate

The primary performance indicators of a communication system are its efficiency and reliability. While efficiency is improved by maximizing frequency band, reliability remains a critical factor, particularly in systems, where maintaining a low error rate is essential. This study evaluates the reliability of MIMO systems combined with F-OFDM, specifically focusing on the Nuttall window filter and the two proposed window filters 1 and 2. For comparison, BER performance of MIMO systems using CP-OFDM filters is also assessed.

Tab. 4. PAPR with different modulation order of CP-OFDM and F-OFDM.

Modulation order	PAPR for CP-OFDM [dB]	PAPR for F-OFDM-based Nuttall window filter [dB]	PAPR for F-OFDM-based prop. window filter 1 [dB]	PAPR for F-OFDM-based prop. window filter 2 [dB]
4	7.8011	9.4640	9.4662	9.4663
16	7.9388	9.6076	9.6070	9.6070
64	8.6504	10.3150	10.3156	10.3159
256	9.6376	11.3052	11.3052	11.3049

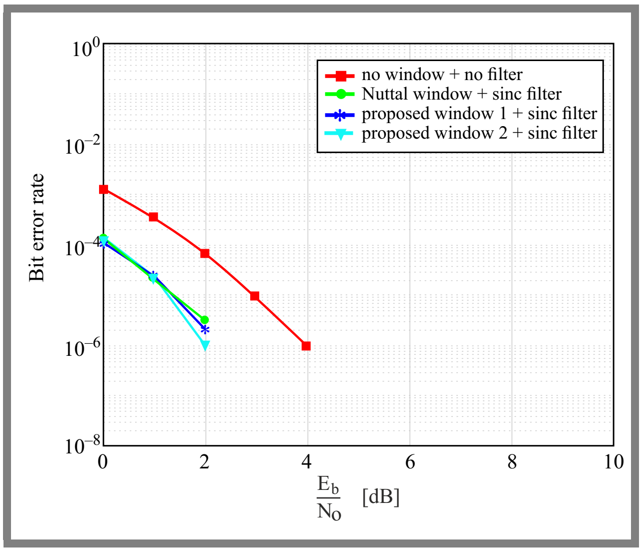

Fig. 7. BER for MIMO CP-OFDM- and F-OFDM-based single window filter and a combination thereof, using QPSK modulation.

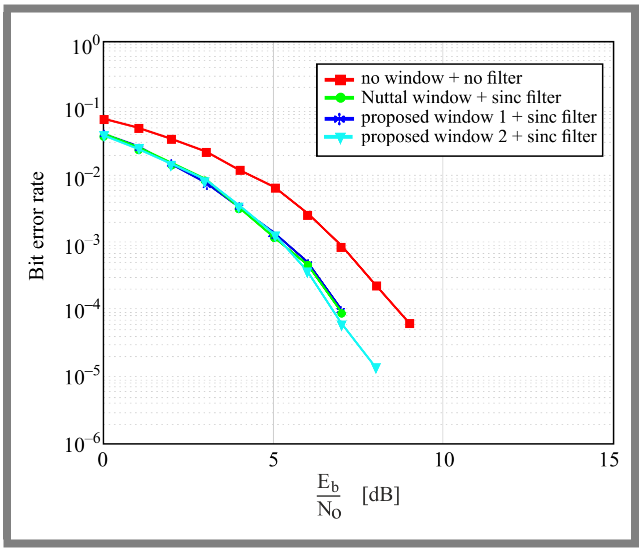

Fig. 8. BER for MIMO CP-OFDM- and F-OFDM-based single window filter and a combination thereof, using 16QAM modulation.

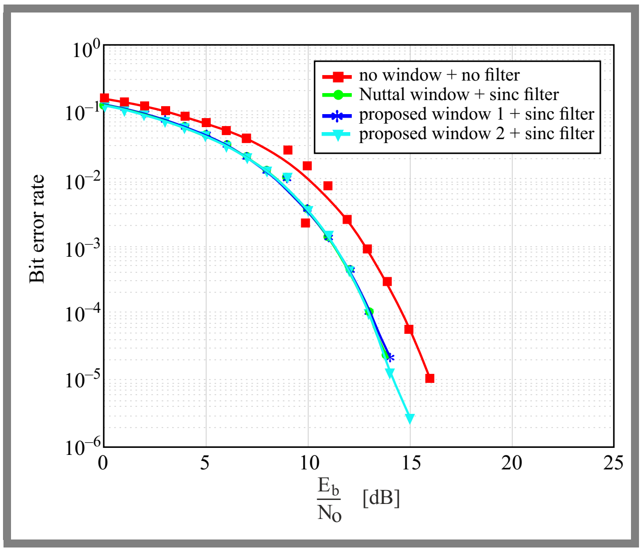

Fig. 9. BER for MIMO CP-OFDM- and F-OFDM-based single window filter and a combination thereof, using 64QAM modulation.

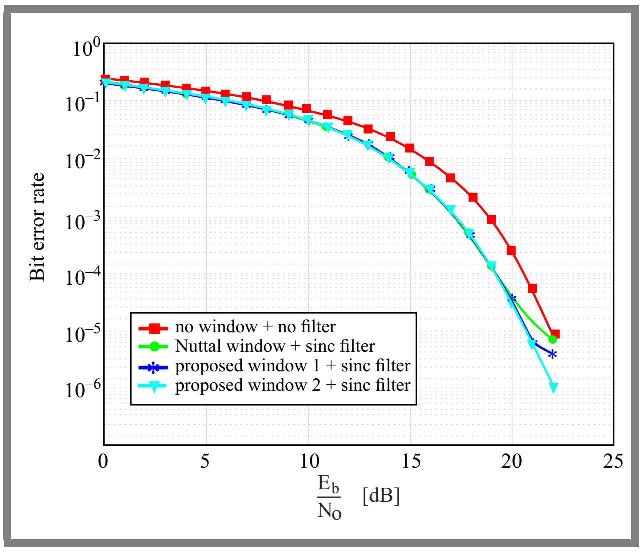

Fig. 10. BER for MIMO CP-OFDM- and F-OFDM-based single window filter and a combination thereof, using 256QAM modulation.

The evaluation is conducted by measuring BER across several modulation schemes, including QPSK, 16QAM, 64QAM and 256QAM, under different conditions. Figures 7–10 display the performance of MIMO CP-OFDM and MIMO F-OFDM systems with single and combined window filters, offering a comprehensive view of BER for each modulation scheme.

The results indicate that MIMO combined with F-OFDM achieves better BER performance compared to MIMO CP-OFDM with all varieties of digital modulation schemes employed. Specifically, when QPSK modulation is used, nearly identical BER values were obtained by MIMO F-OFDM-based Nuttall window filter, proposed window filter 1 (Nuttall-

Blackman) and proposed window filter 2 (Nuttall-Blackman-Hanning). But when SNR values are greater than 1 dB, we notice that proposal no. 2 offers better performance. After that, when employing higher-order modulation schemes, MIMO F-OFDM offers lower BER performance than CP-OFDM. When transmitted over the same Rayleigh channel, nearly identical BER values were obtained by the OFDM filtered with a single and with a combination of window filters when SNR was lower than 5 dB, 13 dB, and 20 dB, respectively.

Although at SNR values greater than those mentioned previously, the BER values achieved for the proposed window filter 2 are the best compared to those observed with the Nuttall window filter and the proposed window filter 1.

Despite the convergent spectral properties of all 3 filters, superior BER performance achieved by the proposed window filter 2 remains a key advantage, particularly in scenarios where spectral efficiency and interference minimization are critical. Therefore, it is recommended that the proposed window filter 2 (Nuttall-Blackman-Hanning) be utilized when designing F-OFDM systems, as it offers an optimal balance between OOBE reduction and system performance in 5G communication environments.

It should be noted that the term *optimal*, as used in this work, refers to the best-performing filter configuration under the defined simulation parameters, including modulation schemes, channel models, and window combinations. It does not imply a universally best solution, but rather one that achieves the most favorable trade-offs in terms of OOBE, BER, and PAPR for the studied MIMO F-OFDM system.

5. Conclusions and Future Outlook

In this paper, we analyze the performance of MIMO combined with F-OFDM for 5G mobile communications and compare it to MIMO using CP-OFDM. The results demonstrated that the proposed window filter 2 (Nuttall-Blackman-Hanning) outperforms other window functions, particularly in reducing OOBE and enhancing overall system performance. Consequently, it is recommended for use in F-OFDM systems to ensure optimal spectral efficiency and system reliability.

Although this study has provided a comprehensive analysis of window functions and their impact on MIMO F-OFDM performance, several opportunities for future research remain open. First, future studies could focus on developing adaptive windowing techniques that adjust dynamically in response to varying network conditions. Such techniques could significantly enhance system performance in rapidly changing environments, including dynamic 5G scenarios.

Additionally, testing the proposed system in more complex propagation environments, such as urban or high-density networks, would provide valuable insight into its robustness and scalability. These tests could help further optimize the system for real-world deployments where signal interference and attenuation are more pronounced.

Future research should also focus on optimizing filter design for energy efficiency, a critical factor for energy-sensitive applications such as IoT networks and mobile devices.

References

[1] I.F. Akyildiz, S. Nie, S.-C. Lin, and M. Chandrasekaran, "5G Roadmap: 10 Key Enabling Technologies", *Computer Networks*, vol. 106, pp. 17–48, 2016 (https://doi.org/10.1016/j.comnet.2016.06.010).

[2] ITU-R, "IMT Vision – Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond", *Recommendation ITU-R M.2083-0*, 2015 (https://www.itu.int/rec/r-rec-m.2083).

[3] S. Tiwari, S. Chatterjee, and S.S. Das, "Comparative Analysis of Waveforms for Fifth Generation Mobile Networks", *IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)*, Bangalore, India, 2016 (https://doi.org/10.1109/ANTS.2016.7947770).

[4] F.-L. Luo and C. Zhang, *Signal Processing for 5G: Algorithms and Implementations*, Hoboken, USA: Wiley, 581 p., 2016 (https://doi.org/10.1002/9781119116493).

[5] S.B. Weinstein, "The History of Orthogonal Frequency-division Multiplexing", *IEEE Communications Magazine*, vol. 47, pp. 26–35, 2009 (https://doi.org/10.1109/MCOM.2009.5307460).

[6] R.Y. Mesleh *et al.*, "Spatial Modulation", *IEEE Transactions on Vehicular Technology*, vol. 57, pp. 2228–2241, 2008 (https://doi.org/10.1109/TVT.2007.912136).

[7] B. Farhang-Boroujeny, "OFDM Versus Filter Bank Multicarrier", *IEEE Signal Processing Magazine*, vol. 28, pp. 92–112, 2011 (https://doi.org/10.1109/MSP.2011.940267).

[8] M.K. Gupta and S. Tiwari, "Performance Evaluation of Conventional and Wavelet Based OFDM System", *AEU - International Journal of Electronics and Communications*, vol. 67, pp. 348–354, 2013 (https://doi.org/10.1016/j.aeue.2012.10.005).

[9] A. Sahin, I. Guvenc, and H. Arslan, "A Survey on Multicarrier Communications: Prototype Filters, Lattice Structures, and Implementation Aspects", *IEEE Communications Surveys & Tutorials*, vol. 16, pp. 1312–1338, 2013 (https://doi.org/10.1109/SURV.2013.121213.00263).

[10] R. Nissel, S. Schwarz, and M. Rupp, "Filterbank Multicarrier Modulation Schemes for Future Mobile Communications", *IEEE Journal on Selected Areas in Communications*, vol. 35, pp. 1768–1782, 2017 (https://doi.org/10.1109/JSAC.2017.2710022).

[11] N. Michailow *et al.*, "Generalized Frequency Division Multiplexing for 5th Generation Cellular Networks", *IEEE Transactions on Communications,* vol. 62, pp. 3045–3061, 2014 (https://doi.org/10.1109/TCOMM.2014.2345566).

[12] A. Farhang, N. Marchetti, and L.E. Doyle, "Low-complexity Modem Design for GFDM", *IEEE Transactions on Signal Processing*, vol. 64, pp. 1507–1518, 2016 (https://doi.org/10.1109/TSP.2015.2502546).

[13] J. Abdoli, M. Jia, and J. Ma, "Filtered-OFDM: A New Waveform For Future Wireless Systems", *IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Stockholm, Sweden, 2015 (https://doi.org/10.1109/SPAWC.2015.7227001).

[14] X. Zhang *et al.*, "Filtered-OFDM-enabler for Flexible Waveform in the 5th Generation Cellular Networks", *IEEE Global Communications Conference (GLOBECOM)*, San Diego, USA, 2015 (https://doi.org/10.1109/GLOCOM.2015.7417854).

[15] F.A.P. de Figueiredo *et al.*, "Comparing F-OFDM and OFDM Performance for MIMO Systems Considering a 5G Scenario", *Preprints*, 2019 (https://doi.org/10.20944/preprints201905.0307.v2).

[16] A. Idris *et al.*, "PAPR Reduction Using Huffman and Arithmetic Coding Techniques in F-OFDM System", *Bulletin of Electrical*

Engineering and Informatics, vol. 7, pp. 257–263, 2018 (https://doi.org/10.11591/eei.v7i2.1169).

[17] F. Di Stasio, M. Mondin, and F. Daneshgaran, "Multirate 5G Downlink Performance Comparison for F-OFDM and W-OFDM Schemes with Different Numerologies", *International Symposium on Networks, Computers and Communications (ISNCC)*, Rome, Italy, 2018 (https://doi.org/10.1109/ISNCC.2018.8530905).

[18] S.S.U. Shah, A.H. Sodhro, H.A. Baber, and M. Imran, "Implementing Enhanced MIMO with F-OFDM to Increase System Efficiency for Future 5G Cellular Networks", *International Journal of Communication Networks and Information Security*, vol. 10, pp. 403–409, 2018 (https://doi.org/10.17762/ijcnis.v10i2.3286).

[19] M.H. Mahmud *et al.*, "Performance Analysis of OFDM, W-OFDM and F-OFDM under Rayleigh Fading Channel for 5G Wireless Communication", *3rd International Conference on Intelligent Sustainable Systems (ICISS)*, Thoothukudi, India, 2020 (https://doi.org/10.1109/ICISS49785.2020.9316134).

[20] M. Liu, W. Xue, Y. Xu, and S.B. Makarov, "Design of Filters Based on Generic Function Model for Reducing Out-of-band Emissions of the F-OFDM Systems", *AEU – International Journal of Electronics and Communications*, vol. 139, art. no. 153908, 2021 (https://doi.org/10.1016/j.aeue.2021.153908).

[21] S. Sarker, L.A. Ara, T. Alam, and T. Debnath, "Design and Analysis of MIMO F-OFDM Systems for 5G and Beyond Wireless Communications", *International Journal of Recent Technology and Engineering (IJRTE)*, vol. 10, pp. 203–210, 2021 (https://doi.org/10.35940/ijrte.B6274.0710221).

[22] D. Ali and Z.Z. Yahya, "An Experimental Study of F-OFDM Spectrum Efficiency for 5G Applications", *International Journal of Microwave and Optical Technology*, vol. 17, pp. 1–9, 2022.

[23] A.H. Babalola, O.A. Abdulkarim, S.A. Salihu, and T.O. Adebakin, "Performance Analysis of MIMO-OFDM Systems in 5G Wireless Networks", *Proc. of International Conference on Applied Informatics*, pp. 278–291, 2024 (https://doi.org/10.1007/978-3-031-75147-9_19).

[24] S.R. Thakre, "Optimal Filter Choice for Filtered OFDM", *3rd International Conference on Electronics, Communication and Aerospace Technology (ICECA)*, Coimbatore, India, 2019 (https://doi.org/10.1109/ICECA.2019.8821847).

[25] A.A. Sahrab and A.D. Yaseen, "Filtered Orthogonal Frequency Division Multiplexing for Improved 5G Systems", *Bulletin of Electrical Engineering and Informatics*, vol. 10, pp. 2079–2087, 2021 (https://doi.org/10.11591/eei.v10i4.3119).

[26] A. Sahin, I. Guvenc, and H. Arslan, "A Survey on Multicarrier Communications: Prototype Filters, Lattice Structures, and Implementation Aspects", *IEEE Communications Surveys & Tutorials*, vol. 16, pp. 1312–1338, 2013 (https://doi.org/10.1109/SURV.2013.121213.00263).

[27] F.J. Harris, "On the Use of Windows for Harmonic Analysis with The Discrete Fourier Transform", *Proceedings of the IEEE*, vol. 66, pp. 51–83, 1978 (https://doi.org/10.1109/PROC.1978.10837).

[28] S.M. Kay, *Fundamentals of Statistical Signal Processing: Detection Theory*, vol. 2., Englewood Cliffs, USA: Prentice Hall PTR, 576 p., 1998 (ISBN: 9780135041352).

[29] M.A. Taher, H.S. Radhi, and A.K. Jameil, "Enhanced F-OFDM Candidate for 5G Applications", *Journal of Ambient Intelligence and Humanized Computing*, vol. 12, pp. 635–652, 2020 (https://doi.org/10.1007/s12652-020-02046-3).

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