

Novel Universal Windowing Multicarrier Waveform for 5G Systems

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Abstract: Fifth Generation (5G) systems aim to improve flexibility, coexistence and diverse service in several aspects to achieve the emerging applications requirements. Windowing and filtering of the traditional multicarrier waveforms are now considered common sense when designing more flexible waveforms. This paper proposed a Universal Windowing Multi-Carrier (UWMC) waveform design platform that is flexible, providing more easily coexists with different pulse shapes, and reduces the Out of Band Emissions (OOBE), which is generated by the traditional multicarrier methods that used in the previous generations of the mobile technology. The novel proposed approach is different from other approaches that have been proposed, and it is based on applying a novel modulation approach for the Quadrature-Amplitude Modulation (64-QAM) which is considered very popular in mobile technology. This new approach is done by employing flexible pulse shaping windowing, by assigning windows to various bands. This leads to decreased side-lobes, which are going to reduce OOBE and boost the spectral efficiency by assigning them to edge subscribers only. The new subband windowing (UWMC) will also maintain comprehensively the non-orthogonality by a variety of windowing and make sure to keep window time the same for all subbands. In addition, this paper shows that the new approach made the Bit Error Rate (BER) equal to the conventional Windowed-Orthogonal Frequency Division Multiplexing (W-OFDM). This platform achieved great improvement for some other Key Performance Indicators (KPI), such as the Peak to Average Power Ratio (PAPR) compared with the conventional (W-OFDM) and the conventional Universal Filtered Multicarrier (UFMC) approaches. In particular, the proposed windowing scheme outperforms previous designs in terms of the Power Spectral Density (PSD) by 58% and the (BER) by 1.5 dB and



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reduces the Complementary Cumulative Distribution Function Cubic Metric (CCDF-CM) by 24%.

Keywords: 5G waveform; window-OFDM; universal filtered multi-carrier; key performance indicators

1 Introduction

Modern wireless telecommunication technologies support many diverse services. The International Telecommunications Union (ITU) classified the fifth generation of wireless communications (i.e., 5G) into an enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC), Ultra-Reliable Low-Latency Communication (URLLC), Industrial Internet of Things (IIoT), and many more use cases [1]. Therefore, a flexible waveform design is required in order to handle such conflicting applications and use cases' requirements. The waveform design is essential for all of these use cases as it is considered the main component of the air interface between the base station and the mobile devices (UE's). So, waveforms for 5G and beyond need to be designed to fulfill the required adaptability and flexibility. Although the Orthogonal Frequency Division Multiplexing (OFDM) and its variant with low Peak to Average Power Ratio (PAPR) [2] and multimedia streaming are widely used in systems and standards before the 5G, they have many drawbacks [3].

Employing OFDM based waveforms offers several attractive attributes, such as effective hardware implementation (low cost, low complexity) hardware implementation, low-complexity equalization in the receiver side, and the straightforward integration with the Multiple Input Multiple Output (MIMO) system architectures [4,5]. However, traditional OFDM systems also incur high PAPR, require complete synchronization between transmitters and receivers, and large Out Of Band Emissions (OOBEs), which has motivated many studies looking for better waveforms for 5G and beyond [6–9]. The incumbent standard shows that 5G numerology requires adaptive waveform parameters with specific subcarrier spacing, such as 15, 30, and 60 kHz for Frequency Range 1 (FR1); and specific symbol length [10]. Future standards will also require improved resilience for these waveforms. OFDM also suffers from losing orthogonality when subcarrier spacing changes, e.g., from 15 to 30 kHz, which causes interference with other sub bands [11]. Interference between the carriers is generally controlled with windowing, filtering or guard band allocation [8]. Although many waveform designs have been considered to provide the required flexibility while improving OFDM spectral efficiency and flexibility [1,12,13], a universal flexible waveform that fits all use cases for 5G and beyond networks remains elusive.

The time domain OFDM waveform uses rectangular windows, equivalent to sinc-shape in the frequency domain. The main OFDM downside for high OOBE are sidelobes (at $1/f$) for the sinc function (f), reducing coexistence for neighboring resources and high adjacent Channel Leakage Ratio (ACLR). Since overhead synchronization would reduce latency and increase power consumption, various waveforms have been proposed to relieve OOBE leakage. A mandatory requirement for the 5G waveform is time domain localization and supporting required latency and short message transmission [5]. Filtering and windowing have been recently proposed to reduce OOBE and provide asynchronous transmission, and can be applied into subcarrier and subband 5G waveforms [14].

Subcarrier filtering approaches, such as Filter Bank Multicarrier (FBMC) [6] and Generalized Frequency Division Multiplexing (GFDM), have better performance than conventional

OFDM [15]. However, FBMC and GFDM filters require a long tail of filter impulse responses to achieve this improved performance, which degrades latency and increases system complexity.

Filtering and windowing subbands are a suitable solution for 5G and beyond waveforms to avoid these shortcomings. Filtered OFDM (F-OFDM) filters the whole transmitter bandwidth using a single filter [16]; whereas full band filtering cannot remove the Inter-Carrier Interference (ICI) and Inter-Symbol Interference (ISI) influences, similar to standard OFDM. Therefore, filter tapes need to be raised to relieve OOB constraints, thereby increasing complexity and latency [17].

The UFMC waveform is well known in 5G and beyond paradigms. Several studies have shown that using UFMC in 5G waveforms improves traffic separation, robustness against asynchronicity (time-frequency misalignment), fragmented spectrum support, sporadic access (short bursts of network access particularly by IoT devices), low-medium complexity, OFDM technology and knowledge base re-use, and short filter length when applying the filter for group of subcarriers.

Window functions are used in digital signal processing to reduce side lobe suppression on the edge of the subcarrier. Gaussian pulses have the same performance in time and frequency domains but leak in orthogonality, hence ICI and ISI can be greatly identified [18]. On the other hand, the selected waveform should also improve spectrum efficiency, time and frequency localization, and orthogonality between subcarriers. Unfortunately, these features cannot all be achieved simultaneously [18]. Therefore, the waveform should be intelligently built to offer reasonable trade-off between time and frequency localization, and increased spectrum performance compared with the current waveform.

This paper proposed a waveform incorporating flexible windowing shapes using the universal windowing multicarrier (UWMC) system and assessed its performance. The UWMC scheme provides flexibility to handle multicarrier signal OOB, with assured trade-off for diverse pulse shape since increasing some parameters or factors in the frequency-time domain can affect time domain performance and vice versa. For example, contributions from OFDM subcarrier sidelobes to OOB. Thus, multiple windowing schemes that suppress side-lobes have been used to edge subcarriers, with smaller windows employed for inner cases, e.g., Kaiser windowing for edge subcarriers with raised cosine (RC) inner windows. However, this method decreases cyclic prefix (CP) length in conventional OFDM, originally intended to reduce multipath effects, which can cause ISI. Kaiser windowing in UFMC with different beta factors provided the required flexibility and additional control over OOB [14], but ICI still occurred even with the enhanced spectral efficiency.

Kaiser and RC windowing have been used with various roll-off factors to control OOB and provide more flexibility. This paper focused on windowing shape diversity to reduce OOB, enhance spectral efficiency, and improve flexible waveform coexistence compared with current systems. The proposed approach also significantly improved bit error rate (BER) and PAPR.

The remainder of this paper is organized as follows. Section 2 discusses foundations for UWMC with different windowing. Section 3 explains the UWMC waveform concept and provides performance assessment parameters. Section 4 summarizes and concludes the paper.

2 Universal Filtering Multi-Carrier (UFMC) Waveform

The UFMC approach is a quadrature amplitude modulation (QAM) multicarrier modulation alternative to OFDM and FBMC waveforms for 5G. UFMC is similar to F-OFDM for subcarriers and filtering, but not the whole band. UFMC divides the whole bandwidth into subbands, and

then filters each subband to reduce filter length of the filter and computational time compared with F-OFDM and FBMC. Subband UFMC is similar to conventional OFDM without filtering. Let OFDM be formulated as

$$x(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X(n) e^{j2\pi \frac{nk}{N}} \quad (1)$$

where X is the OFDM signal representing the inverse discrete time Fourier transform (IDFT) with size N ; k is the time index; n is the frequency domain index. The X set is generated using quadrature Multilevel Amplitude Modulation (M-QAM) mapping and contains identically independent distributed (IID) random variables. The summation in Eq. (1). is either constructive or destructive, hence data coherence summation will result in a large PAPR. The Cyclic-Prefix OFDM (CP-OFDM) adopted for Long-Term Evolution (LTE) in the 4G mobile communications standard can be formed by adding rectangular windowing to the whole band,

$$x = W \cdot X \quad (2)$$

and executing rectangular windowing gives CP-OFDM as

$$w(n) = f(x) = \begin{cases} 1, & \text{if } -\frac{L-1}{2} \leq n \leq \\ \frac{L-1}{2} 0, & \text{otherwise} \end{cases} \quad (3)$$

where L is window length $w(n)$, which should be an odd number in this case; and W is the IDFT matrix with dimension $N \times N$, where N is the number of subcarriers. Rectangular behavior in the frequency domain is achieved using the discrete time Fourier transform (DTFT) of $w(n)$.

$$x = F \cdot W \cdot X \quad (4)$$

where F is for finite impulse response (FIR) filter Toeplitz matrix that provides convolution over the M -th band, where the whole band is subdivided to M subbands. Therefore, the UFMC system can be expressed as

$$x_k = \sum_{r=1}^M F_{r,k} \cdot W_{r,k} \cdot X_{r,k} \quad (5)$$

where M-QAM entries in $X_{r,k}$ are first converted to the time domain using the IDFT matrix column corresponding to the specified subband r within the frequency band; and $F_{r,k}((N + N_{filter} - 1) \cdot N)$ is the corresponding subband filter.

Fig. 1 shows the complete UFMC system derived from Eq. (5). The process starts with zero padding at the receiver end to achieve two-fold up-sampling, and then selects subcarriers (down-sampling) for a juncture using $2N$ -DFT until implementing M-QAM de-mapping to collect the received data.

The filtering operation uses Physical Resource Blocks (PRBs) to facilitate design flexibility. Filter length of $(N + N_{filter} - 1)$ is a critical design parameter, with filter length, $(P_{index} \gg 1)$ and X containing one M-QAM symbol. Provided filter length in the frequency domain is sufficiently long, the time domain tail will be shorter (i.e., in the order of cyclic prefix length of the traditional CP-OFDM) which enables the network to support transmitted short messages (TSM).

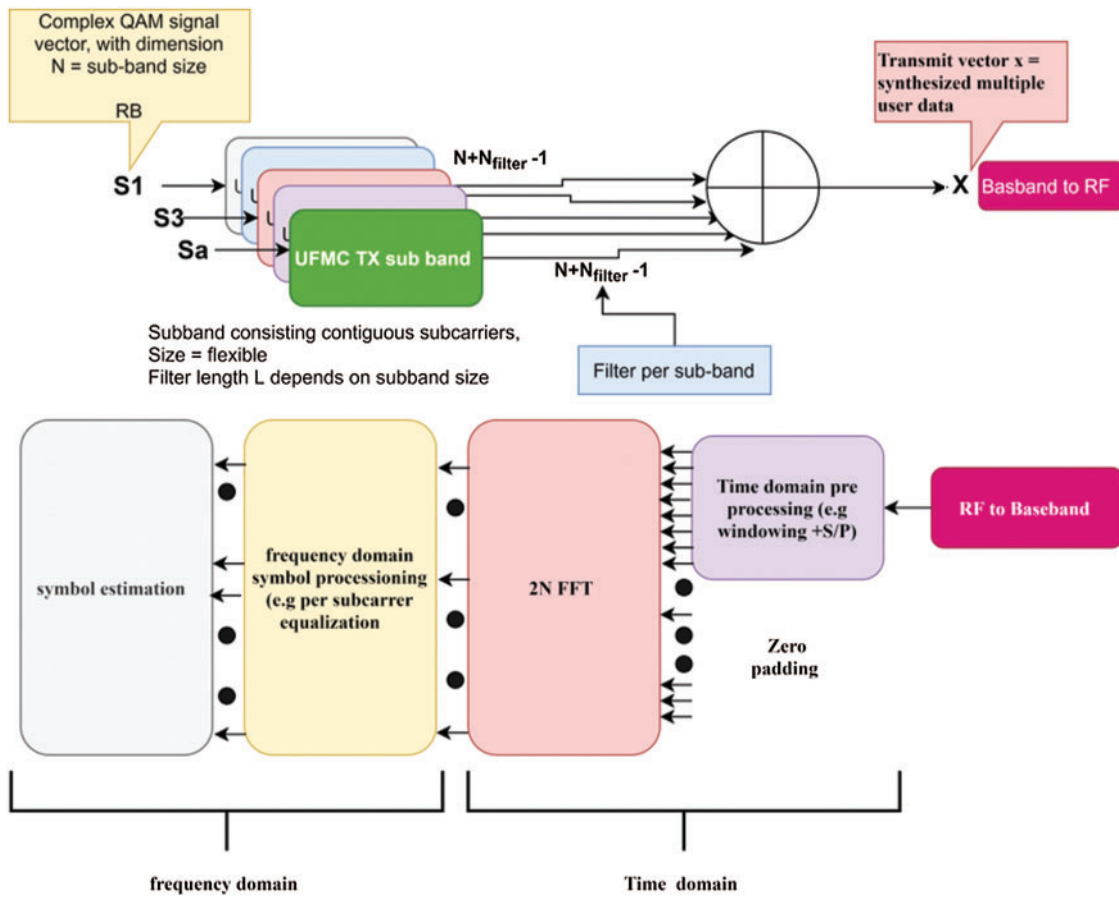


Figure 1: UPMC system architecture

The superior UPMC performance in both frequency and time domains leads to the improvement in the spectrum efficiency and is solely dependent solely on the suggested filter design. A technique which is simple, systematic, and easily implementable online technique, is the windowed-Sinc method [15]. However, many In fact, there are different windows that can be applied here, hence and that is why this design is generally preferred. The filter can be expressed as

$$h(n) = h_r(n) \cdot w_n(n) \tag{6}$$

where $h_r(n)$ is the filter time domain response, and we can apply an ideal low pass filter sinc response [19]. Using different windows can reduce OOB and be more suitable for different numerology subcarrier spacing and secrecy (illegitimate eavesdropping will be unable to subtract the subcarriers). The resulting filter must be shifted in the frequency domain (a modulation property using DTFT) to align it with the allocated bandwidth center.

The Gibbs phenomenon [19] ensures that if sinc filter windowing is applied in the time domain then output frequency ripples will occur near the dedicated bandwidth edge. This ripple frequency can be eliminated by expanding the allocated band for a few subcarriers at the transition edges or starting filter roll-off at the design edges of the subband. Thus, the filter passes frequencies as flat as possible for the allocated subband.

Filter design is critical to system function, and should be approached by selecting the correct window function from the useful choices. Good design can significantly reduce OOB and improve time and frequency localization [18], consequently enhancing spectrum efficiency by releasing more bands for user data, in contrast with conventional CP-OFDM. Section 2.1 shows how such a filtering scheme will increase data throughput. Thus, windowing is an efficient and simple tool to control inter-subband interference in a system with multiple UWMC numerologies multiplexed in the frequency domain [20].

2.1 Proposed UWMC Waveform

The proposed UWMC is a novel modulation scheme for the well-known quadrature-amplitude modulation (64-QAM). The underlying concept is to utilize flexible pulse shaping windowing, i.e., windows with different bands, as shown in Fig. 2, to reduce side-lobes, and then only assign them to edge subcarriers to increase spectral efficiency and decrease OOB. UWMC subband windowing is also thorough to maintain non-orthogonality through various windowing and guarantee that all subbands take the same time window. The UWMC waveform baseband signal with N subcarriers can be expressed as

$$x_k = \sum_{r=1}^M \underline{W}_{r,k} \cdot W_{r,k} \cdot X_{r,k} \quad (7)$$

where $1 \leq r \leq M$; $\underline{W}_{r,k} ((N + w_{KaiserorRC} - 1) \cdot N)$ is the corresponding subband windowing IDFT matrix; and the M-QAM symbol entries in $X_{r,k}$ are first converted to the time domain using the $W_{r,k}$ column corresponding to the specified subband r within the frequency band.

Fig. 2 shows the complete UWMC system derived from Eq. (7). The process starts with zero-padding at the receiver end to achieve two-fold up-sampling, and then conducts 2N-DFT upon juncture subcarriers (down-sampling) until implementing M-QAM de-mapping to collect the received data. Time windowing schemes can be applied for spectral shaping with multiuser interference suppression at the received side,

$$\underline{W}_{r,k} = [(N + w_{KaiserorRC} - 1) \cdot N] \quad (8)$$

$$W_{r,k} = [N \times n_r] \quad (9)$$

$$X_{r,k} = [n_r \times 1] \quad (10)$$

Data symbols $X_{r,k}$ for the r -th subband ($i \in [1 \dots M]$) are transformed to the time domain using a tall IDFT matrix that includes corresponding columns from the inverse Fourier matrix for the respective subband positions in the available frequency range. System parameters can be adjusted according to propagation conditions and time-frequency offset requirements [4,5]. This paper assumed that UWMC waveform subband sizes were equal for simplicity and length of subband windowing. The time domain signal $\underline{W}_{r,k}$ for subband windowing input r is

$$\underline{W}_{r,k} = IFFT[W_r; k^{\rightarrow}_{[1 \times (i-1)M]}, s_r^T, W_r; k^{\rightarrow}_{[1 \times (N(i-1)M)]}]^T \quad (11)$$

where first UWMC symbol consists of $(N + w_{KaiserorRC} - 1)$ samples and the remaining samples values are zero,

$$x = [X_{r,k_{total}}(1), X_{r,k_{total}}(2), \dots, X_{r,k_{total}}(N + w_{KaiserorRC} - 1)]^T \quad (12)$$

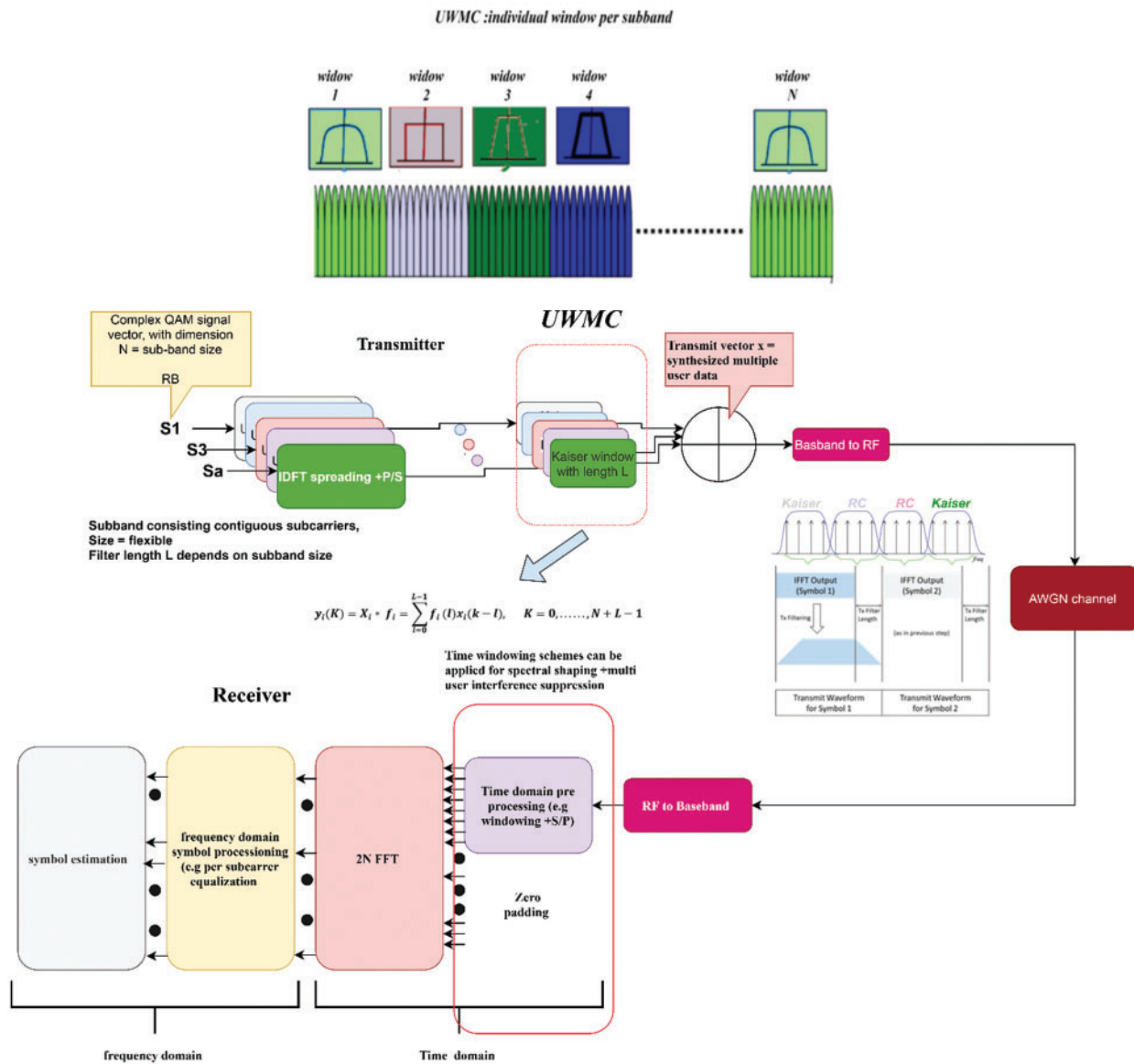


Figure 2: UWMC system architecture

The summation in time domain samples by the IFFT:

$$x_{total} = \sum_{i=1}^M X_{r,k_{full}}^{(i)} \tag{13}$$

with relevant symbol contributions

$$x_k = [x_{total}(1), x_{total}(2), \dots, x_{total}(N + w_{Kaiser\ or\ RC} - 1)]^T \tag{14}$$

The DTFT for $\underline{W}(n)$ will depict windowing behavior in the frequency domain. Applying various algebraic simplifications, $\text{sinc}(w_{\text{KaiserorRC}})$ can be expressed as

$$W(\omega) = DTFT(\underline{W}(n)) = \sum_{n=-\infty}^{n=\infty} \underline{W}(n)e^{-j\omega n} \quad (15)$$

The first windows combine Kaiser and RC windows,

$$W(n) = \frac{\text{Bessell} \sqrt{\left[\left[\frac{N}{2} - \frac{1}{2} \right]^2 - \left[n - \frac{N}{2} + \frac{1}{2} \right]^2 \right]}}{\left[0, \frac{\alpha(N-1)}{2} \right]} \quad (16)$$

where *Bessell* is the zero-order modified Bessel function given as,

$$W(n) = (-1)^n \frac{[M \text{COS}^{-1}(\beta \text{COS}[\pi n/M])] }{[\text{COS}^{-1}(\beta)]} \quad (17)$$

$$\beta = \text{COSh} \left[\frac{1}{M} \text{COSh}^{-1}(10^\alpha) \right] \quad (18)$$

where β input is the control side lobe attenuation in the Kaiser-Bessel window and balance between the main lobe width and side-lobe level is achieved by increasing β to reduce side-lobe level. However, this will increase complexity.

Therefore, the UWMC approach suggests arranging two or more windows in various directions to avoid increasing complexity and or β , creating a new window with a narrow main lobe width and reduced side lobe. For example, convolution in the time domain of two rectangular windows produces the Bartlett window [20],

$$W_{\text{newwindowing}}(n) = W_{\text{kaiser}}(n) \cdot W_{\text{RC}}(n) \quad (19)$$

$$w(n) = \frac{\text{Bessell} \left[\sqrt{\left[\frac{N}{2} - \frac{1}{2} \right]^2 - \left[n - \frac{N}{2} + \frac{1}{2} \right]^2} \right]}{\left[0, \frac{\alpha(N-1)}{2} \right]} \left[1 - \text{co} \left(\frac{2\pi}{w_{\text{windowing length}}} n \right) \right] n < \frac{\alpha N}{2} \frac{1}{2} - \frac{\text{coscos} \left[\frac{2\pi - 2\pi n}{\alpha} \right]}{2} \quad (20)$$

where α is the stopband attenuation expressed in decibels. The Kaiser window product with RC window provides new coefficient windowing in the time domain referring to the frequency domain convolution, and UWMC individual waveforms per subband are more flexible for diverse implementation and specification designs for 5G waveforms.

3 The Performance Evaluation of UWMC Waveform

We evaluate UWMC waveform performance compared with windowed CP-OFDM (W-CP-OFDM), treating all the subcarriers in the same way with respect to side-lobe suppression. Tab. 1 shows the parameters used in the simulation experiments.

Figs. 3 and 4 show that UWMC waveform OOB is less than for W-CP-OFDM and conventional UFMC. Thus, the proposed UWMC waveform provides OOB suppression and better spectral efficiency compared with conventional UFMC and W-OFDM. Conventional UFMC also

requires more side lobe attenuation for Dolph-Chebyshev to achieve the same level. These results are significant in at least two major respects: better coexistence with incumbent systems (e.g., a cognitive radio paradigm), and different numerology concepts. Adjacent channel leakage ratio (ACLR), For UWMC is superior to UFMC and CP-OFDM by 21% and 140%, respectively.

$$ACLR = \frac{power_{adjacent-subband} \text{ in dB}}{power_{main-subband} \text{ in dB}} \tag{21}$$

Table 1: Simulation parameters

Parameter	Value
Window	Kaiser, RC, and Dolph-Chebyshev
β	6
α	0.6
IFFT/FFT	512
No. of sub-carrier in each band	20
No. of symbols in time	14
Windowing length TX, Rx	$1/14 \times 1/\text{subcarrier spacing}$
Sub-carrier spacing	15 KHz
QAM	64
CP	$1/14 \times W\text{-OFDM subcarrier spacing}$
Resource blocks (RBs)	14

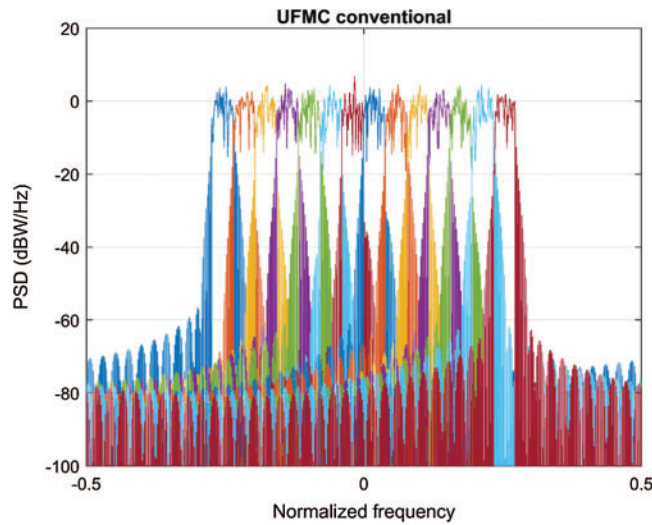


Figure 3: Conventional universal filtered multicarrier (UFMC) power spectral density (PSD)

The complementary Cumulative Distribution Function Cubic Metric (CCDF-CM) is measured in dB,

$$CCDF - CM = \frac{20 \{rms [X_{r,k_{norm}}^3(k)]\} - 20 \{rms [X_{r,k_{ref}}^3(k)]\}}{K} dB \tag{22}$$

and provides a good comparison between different 5G systems. Fig. 5 compares CCDF-CM for UWMC, UFMC, and CP-OFDM. CCDF-CM for conventional UFMC = 4.2 dB, with 3.4 dB for UWMC, i.e., UWMC reduces CCDF-CM by 24%. This enhancement was due to the cutting for the windowing only on the edge, which reduced subcarrier discontinuity compared with conventional UFMC [21].

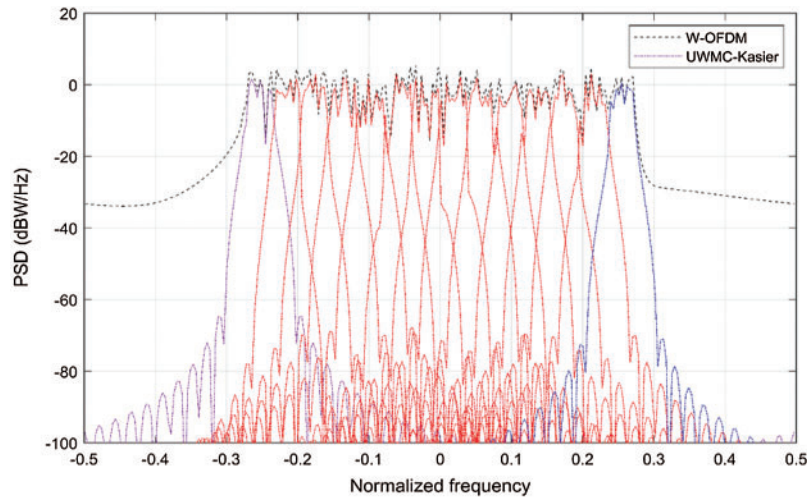


Figure 4: Power spectral density for proposed universal filtered multicarrier (UFMC) and windowed cyclic prefix orthogonal frequency division multiplexing (W-CP-OFDM) platforms

Table 2: Adjacent channel leakage ratio (ACLR) for cyclic prefix orthogonal frequency division multiplexing (CP-OFDM), universal filtered multicarrier (UFMC), and proposed universal windowing multicarrier (UWMC) performance

System	SNR (in dB)	ACLR (in dB)	Main channel power (in dB)	Adjacent channel power (in dB)
CP-OFDM	20	-50.203	14.59	-35.625
UFMC	20	-99.71	19.6	-80.11
UWMC	20	-120.723	20.203	-100.52

Fig. 6 shows BER performance for UFMC, W-OFDM, and UWMC waveforms. Conventional UFMC achieved the poorest performance, requiring more transmission power, whereas W-OFDM and UWMC achieved comparable performance at 20 dB SNR. These findings may help us understand how to control the OOB when using a mixed windowing waveform. In addition, the UWMC waveform is proven to be more suitable when we need to use different windowing and different bands in the receiving side (Rx) and with more secrecy.

Tab. 2 shows that UWMC individual window per subband is a more flexible waveform for designing 5G versatile applications and requirements. Tab. 3 lists UWMC waveform advantages compared with conventional UFMC.

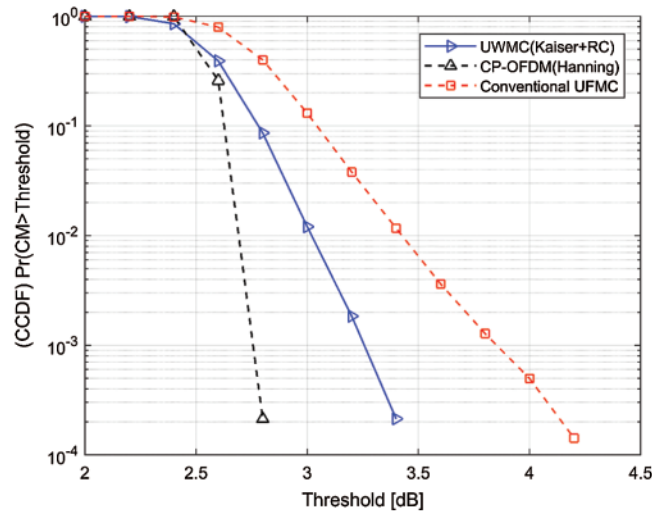


Figure 5: Complementary cumulative distribution function cubic metric (CCDF-CM) for proposed universal filtered multicarrier (UWMC), windowed orthogonal frequency division multiplexing (OFDM), and cyclic preference windowed orthogonal frequency division multiplexing (CP-OFDM) waveforms

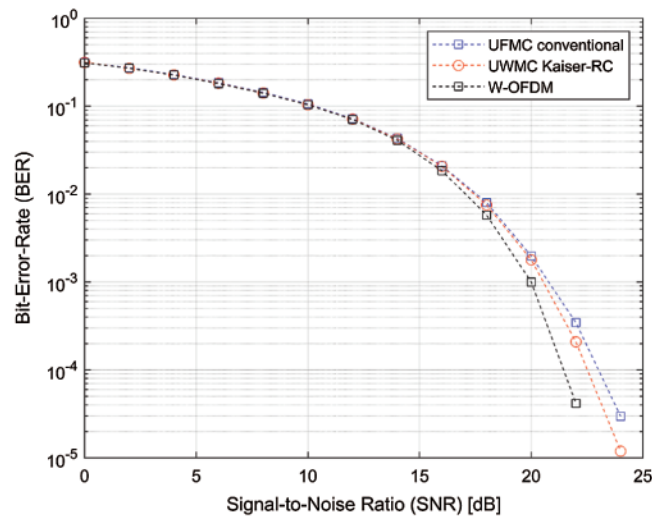


Figure 6: The BER comparison of UFMC,W-OFDM and UWMC waveform

We have focused 5G network parameters OOB, PSD, BER, ACLR/ACPR, and CCDF, but improving some parameters could negatively affect others. For example, improving OOB could also increase computational complexity or BER, and vice versa [22]. Tab. 4 compares the proposed UWMC with benchmarks for related work based on this argument. The most common waveform is CP-OFDM with windowing being applied to CP-OFDM to minimize OOB for the waveform. Subsequently, UFMC is considered a promising waveform for 5G technology because it has lower latency and better BER than CP-OFDM but remains more complex to build. Both

CP-OFDM and UFMC suffer from high OOB, with conventional UFMC being somewhat better than CP-OFDM. The proposed UWMC waveform has not been evaluated, but our approach can simultaneously reduce OOB, PAPR, BER, and CCDF-CM; with lower complexity than conventional UFMC and more suitable for coexistence with legacy systems. However, CP-OFDM has lower complexity than UWMC.

Table 3: The advantages proposed waveform

#	UWMC waveform	UFMC waveform
1-	Significantly improved OOB	Higher OOB
2-	Significantly improved BER	Higher BER
3-	More flexible with different services	Should use the same service
4-	Better coexistence with legacy systems (4G)	Need modernization for coexistence due to OOB [5,12]
5-	More secrecy due to using different windows for different user	Low secrecy due to using the same filter for each subband [23]
6-	More flexible for different numerology for FR1 and FR2	Poor performance in mixed numerology [23]
7-	Nonuniform waveform (easy quantization and low BER)	Uniform waveform [24]
8-	Low complexity (considering OOB)	Filtering causes extra CPU delay. High complexity due increased number of the tape for the filter to reduce the OOB
9-	Enhanced PAPR and consequently reduced PAPR [25]	Enhanced PAPR is possible, but will increase system complexity and cost [1]

Table 4: Comparing our waveform with the benchmark

Reference	Method (waveform)	Analysis KPI types	Remarks
[14]	Kaiser window (UFMC)	<ul style="list-style-type: none"> • PSD • CCDF • ACPR 	<ul style="list-style-type: none"> • Reduces OOB without sacrificing PAPR • Neglects BER • Neglects CCDF-CM
[26]	Windowing (CP-OFDM)	<ul style="list-style-type: none"> • PSD • EVM 	<ul style="list-style-type: none"> • Reduces OOB without reducing EVM • Neglects CCDF-CM • Neglects ACPR
[22]	Windowing (warped waveforms)	<ul style="list-style-type: none"> • PSD • BER 	<ul style="list-style-type: none"> • Reduces OOB without reducing BER • Neglects CCDF-CM • Neglects ACPR
Proposed UWMC approach	Windowing (UFMC)	<ul style="list-style-type: none"> • PSD • CCDF-CM • BER • ACLR 	<ul style="list-style-type: none"> • Reduces OOB without reducing BER • Enhances CCDF-CM • Achieves ACPR

This study indicates that the proposed UWMC framework has better spectral efficiency, can reduce ICI due to improved UWMC signals, and is more flexible for different numerology for FR1 and FR2 for different services compared with current approaches. UWMC shows better performance and consumes lower power than the CP-OFDM and conventional UFMC.

4 Conclusion

This paper proposed a new and flexible waveform suitable for 5G and beyond (UWMC) and evaluated its performance compared with several current approaches using multiple KPIs (PSD, CCDF-CM, BER, and ACLR). UWMC achieved less OOB, better spectral efficiency, and comparable BER to conventional W-OFDM; with better frequency localization, which is critical for asynchronous transmission across adjacent subbands and harmony with different numerologies in the network. These results provide important insights into it and have the resilience to control each side. Hence, it prevents needless OOB from deactivating that lowering spectral efficiency when requirements are different on each side of the band. Future work directions will include integrating the suggested waveform into multi-layer scheduling, precoding, and waveform design, which is strongly required for 4G and 5G network coexistence. The UWMC waveform provides essentially improved flexibility to facilitate this goal.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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