Flexible Sub-bands F-OFDM Configured for Spectrum Efficiency Enhancement in 5G System

Dia M. Ali¹ and Zhraa Zuheir Yahya²
¹Coll. of Electronics Eng. Ninevah University, Ninevah, Iraq
²Dep. Communication Eng., Ninevah University, Ninevah, Iraq
Email: Dia.ali@uioneveh.edu.iq, zhraa.yahya2019@stu.uioneveh.edu.iq

Abstract—The new product of wireless communication systems, the Fifth generation (5G), promises higher data rates and Spectrum Efficiency (SE) enhancements to support the communication of heterogeneous services. The Filtered-OFDM (F-OFDM) technique was proposed as the strongest candidate waveform for the physical layer in 5G to fulfill these requirements. In F-OFDM, the whole band is split into narrow sub-bands, each filtered by a digital Finite Impulse Response (FIR) filter with different specifications to increase the spectrum utilization and allow for asynchronous transmission. This paper proposes a novel F-OFDM design waveform for the first time with four sub-bands in equal and unequal sub-band sizes of seven kinds of window sinc filters and a variety of numerology designs to observe SE enhancement using Matlab-Simulink Software. Simulation results show that F-OFDM can reduce Out-Of-Band Emission (OOBE) and achieve SE of about (5%-6%) higher than conventional OFDM for equal and unequal sized sub-bands, respectively, by optimizing the guard band between the designed sub-bands, which achieves 5G guard band requirements.

Index Terms—F-OFDM, Spectrum efficiency, 5G, Out-Of-Band Emission (OOBE), Sub-band

I. INTRODUCTION

Due to the shortcomings in the performance of Fourth generation (4G) technologies and the massive increase in connected devices, the inspired industry initiatives and investments in the definition, implementation, and deployment of Fifth generation (5G) mobile network systems. The 5G system has been built to meet the demanding device and service requirements of emerging and existing networks. Future connected businesses are marked by a substantial increase in bandwidth and traffic density, network densification, a wide variety of new technologies and applications. Therefore, the efficiency envelope of wireless networks needs to be pushed to new limits to satisfy the criteria for higher network capacity, higher user data rates, more effective use of spectrum, lower latency, lower power consumption, more rellability, and higher link capacity through network function virtualization (NFV) and software-defined network (SDN) [1]. To satisfy the rapidly growing demand for mobile data services fuelled by the proliferation of smartphones and other mobile devices, the current 4G cellular system was created. Subsequent 4G upgrades also meet the needs of other mobile devices, such as public safety, connectivity from vehicle to vehicle (V2V), and the Internet of Things (IoT) that cannot be satisfied by the 4G system. The vision of the 5G system is to extend and encourage different use scenarios and applications that continue beyond the current International Mobile Telecommunications (IMT). 5G applications are classified into three types: enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC) [2]. 5G technologies include allocations of additional spectrum for mobile broadband and versatile spectrum management capabilities. A collection of new frequency bands (licensed, unlicensed, and shared) are used by the new networks to support existing wireless frequencies, allowing for greater bandwidth utilization and greatly improved performance. 5G eventually involves the repurposing of some of the sub-6 GHz spectrum for the introduction of emerging technologies. In indoor and outdoor communication, the requirements to support eMBB and mMTC services at sub-6GHz require enhancement of spectral efficiency to achieve maximum data rate and avoid interference between the sub-channels.

Due to the limitations of Orthogonal Frequency Division Multiplexing (OFDM) as the adopted waveform in the 4G-LTE system [3], new multicarrier waveforms are suggested based on the operation of OFDM to operate in 5G to increase the SE and data rates. Filtered Orthogonal Frequency Division Multiplexing (F-OFDM) is one of the waveforms proposed for the 5G system. F-OFDM divides the band into smaller sub-bands. Each sub-band can have orthogonal subcarriers, and finally, a flexible design of filtering is applied to the end of each sub-band with a flexible design of numerology. F-OFDM reduces the Out-Of-Band Emission OOBE that will manipulate the interference and increase the SE [1]. Filter bank multicarrier (FBMC) is one of the waveforms candidates for 5G. FBMC applies individual filtering for each subcarrier to mitigate Inter- Symbol-Interference (ISI) and Inter-Carrier-Interference (ICI). The SE of FBMC is much better compared to OFDM.
The main drawbacks of FBMC are that it needs a long filter length due to the non-orthogonality of the subcarriers, it is hard to be compatible with MIMO, and it is less localized in the time domain, so that FBMC is not preferred for applications that need low latency due to the complicated process. Universal filtered multicarrier (UFMC) combines the advantages of FBMC and OFDM while avoiding the limitations that exist in both OFDM and FBMC. UFMC applies the filtering to a block of adjacent subcarriers. The flexible Finite Impulse Response (FIR) Chebyshev filter design is used for each block to reduce the OOBE. The main limitation of UFMC is not preferred for applications that need higher data rates and apply the filtering on the transmission only. Generalized Frequency Division Multiplexing (GFDM) is a non-orthogonal waveform with block base transmission where the subcarriers are spaced with more flexibility and pulse shaping is performed on the subcarriers for ICI eliminating, and providing spectral confinement. In addition, CP is inserted to reduce the effect of ISI. GFDM is preferred for services with lower data rates [4].

In this study, we suggest designing a four sub-bands F-OFDM waveform with two scenarios of division. Using several forms of time-domain window functions, we designed a window-sinc FIR filter that applies to each sub-band of orthogonal subcarriers for signal confinement. In addition, a new way of multiplying three different types of windows has been developed for further improvement. The waveform performance is evaluated in terms of Bit Error Rate (BER), SE, and Peak-to-Average Power Ratio (PAPR) with the power spectrum of the sub-bands combination.

II. RELATED WORKS

In [5] filtering based on Resource Block (RB) is proposed to divide the entire available spectrum into different blocks and the filter is applied per block of subcarriers with an efficient polyphase implementation method. The performance is compared with OFDM and F-OFDM under variant Adjacent Channel Interference (ACI) conditions. Compared to F-OFDM, RB-F-OFDM outperforms when ACI is increased and has lower OOBE. The study also included reduction of PAPR using Selective Mapping (SLM) and Partial Transmit Coding (PTC). The authors in [6] discussed several important aspects of the construction of F-OFDM, including filter design and guard frequency arrangement. Besides, it highlights the benefits of F-OFDM and an extensive comparison between the current 5G waveform candidates is also included. The simulations indicated that F-OFDM offers up to 46% of throughput gains over the traditional OFDM scheme in a particular scenario with four distinct types of services. [7] A digital FIR filter with distinct window methods for F-OFDM schemes has been designed. The results indicate higher-order modulation criteria for higher passband and lower OOBE efficiency for more bandwidth. In [8], the authors introduced a kind of filter design that uses the Nuttall’s Blackman-Harris window in the F-OFDM method and analyzed the output of various window functions on two sub-bands of the F-OFDM. The results of the simulation show that the F-OFDM design is simple to implement through the Blackman-Harris window of Nuttal, with very low OOBE and the same BER output compared to the Hamming window-based F-OFDM and traditional OFDM. [9] proposes Window Filter-OFDM for a 5G system with four types of window filter construction, with simulation results indicating that two of the proposed kinds have lower OOBE comparable to FBMC.

Authors in [10] proposed the mathematical model and derived the conditions for achieving interference-free one-tap channel equalization for the F-OFDM system. The study also presents a multi-rate F-OFDM for lower complexity and cost in a communication system.

In [11], the authors suggested the idea of convolution of two window functions in the time domain with various digital filter designs to enhance the performance of F-OFDM to increase the SE. The results of the simulation show that the proposed filter outperforms previous designs in terms of SE.

III. FILTERED-OFDM FRAMEWORK

This section describes the model of F-OFDM proposed for SE enhancement in a 5G system. F-OFDM has a flexible design of digital filters with different time windowing functions to give well time-frequency localization. More features of F-OFDM can be provided, such as a high degree of reducing the OOBE, supporting asynchronous transmission between devices, ease of compatibility with MIMO antennas, multi-services diversity, backward-forward compatibility, and ease of implementation.

F-OFDM was designed in Matlab-Simulink to identify the performance of filtering with a different designation.

A. Filtered-OFDM Waveform Block Diagram

The block diagram of F-OFDM is depicted in Fig. 1 compared to the traditional block of OFDM, the F-OFDM splits the whole band into smaller sub-bands which is processed individually. At the transmitter, the input data for each sub-band is modulated with Quadrature Amplitude Modulator (QAM) in a different order. After that, the modulated data is converted to parallel form to be processed with an Inverse Fast Fourier Transform (IFFT) to probe the orthogonality between the subcarriers. The orthogonal data symbols are converted to serial and a cyclic prefix is added to avoid the ISI. A filter is applied to each sub-band to reduce OOBE and prevent interference between the adjacent sub-bands. Finally, the signals from each sub-band are summed to be transmitted over the channel. The receiving process is the opposite of the transmitter operations. The filter is considered as a matched filter to maximize the Signal to Noise Ratio (SNR) and filter the desired sub-band signal. The simple
equalizer is used to modify the phase and gain of the signal resulting from the filter effect, followed by cyclic prefix removal and FFT processing applied to convert the received signal to the frequency domain. Finally, demodulation of the QAM symbols is applied to produce the baseband data.

$$s(t) = \sum_{i=0}^{N-1} d_i \text{rect}(t - t_s - \frac{T}{2}) e^{j2\pi f_i(t-t_s)}.$$  \hspace{1cm} (1)

where $N$ is the number of subcarriers, $d_i$ is modulated data, $T$ is the interval time of the symbol, $f_i$ frequency of the subcarrier and $\text{rect}(\cdot)$ is a rectangular function.

If the complex data symbol is expressed as $\{S_{n,k}\}_{k=0}^{N-1}$ with $E|S_{n,k}|^2 = \sigma_S^2$ to transmit at nth OFDM symbol, then the OFDM signal expresses as in (2):

$$s_n(t) = \sum_{k=0}^{N-1} S_{n,k} e^{j2\pi k\Delta f t} \hspace{1cm} 0 \leq t \leq T_s.$$  \hspace{1cm} (2)

where $N$ represents the number of sub-channels, $\Delta f$ subchannel spacing, and $T_s$ symbol duration. F-OFDM signal $s(n)$ obtained by convolution of the signal $s(n)$ in the time domain with the filter $f(n)$:

$$\hat{s}(n) = s(n)*f(n).$$  \hspace{1cm} (3)

Depending on the properties of the Fourier transform, it can be express in the F-OFDM signal in the frequency domain as in (4):

$$\hat{S}(e^{j\omega}) = S(e^{j\omega}) F(e^{j\omega}).$$  \hspace{1cm} (4)

At the receiver, the received signal can be expressed as in (5):

$$r(n) = \hat{s}(n)*h(n) + z(n).$$  \hspace{1cm} (5)

where $h(n)$ represents the channel impulse response and $z(n)$ is Additive White Gaussian Noise (AWGN).  

### B. Filter Design Methodology

Filter with a flat top in the passband and a very narrow transition region as a condition criteria for F-OFDM. The filter must be very fast to attenuate in the stopband to prevent interference with other sub-bands. Higher-order filters are required for better performance, but this will increase the computation cost of the filter. The FIR low-pass filter with linear phase properties is designed with different window functions to provide soft truncation of the impulse response. The filter has higher flexibility in the design to meet the requirements of each sub-band.

Five window functions are utilized to provide tapering to the Sinc filter impulse response by reducing the side lobes. Besides, and as a system improvement, a new window function was proposed by multiplying two different types of window functions and three different types of window functions in the frequency domain to obtain higher attenuation of side lobes.

### IV. SIMULINK RESULTS, ANALYSIS AND COMPARISONS

In this paper, the first part of Simulink includes the analysis effect of filtering performance in F-OFDM and compares it with conventional OFDM according to the specifications in Table I.

The effect of the filter on the spectrum in F-OFDM with five orders of QAM modulation is shown in the Fig. 2 higher side lobes attenuation achieved with different
window functions. As it is, the Blackman-Harris window provides better attenuation than others, and more side lobe suppression can be achieved by multiplication of Blackman and Hanning windows as a new proposed window1. Furthermore, the multiplication of the Blackman, Blackman-Harris, and Hanning window functions as proposed window2 to provide more attenuation compared with proposed window1. The higher order of QAM modulation has a slight effect on the lower OOBE and needs a higher passband in filter design.

From the results of the filter effect, it can be seen that any type of window function utilized gives better results compared to the conventional OFDM, where Gaussian window gives 80 dB lower OOBE compared with OFDM, Nuttall Window produces -120 dB, Hanning Window produces -130 dB, while Blackman-Harris and Blackman give approximately -136 dB and -140 dB respectively. The enhancement appears when using the idea of multiplication where the results show that 210 dB, 270 dB are lower than OFDM at proposed window1 and proposed window2 respectively.

The performance of time-domain window functions that are utilized offers the same BER performance over higher-order modulation. Furthermore, the multiplication has a worse case than individual windows.

The analysis of BER due to the effects of filtering with different window functions and modulation order is observed in Figures 3-7. It can be seen that F-OFDM BER curves are worse than OFDM at higher values of ratio of Energy per Bit to the Spectral Noise Density (Eb/No) over different modulation orders.

Table I. Simulink Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Type</td>
<td>Soft Truncation Sinc Filter</td>
</tr>
<tr>
<td>IFFT/FFT</td>
<td>1024</td>
</tr>
<tr>
<td>Filter order</td>
<td>513</td>
</tr>
<tr>
<td>Modulation Type/order</td>
<td>QAM/16,64,128,256,512</td>
</tr>
<tr>
<td>Cyclic Prefix (CP)</td>
<td>64/sub-band</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>15.36 MHz</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>15 KHz</td>
</tr>
<tr>
<td>Bandwidth of Equal Sub-band/Unequal Sub-band</td>
<td>14.535 MHz/13.8 MHz</td>
</tr>
<tr>
<td>Window function</td>
<td>Blackman, Hanning, Nuttall, Blackman-Harris, Gaussian</td>
</tr>
<tr>
<td>Sub-band IFFT/FFT</td>
<td>512,256,128</td>
</tr>
<tr>
<td>Number of used subcarrier/different sub-band size</td>
<td>372,186,93</td>
</tr>
<tr>
<td>Number of used subcarriers/equal sub-band size</td>
<td>200</td>
</tr>
</tbody>
</table>

Fig. 2. F-OFDM power spectrum comparing with OFDM spectrum using different window filters.

![Figure 2](image)

Fig. 3. BER performance of F-OFDM compared to OFDM (16-QAM).

![Figure 3](image)

Fig. 4. BER performance of F-OFDM compared to OFDM (64-QAM).

![Figure 4](image)

Fig. 5. BER performance of F-OFDM compared to OFDM (128-QAM).

![Figure 5](image)

Fig. 6. BER performance of F-OFDM compared to OFDM (256-QAM).

![Figure 6](image)

Fig. 7. BER performance of F-OFDM compared to OFDM (512-QAM).

![Figure 7](image)
Table II illustrates the maximum better (lower) OOBE of the proposed F-OFDM with some of literatures in comparison to OFDM.

<table>
<thead>
<tr>
<th>Research waveform</th>
<th>OOBE compare to OFDM (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed F-OFDM</td>
<td>-270</td>
</tr>
<tr>
<td>Reference [6]</td>
<td>-120</td>
</tr>
<tr>
<td>Reference [7]</td>
<td>-150</td>
</tr>
<tr>
<td>Reference [8]</td>
<td>-200</td>
</tr>
<tr>
<td>Reference [10]</td>
<td>-20</td>
</tr>
</tbody>
</table>

The second part of Simulink includes an F-OFDM system with four equal sub-band size base parameters introduced in Table I. The power spectrum of F-OFDM shows in Fig. 8 using the Blackman window because it is better in terms of BER compared to its peers in addition to its ability to reduce the OOBE. It can be seen that F-OFDM can realize lower OOBE and reduce the interference between the adjacent sub-bands with a minimum guard band. Furthermore, each sub-band can support different modulation orders.

Fig. 8. F-OFDM four sub-bands power spectrum.

Fig. 9. F-OFDM four sub-bands power spectrum for proposed window1.

Fig. 10. F-OFDM four sub-bands power spectrum for proposed window2.

To improve the SE of F-OFDM, a proposed window1 was utilized in the filter design. The obtained power spectrum is depicted in Fig. 9 with minimum side lobes for each sub-band. As well, window2 is utilized in the designed filter for better enhancement in SE, the spectrum depicted in Fig. 10.

The BER for F-OFDM four sub-bands depicted in Fig. 11 can be observed as a worse case in F-OFDM as compared with OFDM, and the multiplication idea is worsened.

The SE for the waveform is also analyzed by minimizing the guard between the sub-bands. The SE calculated equation below:

$$SE = \frac{R}{BW_{optimized}}$$

where, $R$ is the maximum data rates transmitted and $BW_{optimized}$ is the optimized bandwidth.

It can be shown from Fig. 12 that the SE of four sub-bands is higher than OFDM in all cases, where at lower values of Eb/No the SE achieved is approximately 5% while at higher values of Eb/No the SE achieved is approximately 5.2%.

Fig. 11. BER for F-OFDM four sub-bands equal sizes.

Fig. 12. F-OFDM four sub-bands equal sizes normalized SE.

Fig. 13. F-OFDM power spectrum for unequal sub-bands sizes.
The third part of Simulink contains division of the spectrum into different sub-bands of different sizes with different modulation orders and different filter designs. Higher orders of modulation need a higher passband filter design. Fig. 13 shows the power spectrum of the waveforms where it can be seen that the guard band between the sub-bands varies depending on the sub-band size and QAM order.

The two new proposed windows are also utilized with the same case of unequal sub-band size. The spectrum can be seen in Fig. 14 and Fig. 15.

Finally, the PAPR is also discussed for F-OFDM. It is known that OFDM has higher PAPR results from the addition of multiple subcarriers. Table III contains the comparison between the PAPR of OFDM and F-OFDM. It has been shown that F-OFDM has higher PAPR than those for OFDM, for the reason that the utilized filter causes distribution wide power among the samples, which decreases the average value and results in higher PAPR.

The analysis of BER and SE was observed in Fig. 16 and 17. It can be seen that higher SE can be achieved in the case of unequal-sized sub-bands divisions compared with equal-sized sub-bands. Lower Eb/No values result in SEs of 6%, 5.5%, and 4.6% for the Blackman window, proposed window 1 and 2 filters, respectively, while higher Eb/No values result in SEs of 5.25%, 5.3%, and 6% for the Blackman window filter, proposed window filter1, and proposed window filter2, respectively.

V. CONCLUSION

This paper has proposed F-OFDM as one of the waveform contenders in the 5G system. F-OFDM splits the whole band into narrow sub-bands with equal and unequal sizes to support diversity for 5G services. Each sub-band is filtered with a digital filter that can be adapted to match sub-band specifications. The filter effect using different time-domain window functions has been presented to evaluate the performance on the one hand of BER and OOB suppressions. The simulation results show that F-OFDM sub-bands can increase the SE (5%-6%) compared with conventional OFDM by allowing the sub-bands to overlap at the transition region without interference, thus reducing the guard band.
Furthermore, the performance of F-OFDM in unequal sub-bands provides better SE enhancement, which achieves the requirements of the 5G system guard band. The BER of F-OFDM was also evaluated, and it was observed that at lower values of Eb/No, F-OFDM approximates the performance of conventional OFDM, while at higher Eb/No values the BER performance diverges. The main drawback of using the proposed F-OFDM is higher PAPR nearly (2.5 dB) compared with conventional OFDM, which might affect the performance of the power amplifier at the transmitter.

**CONFLICT OF INTEREST**

The authors declare that they have no conflict of interest regarding this paper.

**AUTHOR CONTRIBUTIONS**

Zhraa Zuheir Prepare the model to be simulate, Data analysis and validation by Dia M. Ali. Manuscript and revisions process prepared by both.

**ACKNOWLEDGMENT**

The authors wish to thank Asst Prof Dr Younis M. Abbosh Head of communication Eng. Dept. for his support and kindness.

**REFERENCES**


Copyright © 2022 by the authors. This is an open access article distributed under the Creative Commons Attribution License (CC_BY-NC-ND 4.0), which permits use, distribution and reproduction in any medium, provided that the article is properly cited, the use is non-commercial and no modifications or adaptations are made.

**Dia M. Ali** was born in Ninevah Province, Iraq, in 1971. He received the B.S. degree from the University of Mosul Iraq, in 1992 and the M.S. degree and Ph.D. from the same University in 1997 and 2008 respectively both in Communication engineering. He is currently Assr. Prof. in Communication Department, Ninevah university. His research interests include Networking, Software Defined Radio and Automation.

**Zhraa Zuheir** was born in 1993 in Mosul/ Iraq. She received B.Sc. In Communication Engineering in 2018 form Communication Department College of Electronics Engineeritg. She is an M.Sc student in Ninevah University College of Electronics Engineering. Now, she is specialized in Simulation, Modeling and SDR.