Architecture Optimization for Filtered Multicarrier Waveforms in 5G

Muhammad Abid1 · Farman Ali2 · Ammar Armghan3 · Fayadh Alenezi3 · Sharoz Khan2 · Fazal Muhammad4 · Maqsood Ahmad Khan2 · Muhammad Salman Qamar2

Accepted: 7 January 2022 / Published online: 2 February 2022
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract
Wireless communication network is the backbone of each and every organization of today modern globe. The rapid emergence of smart devices, smart homes, internet of things and clean energy become key sources in today society. In result the data traffic, emerging of new service and application are increased every year. Hence, there is a growing demand for 5G technology in all above mentioned fields. Therefore, better waveform types for 5G technology is needed, which has ability of high spectral efficiency, lower latency and less complexity. It is predicted that the data traffic will arise 1000× in near future. In this work filtered orthogonal frequency division multiplexing (F-OFDM) and universal filtered orthogonal frequency division multiplexing (UF-OFDM) techniques are discussed to degrade key issues such as computational complexity, peak average power ratio (PAPR), lower spectral efficiency, and higher latency. The suggested work decreases the drawbacks faced by previous work like limited capacity and complexity. We also analyze algorithms and simplification for F-OFDM and UF-OFDM waveforms from an implementation perspective towards low complexity and efficient transceiver design. Moreover, F-OFDM and UF-OFDM are studied based on multicarrier modulation and enabled to reduce to out-of-band power leakage (OOBPL) of OFDM.

Keywords UF-OFDM · F-OFDM · Multicarrier · 5G wireless communication framework

Farman Ali
farman_pukhtun@yahoo.com
1 Department of Electrical Engineering, CECOS University of IT and Emerging Sciences, Peshawar, Pakistan
2 Department of Electrical Engineering, Qurtuba University of Science and IT, D.I. Khan 29050, Pakistan
3 Department of Electrical Engineering, College of Engineering, Jouf University, Sakaka 72388, Saudi Arabia
4 Department of Electrical Engineering, University of Engineering Technology, Mardan 23200, Pakistan
1 Introduction

The Wireless communication network is the heart of each and every organization of today odern globe and the fast emergence of smart devices internet of things clean energy and the smart homes become key sources in today society. The data traffic in result emerging of new service and the application are increase every year. So, there is a growing demand for 5G technology in all above mentioned fields [1]. Therefore, good waveform types for 5G technology is required which has the power of high spectral efficiency less complexity and lower latency. The data traffic is predicted that it will increase by 1000× in near future [2]. The work filtered orthogonal frequency division multiplexing (F-OFDM) and the universal filtered orthogonal frequency division multiplexing (UF-OFDM) techniques will be explained to degrade key issues such as lower spectral efficiency peak average power ratio (PAPR) higher latency and computational complexity [3]. The drawbacks faced by previous work like limited capacity and complexity would clearly vanish by this suggested work. For FOFDM and UFOFDM waveforms we also analyze algorithms and simplification from an implementation perspective towards low complexity and the efficient transceiver design [4]. Furthermore, F-OFDM and UF-OFDM are explores mainly based on multicarrier modulation and this will be enabled to reduce to out of band power leakage OOBPL of OFDM.

1.1 Background of OFDM

The OFDM modulation procedure was firstly developed by Weinstein [5] and due to various properties is widely applied in communication networks. Moreover, OFDM is a multicarrier modulation system which splits the bandwidth into multi narrow band of waves called subcarriers [6]. These subcarriers are then modulated with complex valued symbols from digital modulation system like quadrature amplitude modulation (QAM) for transmission. As a result each propagated subcarrier takes the shape of sin function spectrum, including side lobes that overlapping on each other as declared in Fig. 1. The ∆f represents the frequency spacing and the orthogonally outcomes provides symbols with less distortions. The inverse fast Fourier transform (IFFT) is implemented for OFDM transmitter with N number of size [7].

To transmit the latter are the allocated subcarriers. Here input indexes of the IFFT are directly related to the subcarrier indexes. NC QAM symbols are therefore feed to the corresponding input.

The IFFT obtains time domain of N samples, where then CP is inserted before the first sample of the time domain signal. Thus, obtained time domain signal is written as LCP + N. These steps are repeated for each OFDM symbol for transmitting. The time duration of one OFDM symbol is derived as

\[ T = \frac{(N + CP)}{f_s} \]  

(1)

where \( f_s \) is the frequency sampling in Hz. The used bandwidth is represented by NCΔf, and list of elements used by 4 G are explained in Table 1 with their classification. The duration of each symbol of OFDM is recorded 70.45 µs, which is minimum resource size and is provided for a customer in one resource block (RB). The effective bandwidth as presented in Table 1 is measured as
where $N_{rb}$ is used for number RB. The classification of bandwidth in Table 1 explains that OFDM parameters must be selected for the propagation in the available bandwidth. This concludes that effective bandwidth in 4G LTE is recorded less and available bandwidth as a guard band is limited.

The received baseband signals from OFDM symbol are then transmit to radio frequency (RF) interface which include the following elements.

- To minimize the OOBPL analog filter is applied
- To induce analog signals digital to analog converter is used.
- To amplify the power of signal high power amplifier (HPA) is installed
- To attain radio form of signals Antenna is selected.

The attained signals $r(t)$ by antenna are defined as

$$\text{NC}\Delta f = 12N_{rb}\Delta f \quad (2)$$
\[ r(t) = \int_{0}^{\tau_{d}} h(\tau) s(r - \tau) d\tau \]  
(3)

where \( \tau_{d} \) is the difference among 1\textsuperscript{st} and last signals. The RF waves are calculated as

\[ RF(k) = \sum_{i=0}^{t_{d}-1} h(it_{s}) s((k - i)t_{s}) + z(k) \]  
(4)

The term \( t_{d} \) is the duration in no of sample of the delay and is equal to \( 1/f_{s} \), the noise \( z \) term is added in Eq. (4) due to unbalance among electronic component and RF waves. The multipaths channels introduce a new phenomenon called inter symbol interference (ISI) which cause of the delay samples coming out from OFDM. Furthermore, the CP helps in the compensation of ISI so, for shorter duration the ISI can be ignored. Linear convolution of the FFT is equivalent to circular convolution by reason of CP and can be estimated as

\[ FFT(s \circledast h) = FFT(s) FFT(h) \]  
(5)

The term \( \circledast \) defines the circular convolution. After FFT the achieved signals (X(n)) in the frequency domain are written as

\[ X(n) = Z(n) Y(n) + \alpha(n) \]  
(6)

The orthogonal behavior of time and frequency domains are strengthen for multipath channel transmission with linear implementation applying FFT scheme the OFDM methodology is considered a highlighted solution for IMBB scenario. Furthermore, OFDM has ability to support spatial multiplexing and MIMO services. Suggesting the new multiple services and need of upcoming 5-G technology it is noted that is OFDM has quality of ability to support the 5-G massive data rates challenges.

For 5-G scenario several modified form of OFDM like filtered bank multi carrier (FBMC), UF-OFDM, F-OFDM, and zero tail-OFDM (ZT-OFDM) are analyzed from last decade. This work investigates the F-OFDM and UF-OFDM mechanisms to filter the transmitted symbols.

### 1.2 Background of UF-OFDM Modulation Form

This approach was first developed through the name of universal filtered multi carrier (UFMC). The UF-OFDM aiming to divide the complex samples into sub bands groups, where each group consists of W subcarriers. These complex samples are provided by QAM constellation, using K/W subbands, where K means total number of subcarriers [8]. With addition, each sub band uses filter with length D samples and integral process of filtering of all sub bands is defined as

\[ F_T = N + I - 1 \]  
(7)

The block description of UF-OFDM transmitter is mentioned in Fig. 2, where sub band mapping inserts the complex samples, carrying data into subcarrier. Then N numbers of IFFT size are allocated for each sub band. After IFFT the filtering process is started for each sub band using linear convolution system. The whole filtering procedure are then summed to make UF-OFDM symbol. The important point is in the UF-OFDM mechanism that there is no need of CP.
1.3 Related Work

For the development of the property of the current wireless communication system a range of research processes are investigated. There are some of them discussed as follow. The authors in [12] compare the most favorite candidates for the 5G air interface thoroughly and fairly. The waveform candidates consider are Universal filtered Multicarrier (UFMC), generalized frequency division multiplexing (GFDM), resource block filtered orthogonal Frequency division Multiplexing (RBFOFDM) and Filter bank Multicarrier (FBMC) are called waveform candidates.

These are matched to OFDM used in 4G in form of spectral efficiency numerical complexity toughness towards multi user interference (MUI) and the resilience to power amplifier nonlinearity. The FBMC shows the best spectral containment and to reveals to be almost insensitive to multi user interference. Therefore it suffers from its bad spectral efficiency for short bursts and due to its poor multiple input multiple output (MIMO) compatibility. The GFDM reveals to be the most favorable candidate with the best spectral efficiency and its smallest complexity overhead compared to OFDM. It is also the toughest to multi user interference after FBMC and is MIMO well-matched as soon as the interference can be managed. The UFMC and RB-F-OFDM are lastly the next to OFDM and advantage so form a better compatibility with existing systems even if their performance is normally lower than FBMC and GFDM.

The development in wireless communication the applications inspires the use of active and wellorganized channel estimation (CE) methods because of the fluctuating behavior of the Rayleigh fading channel is analyzed in [13]. Mainly the importance of most proposed CE arrangements is to recover the CE presentation and complication for guaranteeing quality signal reception and better-quality system throughput. The Contender waveforms whose enterprises are based on FBMC modulation methods such as Filter bank orthogonal frequency division multiplexing centered on OFDM-OQAM, UFMC and GFDM-OQAM are no compromise to the use of these offered CE methods in the literature. These activities are considered as potential waveform contenders for the physical media access control layer of the developing fifth generation (5G) networks. So, these pinpoint techniques reflect a huge need for this wave form to reach their maximum potential. In this respect this paper analysis the concept of CE is true for these wave forms and other candidates for waveforms considered in the emerging 5-G technology. So, the plan of the majority of the waveform contenders is filter based analysis of the general filter design considerations is presented in this

Fig. 2 Principle of the UF-OFDM transmitter
paper. Furthermore we examine general CE methods for contender waveforms of next generation networks and categorize some of the studied CE methods. Especially we categorize the CE activities used in filter bank OFDM-QAM and GFDM-QAM based transceivers and present a presentation comparison of some of these CE activities. Similarly for two FBMC Based waveform candidates assuming near perfect reconstruction (NPR) and the non-perfect reconstruction (non NPR) filter design over slow and fast frequency selective Rayleigh fading channel, we examine the presentation of two linear CE activities and three adaptive based CE activities. The findings are recorded through computer simulations, where the efficiency of the studied CE operation is analyzed in term of the normalized mean square error (NMSE). Lastly we summaries the verdicts of this work and propose possible research directions in order to advance the abilities of the studied contender waveforms over Rayleigh fading channels. The authors proposed an assessment under the main key metrics of various 5G waveform entrants OFDM, UFMC, FBMC, and GFDM (KPIs). The scientists and developers are analyzing the specifications of 5G networks for ideal waveform, which will lead to high performance and lower stunted growth with less device complications. This assesses that the main KPI specifies the numerical complexity of the spectral latency and duration from the average power ratio. In the last study, the authors highlighted the strengths and disadvantages of any wave form contain based on the factors of KPI for improved results in the enterprise. The authors also addressed KPI factors in different 5-G waveforms. Indecision The current analysis recommends the use of optimized FBMC and UFMC waveforms to improve the stiffness of early studies to resolve the disadvantages.

As regards FBMC and UFMC, the coexistence in 4G networks with a new framework has improved for the CP-OFDM. The discovery of the new OFDM dependent waveform in 5G and the new modulation scheme should mainly allow for higher specimen performance than the predecessor studied in [14] are among the major open problems of successive wireless networks.Here the key contenders of 3GPP are a new version of OFDM called Filtered OFDM similar to OFDM but with additional filtering, with the goal of reducing OOB emissions from Out Of Band and achieving a better spectral position. The second choice is the OFDM window which is essentially a classic OFDM system with a window and overlap of each symbol in the time domain. In this work we compare classic OFDM signals, each with a number of parameter options and numerologies with the use of Cyclic prefix OFDM with OFDM and WOFDM.

A multirate transmitter operating simultaneously with various numerologies is considered to evaluate and interpolate the transmitted sub bands to generate signal. Sliding window is generalized by time domain linear minimum mean square error (TD-LMMSE) method for 5-G waveform in [15]. In another work [16], the researchers analyzed (F-OFDM) and UF-OFDM based on key performance indicators technique. Finite impulse response (FIR) filter technique is implemented in [17] for F-OFDM waveforms to enhance suitability of 5-G in terms of complexity and vehicle to vehicle communication. In [18], the authors have studied a novel Stochastic Learning Automata has been suggested as the load balancing function in which approximately the same quality level is provided for each subscriber. This framework can also be effectively extended to cloud-based systems, where adaptive approaches are needed due to unpredictability of total accessible resources, considering cooperative nature of cloud environments. All these mentioned trends are limited either by the complexity or less analyzed techniques. Hence forth, in this work, multiple candidate waveforms for 5-G is investigated, such as Universal-Filtered Orthogonal Frequency-Division Multiplexing (UF-OFDM) and Filtered- Orthogonal Frequency-Division Multiplexing (F-OFDM).
These two candidate waveforms are mainly based on multicarrier modulation with specific filtering scheme used on the top of the OFDM basis. The filtering operation is applied in digital domain, before transmitting the baseband discrete signal to the digital-to-analog converter (DAC).

2 Novel Short Prototype Filters for FBMC

Recent research groups have found the OQAM or FBMC to be one of the most effective rivals in waveform to meet the requirements for new 5G communication channel, which produced excellent spectral form and boosts support for mobility in comparison to OFDM using a frequency and time localized PF. In fact, in response to the edge structure in the communication system, the choice of this philtre will affect the changed level of performance knowingly. The length of the prototype philtre also greatly impacts the complication and expectation of the transceiver. The careful design of new prototype philtres is therefore extremely useful in increasing FBMC and OQAM intensity against channel deficiencies and in fulfilling the new requirements imposed by 5G scenarios. A new short prototype philtre is developed and provided in this chapter. In this context, this proposed philtre enables almost complete reconstruction and has the same size as the 1 OFDM symbol.

2.1 Transceivers FBMC/OQAM

The multicarrier FBMC is a transmission pattern that presents a filter bank to enable well-organized pulse shaping for the signal taken on each individual subcarrier. The additional element signifies a collection of band pass filters that distinct the input signal into numerous components or subcarriers each one carrying a sole frequency sub band of the original signal. For instance a promising variant of filtered modulation patterns FBMC originally proposed in [18] and also known as OFDM and OQAM [24] or Stunned Modulated Multirole (SMT) [19] can possibly achieve a developed spectral efficiency than OFDM since it does not require the insertion of a CP. The Further benefits include the toughness against highly irregular fading channel conditions and faulty synchronization by selecting the appropriate PF type and coefficients [20]. The practice of digital poly phase filter bank structures [21, 22], together with the rapid growth of digital processing capabilities in recent years have made FBMC a practically possible approach and in this literature 2 types of implementation for the FBMC modulation exist each having different hardware complexity and performance. The first one is the PPN implementation [23] which is based on an IFFT and a PPN for the filtering stage and enables a low complexity implementation of the FBMC transceiver. The 2nd type of implementation is the FS implementation suggested in [24], with the PF with a corresponding factor equal to 4 considered for FBMC during PHYDYAS Project [25]. The unique idea was to shift the filtering stage into the frequency domain in order to enable the use of a low difficulty per subcarrier equalizer as in OFDM. And the hardware difficulty is supposed to be higher than the difficulty of the PPN implementation as a minimum for long PFs. In fact, it requires one FFT of size $L = KM$ per FBMC symbol, where $K$ is the overlapping factor of the PF and where miss the total no of available subcarriers. But in the short PF case ($K = 1$) the size of the FFT is same as for the PPN implementation.
2.2 Fundamentals of CP-OFDM with Spectral Enhancement Techniques

The start of OFDM in wireless networks has changed telecommunications in a way that OFDM is fundamental to most wireless technology today. The OFDM separates the range into orthogonal and overlapping minor bands known as subcontractors. If the difference between the subcompanies is small with respect to the coherence of the channels bandwidth, on each subcarrier simplifying the equalisation phase, the channel properties could be approximated as constant [26]. In addition, OFDM transmits cyclic prefix (CP) information with circular extension, allowing us to model the frequency selective channel effect as a circular convolution. This further simplifies the method of channel equalization. In addition, OFDM is efficiently applied with the fast Fourier transformation (FFT) leading to very basic machine complexity multiaccess schemes. Therefore, OFDM based on FFT will simplify the manipulation of bandwidths and central frequencies between various users. OFDM also makes it easy to incorporate MIMO deployments directly [27]. OFDM has its own drawbacks, however which threaten its use in 5G NR. The OFDM usually leaks highly powered side lobes around the active bands, ensuring that high power OOB leakage forces hold guard bands around active bands on every OFDM channel. In order to prevent ISI and ICI, OFDM should also ensure a timely and frequency synchronisation. In addition, OFDM performance has a significantly high PAPR, which results in spectrum development due to nonlinearity of the power amplifier (PA).

2.3 CP-OFDM implementation

The arriving low rate specific samples of rated orthogonal alternating subbands which are usually referred to as subcontractors are modulated by NormalCP-OFDM transmitters. The CP-OFDM transmitter is only used by IDFT, which modulates input data at cheap rates to orthogonal frequencies. The Fourier Rate Transform (ITFT) algorithms like radix2 or break radix can be used to apply the IDFT block efficiently. Using the IFFT block, the categorization of the block sample stream into blocks of IFFT size N is required. After the IFFT, the samples are repeated at the end.

3 Proposed Filtered-OFDM

This section discusses the description of OFDM with its internal framework and features compare to current system. This waveform is much more compatible in several forms as compared to conventional OFDM. First of all, in light of conventional OFDM is commonly used in LTE/LTE-A in these days. In which a fused numerology is used in all assigned bandwidth. Available bandwidth in F-OFDM has man sub-bands which perform multiple services and has different numerology. To empower extensibility of physical layer F-OFDM is the best available integrant and this will be the essential need in the upcoming mobile communication technology e.g. (5G). Secondly, although OFDM is inspected more spectrum efficient, 10% BW is destructed because of allowance of signal attenuation. F-OFDM is better solution and certainly we can do more precisely. Because of the suppressed OOB filters the necessity of guard band is compromised. Thirdly, orthogonality can be achieved in OFDM regarding frequency and time, additional signaling is required to ensure synchronization especially for up-link transmission. Reduction in performance occurs due to
failure in perfect synchronization. Uncompromising synchronization is relaxed in f-OFDM. Also, the filter parameters and techniques will be examined. This chapter is all about initial framework for f-OFDM.

3.1 General Framework

To increase the data rate in 5G larger bandwidth (100–200 MHz) will be required. In f-OFDM technique sub banding of the bandwidth will happen each band will be filtered individually. This is how we can break apart time domain orthogonality across f-OFDM symbols for lower OOB.

Consecutively, the supportive asynchronous transmission in sub-bands occurs. Sub carrier spacing, length of CP and transmission time interval is different in each sub-band. Type of traffic will decide which type of service different band will provide (Fig. 3).

We can see in Fig. 4 frequency time changes according to the type of service, this shows the different f-OFDM waveform. Let us take IOT, in IOT single carrier modulation scheme will be used instead of OFDM.
While in case of M2M communication, high reliability and ultra-low latency are must. Hence, to achieve lower latency in transmission a very short TTI is required. Different numerology is needed in different services and f-OFDM has power to enable it. Nonetheless, to design proper filter the performance is bounded in different situations.

3.2 F-OFDM Transceiver

We can see in Fig. 5, down link of f-OFDM, in this scenario-based station (BS) which is depending on service request, multiple numerology can be applied. CP length, IFFT length and different subcarrier spacing are the main examples.

To match the BS side and to take the required service UE perform filtration under filtering parameters at the user’s equipment (UE).

We can also use same example in uplink case in which every UE will forward data to BS and perform filtration in every sub-band resided for many types of services.

This is important to notice in case of uplink of f-OFDM due to the well reside frequency the synchronization of wavelength is relaxed. The f-OFDM symbol can be mathematically explained. Operation which are need at the receiver and transmitter are important to understand. To know how it is done, consider an uplink contain M UE transmitting at BS. Let us start from discrete time.

\[
W_u(x) = \frac{1}{\sqrt{X}} \sum_{i=0}^{l-1} c_i e^{j2\pi i x/X}
\] (8)

Fig. 5 Block description of F-OFDM
And reminding that filtering operation is a convolution operation from the mathematical point of view, we can finally write:

\[ W_u(x) = w_u \ast \theta_u(x) \]  

(9)

where \( W_u(x) \) is the signal of the u-th UE and \( \theta_u(x) \) is the particular filter. The spectrum shaping filter \( \theta_u(x) \) should be appropriately designed in order to suppress only the out of band emissions. It shows that the central frequency must be located in middle of subcarriers which are assigned and filtered band pass must be included in all subcarriers of OFDM symbol.

The below form of equation representing the signal received at BS end:

\[ g(x) = \sum_{u=1}^{M} S_u(x) \ast h_u(x) + w_u(x) \]  

(10)

where \( M \) is the number of UEs, \( S_u(x) \) is the signal coming from u – the UE, \( h_u(x) \) is the channel impulse response of the u – th channel and \( w_u(x) \) is the noise. The BS receives the signal \( g(t) \) and passes it through the filter \( \theta_u^*(x) \) which is matched with the transmitter filter of each UE \( \theta_u^* \).

\[ g_u(x) = g(x) \ast \theta_u^*(x) \]  

(11)

The part of the coordinated channel is to dismiss the obstruction from other UEs and it boosts the signal to noise (SNR). The BS ought to have a bank of channels, to get the symbol from every UE. To avoid degraded performance each filter, BW and centered frequency should be matched. The end-to-end channel \( \theta_x(x) \ast h_x(x) \ast \theta_u^*(-x) \) should be estimated and equalized at the receiver. While maintaining all the advantages we will still have increased complexity because of filtration at receiver and transmitter.

### 3.3 Filter Design

Whenever we have to design and implement a filter, we have to take into account the trade off between time and frequency localization of the filter [13, 14]. Long filtration in time domain would give us much better spectrum containment, that means much better suppressing of the band emissions and vice versa. To take advantages of f-OFDM a well-designed technique must be implemented. It is very complicated to choose a best filter. Yet in the related scientific papers, in topics [12, 15], we’ll choose soft-trimmed filter.

#### A. Soft-Truncated Filter

As we know, an infinite sinc function within the time domain, gives us the perfect low pass filter. With unitary amplitude all frequencies below the stop are going to be passed and other frequencies are going to be blocked. This is able to be ideal if we will implement it, however we cannot filter our signal for an infinite time. Therefore, it’s important to truncate the sinc-function, leading us to the windowed-sinc filter or called differently soft truncated filter. We’ll implement the filter within the discrete time domain, so we’ll consider the discrete time representation of the filter. Known windowing capacities [16] are needed to shorten sinc work:

Rectangular:
While taps of the discrete time filter shown by M and it calls the filter length and I1 to I4 are the normalization factors. \( n = 0; 1; \ldots; M \)

Analyzing these equations, it is obvious that the window which allows to have a better attenuation in the stop band is the Blackman window. On cost of high transition band, it gives less ripples in the pass band, is one of the advantages. For performing simulations, we are going to choose the Blackman windowed sinc filter. Any kind of window can be a good choice rather than using rectangular one.

Hence the below mathematical equation is expressing our filter:

\[
 h(x) = I_4 \sin \left( x - \frac{M}{2} \right) \left[ 0.2 - 0.5 \cos \left( \frac{2\pi x}{M} \right) + (0.04) \cos \left( \frac{4\pi x}{M} \right) \right]
\]

4 Proposed Low-Complexity Transmitters for UF-OFDM

The promising waveform is UF-OFDM waveform as it combines the better spectral properties with the advantages of OFDM and with better-quality strength against time frequency randomness. Though, its key disadvantage exist in the transmitter computational complexity to reaching up to two hundred times that of OFDM. If no oversimplification is applied. While still of great complexity new proposed simplification methods meaningfully negotiate the gained spectral detention by approximations of signal. Considering this a UF-OFDM transmitter having unique low complexity deprived of any signal value loss is suggested and for little subbands sizes the difficulty becomes same like OFDM without no of owed subbands. Moreover, the suggested style of transmitter is elastic and without any difficulty it can be modified to sustenance modulation of OFDM. The section is ordered as follows. The first part offers a analysis on present implementations of transmitter (UFOFDM) and the great difficulty of these methods is pointed and the requirement to find out the less difficulty practices deprived of debasing the quality of signal point us to present a unique transmitter (OFDM) and the plan of style of the given transmitter are complete which is revealed that the presented transmitter which is offered of UFOFDM can be simply adjusted to sustenance OFDM broadcast. The Logical complication link is
delivered for multiple formations matching to the exciting cases when a client reside all the existing bandwidth (BW) to attain larger rates of data.

4.1 UF-OFDM Baseline Source

The standard regarding modulation of UF OFDM is the collection of the composite trials transporting info into some sub-bands each self-possessed of $Q$ subcarriers and these difficult samples can be, for example signs from a QAM group. The extreme of $K = \frac{N}{Q}$ small bands can be used for carrying these $Q$ carriers where $N$ is the overall no of subcarriers, and here $\lfloor x \rfloor$ shows the biggest value of integer fewer than or equivalent $x$ operator of floor. The second portions having the residual power exterior to each small bands are attenuated by self-regulating subbands wise filtering of length $L$ samples and ensuing distinct signals interval shows the summation of the cleaned subbands signals originating which also make the UF OFDM sign and made of $N + L - 1$ trials. This starting position of UFOFDM transmitter is signified in Fig. 6

Several Methods with small calculation difficulty have been examined in the works. Also between current methods one spread over the small band domain of frequency in place of the interval of time domain and a 2nd part which estimates the UF OFDM signal by decaying it into more than one part signals of OFDM which are collected. And these methods are studied in the subsequent subsets which reduces the calculation difficulty of source of UFOFDM. Then the price of a lowering of the genuine signal.

4.2 The Proposed Low Complexity UF OFDM Transmitter

The Easiest UFOFDM transmitters, a negotiation must be found b/w quality and difficulty. Therefore a original UF OFDM method that decrease the calculation difficulty to an satisfactory range without changing the unique signal is of larger attention. Here the suggested method fulfill this area by dividing an exact breakdown into small band and subcarrier processing.
So, this proposed method feats 2 major thoughts to decrease the calculation difficulty of the UF OFDM starting position application. In beginning the essential treating of UF OFDM is distributed into small band-wise and in a way the subcarrier wise calculations is evaded to terminated processes particularly when a high no of small bands are allocated and the 2nd main impression is to allocate into the prefix core of the UF/OFDM sign into and the suffix section. Which are proficiently treated by developing the earlier subbands wise decay and the subcarrier wise decay management. Here the portion of suffix is gathered through the central and the portion of the prefix by a humble deduction and 2 core thoughts feat the UF-OFDM starting equation. So, the resultant signal is without change when linked to this initial solution.

Here the presented UF OFDM source is explained in Fig. 7 and are discussed in short 8 steps:

1. In here the compound Part of transmitter symbols $c$ into Q subcarriers of B subbands.
2. To Figure out the extent of IFFT the $K$ is divided into trials from point 1 analogous to the subcarrier $q$ of every of the $K$ small bands and these IFFT need to be calculated multiple times for every small bands $q \in J_0$, $Q-1$ $K$ to gain the $xq(n)$ trials.
3. Next is to Increase the $xq(n')$ trials from point 2 by the constants of SBF $Fq(n')$ to get the trials $zq(n')$.
4. To Analyze IFFT the extent $Q$ of the trial $zq(n')$ for the $n$-th specimen key of every of the $Q$ carriers and the given IFFT need to be calculated $K$ times, for each model, to gain the divided examples $yp(n')$.
5. To Improve the central UF OFDM portion of the sign by the uneven examples $yp(n')$.
6. To Examine the preface UF OFDM share of the $x$ sign by increasing the $xq(np)$trials by the preface end constants $P q (n p)$, and by adding $t q \in J_0$, $Q-1$ $K$.
7. To Calculate the UF OFDM affix portion of the sign $y$ affix ($ns$) by deducting the examples of the central part $y$ core ($ns$) by the trials of the append section $y$ append ($ns$) for $ns \in J_0$, $L2K$.

Fig. 7 Proposed UF-OFDM transmitters
Step 8) the prefix section need to be Concatenate to the core section and the affix section to gain the UF OFDM sign.

5 Results and Discussion

In order to explore the outcomes of the projected objectives MATLAB simulation software is used in this research work, which gives the results related to real world applications and can be applied for practical implementations. Table 2 explains the list of parameters used for simulation analysis.

Figure 8 contains the results related to F-OFDM, UF-OFDM and OFDM in terms of normalized signal to noise ratio and bit error rate (BER). The results clarify that the results of UF-OFDM and F-OFDM are efficient than current OFDM format.

The symbols of UF-OFDM and F-OFDM are less interrupted from the ripples as compare to OFDM format. Thus, due to these reason the performance of the OFDM and other modulation schemes are slower. Moreover, above one normalized signal to noise ratio difference is recorded among the presented and modulation formats and current modulation formats. In order to investigate the PAPR of the proposed technique the complementary cumulative distributed function (CCDF) is described. The CCDF is

| Parameter                      | Values         |
|--------------------------------|----------------|
| FFT/IFFT size                  | 512–2048       |
| Number of resources blocks     | 50             |
| Number of subcarriers per resource block | 12–24       |
| Cyclic prefix length           | 40             |
| Filter length                  | 513            |
| Channel model                  | AWGN           |
| Channel bandwidth              | 5 (MHz)        |

Fig. 8 Performance of comparison of the proposed F-OFDM, UF-OFDM with OFDM
probabilistic mechanisms includes further several methods for evaluating the PAPR for the model which are clipping, coding and signal processing. In this work the PAPR is estimated utilizing the properties of OFDM, UF-OFDM and F-OFDM signals. PAPR is actually however the ratio among maximum instants power and average power.

Figure 9 elaborates the performance comparison of UF-OFDM, F-OFDM, OFDM and UMFC techniques for reduction of PAPR using CCDF methodology. The efficient reduction in PAPR is noted for the system working on UF-OFDM based modulation scheme. About 6.5 dB is recorded while 9 dB PAPR is attained using the F-OFDM system. So, it is found from Fig. 9 that UF-OFDM and F-OFDM based communication frameworks are designed less complex as discussed in Sects. 3 and 4 which in turn gives fast response as compare to complex OFDM and UFMC procedures. The highest PAPR noises are included in UGMC based model which is about 12 dB; it takes huge amount of input power to transmit the high capacity data.

Power spectral density (PSD) is widely used for calculating modulated carrier signals and orthogonally properties. The PSD is measure as

$$PSD_x(t) = \sum_{i=-\infty}^{\infty} c(i)p(t-iT)$$

where \(c(i)\) is infinite number of symbols, \(PSD_x(t)\) is the random process of stationary signals.

Based in the valuable properties of the PSD the proposed is analyzed and compared with current used techniques in terms of PSD. Figure 10 presents the PSD against the frequency, which shows the smooth orthogonal behavior of the proposed UF-OFDM signals. As to the PSD characteristics of UF-OFDM technique the F-OFDM gives a bit distort PSD as depicted in Fig. 11.

Similarly, Figs. 12 and 13 include the PSD performance of the current OFDM and UFMC procedures, and clarify that is model provides worst orthogonally as compare to F-OFDM and UF-OFDM. The quality of the achieved are distorted badly, hence, more filter process and modification mechanisms are required to improve the quality of the
signals. As a result, the system efficiency, cost, latency, and complexity is increased several folds as compared to the proposed model.

Another fruitful methodology known as impulse response is used for estimating the channel estimation to check the response and quality of the achieved signals. Figures 3.7 to 3.10 simulate the efficiency of the impulse response for UF-OFDM, F-OFDM, OFDM, and UFMC techniques. The results in Figs. 14 and 15 conclude that the efficient response is attained by the UF-OFDM and F-OFDM while the diverse response is noted by the techniques like OFDM and UFMC as mentioned in Figs. 16.
and 17. The outcomes of F-OFDM and UF-OFDM presented 5-G waveforms are compared with current approaches as mentioned in Table 3.

6 Conclusions

The demands of high capacity and securable wireless communication are increasing exponentially from last decade. To facilitate users with these demands the current system induces huge amount of impairments such as peak to average power ratio, and signal degradation etc. This thesis elaborates the background of wireless communication and issues
which are generated in current 4 G wireless technology. The fundamental elements of orthogonal frequency division multiplexing (OFDM) modulation schemes, including limitations to support current demands are investigated. The proposed filter-OFDM (F-OFDM) and universal-F-OFDM (UF-OFDM) are discussed briefly in this chapter. The problem statement and key objectives of the proposed approach are analyzed in detail. This thesis explains the background of OFDM modulation schemes and its functions in 4-G technology. It is studied that demands of massive capacity, lower latency and high reliable communication set up are increased. The current OFDM system is insufficient to accommodate the high capacity users. The upcoming 5-G technology is explained in detail with outstanding features. In this thesis the background of the study is discussed. It is conducted from related work that the current model contains complex and costly structures. The mechanisms like MIMO-OFDM, UFML, RB-F-OFDM and GFDM are limited to support current

![Impulse Response](image1)

**Fig. 14** Impulse response of F-OFDM

![Impulse Response](image2)

**Fig. 15** Impulse response of UF-OFDM
Table 3  Comparison of the proposed candidates with current systems

| Methodology          | [40] | [41] | Presented work          |
|----------------------|------|------|-------------------------|
| Candidate for 5-G    | UFMC | F-OFDM | F-OFDM, UF-OFDM         |
| waveforms            |      |      |                         |
| PAPR                 | 13   | 11   | 7 to 8                  |
| BER                  | $10^{-4}$ | $1.4 \times 10^{-5}$ | $10^{-7}$          |
| Data rate            | 10 Gbps | 60 Gbps | 100 Gbps               |
| Channel model        | AWGN | AWGN | AWGN                    |
| filter length        | 513  | 500  | 450                     |
demands. In this research work F-OFDM is presented. OFDM was compared to other techniques and the main feature F-ODM was studied. The process to analyze f-OFDM filter which are characterized and Interpretation of F-OFDM was shown. The new UF-OFDM method with little computational difficulty is presented and the major characteristics of this new method is that different from the ones proposed in the literature it does not present any estimate of the original signal and additionally suitable results have been complete to back up any small bands size as distinct in 4G LTE numerology. The Comparisons were done with the methods existing in the literature utilizing altered sets of small bands allocations and the subbands sizes. So, this effects show that the suggested UF-OFDM method offers significant computational difficulty decrease in utmost cases and at last power spectral density appraisals were performed displaying that the suggested method reserves the spectral confinement of UF-OFDM, differing from the newly presented TDW-UF-OFDM method Which proves that for the 1st time the chances to design a low complexity UOFDM transmitter without decreasing he quality of any signal making the UF-OFDM mainly appealing for adoption in upcoming wireless uses and standards. Acceptable framework of communication system is the key goal of current era, which can provide high data rate and high capacity services to the users with less error rate. This research work proposes the achievements of F-OFDM and UF-OFDM schemes based accurate transmission, including high capacity and less error rate. In the previous chapters the background and proposed models are studied for F-OFDM and UF-OFDM in detail with mathematical approaches. The performance assessments of F-OFDM and UF-OFDM related with current methodologies are analyzed in this chapter using simulation setups. Analyzing the UF-OFDM and F-OFDM parameters to boost up the wireless communication system are the goals of this research model. This simulation model is explored based on the mathematical background explored in Sects. 3 and 4. The simulation results are designed for the important parameters like PAPR, frequency, normalized signal to noise ratio using BER and PSD modern approaches. The results are compared among different already used approaches such as OFDM and UFMC. It is found that the proposed UF-OFDM and F-OFDM are out performed as compare to OFDM and UFMC models.

Authors’ Contribution Conceptualization, FA, MA; methodology, AA, MA; software, FA, MSQ; validation, FM, ST; formal analysis, MAK, FA; data analysis, MA; writing–original draft preparation, FA, MA.

Funding Not Applicable.

Data Availability Any kind of data related to research work can be provided as per Requirement.

Code Availability The code is available as per requirement.

Declarations

Conflict of interest The authors declare no conflict of interest.

References

1. Nissel, R. et al. (2017). Filter bank multicarrier modulation schemes for future mobile communications. *IEEE Journal on Selected Areas in Communications*
2. Haykin, S. O. (2013). Adaptive filter theory. Pearson Higher Ed.
3. Nadal, J., Nour, C., & Baghdadi, A. (2016). Low-complexity pipelined architecture for FBMC/OQAM transmitter. *IEEE Transactions on Circuits and Systems II: Express Briefs*, 63(1), 19–23.

4. Nam, H., et al. (2016). A new filter-bank multicarrier system with two prototype filters for qam symbols transmission and reception. *IEEE Transactions on Wireless Communications*, 15(9), 5998–6009.

5. Vakilian, V. et al. (2013). Universal-filtered multi-carrier technique for wireless systems beyond lte. In: Globecom Workshops (GC Wkshps), IEEE. IEEE, 2013, pp. 223–228.

6. Berardinelli, G., et al. (2016). Generalized dft-spread-ofdm as 5g waveform. *IEEE Communications Magazine*, 54(11), 99–105.

7. Fuhrwerk, M., et al. (2017). Scattered pilot-based channel estimation for channel adaptive fbmc-oqam systems. *IEEE Transactions on Wireless Communications*, 16(3), 1687–1702.

8. Zhou, J. et al. (2016). FOFDM based on discrete cosine transform for intensity-modulated and direct-detected systems. *Journal of Lightwave Technology* 34(16), 3717–3725. https://doi.org/10.1109/JLT.2016.2586526.

9. Zhou, J., Qiao, Y., Cai, Z., & Ji, Y. (2015). Asymmetrically clipped optical fast ofdm based on discrete cosine transform for IM/DD systems. *Journal of Lightwave Technology*, 33(9), 1920–1927.

10. Qiu, Y., Liu, Z., & Qu, D. (2017). Filtered bank based implementation for filtered OFDM. In: 2017 7th IEEE International Conference on Electronics Information and Emergency Communication (ICEIEC), Macau, 2017, pp. 15–18. https://doi.org/10.1109/ICEIEC.2017.8076502.

11. Balint, C. & Budura, G. (2018). OFDM-based multi-carrier waveforms performances in 5G. In: 2018 International Symposium on Electronics and Telecommunications (ISETC), Timisoara, pp. 1–4.

12. Hammoodi, A., Udah1, L., & Abas Taher, M. green coexistence for 5G waveform candidates: A review’, *IEEE Access*. https://doi.org/10.1109/ACCESS.2019.2891312

13. Shahbaz, M. M., Wakeel, A., Junaid-ur-Rehman, & Khan, B. (2019). FPGA based implementation of FIR filter for FOFDM waveform. In: 2019 2nd International Conference on Communication, Computing and Digital systems (C-CODE), Islamabad, Pakistan, 2019, pp. 226–230.

14. Matthe, M. Zhang, D., Schaich, F., Wild, T., Ahmed, R. & Fettweis, G. (2016). A reduced complexity time-domain transmitter for UF-OFDM. In: 2016 IEEE 83rd Vehicular Technology Conference (VTC Spring), pp. 1–5.

15. Pérez Santacruz, J., Rommel, S., Johannsen, U., Jurado-Navas, A., & Tafur, M. I. (2020). Candidate waveforms for ARoF in beyond 5G. *Applied Sciences*, 10(11), 3891. https://doi.org/10.3390/app10113891

16. Noque, D. F., et al. (2018). Thermal and dynamic range characterization of a photonicsbased RF amplifier. *Optics Communications*, 414, 191–194.

17. Mohajer, A., Bavaghar, M., & Farrokhi, H. (2020). Reliability and mobility load balancing in next generation self-organized networks: Using stochastic learning automata. *Wireless Personal Communications*, 114(3), 2389–2415.

18. Luvisotto, M., Pang, Z., & Dzung, D. (2019). High-performance wireless networks for industrial control applications: New targets and feasibility. *Proceedings of the IEEE*, 107(6), 1074–1093.

19. Yusuf, İ. T., Elif, B. T., Asuman, S., & Ali, Ö. (2021). A new PAPR and BER enhancement technique based on lifting wavelet transform and selected mapping method for the next generation waveforms. *AEU—International Journal of Electronics and Communications* 138, 153871.

20. FANTASTIC-5G, Deliverable D2.1. (2016). Air interface framework and specification of system level simulations.

21. Abdullahi, A. B., Uggalla, L. C., Caldeirinha, R. F. S., & Eastment, J. (2021). Proposed 5G waveforms performance evaluation with multi-antenna MIMO system. *Telecoms Conference (ConTEL), 2021*, 1–6. https://doi.org/10.1109/ConTEL50222.2021.9435484

22. Bockelmann, C., Pratas, N., Nikopour, H., Au, K., Svensson, T., Stefanovic, C., Popovski, P., & Dekorsy, A. (2016). Massive machine-type communications in 5g: Physical and mac-layer solutions. *IEEE Communications Magazine*, 54(9), 59–65.

23. Khan, B. & Velez, F. J. (2020). Multicarrier waveform candidates for beyond 5G. In: 2020 12th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), 2020, pp. 1–6. https://doi.org/10.1109/CSNDSP49049.2020.9249568

24. Hofeld, B., Wieruch, D., Wirth, T., Thiele, L., Ashraf, S. A., Huchshe, J., Aktas, I., & Ansari, J. (2016). Wireless communication for factory automation: An opportunity for lte and 5g systems. *IEEE Communications Magazine*, 54(6), 36–43.

25. Zaidi, A. A., Baldemair, R., Tullberg, H., Bjorkegren, H., Sundstrom, L., Medbo, J., Kilinc, C., & Silva, I. D. (2016). Waveform and numerology to support 5g services and requirements. *IEEE Communications Magazine*, 54(11), 90–98.
26. Eldessoki, S., Holfeld, B., Wieruch, D. (2017) Impact of waveforms on coexistence of mixed numerologies in 5G URLLC networks. In: WSA 2017; 21th International ITG Workshop on Smart Antennas, pp. 1–6.
27. Qu, D., Wang, F., Wang, Y., Jiang, T., & Farhang-Boroujeny, B. (2017). Improving spectral efficiency of fbmc-oqam through virtual symbols. *IEEE Transactions on Wireless Communications, 16*(7), 4204–4215.
28. Wang, J., et al. (2017). ‘Spectral efficiency improvement with 5G technologies: Results from field tests.’ *IEEE Journal on Selected Areas in Communications, 35*(8), 1867–1875.
29. Ijaz, A., Zhang, L., Xiao, P., & Tafazolli, R. (2016). Analysis of candidate waveforms for 5G cellular systems. Towards 5G Wireless Networks—A Physical Layer Perspective, H. K. Bizaki, Ed. Rijeka, InTech, 2016, ch. 1.
30. Ahmed, R., Wild, T., & Schaiach, F. (2016). Coexistence of UF-OFDM and CP-OFDM. In: Proceedings of IEEE 83rd Vehicle and Technology Conference (VTC Spring), pp. 1–5.
31. Vannithamby, R., & Talwar, S. (2017). Towards 5G: Applications, Requirements and Candidate Technologies. Wiley.
32. Bandari, S. K., Vakamulla, V. M., & Drosopoulos, A. (2017). ‘PAPR analysis of wavelet based multi-taper GFDM system.’ *AU-International Journal of Electronic and Communications, 76*, 166–174.
33. Tipøn, M. N., Jimønez, M. N., Cano, I. N., ArØvalo, G. (2017). Comparison of clipping techniques for PAPR reduction in UFMC systems. In *Proceeding of IEEE 9th Conference Latin-American Conference Communications. (LATINCOM)*, 2017, pp 1–4.
34. Rong, W., Cai, J., & Yu, X. (2017). ‘Low-complexity PTS PAPR reduction scheme for UFMC systems.’ *Cluster Comput.*, 20(4), 3427–3440.
35. Huawei, H. (2016). f-OFDM Scheme and Filter Design, R1–165425. [Online]. Available: www.3gpp.org
36. 4G America Community, (2015). 5G Spectrum Recommendation, White Paper. 5GA 5G Spectrum Recommendations 2017 FINAL.pdf. http://www.5gamericas.org/files/9114/9324/1786/
37. Robin, G., Nikolaos, B., Leonardo, G. B., Vincent, B., Jean-Baptiste, D., Dimitri, K., Oriol, F.-B., Xavier, M., Miquel, P., Michael, F., & Kilian, R. (2017). The 5G ‘candidate waveform race: a comparison of complexity and performance. *EURASIP Journal on Wireless Communications and Networking* 2017(1), 29.

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Muhammad Abid did B.Sc. and M.Sc. in Electrical Engineering from CECOSE University of Engineering and Technology Peshawar- His research area are Photonics and Optical Communications.

Farman Ali did his B.Sc. and MS in Electrical Engineering from Sarhad University of Information Technologies Peshawar in Electrical Engineering in 2011 and 2014, and the Ph.D. degree from the Iqra National University, Peshawar, Pakistan in 2019. Currently he is working as an Assistant Professor at Qurtuba University of Science and IT, Dera Ismail Khan, Pakistan. His research area is Long haul Optical Networks and nonlinear issues in optical communications, Wireless Sensor Network, Smart Grid, Power Generation and Distribution and Machine Learning.

Ammar Armghan was born in Faisalabad, Pakistan, in February 1984. He received B.S. degree in Electrical Engineering from COMSATS University in 2006 and M.S. degree in Electronics and Communication Engineering from University of Nottingham in 2010. In 2006, he joined School of Electrical Engineering, The University of Faisalabad, as a Lecturer. In 2016, he received a Ph.D. degree from the Wuhan National lab of optoelectronic, Huazhong University of Science and Technology, Wuhan, China. He is currently
working as an Assistant Professor. His research interest includes complementary metamaterial based microwave and terahertz devices.

Dr. Fayadh S. Alenezi is an Assistant Professor in the Department of Electrical Engineering at Jouf University, Sakaka, Saudi Arabia. He received the B.Sc. degree (Hons.) in Electrical Engineering Electronics and Communications Track from Jouf University, Saudi Arabia in 2012, and the M.S. degree Electrical Engineering from Southern Illinois University Carbondale, Illinois, the USA in 2015, and the Ph.D. degree in Electrical Engineering from the University of Toledo, Ohio, the USA in 2019. Alenezi has authored several journal and conference papers. His research interests include artificial intelligence, image processing, signal processing, image enchantment, machine learning, neural networks, and facial recognition. Over 20 scholars have cited his research on image processing.

Sharoz Khan did his B.Sc. in Electrical Engineering from Qurtuba University of Science and Information Technology, Dera Ismail Khan, Pakistan in 2021. During his bachelor’s, he had a keen research interest he started to learn and develop research-based skills which ultimately led him to wrote his research paper. Currently, is looking forward to pursuing his MS in Electrical Engineering from Hungary on a fully-funded scholarship. He is currently working as Sales Engineer Solar at Exide Pakistan Limited, Lahore Pakistan and his research interests include Renewable energy, Internet of Things, Artificial intelligence, Radar & Communication.

Dr. Fazal Muhammad received the B.Sc. and M.S. degrees in Electrical Engineering from the University of Engineering and Technology, Peshawar, Pakistan, in 2004 and 2007, respectively, and the Ph.D. degree from the Ghulam Ishaq Khan Institute of Engineering Science and Technology, Topi, Pakistan, in 2017. In 2017, he joined the City University of Science and Information Technology, Peshawar, as an Assistant Professor. His research is focused on the modeling and analysis of heterogeneous cellular networks using tools from stochastic geometry, point process theory, and spatial statistics. His other research interests include interference channels, cognitive radio networks, and optical networks.

Maqsood Ahmad Khan did his BSc in Electrical Engineering from UET Peshawar and MSc from Sarhad University Peshawar. His research interest is wireless communication and optical communication systems. Currently, he is working as a lecturer at Qurtuba University of Science and IT.

Muhammad Salman Qamar did his B.Sc. in Electronics Engineering from COMSATS University, Abbottabad, Pakistan in 2011, M.Sc. Electrical Engineering from COMSATS University, Attock, Pakistan in 2014 and currently he is pursuing his PhD in Electrical Engineering from International Islamic University Islamabad, Pakistan. He is working as an Assistant Professor at Qurtuba University of Science & IT D.I.Khan, Pakistan and his research interests include Artificial intelligence, Wireless Communication, Radar & Communication.