Hindawi
Journal of Electrical and Computer Engineering
Volume 2023, Article ID 7232488, 16 pages
https://doi.org/10.1155/2023/7232488

Research Article

BER and PSD Improvement of FBMC with Higher Order QAM Using Hermite Filter for 5G Wireless Communication and beyond

Hise Teferi Dumari, Demissie Jobir Gelmecha, Rajeev K. Shakya, and Ram Sewak Singh

Adama Science and Technology University, School of Electrical Engineering and Computing,
Department of Electronics and Communication Engineering, Adama, Post Box: 1888, Ethiopia

Correspondence should be addressed to Demissie Jobir Gelmecha; gelmechad@gmail.com

Received 20 August 2022; Revised 8 December 2022; Accepted 21 December 2022; Published 9 January 2023

Academic Editor: Iickho Song

Copyright © 2023 Hise Teferi Dumari et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Nowadays, multicarrier modulation schemes are being widely used in wireless communication system than single-carrier modulation techniques. Single-carrier modulation schemes are less capable of dealing with multipath fading channels than multicarrier modulation schemes, which results in lower spectral efficiency. Multicarrier modulation schemes have the ability to overcome multipath fading channels. Multicarrier modulation technique currently used in 4G technology in many countries is OFDM and it is easy for implementation, immune to interference, and provide fast data rate. However, the rising users demand on wireless communication resulted in need for further advancement of wireless communication system. The present OFDM transmission does not fulfill the requirements of 5G wireless communication system and beyond due to major limitations such as out of band emission and usage of cyclic prefix. To overcome the challenges of OFDM, different modulation schemes like Filter Bank Multicarrier with Offset-QAM, Filter Bank Multicarrier with QAM, Universal Filter Multicarrier, Filtered-OFDM, and Weighted Overlap and Added-OFDM are proposed. In this study, the Filter Bank Multicarrier with QAM using Hermite prototype filter is proposed to overcome drawbacks of OFDM and all other proposed waveforms. The performances of each multicarrier technique are analyzed based on power spectral density and bit error rate. Simulation result shows that the power spectral density of FBMC with QAM using Hermite filter resulted in 4.7 dB reduction of out of band emission compared to FBMC with QAM using PHYDYAS filter. The bit error rate is also reduced for Vehicular A, Vehicular B, Pedestrian A, and Pedestrian B channel models.

1. Introduction

The wireless communication industry is currently expanding at the highest rate. The reason for the fast growth of the wireless communication technologies market is the rising number of subscribers [1]. As a result, cellular networks are required to expand in order to meet the growing demand for wireless communication. In today's world, a cell phone is an essential tool and its development is accelerating. The increasing load on existing wireless communication networks necessitates the improvement of wireless communication networks' data rates and reliability to cope with the ever-increasing mobile traffic. To satisfy the users' needs, cellular network technologies have evolved [2] from first-generation to fifth-generation and beyond [3].

The current 4G technology uses OFDM as multicarrier modulation technique. In this modulation scheme, a number of orthogonal closely spaced subcarriers are used as data carrier. Because of the orthogonality of subcarriers, no need to insert guard band between each subcarrier to avoid intercarrier interference. This modulation scheme uses cyclic prefix to avoid the interference between each symbol in turn reducing the spectral efficiency. This modulation scheme has high PAPR and poor out of band emission. Due to these demerits, OFDM cannot be a promising and capable technique for 5G and beyond wireless communication.

5G and beyond technology has special differences compared to current OFDM. It supports Internet of Things enabled devices, machine to machine communication and smart vehicles, and high speed data rate ranging up to

10 Gbps and above [4]. To achieve the requirements of future wireless communication, different multicarrier modulation techniques [5] like Filter Bank Multicarrier with Offset Quadrature Amplitude Modulation (FBMC/OQAM) [6, 7], Filter Bank Multicarrier with Quadrature Amplitude Modulation (FBMC/QAM) [8], Universal Filter Multicarrier (UFMC) [9], Filtered-OFDM (F-OFDM) [5], and Weighted Overlap and Added-OFDM (WOLA-OFDM) [10] are proposed by different researchers as candidate waveforms.

Analysis of different multicarrier modulation techniques are provided in [11, 12]. From their analysis, the recommended multicarrier scheme that is expected to fulfill the criterion of 5G still needs improvement [13]. In this study, filter bank multicarrier with higher order quadrature amplitude modulation using hermit filter is proposed by taking the order of QAM like 64 QAM, 256 QAM, and 1024 QAM.

2. Related Works

Peak to Average Power Ratio and Bit Error Rate Analysis of Multicarrier Modulation Techniques is studied in [14]. The multicarrier modulation techniques compared in this paper were OFDM, SC-OFDM, and FBMC. The Poly-Phase Networking (PPN) filter banks are used in the implementation of FIR filters in FBMC. This, in turn, decomposes the wideband signals into a narrowband signal, resulting in lower PAPR of the whole system. Parameters like Signal to Noise Ratio (SNR), BER, and PAPR are used as performance metrics to analyze OFDM, SC-FDMA, and FBMC. Performance Metrics are compared across various channels like Rayleigh, Rician, and Double Selective and their influence on the modulation techniques, but the way to enhance the weakest side of the technique is not addressed.

Characteristic Analysis of OFDM, FBMC, and UFMC Modulation Schemes for Next Generation Wireless Communication Network Systems is provided in [15]. The basis for comparison was spectral efficiency, bit error rate, peak average power ratio by utilizing various subcarriers, and modulation techniques. The results evidently prove that the spectral efficiency is quite insufficient in the case of OFDM. FBMC and UFMC prove to be highly fictional, and the drawbacks in the previous case are neutralized by the usage of separate filters for each subcarrier, which further increases the PAPR value [16]. On advanced analysis, we derive to conclusions that UFMC waveform technique is preferable for 5G on considering the value of PAPR. Optimization will add to the betterment of the situation. However, PSD and PAPR can be reduced by choosing appropriate filter.

In [10], WOLA-OFDM, a potential candidate for asynchronous 5G, investigated the performance in relaxed synchronization scenario of a new contender waveform making its appearance recently named Weighted Overlap and Add-Based OFDM (WOLA-OFDM). In this paper, they compared cyclic prefix OFDM with WOLA-OFDM and UFMC. The bases for comparison were power spectral density, bit error rate, and mean square error. The study shows that WOLA-OFDM [17] could be a promising candidate waveform, outperforming both CP-OFDM and UFMC in any synchronous scenario. However, the power spectral density and bit error rate of WOLA-OFDM need further improvement to make ready for 5G and beyond technology, but the performance of WOLA-OFDM does not exceed as compared to FBMC.

Implementation of a 5G Filtered-OFDM Waveform Candidate and FBMC-New Multicarrier Modulation Technique is provided in [18, 19]. OFDM is the basic multicarrier modulation technique for both wireless and cellular communications. OFDM is a perfect choice for point-to-point communication, which offers minimum complexity and achieves very high bandwidth. However, it has several challenges such as limited spectral efficiency and large out of band emissions. In order to overcome these challenges, there are several modulation techniques being developed in these days; among these, Filter Bank Multicarrier (FBMC) is one of the techniques. However, the power spectral density and bit error rate of FBMC need further improvement to make ready for 5G and beyond technology.

3. Conventional Multicarrier Modulation Techniques

3.1. Orthogonal Frequency Division Multiplexing (OFDM). OFDM is a multicarrier transmission method that divides the frequency band into a number of subchannels. It consists of IFFT and FFT block in both transmitter and receiver, respectively. The mathematical expression of OFDM signal, which obtained from modulated N subcarriers, can be expressed as in [11].

$$s(t) = \sum_{n=0}^{N-1} d_n e^{j2\pi f_n t} \text{ for,} \quad 0 \le t \le T_s, \tag{1}$$

where d_n is the complex data symbol, which modulates the N^{th} subcarrier at the modulation interval, while T_s is the time duration of OFDM symbols, which is $T_s = \mathrm{N}T_d$, and T_d is the serial symbol duration. The orthogonality of the subcarrier [11] is ensured, if the distance between neighboring subcarrier frequencies is equal and subcarriers are located at

$$f_n = \frac{n}{T_s} \text{ for,} \quad n = 0, 1, 2, \ldots, N-1. \tag{2}$$

The output of the channel, after radio frequency conversion, is the received signal $r(t)$ obtained from convolution of $s(t)$ with the channel impulse response $h(t)$ and addition of a noise signal $n(t)$ [11].

$$r(t) = \int_{-\infty}^{\infty} s(t-\tau) h(\tau, t) \mathrm{d}\tau + n(t). \tag{3}$$

The output of the FFT is the multicarrier demodulated sequence of N complex valued symbols [20].

$$d_n = \sum_{m=0}^{N-1} r_m e^{-(j2\pi nm/N)} \text{ for,} \quad n = 0, 1, 2, \ldots, N-1. \tag{4}$$

Generally, time domain expression of OFDM is given as in [11].

$$X_{\text{OFDM}} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} x_k \times \prod(t) \times e^{-j2\pi f_k t}, \quad \text{for}\, n = 0, 1, 2, \ldots, N-1, \tag{5}$$

where x_k denotes the complex symbols that emanate from a given constellation, $\prod(t)$ denotes the rectangular waveform filter, and N is the number of subcarriers.

Figure 1 shows that the digital data bits are mapped to complex symbols QAM. These data symbols are converted to N streams, which correspond to subcarrier frequencies by serial to parallel convertor. Then, it passes through IFFT to produce time sequence of the streams. In the OFDM signal, the complex values modulating subcarriers in each symbol period are statistically independent of each other, which are orthogonal. Orthogonality of subcarriers prevents inter-carrier interference [11]. Cyclic prefix is added at transmitter and removed at receiver. It is used to avoid intersymbol interference between different symbols.

3.2. Filtered Orthogonal Frequency Division Multiplexing (F-OFDM).

The Filtered Orthogonal Frequency Division Multiplexing (F-OFDM) is a spectrum shaping mechanism using filter process, which is shown in Figure 2. The prototype filter used in this candidate waveform is a rectangular pulse mask of the OFDM symbol, again also cyclic prefix. Filtering is very essential to reduce side lobes leakages. F-OFDM is multicarrier modulation technique that introduces filtering operation to overcome the weakness of OFDM [5].

Two types of filters were considered for generating F-OFDM signal. In the case of the soft truncated sinc filter, the sinc function is soft-truncated with different window functions, as a result the impulse response vanishes promptly and the ISI is circumscribed. In the second type, the equiripple filter structure uses the Remez algorithm associated with equiripple filters to get a sharper transition band so that to alleviate the inter sub-band interference.

Generally, time domain expression of F-OFDM is given as [20]

$$X_{F-\text{OFDM}} = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_k \times f(n) \times e^{-(j2\pi nm/N)}. \tag{6}$$

3.3. Weighted Overlap and Added Orthogonal Frequency Division Multiplexing (WOLA-OFDM).

Figure 3 depicts Weighted Overlap and Add-Based OFDM (WOLA-OFDM) candidate waveform for 5G and beyond wireless communication. In it, the conventional usage of rectangular pulse shape is avoided and a pulse with soft edges is used instead. These soft edges are added to the cyclic extension by a time domain windowing. This results in a better spectral containment. The smooth transition between the last sample of a given symbol and the first sample of the next symbol is provided with point-to-point multiplication of the windowing function and the OFDM symbol with cyclic prefix and cyclic suffix [10].

To create the cyclic prefix, we copy and append the CP + W samples from the last part of a given symbol and first W samples of a given symbol to its end. Thus, the WOLA-OFDM time domain symbol is cyclically extended from N samples to $N + \text{CP} + 2W$. In WOLA-OFDM, after cyclic extension, a window of length $L = N + \text{CP} + 2W$ samples is applied. Many windowing functions are studied and compared in terms of enhancing side lobe suppression [10]. The Meyer Root Raised Cosine considered as best windowing for WOLA-OFDM. WOLA-OFDM is good to suppress inter-user interference.

Generally, time domain expression of WOLA-OFDM is given as in [10].

$$X_{\text{WOLA-OFDM}}(n) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_k \times W(n) \times e^{-(j2\pi nm/N)}, \tag{7}$$

where $n = 0,\ 1,\ 2,\ \ldots,\ N-1$ and $W(n)$ the discrete time domain representation of raised cosine window function can be written as in [10].

3.4. Universal Filter Multicarrier (UFMC).

Universal filtered multicarrier (UFMC) technique can be considered as a derivative of OFDM with sub-band filtering operation. This postfiltering process leads to a lower out of band leakage than for OFDM. The orthogonality between subcarriers in each sub-band unit is maintained. UFMC is a technique that combines the benefits of both OFDM and FBMC. Rather than filtering each carrier individually like in FBMC, a group of subcarriers (called sub-bands) is filtered [9, 21]. The filter parameters and number of carriers per sub-band are typically common, which prevents aliasing. Nonetheless, non-contiguous sub-bands are possible to allow flexible utilization of the available spectrum. Therefore, UFMC can be considered as a compromise between OFDM and FBMC.

Let us assume that the UFMC transmit signal consists of N subcarriers and is divided in to B sub-bands. Each sub-band contains N/B subcarriers. The input to the UFMC waveform generator block is a set of constellation QAM mapped symbols, which is shown in Figure 4. The symbols S are divided into frequency blocks S where each frequency block is made up of p subcarriers. If B is the number of frequency blocks, then B data vectors are processed with IFFT submatrix (each of dimension $N \times P$), respectively. Then, each sub-band is filtered by a sub-band filter of length L, and response from the different sub-band is summed.

The discrete baseband UFMC signal is expressed mathematically as in [20]:

$$X_{\text{UFMC}} = \sum_{k=0}^{K-1} S_k(n) * f_k(n), \tag{8}$$

where K is the number of sub-bands, $f_k(n)$ shows the filter coefficients in sub-band of order k, and $S_k(n)$ refers to the equivalent OFDM modulated signal over sub-band of order k expressed as in [20].

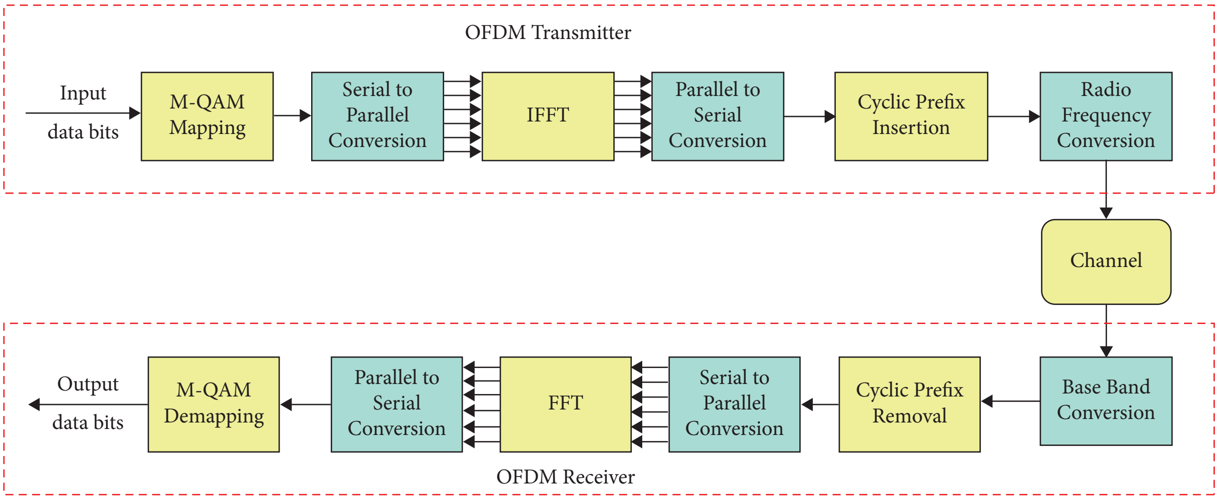

Figure 1: Orthogonal frequency division multiplexing system.

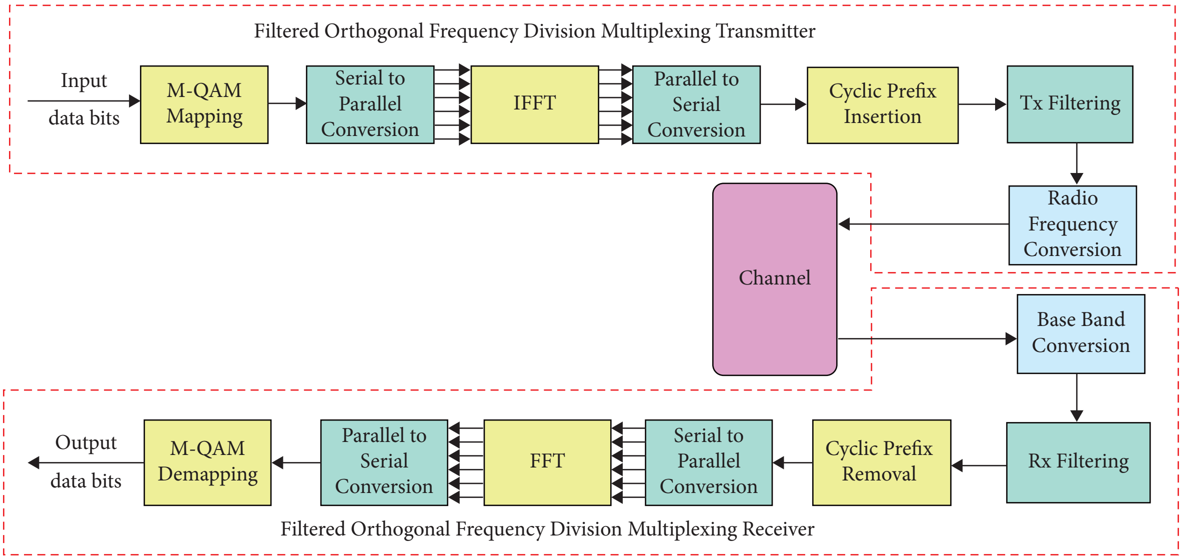

Figure 2: Filtered orthogonal frequency division multiplexing.

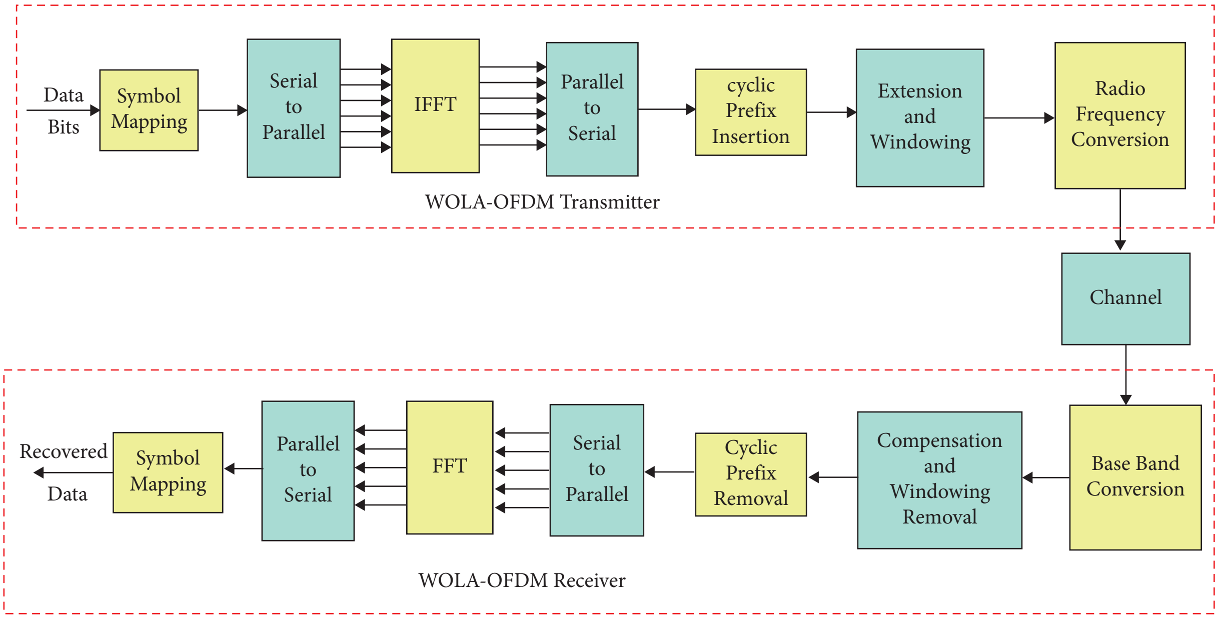

Figure 3: Weighted overlap and added orthogonal frequency division multiplexing (WOLA-OFDM).

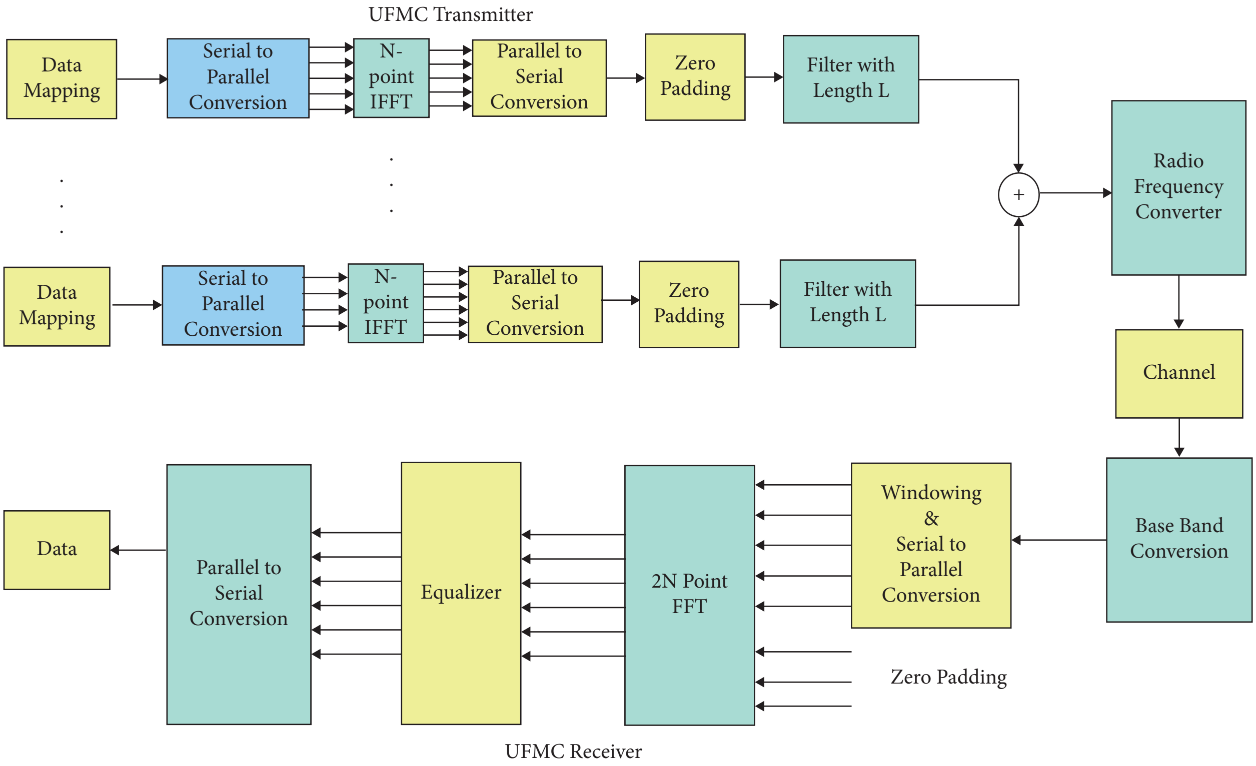

Figure 4: Universal filter multicarrier (UFMC).

3.5. Filter Bank Multicarrier with Offset Quadrature Amplitude Modulation (FBMC/OQAM). Figure 5 represents FBMC-OQAM, which is based on real valued symbol transmission and reception. There is OQAM preprocessing and OQAM postprocessing to convert complex to real and real to complex values, respectively [8]. The orthogonality of FBMC-OQAM is maintained by the pulse shape of the prototype filter and the real value detection of OQAM. In this case, the real and imaginary part of complex data is transmitted via single prototype filter called PHYDYAS. The transmitted signal of a discrete time FBMC-OQAM system is expressed in [8] as follows:

$$s(n) = \sum_{-\infty}^{\infty} \sum_{m=0}^{M-1} d_{m,k} \theta_{m,k} f\left[n - k\frac{M}{2}\right] e^{j2\pi/Mm(n-D)}, \qquad (9)$$

where n indicates the time index, m represents the subcarrier index, k indicates the symbol index, $d_{m,k}$ represents the real valued symbol, M represents the number of subcarriers, and $f(n)$ shows the synthesis impulse response, which maps $d_{m,k}$ in to the signal space. $\theta_{m,k} = j^{k+m}$ is the additional phase term. The filter delay, which is represented by D, appears to generate a causal discrete time prototype filter $f(n)$, and it is fixed $D = (L-1)/2$ with filter length equal to L as in [8].

3.6. Proposed Filter Bank Multicarrier with Offset Quadrature Amplitude Modulation (FBMC/QAM). FBMC-QAM transmits complex symbols using two different prototype filters, which is termed as even and odd filters to deliver even and odd subcarriers, respectively. The orthogonality of FBMC-QAM is maintained by the pulse shapes of two prototype filters. In the baseband discrete-time model, FBMC-QAM signal at transmitter side is written as in [8]:

$$s(n) = \sum_{-\infty}^{\infty} \left[\sum_{p} a_{p,k} g^{e}[n-kM] e^{j2\pi/Mm(n-D)} + \sum_{p} a_{p,k} g^{o}[n-kM] e^{j2\pi/Mm(n-D)}\right], \qquad (10)$$

where $g^e[n]$ represents even filter, $g^o[n]$ represents odd filter, and $a_{p,k}$ represents a complex data symbol in terms of QAM constellation. In this study, Hermite Filter is proposed as a prototype filter in both transmitter and receiver as even and odd filter to improve the out of band emission and the bit error performance of FBMC-QAM.

The Hermite pulse shaping filter is the linear combination of the function of the Hermite and Gaussian filter,

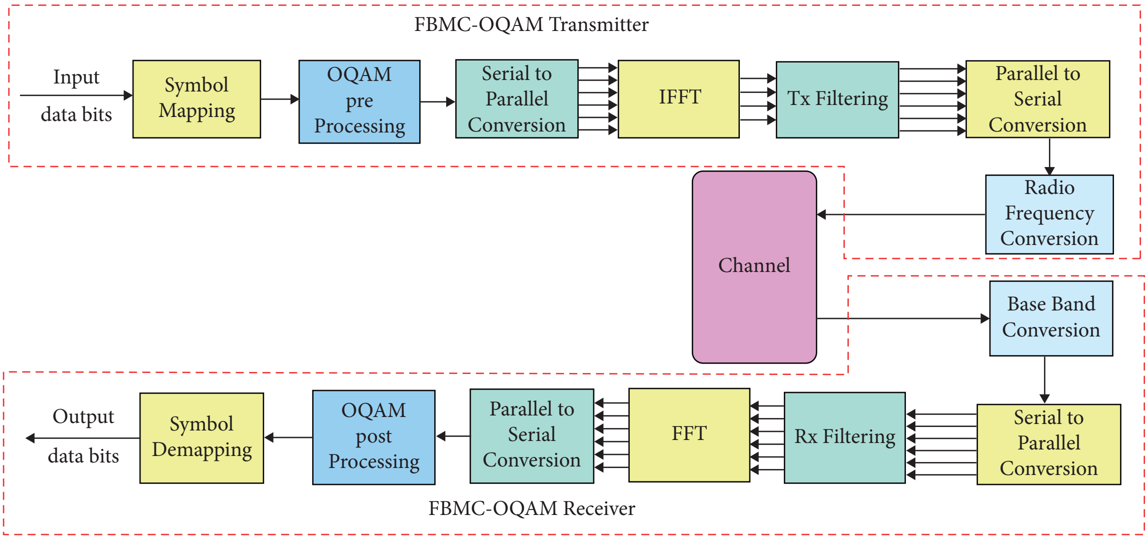

Figure 5: Filter bank multicarrier with offset quadrature amplitude modulation (FBMC/OQAM).

which achieves the Nyquist-I criterion. Thereby, the Hermite prototype filter coefficients are given by Hermite polynomials in [20].

The Hermite filter impulse response can be described by the following equation [20]:

$$p_{\text{hermite}}(t) = \frac{1}{\sqrt{T_0}} e^{\left(-2\pi\left(t/T_0\right)^2\right)} \times \sum a_i H_i\left(2\sqrt{\pi}\,\frac{t}{T_0}\right), \tag{11}$$

where $i = 0$, 4, 8, 16, 20 and H_i is the Hermite Polynomial.

4. Simulation Parameters

In this section, the performance of candidate multicarrier modulation techniques is compared with the existing OFDM systems. The comparison is based on key performance indicators like power spectral density, bit error rate, spectral efficiency, and computational complexity. The performances of different multicarrier modulation techniques are assessed in terms of their potential to fill the major requirements of new communication networks. The simulation parameters are taken keeping the ITU standard, which is listed in Table 1.

5. Results and Discussion

5.1. Power Spectral Density Analysis. Normalization is a means to have a measure for signals in the same, fixed, and easy to use range. Normalized frequency is a quantity having dimensions of frequency expressed in units of cycle per sample. It equals $f(n) = f/f_s$, where f is an ordinary frequency quantity and f_s is the sampling rate.

Figure 6 shows the power spectral density versus normalized frequency of different prototype filters in frequency domain. Filters can affect the out of band emission of multicarriers modulation techniques. To have better multicarrier modulation technique with minimum out of band emission, the filter with small side lobe is required. The PSD versus normalized frequency of different prototype filters for subcarrier spacing of 15 kHz and 1024 numbers of subcarriers shows that Hermite decays faster than all other filters, as it can be seen from Figure 6.

By using Hermite filter as prototype filter in filter bank multicarrier with quadrature amplitude modulation techniques, the out of band emission of filter bank multicarrier with quadrature amplitude modulation improved in some amount. As it can be seen from the power spectral density versus normalized frequency plot of each prototype filter from Figure 6, all filters side lobe decays after normalized frequency of −6 and 6 left hand side and right hand side to normalized frequency zero, respectively. Out of band emission of multicarrier modulation techniques depends on the power spectral distribution of filters. The main requirement to choose a better filter is choosing a filter with smaller side lobe.

There are a number of filters that are recommended to improve the out of band emission of multicarrier modulation techniques. However, analysis of this study is limited to PHYDYAS filter, root raised cosine filter, Hermite filter, rectangular filter, raised cosine filter, exact hamming filter, and exact Blackman filter. Most researchers recommend filters to improve the performance of different multicarrier modulation techniques. Generally, the power spectral density decay rate of Hermite prototype filter is better in some amount than all other filters. Based on this reason, Hermite filter is chosen as the best prototype filter to improve the performance of FBMC-QAM.

Figure 7 is a result that simulated for 1024 number of subcarriers by taking the overlapping factor of 4. Overlapping 4 is chosen for better side lobe. Spacing of subcarrier is chosen 15 kHz, the same as the long-term evolution (LTE) standard. Overlapping factor is one parameter of the Hermite filters that determines the performance of the system. Generally, as the overlapping factor increases, the side lobe energy of the filter decays fast which is very important to reduce the out of band emission and the system can support the coexistence of multiple services, but the complexity of the system increases and degrades the bit error performance; so, optimization is important here. For overlapping factor 2 and 3, there are some side lobe

Table 1: Simulation parameters.

General parameters	
Subcarrier spacing	15 KHz
Sampling frequency	15.36 MHz
Number of subcarriers	64
QAM modulation order	64/256/1024
Number of symbols	30
OFDM	
Length of cyclic prefix	72
F-OFDM	
Filter type	Windowed sinc
UFMC	
Chebyshev filter length	73
Sub-band size	12
Guard interval length	72
Side-lobe attenuation	40 dB
FBMC/OQAM	
Overlapping factor	4
Prototype filter	Hermite filter and PHYDYAS filter
WOLA-OFDM	
Cyclic prefix	72
Windowing	Meyer RRC
Windowing length	32
FBMC/QAM	
Overlapping factor	4
Prototype filter	Hermite filter and PHYDYAS filter

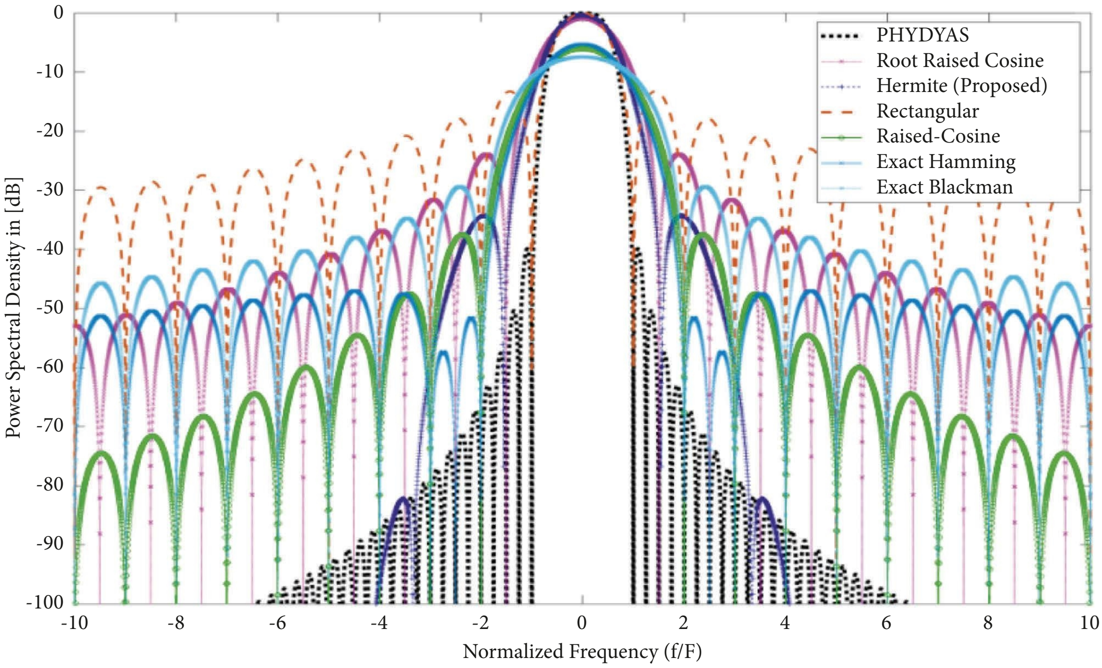

Figure 6: Power spectral density versus normalized frequency of different prototype filters for subcarrier spacing of 15 kHz and number of subcarriers of 1024.

energy, which may degrade the out of band emission, but for overlapping factor 4, the side lobe energy is minimum, which can help to improve the out of band emission of the system. For the overlapping factor more than 4, the system complexity greatly increases. Due to this reason, most researchers choose overlapping factor 4 to have better side lobe energy.

Table 2 shows the power spectral density of multicarrier modulation techniques at normalized frequency of 20, 30, 40, and 50. The PSD of OFDM becomes −29.05 dB, the PSD of WOLA-OFDM becomes −37.45 dB, the PSD of UFMC becomes −50.51 dB, the PSD of F-OFDM becomes −65.5 dB, the PSD of FBMC-OQAM using PHYDYAS filter becomes

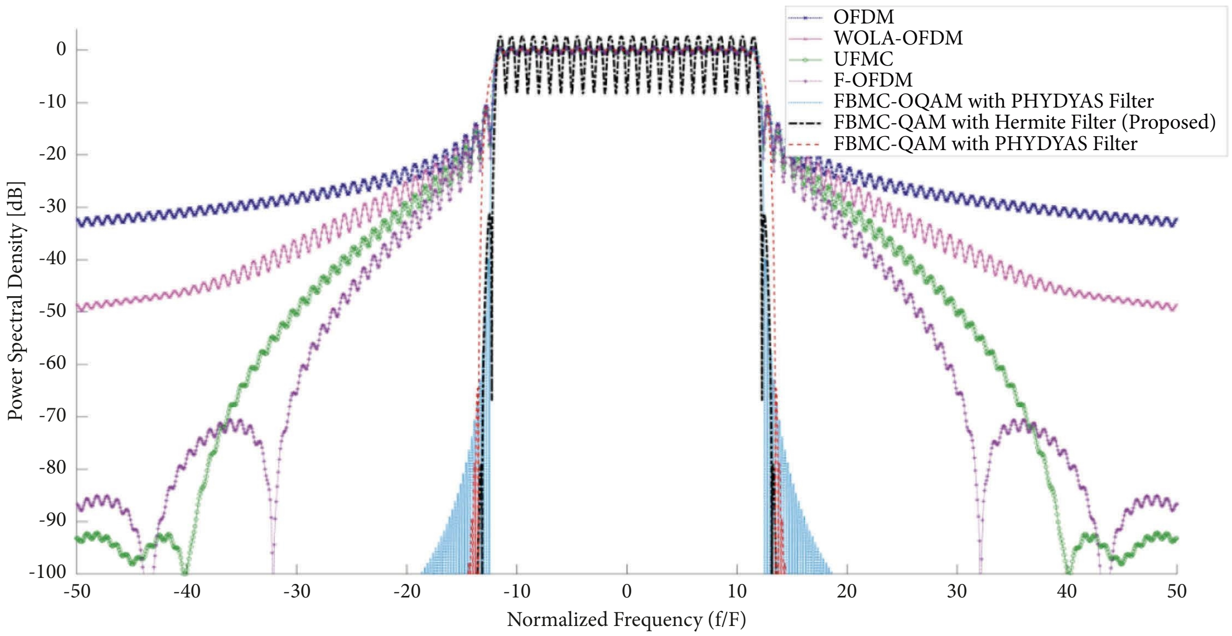

Figure 7: Power spectral density versus normalized frequency of different multicarrier modulation techniques for subcarrier spacing of 15 kHz and number of subcarriers of 1024.

Table 2: Power spectral density of different modulation schemes at 20, 30, 40, and 50 normalized frequency.

Waveforms		Normalized frequency			
		$f_n = 20$	$f_n = 30$	$f_n = 40$	$f_n = 50$
OFDM	Power spectral density in (dB)	−22.06	−29.05	−31.2	−33.27
F-OFDM		−33.94	−65.5	−45.63	−48.66
WOLA-OFDM		−25.61	−50.51	−90.92	−93.2
UFMC		−29.65	−50.51	−90.92	−93.2
FBMC/OQAM with PHYDYAS		−111.1	−121	−144.5	−151.2
FBMC/QAM with PHYDYAS		−180.7	−221	−214.4	−215.7
FBMC/QAM with Hermite (proposed)		−319.5	−323	−323.2	−315.8

−121 dB, the PSD of FBMC-QAM using PHYDYAS becomes −221 dB, and the PSD of FBMC-QAM using Hermite filter becomes −323 dB at normalized frequency 30. From the result, it can be concluded that FBMC-QAM with Hermite filter has the smallest out of band emission because of Hermite filter, a filter which has a small side lobe. The side lobe created by FBMC-QAM using Hermite filter is the smallest which helps to support the coexistence of different services.

Generally, because of the adoption of Hermite filter in filter bank multicarrier with quadrature amplitude modulation, certain amount of improvement is achieved. To understand the amount of improvement, PSD in dB is converted into linear scale. When we compare the PSD of FBMC-QAM using PHYDYAS filter and FBMC-QAM using Hermite filter in linear scale and convert their difference in to dB scale for normalized frequency 30, 4.7 dB improvement is observed.

5.2. Bit Error Rate Comparison. Bit error rate comparison is another performance metric to compare the performance of multicarrier modulation techniques in the communication system. To support a large number of users' higher order, QAM is the best solution. However, the main drawback of using the higher order QAM system is complexity and it degrades the BER performance. The BER value has to be small in number to improve the system performance because BER is error bit divided by total number of bit. The system with small number of BER has good performance than a system with higher number of BER. The one main aim of this new method is to reduce the BER value compared to the existing system. The simulation results are done on MATLAB 2021 with the same modulation order, the number of subcarrier, and peak power constraint. The input signal used for the system is random signal.

Figure 8 shows the BER performance of the OFDM system under different signal to noise ratios. The simulation is done for the Rayleigh channel model using the signal to noise ratio of 0 to 50 dB, QAM order (4, 16, 64, 256, and 1024), and the number of symbol transmitted 1000. The main aim of the simulation of this result is just to show the effect of higher order QAM on BER. The result shows that as QAM order increases, the OFDM system can support greater number of signal to noise ratio. However, the BER performance is not good compared to BER result of OFDM

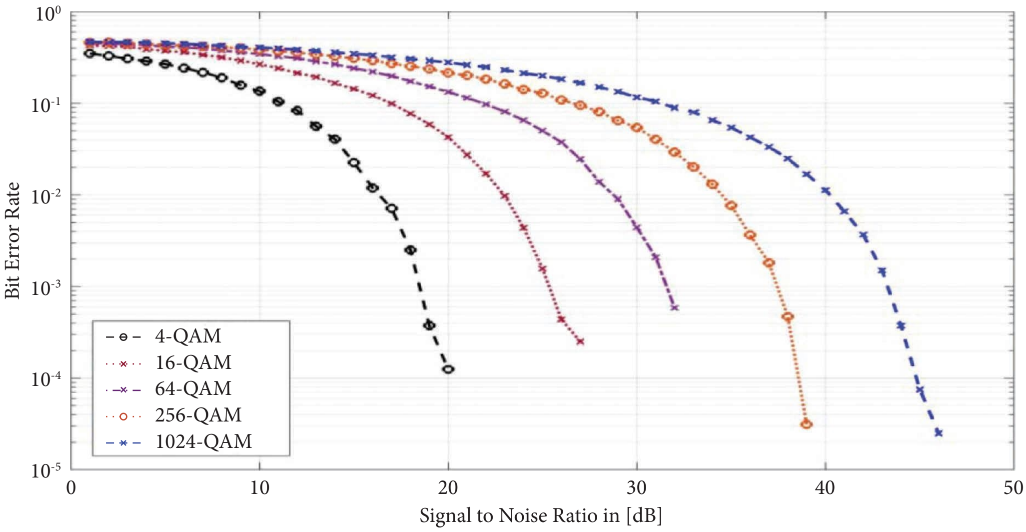

Figure 8: OFDM at different QAM orders.

with lower order QAM. According to the simulation result, in order to improve the BER performance, the lower order QAM is preferable than the higher order QAM. However, lower QAM order cannot support the large signal to noise ratio and cannot support large number of users. To support massive communication in future, we are supposed to use higher order QAM. The objective of the research comes here to answer the best way to improve BER by finding the better system, which gives lower BER value at higher order QAM.

Figure 9 shows the bit error rate performance of OFDM, WOLA-OFDM, F-OFDM, UFMC, and FBMC/OQAM with PHYDYAS, FBMC/QAM with PHYDYAS, FBMC/QAM with Hermite for Vehicular A channel model with modulation order of 64, number of subcarriers of 64, subcarrier spacing of 15×10^3, and signal to noise ratio of 0–60 dB. All systems in Figure 9 are simulated under these common parameters to analyze their performance. Bit error rate performance of multicarrier modulation techniques with 64 QAM, 256 QAM, and 1024 QAM for Vehicular A channel model is listed in Table 3. To justify the performance increases numerically, the BER value of all system at modulation order 64 and 40 dB is shown as follows: OFDM has BER value of 1.05×10^{-3}, F-OFDM has BER value of 1.55×10^{-3}, WOLA—OFDM has BER value of 1.15×10^{-3}, UFMC has BER value of 5.7×10^{-2}, FBMC/OQAM with PHYDYAS has BER value BER value of 1.58×10^{-3}, FBMC/QAM with PHYDYAS has BER value of 4.1×10^{-4}, and FBMC/QAM with Hermite has BER value of 3.8×10^{-4}. The BER value of FBMC/QAM with Hermite filter is least, which has technical meaning of better BER performance. The error making possibility of FBMC/QAM with Hermite filter is less compared to all other systems. In Figure 9, the bit error performance of FBMC-QAM with Hermite filter outperforms than all other techniques.

Figures 10 and 11 show the bit error rate performance of different multicarrier modulation techniques for vehicular A channel model at 256 QAM and 1024 QAM, respectively. Generally, higher order QAM can support large signal to noise ratio. In both figures, FBMC/QAM with Hermite filter has the least BER value, which makes the system better compared to all other systems to improve BER performance. Generally, we know that every system has to be tested under common criterion. So, the BER analysis for all systems is done using modulation order 64, 256, and 1024 under Vehicular A. The proposed multicarrier modulation techniques outperform than all other in all cases.

From Table 4, it can observed that at signal to noise ratio of 30 dB and 64 QAM, the bit error rate of OFDM is 0.09847, the bit error rate of FBMC-QAM with PHYDYAS filter is 0.008895, and the bit error of proposed multicarrier FBMC-QAM with Hermite filter is 0.004334. When both OFDM and proposed method are compared, its difference becomes 0.094136. This shows that the proposed method reduces the bit error by 95.598% of OFDM. When the bit error rate of FBMC-QAM with PHYDYAS and FBMC-QAM with Hermite filter is compared, its difference becomes 0.004561. This shows that FBMC-QAM with Hermite filter reduces the bit error rate by 51.276% of FBMC-QAM with PHYDYAS.

Generally, when the bit error performance for Vehicular A and Vehicular B channel model is observed, the bit error performance for Vehicular A channel model is comparably good. From overall view of those channel models, as SNR increases, the BER decreases, but as QAM order increases, the BER decreases. To support large signal to noise ratio value, higher order QAM is recommended because higher order QAM increases the spectral efficiency of the system. As it can be seen from the result of both Vehicular A and Vehicular B channel model, the FBMC-QAM with Hermite filter outperforms better than all other waveforms.

Figures 12–14 show the bit error rate performance of different multicarrier modulation techniques for Vehicular B channel model at 64 QAM, 256 QAM, and 1024 QAM, respectively. In all figures, the FBMC/QAM with Hermite filter has the least BER value, which makes the system better compared to all other systems to improve BER performance for vehicular B channel model.

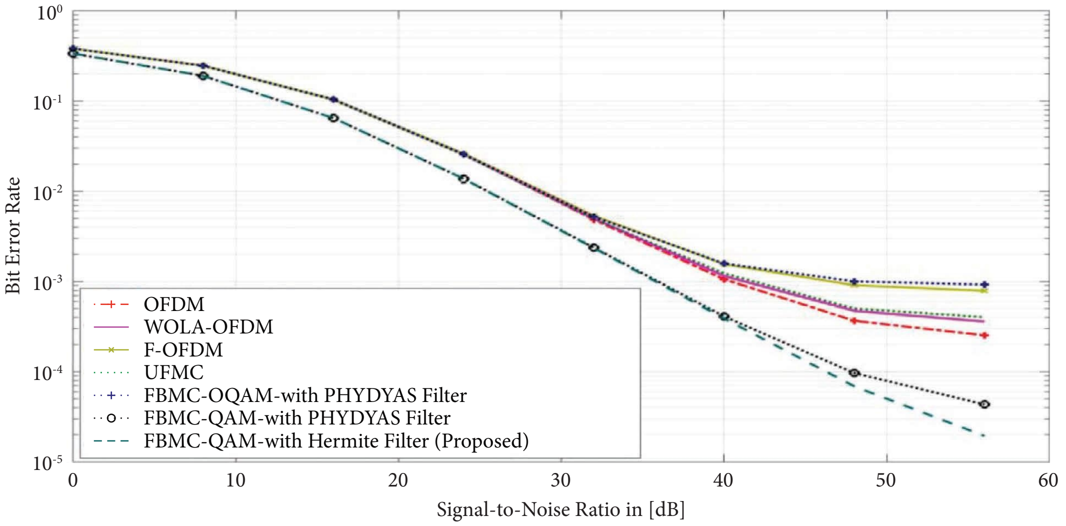

Figure 9: Bit error rate performance of different multicarrier modulation techniques for vehicular A channel model at 64 QAM.

Table 3: Bit error rate performance of multicarrier modulation techniques with 64 QAM, 256 QAM, and 1024 QAM for Vehicular A channel model.

Waveforms	QAM order		Signal to noise ratio		
			20 dB	30 dB	40 dB
OFDM	64 QAM	Bit error rate	2.580×10^{-2}	4.800×10^{-3}	1.050×10^{-3}
	256 QAM		6.340×10^{-2}	1.440×10^{-2}	3×10^{-3}
	1024 QAM		1.205×10^{-1}	3.940×10^{-2}	1.010×10^{-2}
F-OFDM	64 QAM		2.61×10^{-2}	5.4×10^{-3}	1.55×10^{-3}
	256 QAM		6.47×10^{-2}	1.64×10^{-2}	4.9×10^{-3}
	1024 QAM		1.23×10^{-1}	4.61×10^{-2}	1.78×10^{-2}
WOLA-OFDM	64 QAM		2.57×10^{-2}	5×10^{-3}	1.15×10^{-3}
	256 QAM		6.31×10^{-2}	1.48×10^{-2}	3.5×10^{-3}
	1024 QAM		1.201×10^{-2}	3.98×10^{-2}	1.12×10^{-2}
UFMC	64 QAM		2.54×10^{-2}	4.9×10^{-3}	5.7×10^{-2}
	256 QAM		6.25×10^{-2}	1.46×10^{-2}	3.6×10^{-3}
	1024 QAM		1.193×10^{-2}	3.98×10^{-2}	1.14×10^{-2}
FBMC/OQAM with PHYDYAS	64 QAM		2.59×10^{-2}	5.2×10^{-3}	1.58×10^{-3}
	256 QAM		6.46×10^{-2}	1.71×10^{-2}	5.8×10^{-3}
	1024 QAM		1.215×10^{-1}	4.45×10^{-2}	1.73×10^{-2}
FBMC/QAM with PHYDYAS filter	64 QAM		1.38×10^{-2}	2.4×10^{-3}	4.1×10^{-4}
	256 QAM		3.71×10^{-2}	7.2×10^{-3}	1.2×10^{-3}
	1024 QAM		8.31×10^{-2}	2.18×10^{-2}	4.4×10^{-3}
FBMC/QAM with Hermite filter	64 QAM		1.376×10^{-2}	2.34×10^{-3}	3.8×10^{-4}
	256 QAM		3.7×10^{-2}	7×10^{-3}	1.13×10^{-3}
	1024 QAM		8.310×10^{-2}	2.15×10^{-2}	4×10^{-3}

Generally, when the bit error performance for Vehicular A, Vehicular B, and Pedestrian B channel models is seen, the bit error performance for Pedestrian B channel model is better. From overall view of those channel models, as signal to noise ratio increases, the bit error rate decreases, but as QAM order increases, the bit error rate decreases. To support large signal to noise ratio value, higher order QAM is recommended because higher order QAM increases the spectral efficiency of the system. As it can be observed from the result of Vehicular A and Vehicular B and Pedestrian B channel models, the FBMC-QAM with Hermite filter outperforms better than all other waveforms.

Figures 15–17 show the bit error rate performance of different multicarrier modulation techniques for Pedestrian B channel model at 64 QAM, 256 QAM, and 1024 QAM, respectively. In all figures, the FBMC/QAM with Hermite filter has least BER value, which makes the system better compared to all other systems to improve BER performance for Pedestrian B channel model.

From Table 5, we see that at signal to noise ratio of 40 dB and 64 QAM, the BER of OFDM is 0.0046, the BER of

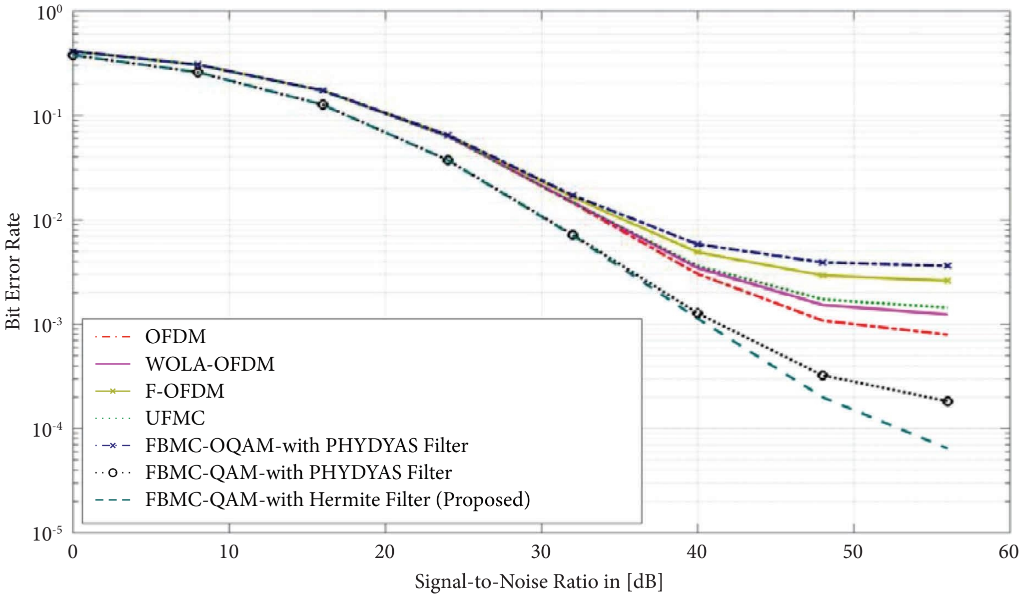

Figure 10: Bit error rate performance of different multicarrier modulation techniques for vehicular A channel model at 256 QAM.

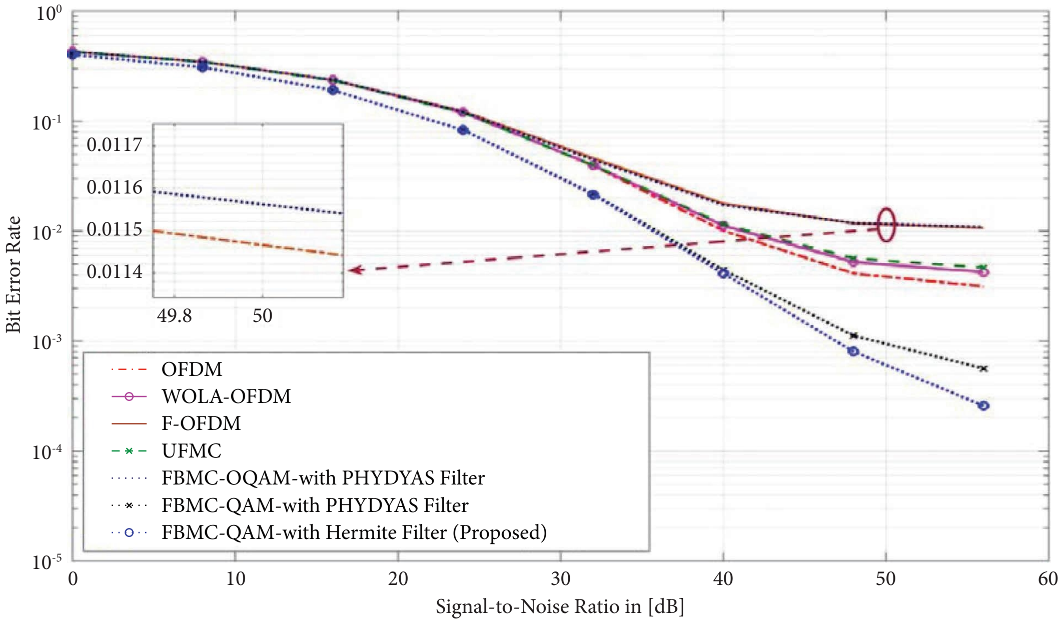

Figure 11: Bit error rate performance of different multicarrier modulation techniques for vehicular A channel model at 1024 QAM.

FBMC-QAM with PHYDYAS filter is 0.0021, and the BER of proposed multicarrier FBMC-QAM with Hermite filter is 0.0003385. When both OFDM and proposed method are compared, its difference becomes 0.0.0025. This shows that the proposed method reduces the bit error by 54.35% of OFDM. When we compare the bit error rate of FBMC-QAM with PHYDYAS and FBMC-QAM with Hermite filter, its difference becomes 0.004561. This shows that FBMC-QAM with Hermite filter reduces the bit error rate by 92.64% of FBMC-QAM with PHYDYAS.

Table 4: Bit error rate performance of multicarrier modulation techniques with 64 QAM, 256 QAM, and 1024 QAM for Vehicular B channel model.

Waveforms	QAM order		Signal to noise ratio		
			SNR = 15 dB	SNR = 20 dB	SNR = 30 dB
OFDM	64 QAM	Bit error rate	1.584×10^{-1}	1.265×10^{-1}	9.847×10^{-2}
	256 QAM		2.145×10^{-1}	1.643×10^{-1}	1.513×10^{-1}
	1024 QAM		2.742×10^{-1}	2.265×10^{-1}	2.121×10^{-1}
F-OFDM	64 QAM		1.696×10^{-1}	1.416×10^{-1}	1.172×10^{-1}
	256 QAM		2.256×10^{-1}	1.828×10^{-1}	1.724×10^{-1}
	1024 QAM		2.830×10^{-1}	2.431×10^{-1}	2.315×10^{-1}
WOLA-OFDM	64 QAM		1.658×10^{-1}	1.368×10^{-1}	1.112×10^{-1}
	256 QAM		2.214×10^{-1}	1.760×10^{-1}	1.644×10^{-1}
	1024 QAM		2.806×10^{-1}	2.382×10^{-1}	2.259×10^{-1}
UFMC	64 QAM		1.647×10^{-1}	1.335×10^{-1}	1.103×10^{-1}
	256 QAM		2.201×10^{-1}	1.748×10^{-1}	1.636×10^{-1}
	1024 QAM		2.788×10^{-1}	2.362×10^{-1}	2.235×10^{-1}
FBMC/OQAM with PHYDYAS	64 QAM		1.476×10^{-1}	1.11×10^{-1}	7.654×10^{-1}
	256 QAM		2.025×10^{-1}	1.419×10^{-1}	1.24×10^{-1}
	1024 QAM		2.644×10^{-1}	2.047×10^{-1}	1.831×10^{-1}
FBMC/QAM with PHYDYAS filter	64 QAM		7.214×10^{-2}	3.821×10^{-2}	8.895×10^{-2}
	256 QAM		7.214×10^{-2}	3.821×10^{-2}	2.149×10^{-2}
	1024 QAM		1.951×10^{-1}	1.017×10^{-1}	5.799×10^{-2}
FBMC/QAM with Hermite filter	64 QAM		6.974×10^{-2}	3.465×10^{-3}	4.334×10^{-3}
	256 QAM		1.211×10^{-1}	3.622×10^{-2}	1.055×10^{-2}
	1024 QAM		1.918×10^{-1}	8.87×10^{-2}	3.42×10^{-2}

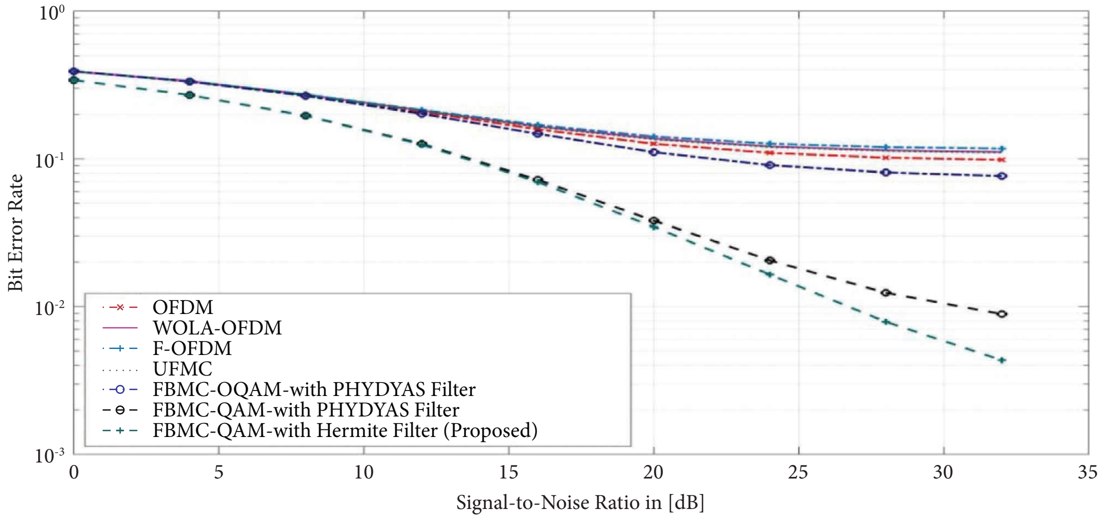

Figure 12: Bit error rate performance of different multicarrier modulation techniques for Vehicular B channel model at 64 QAM.

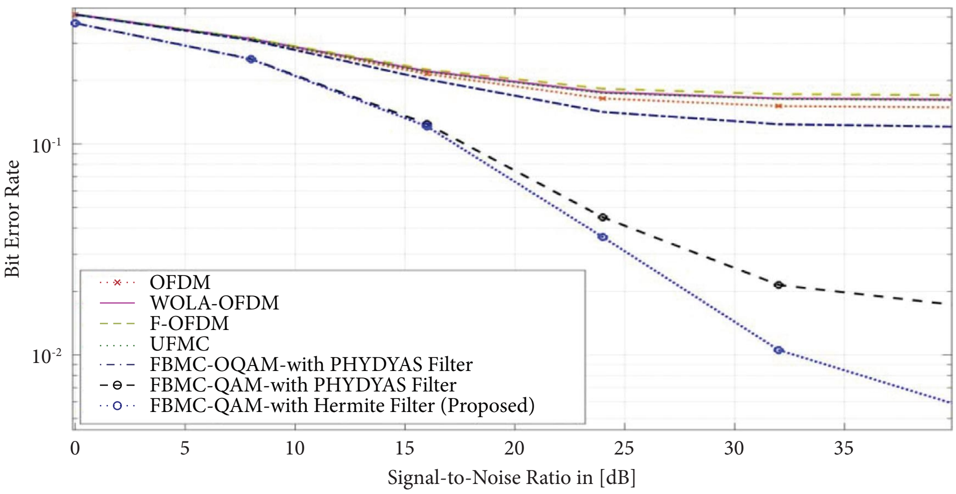

Figure 13: Bit error rate performance of different multicarrier modulation techniques for Vehicular B channel model at 256 QAM.

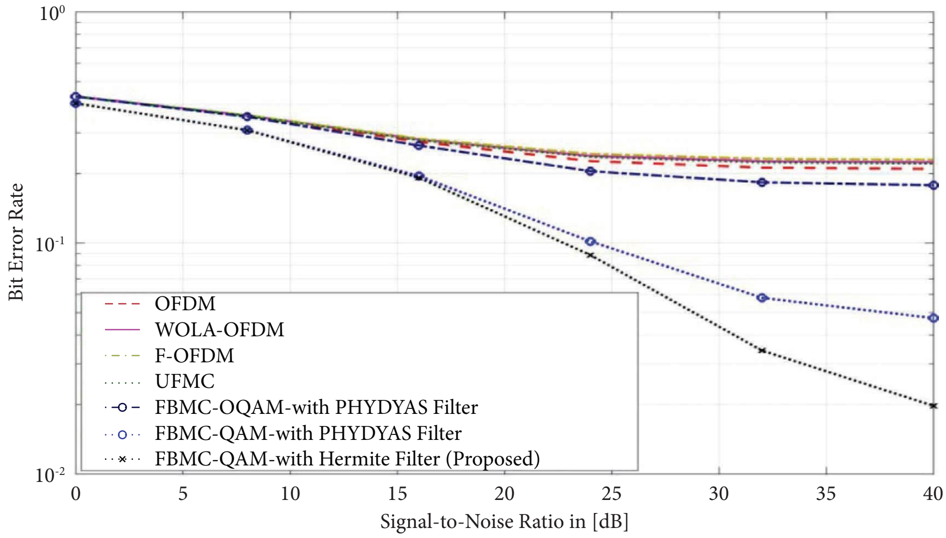

Figure 14: Bit error rate performance of different multicarrier modulation techniques for Vehicular B channel model at 1024 QAM.

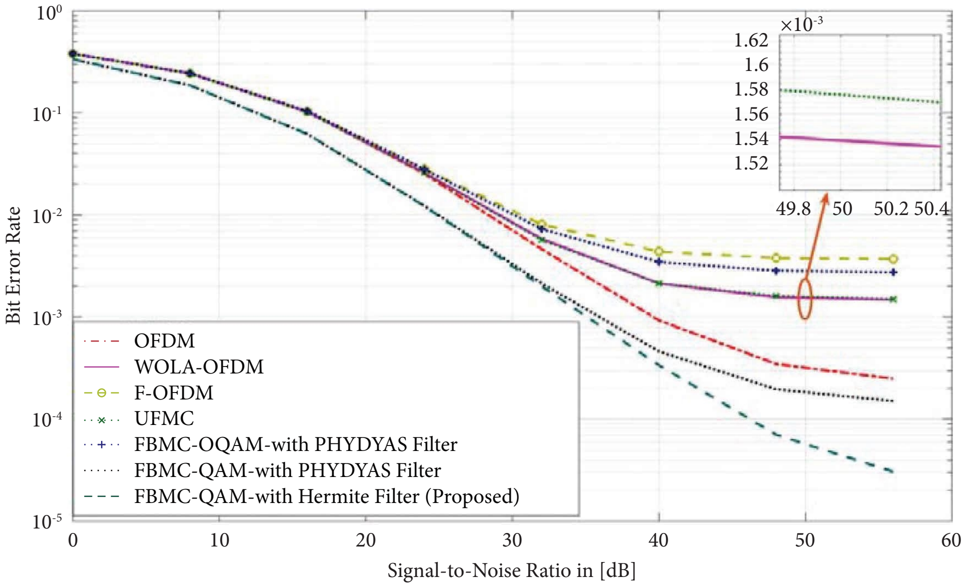

Figure 15: Bit error rate performance of different multicarrier modulation techniques for Pedestrian B channel model at 64 QAM.

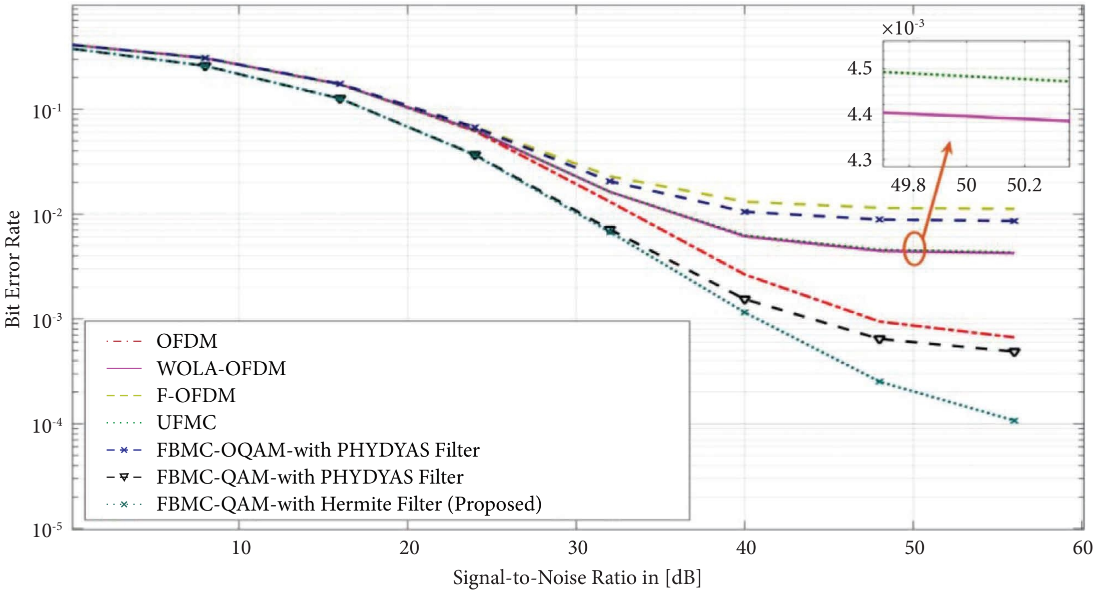

FIGURE 16: Bit error rate performance of different multicarrier modulation techniques for Pedestrian B channel model at 256 QAM.

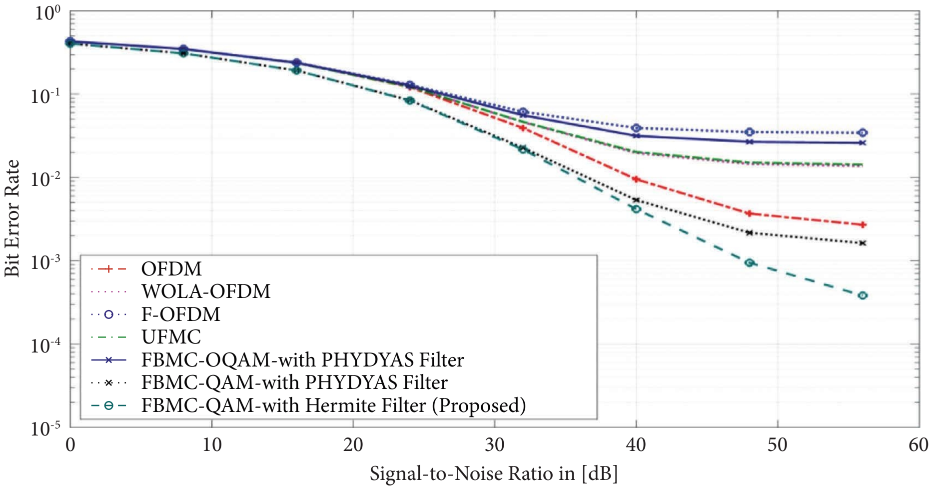

FIGURE 17: Bit error rate performance of different multicarrier modulation techniques for Pedestrian B channel model at 1024 QAM.

Table 5: Bit error rate performance of multicarrier modulation techniques with 64 QAM, 256 QAM, and 1024 QAM for Pedestrian B channel model.

Waveforms	QAM order		Signal to noise ratio		
			SNR = 15 dB	SNR = 20 dB	SNR = 30 dB
OFDM	64 QAM	Bit error rate	1.029×10^{-1}	2.53×10^{-2}	4.6×10^{-3}
	256 QAM		1.724×10^{-1}	6.16×10^{-2}	1.31×10^{-2}
	1024 QAM		2.372×10^{-1}	1.209×10^{-1}	3.91×10^{-2}
F-OFDM	64 QAM		1.038×10^{-1}	2.82×10^{-2}	8.1×10^{-2}
	256 QAM		1.737×10^{-1}	6.78×10^{-2}	2.29×10^{-2}
	1024 QAM		2.385×10^{-1}	1.292×10^{-1}	6.12×10^{-2}
WOLA-OFDM	64 QAM		1.026×10^{-1}	2.59×10^{-2}	5.8×10^{-3}
	256 QAM		1.724×10^{-1}	6.33×10^{-2}	1.63×10^{-2}
	1024 QAM		2.372×10^{-1}	1.228×10^{-1}	6.4×10^{-2}
UFMC	64 QAM		1.016×10^{-1}	2.58×10^{-2}	5.7×10^{-2}
	256 QAM		1.714×10^{-1}	6.27×10^{-2}	1.636×10^{-2}
	1024 QAM		2.36×10^{-1}	1.222×10^{-1}	4.63×10^{-2}
FBMC/OQAM with PHYDYAS	64 QAM		1.046×10^{-1}	2.81×10^{-2}	7.3×10^{-3}
	256 QAM		1.741×10^{-1}	6.69×10^{-2}	2.05×10^{-2}
	1024 QAM		2.375×10^{-1}	2.267×10^{-1}	5.57×10^{-2}
FBMC/QAM with PHYDYAS filter	64 QAM		6.21×10^{-2}	1.23×10^{-2}	2.1×10^{-3}
	256 QAM		1.261×10^{-1}	3.670×10^{-2}	7.1×10^{-3}
	1024 QAM		1.917×10^{-1}	8.42×10^{-2}	2.26×10^{-2}
FBMC/QAM with Hermite filter	64 QAM		1.221×10^{-2}	1.998×10^{-3}	3.385×10^{-3}
	256 QAM		3.636×10^{-2}	6.765×10^{-3}	1.153×10^{-3}
	1024 QAM		8.364×10^{-2}	2.157×10^{-2}	4.165×10^{-3}

6. Conclusion

The performance of multicarrier modulation techniques like F-OFDM, WOLA-OFDM, UFMC, FBMC with OQAM using PHYDYAS filter, FBMC with QAM using PHYDYAS filter, and FBMC with QAM using Hermite filter is compared to that of existing OFDM. The analysis is carried out based on power spectral density and bit error rate. The PSD versus normalized frequency analysis shows that the out of band emission of FBMC-QAM using Hermite filter is smaller compared to all other waveforms. The PSD difference in dB between FBMC-QAM using PHYDYAS filter and FBMC-QAM using Hermite filter (proposed) is 4.7 which shows the out of band emission reduction amount due to Hermite filter and this helps for coexistence of different services. The bit error rate analysis is carried for Vehicular A, Vehicular B, and Pedestrian B channel models at 64 QAM, 256 QAM, and 1024 QAM. The simulation result shows the bit error rate of FBMC with QAM using Hermite filter is better than all other waveforms in these three channel models. It is observed that the BER performance of FBMC with QAM using Hermite filter reduced the bit error for Vehicular A, Vehicular B, and Pedestrian B ITU standard channel model at 64 QAM, 256 QAM, and 1024 QAM. Generally, from analysis, it can be concluded that FBMC with QAM using Hermite filter is the good multicarrier modulation technique that fits the requirement of 5G wireless communications and beyond.

Data Availability

Data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] C. S. Patil, R. R. Karhe, and M. A. Aher, "Review on generations in mobile cellular technology," *Int. J. Emerg. Technol. Adv. Eng*, vol. 2, no. 10, pp. 614–619, 2012.

[2] P. Sharma, "Evolution of mobile wireless communication networks-1G to 5G as well as future prospective of next generation communication network," *Int. J. Comput. Sci. Mob. Comput. - not index*, vol. 2, pp. 47–53, 2013.

[3] R. Chataut and R. Akl, "Massive MIMO systems for 5G and beyond networks—overview, recent trends, challenges, and future research direction," *Sensors*, vol. 20, no. 10, pp. 2753–2835, 2020.

[4] X. Zhang, L. Chen, J. Qiu, and J. Abdoli, "On the waveform for 5G," *IEEE Communications Magazine*, vol. 54, no. 11, pp. 74–80, 2016.

[5] X. Zhang, M. Jia, L. Chen, J. Ma, and J. Qiu, "Filtered-OFDM - enabler for flexible waveform in th 5th generation cellular networks," in *Proceedings of the 2015 IEEE Global Communications Conference (GLOBECOM)*, San Diego, CA, USA, December, 2015.

[6] N. Varghese, J. Chunkath, and V. S. Sheeba, "Peak-to-average power ratio reduction in FBMC-OQAM system," in *Proceedings of the 2014 Fourth International Conference on Advances in Computing and Communications*, pp. 286–290, Kerala, India, August, 2014.

[7] H. M. Abdel-Atty, W. A. Raslan, and A. T. Khalil, "Evaluation and analysis of FBMC/OQAM systems based on pulse shaping filters," *IEEE Access*, vol. 8, pp. 55750–55772, 2020.

[8] D. Jeon, S. Kim, B. Kwon, H. Lee, and S. Lee, "Prototype filter design for QAM-based filter bank multicarrier system," *Digital Signal Processing*, vol. 57, pp. 66–78, 2016.

[9] R. T. Kamurthi and S. R. Chopra, "Review of UFMC technique in 5G," in *Proceedings of the 2018 International Conference on Intelligent Circuits and Systems (ICICS)*, pp. 121–125, Phagwara, India, April, 2018.

[10] R. Zayani, Y. Medjahdi, H. Shaïek, and D. Roviras, "Wola-Ofdm: A potential Candidate for Asynchronous 5G," in *Proceedings of the 2016 IEEE Globecom Work. GC Wkshps*, Washington, DC, USA, December, 2016.

[11] F. Tazeb and C. A. Kassaw, "Comparative performance analysis of modulation formats for 5g wireless system,"Addis Ababa Institute of Technology, Addis Ababa, Ethiopia, 2019.

[12] C. An, B. Kim, and H.-G. Ryu, "Waveform comparison and nonlinearity sensitivities of FBMC UFMC and W-OFDM systems," in *Proceedings of the Eighth International Conference on Networks & Communications*, pp. 83–90, Bangalore, India, January, 2016.

[13] A. Lizeaga, P. M. Rodríguez, I. Val, and M. Mendicute, "Evaluation of 5G modulation candidates WCP-coqam, GFDM-OQAM, and FBMC-OQAM in low-band highly dispersive wireless channels," *Journal of Computer Networks and Communications*, vol. 2017, Article ID 2398701, 11 pages, 2017.

[14] J. Marian Joseph Jeffery, L. Masapalli, V. M. Nookala, S. P. Dasari, and S. Kirthiga, "Peak to average power ratio and bit error rate analysis of MultiCarrier modulation techniques," in *Proceedings of the 2020 International Conference on Communication and Signal Processing (ICCSP)*, pp. 1443–1446, Chennai, India, July, 2020.

[15] S. Kundrapu, S. I. Dutt Vbs, N. K. Koilada, and A. C. Raavi, "Characteristic analysis of OFDM, FBMC and UFMC modulation schemes for next generation wireless communication network systems," in *Proceedings of the 2019 3rd International conference on Electronics, Communication and Aerospace Technology (ICECA)*, pp. 715–721, Coimbatore, India, June, 2019.

[16] K. K. Kishore, P. R. Umar, and V. J. Naveen, "Comprehensive analysis of UFMC with OFDM and FBMC," *Indian Journal of Science and Technology*, vol. 10, no. 17, pp. 1–7, 2017.

[17] R. Zayani, H. Shaiek, X. Cheng, X. Fu, C. Alexandre, and D. Roviras, "Experimental testbed of post-OFDM waveforms toward future wireless networks," *IEEE Access*, vol. 6, pp. 67665–67680, 2018.

[18] S. A. Khudhair and M. J. Singh, "Review in FBMC to enhance the performance of 5G networks," *Journal of Communications*, vol. 15, no. 5, pp. 415–426, 2020.

[19] R. Nissel, S. Schwarz, and M. Rupp, "Filter Bank multicarrier modulation schemes for future mobile communications," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 8, pp. 1768–1782, 2017.

[20] M. Y. Bendimerad, S. Senhadji, and F. T. Bendimerad, "Prototype filters and filtered waveforms for radio air-interfaces: a review," pp. 1–26, 2021, http://arxiv.org/abs/2104.01373.

[21] R. A. Kumar and K. S. Prasad, "Comparative analysis of OFDM, FBMC, UFMC & GFDM for 5G wireless communications," *Int. J. Adv. Sci. Technol*, vol. 29, no. 5, pp. 2097–2108, 2020.