Performance Optimization of Universal Filtered Multicarrier Technique for Next Generation Communication Systems

Original Scientific Paper

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Abstract *– Next generation communication systems require better performance to support high - bandwidth, peak data rate, spectral efficiency, mobility, connection density, positioning accuracy, etc. Investigation on efficient modulation technique for next generation has become very important so as to meet its expectations. In this paper performance optimization of universal filtered multicarrier (UFMC) technique for next generation communication systems have been investigated. Dolph-Chebyshev (DC) and Kaiser-Bessel-derived (KBD) filters have been used to optimize power spectral density, channel equalization, bit error rate, and peak to average power ratio (PAPR). It has been observed that KBD filter response is comparatively better than DC filter. Effect of filter length also influences the system performance, filter with bigger length improves performance at the cost of computational complexity. Performance of UFMC has been compared with that of orthogonal frequency division multiplexing (OFDM) technique. The present work of investigations on UFMC that is based on subband filtering is our original research work that has been carried out for its suitability for next generation communication systems. It has simple design structure, lower computational complexities and better performance in terms of BER compared to OFDM and f-ODFM systems. It has comparatively low PAPR than GFDM and FBMC techniques.*

Keywords*: BER, Dolph-Chebyshev Window, Kaiser-Bessel-derived window, OFDM, OOB, UFMC*

1. INTRODUCTION

5G communication systems require better performance in terms of heterogeneity for services and should support high - bandwidth, peak data rate, spectral efficiency, mobility, connection density, positioning accuracy, and low latency, etc. Investigation on efficient modulation technique for 5G and beyond has become very important so as to meet its expectations. Orthogonal frequency division multiplexing (OFDM) has been used as multicarrier communication system in 4G and performs better below 6 GHz signal transmission [1]. it is not suitable for 5G and beyond due to poor out of band (OOB) leakage, poor spectral efficiency, high peak to average power ratio (PAPR), synchronization of data, etc.

To overcome these limitations, several modulation techniques have been investigated in the recent past. These new techniques have been studied under novel orthogonal and non-orthogonal category. Non orthogonal wave shaping has been further investigated under power domain, code domain and multiple domain techniques. Whereas, novel orthogonal technique has been studied under pulse shaping, subband filtering and few other techniques. Modulation based on novel orthogonal techniques uses either filtering or windowing in frequency or time domain [2].

FBMC and GFDM are pulse shape-based techniques, FBMC uses offset quadrature amplitude modulation (OQAM) and prototype filters: synthesis filter in transmitter and analysis filter in receiver. Among the different types of filters used, PHYDYAS filter has better frequency response [3]. FBMC is better than OFDM in terms of PAPR, channel achievable capacity, SNR, and OOB leakage [4]. GFDM uses circular convolution to apply filtering on a time-frequency block. GFDM has low complexity and better performance and it is suitable for burst signal transmission [5-6].

Universal Filtered Multicarrier (UFMC) and Filtered OFDM (f-OFDM) modulation techniques are based on subband filtering. UFMC is better than other techniques in terms of spectral efficiency, OOB leakage, robustness to time and frequency offset. Owing to its improved performance, UFMC can be used for high data rate transmission. Whereas, f-OFDM filters signal in time domain to reduce mutual interference and attenuation of side lobes. UFMC and f-OFDM have similar power spectral density but f-OFDM has better timing offset due to use of receiving filters.

The present investigations on UFMC that is based on subband filtering is our original research work that has been carried out for its suitability in 5G and beyond cellular communication applications. Literature review reveals that in the recent past, there has been lot of investigation carried out by researchers that suggests UFMC has better performance than OFDM. Such as, in order to mitigate the effect of interference due to carrier frequency offset (CFO) in uplink systems, adaptive filter has been proposed in [7]. It has been demonstrated that the system performance is getting directly affected by the interference caused by CFO. The parameters of the filter can be adaptively designed to improve data transmission rate and bit error rate (BER). The proposed filter can also be used for different subband bandwidths. A least square (LS) technique-based complexity reduced receiver for UFMC has been proposed in [8] which is computationally efficient. Its symbol error rate (SER) and mean square error (MSE) performance are almost equal to the complex receivers. Its simulation results for number of subcarriers, N = 128, subbands, B = 8, and successive carriers, Q =16 with a 6- ray Rayleigh fading channel, Lh= 6 indicates that symbol error rate decreases with increase in signal to noise ratio (SNR). In order to study the frequency response of overall subcarriers, an efficient channel estimation technique has been proposed in [9]. Simulation result with number of subcarriers, N = 128, subbands, B = 8, and successive carriers, Q =16 and 40 dB of sidelobe attenuation indicates that MSE decreases and SER increases with an increase in the SNR value. They have demonstrated that their system has better performance with reduced computational complexities. A simplified UFMC structure has been proposed by [10], in which they have eliminated redundant IFFT computations by linking a direct relation between number of subcarriers and number of IFFT elements in a frequency block. They have demonstrated that for a single frequency block with 12 subcarriers, 42 % and 65% computations can be reduced for N (elements) = 64 and 1024 IFFT respectively. In [11], computational complexities of the UFMC system has been reduced by using a poly-phase filter with finite impulse response (FIR) structure. They have demonstrated that the system performance can be improved by adjusting their proposed filter structure. A multi user UFMC has been studied in [12] that is based on optimal filter and zero padding length. They have demonstrated that under a given set of criteria, the system capacity can be maximized with optimal filter length and zero padding / filter tail cutting length. A sparse code multiple access UFMC uplink system in the frequency domain has been investigated in [13]. Using maximum likelihood method, they have analyzed the odd and even component of multiuser detection of frequency domain received signal and demonstrated that the average symbol error probability is sub band independent. A low complexity reliability-based detection of UFMC system has been proposed in [14] that demonstrated that a two-stage detection first, initial subcarrier wise estimation and then an update of the unreliable signal has better performance with less complexity. A baseband UFMC transmitter based on reconfigurable architecture has been proposed in [15] that has an option to choose number of subcarriers in a subband and type of pulse shaping filters as per the required figure of merit without having significant change in the hardware resources. Side lobe suppression in UFMC system using Kaiser-Bessel window has been investigated in [16] and its performance have been compared with Dolph-Chebyshev window. It has been demonstrated that Kaiser-Bessel has better side-lobe suppression capability even in noisy channel than Dolph-Chebyshev window with similar peak to average power characteristics. Comparative study of OFDM and UFMC systems based on uniform and probabilistic shaping have been reported in [17]. It has been observed that for UFMC system with uniform shaping, there is 3-dB improvement in the receiver sensitivity at the bit error rate of 3.8×10^{-3}, whereas it is reduced to 1.5 dB for the case of probabilistic shaping. It can support high order modulation with enhanced transmission rate [18].

In the remaining part of the paper, universal filtered multicarrier is presented in section-2, section-3 describes the proposed filter-Dolph-Chebyshev (DC) and Kaiser-Bessel-derived (KBD) window and effect of filter length on the system performance. Performance analysis has been presented in section-4, that describes system performance in terms of PSD, Effect of channel equalization, BER, and PAPR. Section-5 deals with result analysis and conclusion of the work is presented in section-6.

2. UNIVERSAL FILTERED MULTICARRIER

Universal Filtered Multicarrier (UFMC) is a subband filtering based modulation technique that has many advantages over other techniques such as, low OOB, low ICI, and better spectrum efficiency as cyclic prefix is not used. The given bandwidth is divided into multiple sub-bands. These sub-bands are made of a group of sub carriers [19]. These sub carriers are filtered individually with help of a finite impulse response (FIR) filters. The filters used are having low side-lobes that gives low OOB, low PAPR, and low inter block interference (IBI).

Fig. 1 shows the transceiver structure of UFMC. First the given 512 subcarriers is divided into 16 subbands and 32 carriers. Each subband input with 32 subcarriers is fed in the transmitter first to the N-point IFFT. Here the signal is de-spreaded and passed to the filter. Zero padding are done in the UFMC to make FFT of 2N point size. No cyclic prefix is added and because of independent subband filtering this system is considered to be more flexible [20]. It has total N number of subcarriers, B is the number of subbands and each subband consists of Q number of successive subcarriers in a particular subband, where, $N = Q \times B$.

The received signal X_k is represented by equation (1), where Y_{ik} is the baseband data symbols that is being sent on the i-th subband (1≤ I ≤ B), Z_{ik} is the N point IFFT, F_{ik} is the Toplitz matrix that is impulse response of the FIR filter of length L [21].

The output signal of the filters is added together and transmitted through the channel after transforming it into radio frequency (bandpass) form, where signals from other users are also added along with additive white Gaussian noise (AWGN) n in the channel. In the receiver, the bandpass signal is re-transformed into baseband signal and processed in the time domain that includes zero padding and windowing [22]. Then it is converted into frequency domain with the help of 2N point FFT followed by symbol estimation and sub-carrier equalization [23].

$$X_k = \sum_{i=1}^{B} F_{ik} \cdot Z_{ik} \cdot Y_{ik} \quad (1)$$

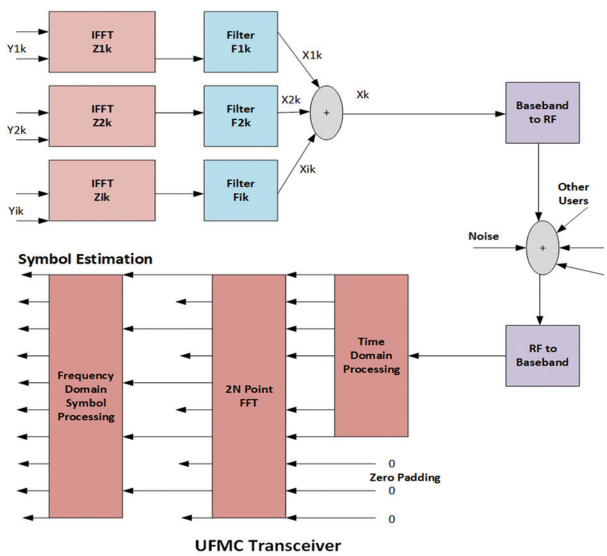

Fig. 1. UFMC Transceiver

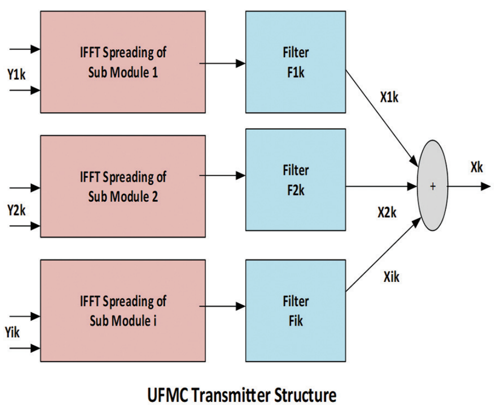

Fig. 2. UFMC Transmitter

Fig. 2 depicts the structure of an UFMC transmitter where the time domain baseband vector X_i is generated by the ith sub-module, it has B number of subbands with N number of samples per symbol. QAM technique has been used as the baseband modulation [24]. First the baseband QAM symbol vectors are spreaded and converted into time domain using IFFT for a particular subband, then it is filtered first using a FIR Kaiser-Bessel window and then by a Dolph-Chevishev filter [25].

The output of the transmitter is represented by equation 1. The individual matrix vector can be represented by equations 2, 3 and 4.

$$\overline{F} = [F_1, F_2, \ldots\ldots F_B] \quad (2)$$

$$\overline{Z} = \text{daig}[F_1 . F_2 \ldots\ldots F_B] \quad (3)$$

$$\overline{Y} = [Y_1^T, Y_2^T, \ldots\ldots Y_B^T]^T \quad (4)$$

After processing the data symbols into a single column, output is represented by equation 5.

$$\text{X} = \overline{F}\,\overline{Z}\,\overline{Y} \quad (5)$$

$$W_{ZF} = (\overline{FZ})^{+} = T^{+} \quad (6)$$

UFMC receiver structure is shown in Fig. 3 where the received signal is given by $X_k + n$, n is the AGWN noise added in the channel. The receiver can be designed with any efficient filter, here zero forcing (ZF) and minimum mean square error (MMSE) filter has been considered that is represented by equation 6 and 7.

$$W_{ZF} = (\overline{FZ})^{+} = T^{+} \quad (7)$$

$$W_{MMSE} = (T^H . T + \sigma^2 I)^{-1} . T^H \quad (8)$$

Where in, T^H is Hermitian transpose, T^+ is Moore-Pensore inverse, I is identity matrix and σ^2 is the variance of the noise.

After padding with zeros, FFT is of 2N length, where N is the number of elements [26].

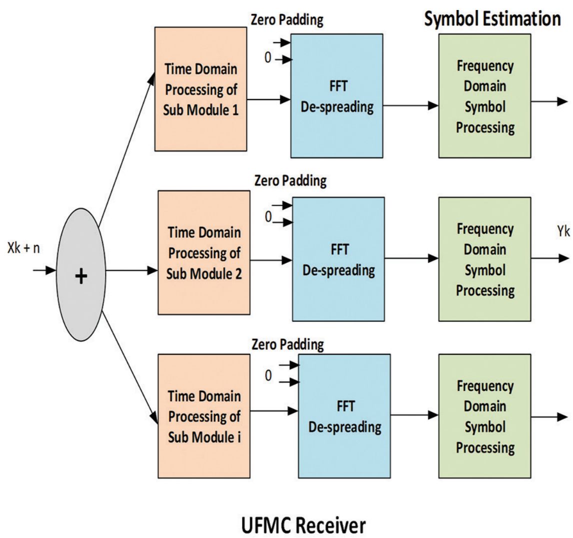

Fig. 3. UFMC Receiver

3. PROPOSED FILTER

Dolph-Chebyshev (DC) and Kaiser-Bessel-derived (KBD) window based low pass FIR filters have been used for investigation of the proposed UFMC transceiver system [27]. The choice of the filter is based on the fact that it has accurate edges for both passband and stopband, low OOB, lower power leakage, lower sideband lobe, and better power spectral density performance, etc. [28].

It has been observed that KBD has comparatively lower spectral leakage than the DC window.

3.1 KAISER-BESSEL-DERIVED WINDOW

The coefficient of KBD window is represented by equation (8).

$$s_k(n) = \begin{cases} \dfrac{I_0\left(\beta\sqrt{1-\left(\frac{n}{\frac{N}{2}}\right)^2}\right)}{I_0\ (\beta)};\ for\ -\frac{N-1}{2} \leq n \leq \frac{N-1}{2} \\ 0;\ elsewhere \end{cases} \quad (8)$$

Here, N is the length of the filter, β is the tuning parameter and I_0 is the modified Bessel function of first kind and zero order.

The Fourier transform of KBD window is given by equations 9 and 10.

$$S(f) = \frac{N}{I_0\ (\beta)} \frac{\sinh\left[\sqrt{\beta^2-\left(\frac{N_f}{2}\right)^2}\right]}{\sqrt{\beta^2-\left(\frac{N_f}{2}\right)^2}} \quad (9)$$

$$S(f) = \frac{N}{I_0\ (\beta)} \frac{\sin\left[\sqrt{\left(\frac{N_f}{2}\right)^2-\beta^2}\right]}{\sqrt{\left(\frac{N_f}{2}\right)^2-\beta^2}} \quad (10)$$

Where, the modified Bessel function of first kind and zero order, I_0 is given by equation (11).

$$I_0\ (y) = \sum_{k=0}^{\infty}\left[\frac{\left(\frac{k}{2}\right)^k}{k!}\right]^2 \quad (11)$$

Fig. 4 shows the KBD window with sample length of 32 and side lobe of 40 dB in time and frequency domain.

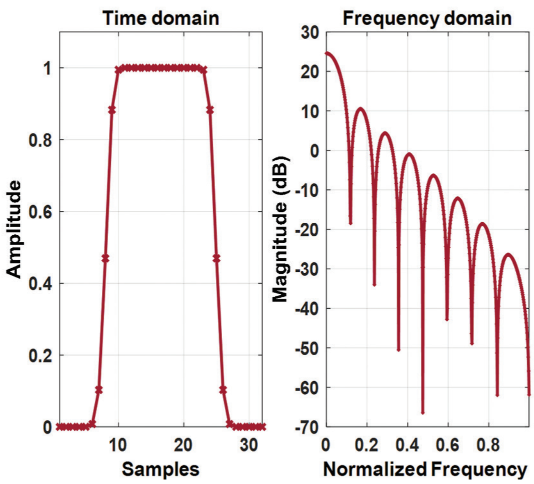

Fig. 4. Kaiser-Bessel-derived (KBD) window with N = 32 and side lobe = 40 dB.

Similarly, Fig. 5 depicts KBD window with sample length of 32 and side lobe of 20, 30 & 40 dB both in time and frequency domain.

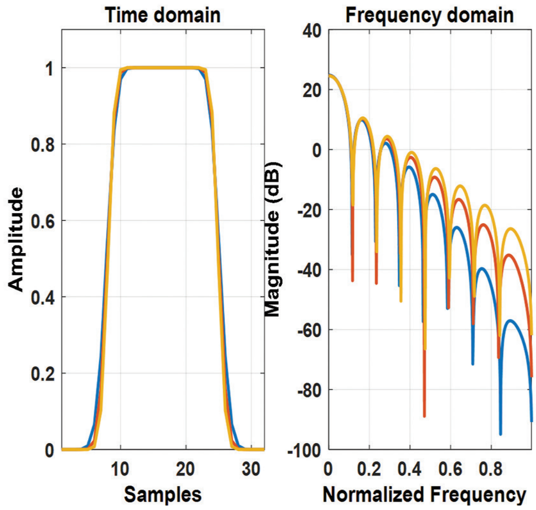

Fig. 5. Kaiser-Bessel-derived window with N=32, side lobe =20, 30 & 40 dB

3.2 DOLPH-CHEBYSHEV WINDOW

The Dolph-Chebyshev window transform is represented by equation (12). Fig. 6 reflects the DC window with sample length of 32 and side lobe of 40 dB in time and frequency domain.

$$S(k) = -1^k \frac{\cos\{N\cos^{-1}\left(\beta\cos\left[\frac{\pi k}{N}\right]\right)\}}{\cosh\left[\frac{1}{N}\cosh^{-1}(\beta)\right]} \quad (12)$$

β is defined in equation (13) and α is the representation of the side lobe attenuation.

$$\beta = \cosh\left[\frac{1}{N}\cosh^{-1}(10^{\alpha})\right] \quad (13)$$

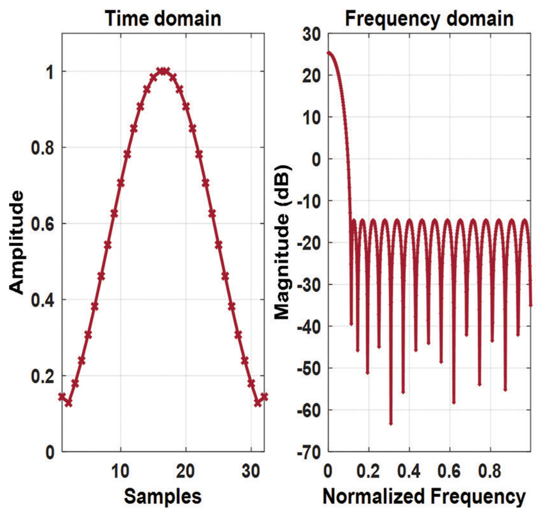

Fig. 6. Dolph-Chebyshev window with N = 32 and side lobe = 40 dB.

Whereas, Fig. 7 shows DC window with sample length of 32 and side lobe of 20, 30 & 40 dB both in time and frequency domain [29].

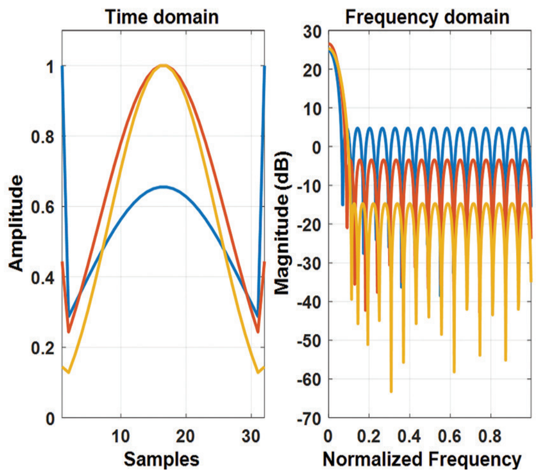

Fig. 7. Dolph-Chebyshev window with N= 32 side lobe = 20, 30 & 40 dB

3.2 EFFECT OF FILTER LENGTH

The UFMC system performance depends upon the length of the filter. In the case of longer filter length its performance is better in terms of low OOB leakage, more robust to synchronization, and better frequency localization or frequency selectivity. On the other hand, longer filter leads to larger overhead, reduced transmission efficiency, narrow bandwidth, performance loss due to less effective power allocation for a subcarrier in a subband.

Cyclic prefix/ zero padding (CP/ZP) is required to be added in order to nullify the effect of multipath fading. But it causes overhead on the system, reducing spectrum and transmission efficiency with marginal improvement in system performance. To get the optimum efficiency of the system, trade off has to be made to justify the length of CP/ZP with transmission efficiency.

Similarly, filter tail cutting (TC) is required in order to reduce the overhead of the system. To make the system robust to imperfections like, inter carrier interference (ICI), inter symbol interference (ISI), carrier frequency offset (CFO) and timing offset, etc. it is required to choose the optimum length of the filter, CP/ZP, and TC.

4. PERFORMANCE ANALYSIS

Performance analysis using mathematical modelling and Matlab simulations have been carried out for the proposed UFMC system with Dolph-Chebyshev (DC) and Kaiser-Bessel-derived (KBD) window. It has been observed that KBD has comparatively lower spectral leakage than the DC window. Moreover, DC filter does not give optimal result for the UFMC system under considerations due to the fact that its high out of band emissions. On the other hand, performance of KBD filter is better in terms OOB and other desired parameters.

4.1 POWER SPECTRAL DENSITY

Power spectral analysis has been obtained using Matlab simulations using the parameters as depicted in table 1 for UFMC systems using Dolph-Chebyshev window and Kaiser-Bessel-derived window. From Fig. 8, 9 and 10, it is observed that Kaiser-Bessel-derived window has low power leakage and gives better performance than Dolph-Chebyshev window.

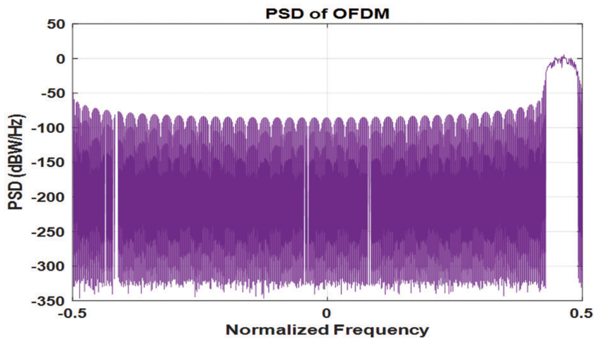

Fig. 8. PSD of OFDM

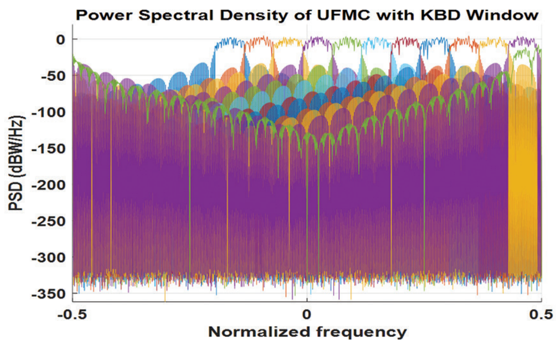

Fig. 9. PSD of UFMC with Kaiser-Bessel-derived window

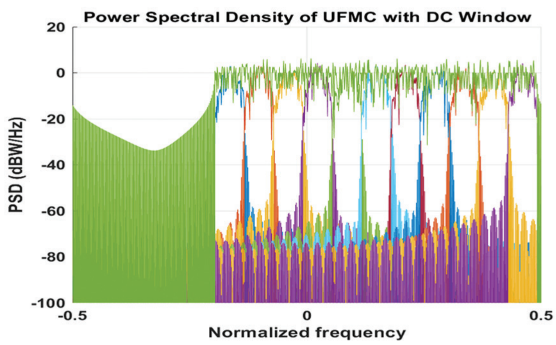

Fig. 10. PSD of UFMC with Dolph-Chebyshev window

Table 1. Simulation Parameters

Description	Value
FFT Size	512
Subband Size (No of Carriers)	32
Number of Subbands	16
subband Offset	156
Filter Length	42
Side Lobe Attenuation	40 dB
Modulation Type	16 QAM
Bits per Sub Carrier	4
SNR	15 dB

4.2. CHANNEL EQUALIZATION

Effect of channel equalization have been studied for the receiver imperfections and insufficient cyclic prefix, zero padding, and tell cutting length (CP, ZP and TC). For its analysis zero forcing (ZF) and minimum mean square error equalizers (MMSE) have been used. Performance of the equalizer for its nth subcarrier is expressed by equation 14.

$$S_n = \frac{\beta(n,n\ 0)^H}{|\beta(n,n\ 0)|^2 + m\ \sigma_{eff}{}^2/p_{sym}{}^2} \qquad (14)$$

Where, the parameter m is defined in equation (15) for zero forcing (ZF) and minimum mean square error equalizers (MMSE).

$$m = \begin{cases} o & for\ ZF\ Receiver \\ 1 & for\ MSME\ Receiver \end{cases} \qquad (15)$$

The effective noise power, $\sigma_{eff}{}^2$ is represented by equation (16), where, P_{ISI} is the noise power due to inter symbol interference (ISI), P_{ICI} is the noise power due to inter carrier interference (ICI), L is the length of the filter and N is period of the received signal.

$$\sigma_{eff}{}^2 = P_{ISI} + P_{ICI} + \frac{L_2\,k}{N}\sigma^2 \qquad (16)$$

ZF receiver response is represented by equation (17). But ZF receivers amplify noise also along with received signal.

$$g = B^+ . f_e \qquad (17)$$

$$B^+ = (B^H\ B)^{-1} . B^H \qquad (18)$$

Whereas, MMSE receiver does not amplify noise as it uses transformation matrix and minimizes the mean square error distance between the transformed vector and the transmitted signal vector. Its BER performance is better than ZF receivers. The response of the MMSE receiver is represented by equation (19) and (20).

$$g = B^{\ddagger} . f_e \qquad (19)$$

and,

$$B^{\ddagger} = \left(\frac{\delta_n^2}{\delta_d^2} I + B^H\ B \right)^{-1} . B^H \qquad (20)$$

Fig. 11 depicts pre-equalization performance of 16QAM UFMC signals.

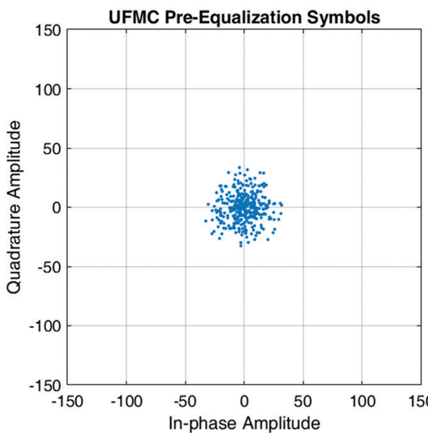

Fig. 11. UFMC Pre- Equalization Symbols

Whereas, Fig. 12 describes post-equalization performance of 16QAM UFMC signals. It is evident from figure 12 that performance of post-equalization is much better than pre-equalization operation.

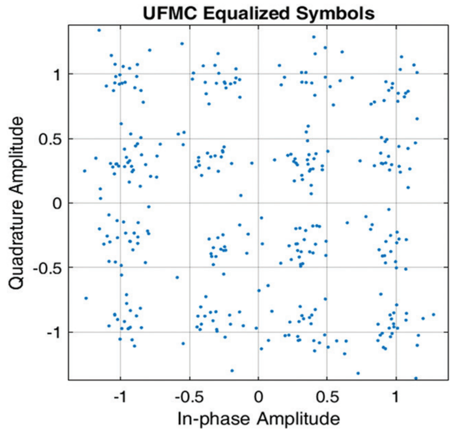

Fig. 12. UFMC Equalized Symbols

4.3. BIT ERROR RATE

BER of UFMC system for 16 QAM baseband format is expressed by equation 21.

$$\text{BER(x)} = 2(1-\frac{1}{\sqrt{16}})\ Q\left(\sqrt{\frac{3\ SNR\ (x)}{16-1}}\right) \qquad (21)$$

But analysis using equation 21 is tedious and complex due to the use of Q-function. So, in order to get the result in simplified way, approximation of Q-function has been used as represented in equation 22.

$$Q(n) \approx \frac{1}{12}e^{-\frac{n^2}{2}} + \frac{1}{6}e^{-\frac{2n^2}{3}} \qquad (22)$$

Fig. 13 depicts the BER performance of OFDM and UFMC technique with KBD and DC filters. It can be observed that BER performance of OFDM is better than UFMC technique.

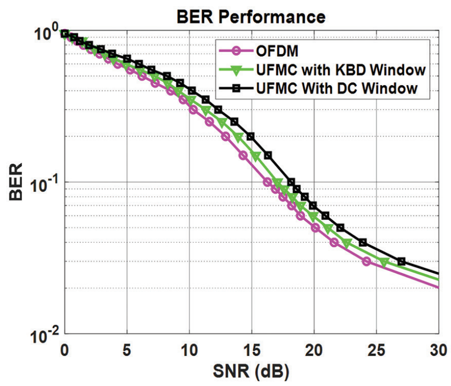

Fig. 13. BER Performance of UFMC with Filters

Performance of the UFMC system in terms of BER has been analyzed using mathematical modelling and Matlab simulations and it has been compared with that of OFDM, f-OFDM, GFDM and FBMC, systems as depicted in Fig. 14. It has been observed that for a given signal to noise ratio, FBMC has highest BER, followed by GFDM, UFMC, f-OFDM, and OFDM has lowest BER.

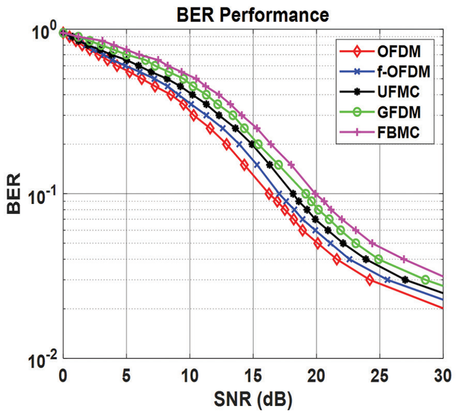

Fig. 14. BER Performance of Different Techniques

4.4. PEAK TO AVERAGE POWER RATIO

PAPR is defined as the ratio of peak power to average power of the given signal. It is a measure of fluctuations in the output of a multicarrier system. For a complex valued multicarrier signal *x* (*t*), its PAPR is expressed by equation 23.

$$PAPR\ \{x\ (t)\} = \frac{\max\{x(t)\}^2}{Avg\ \{x(t)\}^2} \quad (23)$$

To find out the probability that PAPR of a system exceeds a given threshold value, complementary cumulative distribution function (CCDF) is used. CCDF has been expressed by equation 24, where x is the threshold value, P is the probability that the maximum value is greater than the threshold value x, and C is the CCDF.

$$\begin{aligned} Cx_{max}\ (x) &= P\ (x_{max} > x) \\ &= 1 - P\ (x_{max} \leq x) \\ &= 1 - Cx_{max}\ (x) \end{aligned} \quad (24)$$

Fig. 15 shows the CCDF performance of the UFMC system. It can be observed from the figure15 that at 6 dB of PAPR value, CCDF value is 0.01 and 0.007 for Dolph-Chebyshev and Kaiser-Bessel-derived window respectively.

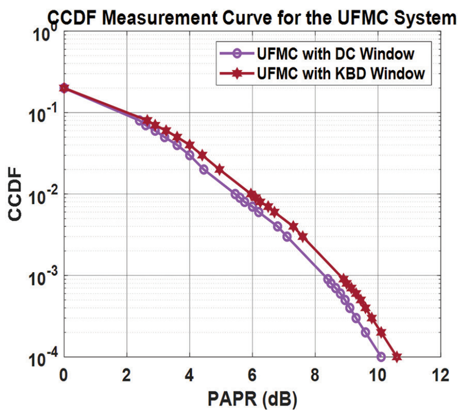

Fig. 15. CCDF Measurement of the UFMC System

Fig. 16 depicts the PAPR performance of OFDM and UFMC technique with KBD and DC filters. It can be observed that PAPR performance of UFMC with DC filter is better than UFMC with KBD filter, and OFDM technique. OFDM has the highest PAPR for the given number of sub carrier.

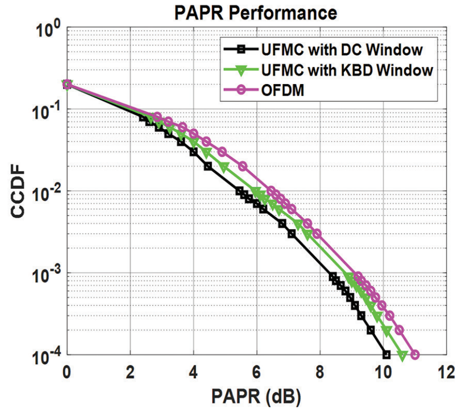

Fig. 16. PAPR Performance of UFMC with Filters

PAPR of UFMC has been computed and it has been compared with that of OFDM, f-OFDM, GFDM and FBMC, systems as depicted in Fig. 17. It Reveals that OFDM has highest PAPR followed by f-OFDM, UFMC, GFDM and FBMC has lowest PAPR. It can be concluded that BER and PAPR are inversely proportional to each other. UFMC system has better performance in terms of PAPR compared to the OFDM system.

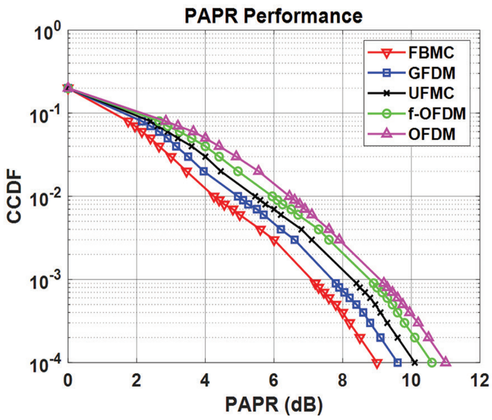

Fig. 17. PAPR Performance of Different Techniques

5. RESULT ANALYSIS

The study reveals that Kaiser-Bessel-derived window has low power leakage and gives better performance than Dolph-Chebyshev window. KBD filter response is comparatively better than DC filter in the case of power spectral density and out of band leakage, and side lobe area. The study further suggests that effect of post-equalization has greater impact on the received signal quality.

Table 2 depicts the performance of different modulation techniques in terms of its BER and PAPR values. It can be observed from the table that UFMC has comparatively average performance without any computational complexities with simple transceiver structure.

Performance of the UFMC system in terms of its BER and PAPR has been compared with that of OFDM, f-OFDM, GFDM and FBMC, systems. It has been observed that for a given signal to noise ratio, FBMC has highest BER, followed by GFDM, UFMC, f-OFDM, and OFDM. It further reveals that for a given number of subband carrier, OFDM has highest PAPR followed by f-OFDM, UFMC, GFDM and FBMC. The result obtained indicates UFMC performance is much superior in the case of PAPR, spectrum efficiency, etc. than OFDM technique.

Table 2. System Performance

Sl. No.	Modulation Technique	SNR (dB)	BER (dB)	PAPR (dB)	CCDF
1	OFDM	20	0.05	8	0.003
2	F-OFDM	20	0.06	8	0.001
3	UFMC	20	0.07	8	0.0008
4	GFDM	20	0.08	8	0.0006
5	FBMC	20	0.09	8	0.0004

Performance of the UFMC system in terms of its BER and PAPR has been compared with that of OFDM, f-OFDM, GFDM and FBMC, systems. It has been observed that for a given signal to noise ratio, FBMC has highest BER, followed by GFDM, UFMC, f-OFDM, and OFDM. It further reveals that for a given number of subband carrier, OFDM has highest PAPR followed by f-OFDM, UFMC, GFDM and FBMC. The result obtained indicates UFMC performance is much superior in the case of PAPR, spectrum efficiency, etc. than OFDM technique.

6. CONCLUSION

In the present work, investigations on UFMC that is based on subband filtering have been carried out for its suitability for next generation communication systems. It has been observed that UFMC is better than other techniques in terms of spectral efficiency, OOB leakage, robustness to time and frequency offset. Owing to its improved performance, UFMC can be used as multi carrier communication system with high data rate transmission capability. Its PAPR performance is far better than the OFDM system.

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