Prototype filter design for filter bank multicarrier modulation

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Abstract. The use of the cyclic prefix in the orthogonal frequency division multiplexing (CP-OFDM) system recently it is the technique widely used method in many wireless communication systems, which depends on the use of the rectangular pulse shape for the transmission. However, the use of the rectangular pulse shape in the filter leads to appearance of many problems such as out of band emission and also the necessary need to use what is known as the cyclic prefix for the purpose of preventing interference, which leads to decrease the spectral efficiency due to the exploitation of part of the spectrum for the purpose of protection from interference. For the purpose of getting rid of these problems, the filter bank multicarrier (FBMC) system has been proposed who uses filters to construct the typical pulse that can be used in this system. The main idea in this system is how to choose the appropriate filter system for the FBMC/OQAM because this filter plays a fundamental role in the system. In this research, we will be focused on presenting a new prototype pulse shape that can be used in the fifth-generation networks (5G) of communications and also for the purpose of improving the performance of this system and overcoming the previously mentioned obstacles. During this research we will present two models to form the used pulse model, and then we compare these shapes with the most common pulse shape like (Rectangular, RC, PHYDYAS, Hermite). Through this comparison, the efficiency of these pulses can be determined by studying several different parameters that have a direct impact on performance, such as (BER, SIR, PAPR).

1. Introduction
Communication systems in the next generation require improving wireless systems and providing better services because of the great developments that are occurring on the network and the high demand for the services it provides and the entry of many systems and industrial applications within the network such as the Internet of things and others. Therefore, it has become necessary to provide high reliability, low access time, and improve performance mobiles and extend the life of batteries. In order to achieve the above, multi carrier modulation (MCM) has been widely used due to the distinctive properties. Whereas, (MCM) is the main element in wireless networks [1]. And the (OFDM) technology is the common one that uses this system [2]. This is done by using the shape of a
rectangular pulse and used in the fourth generation of communications 4G. However, this system faces many challenges such as the presence of interference between channels and high out of band emission (OOBE), and also because we need to use the (CP) that provides sufficient time to avoid interference between pulses which is at the expense of the spectral efficiency. Therefore, time synchronization and repetition are required greatly for the purpose of removing and terminating get interference. On this basis, this pulse shape can be considered as not the best form to provide services that are constantly in high demand [3],[4]. Several studies and researches have been presented on how to overcome these problems. And so, by using a new pulse shape design. The process of design pulse shape is very important, because this is due to the heavy reliance on telecommunications on this process in wireless communication is based on this design, and therefore it is the main nerve and the first step in designing the new system and building communication schemes and associated networks. Therefore, these studies and researches have changed the pulse shape in order to provide better characteristics such as low response time, increased signal strength and coherence in signal, elimination of synchronization, increased bandwidth, increased spectral efficiency after elimination of (CP), increased safety and reliability, and thus increased network absorption of new requirements. Filter bank (FBMC) was presented as one of the alternative solutions to the defects of (OFDM) and as one of the new pulse shapes [5],[6]. Whereas, The filter model exploits the waveform of all sub-carriers in order to make full use of them, especially during the frequency domain this differs from the rectangular pulse shape used in (OFDM). In order to reduce the interference of carriers [6],[7] and the radiation out of band. And as a result of the good characteristics and features provided by (FBMC), this system enables it to address the critical points facing communication systems now or in the future. There are different methods and techniques that can be used to represent the system of FBMC. In our current research, we will use schemes based on the system of Saltzberg and FBMC/OQAM. As the orthogonality in this system will be only in the real domain that leads to the revitalization of the conditions of orthogonality, because these conditions must be fulfilled in the complex domain of the system of (OFDM). First of the advantages of FBMC/OQAM is that it modulated the data of transmitted symbols followed by the interference caused by the adjacent transmitting symbol in the frequency-time domain [8]. However, this interference is a weakness of the FBMC system when dealing with the association of MIMO. In the technique of FBMC/OQAM, the schemes of (TMUX)trans multiplexer are used as a basic element in the system, where the (SFB) filter includes the transmitter filter, while on the opposite side, the (AFB) contains the receiver filter [8]. The design of (TMUX) depends mainly on the design of the PF, where this design determines how the shape of these symbols also associated with the dispersive-channel robustness and their correlated will be in this system. On this basis, the PF is designed in time selective and frequency selective channels to be suitable for communications. Also, PF has a significant effect on the interference in the space of time and frequency between data symbols (ISI) as well as the (ICI) [9][10]. Therefore, great attention must be paid to the design model in order to achieve the required performance [11]. And through evaluating the performance of FBMC and comparing it with the OFDM studies have shown that the MIMO technique and channel estimation are the two main problems facing this system. there are several studies to solve these problems. as in [12], there is a problem of determining the orthogonality when dealing with time-varying channels and also the amount of data throughout the packet, and implementation of the transmitter and receiver. despite the obstacles that face this system, however, when comparing this system with the OFDM system, we find that this system provides higher spectral characteristics due to choosing the type of PF and getting rid of the CP Therefore, the FBMC can be considered a practical candidate in the next generation of wireless communications. In some studies, as in [13], where the researchers demonstrated that the filter bank system can be more effective. Where a new system called the frequency spreading system (FS-FBMC) was proposed. In another source, fast convolution was used based on multi-rate filter bank highly tuneable rate schemes. Through the study of several techniques and schemes for implementing the FBMC, the IFFT technology appears to be the most effective due to the rapid response and the reduction of complexity.
significantly. Therefore, this technique will be relied upon during this research. As a basic element in the FBMC/OQAM scheme, PFs greatly influences two basic properties of the system's performance [13]. The first is the determination of the PSD for the signal transmitted to FBMC/OQAM and thus affects the emission value of OOB [14], and the second is that (PF) contributes to determining the interference, because this interference greatly contributes to determining the channel estimation and also in the ability to guess the channel estimation, and where the (OOBE ) is low, this increases the improvement of specifications and spectral efficiency [15]. The design of the prototype pulse shape filter is of great importance on communication system. There are several studies and researches that focus mainly on the effect of different pulses shape on the formation and performance of filters as in [16] and [17] for the purpose of minimizing the ICI where different types such as (RC, RRC, BTRC, SP, ISP, PMSP) have been proposed in order to reduce the ICI in the OFDM system. The design of PF that uses the technique of frequency spreading in [14]. Another benefit of this technique is that the closed representation of this system can be expressed and gives the value closest to the ideal values or near-perfect reconstruction characteristics. PHYDYAS is another pulse shape that proposed in EU-FP7 [18]. (RC-OFDM) raised cosine windowed OFDM and PHYDYAS and ( isotropic orthogonal transform algorithm IOTA) was proposed to improve the performance of FBMC [19]. Another research on comparative between FBMC, PFs was introduced in [20], Rectangular, Extended rectangular, RRC, Hermite, PHYDYAS, IOTA. Were IOTA, Hermite show elimination the CP use and achieve a good SIR especially in higher frequency dispersion and low side lobe. PHYDYAS It provides better performance and at the same time gives less complexity in transmitter and reception structures.

![Figure 1. The transmitter and receiver scheme for FBMC/OQAM [14].](image)

In this paper, we propose a new pulse shape in order to use it in FBMC/OQAM systems and study the characteristic of the proposed pulse and compare the result with the most common pulse shape like (Rectangular, RRC, PHYDYAS, Hermite),and we do the study over various channels in term of the PSD,SIR,BER, PAPR peak average power ratio. We will summarize the research in steps.

1) Proposed a new pulse shape filter to improve the FBMC/OQAM performance.
2) New shape1, shape2 may be promising to use in PFs for FBMC
3) Compare the shape1 and shape2 with another pulse shape
Show the results for each one and study the effect of the design on (PSD, BER, SIR, PAPR).

2. FBMC/OQAM

Let \( x_{m,n} \) represent the complex transmitted symbol at \( m \) is the subcarrier and \( n \) the time, The shape of each sub-bus uses the best representation in the filter model (well-localization PF \( g_{m,n}(t) \)), and accordingly we can express the transmitted signal by the following equation

\[
 s(t) = \sum_{n=1}^{N} \sum_{m=1}^{M} g_{m,n}(t) x_{m,n}(t) \quad (1)
\]

\[
 g_{m,n}(t) = p_{tx}(t - NT_0/2)e^{j2\pi mf(t-NT_0)}e^{j\theta_{m,n}} \quad (2)
\]

Where \( p_{tx}(t) \) is the pulse shaping PF were \( g_{m,n}(t) \) is the frequency shifted and version time of the PF. \( T_0 \) is the time spacing. \( F \) represent the subcarrier spacing. \( N \) is the no. of symbols and \( M \) is the number of subcarriers. In the receiver side, the symbol that received can be expressed as \( r(t) \) and received PF.

\[
 y_{m,n}(t) = (r(t), q_{m,n}(t)) = \int_{t}^{0} r(t)q_{m,n}^*(t)dt \quad (3)
\]

Where \( q_{m,n}(t) \) defined similar as \( g_{m,n}(t) \), except that may be use a different PF.

\[
 q_{m,n}(t) = p_{rx}(t - NT_0/2)e^{j2\pi mf(t-NT_0)}e^{-j\theta_{m,n}} \quad (4)
\]

Where the PF \( q_{m,n}(t) \) received can be described as a transmitted one. if we use the channel (AWGN additive white gaussian noise) the \( g_{m,n}(t) = q_{m,n}(t) \),in a selective fading channel the \( g_{m,n}(t) \) will differ from \( q_{m,n}(t) \). In [18] the FBMC may called FBMC/OQAM or called staggered modulated multitone (SMT), The use of the (OQAM) system instead of the (QAM) system represents a promising technique through which it is possible to strengthen and enhance the conditions of orthogonality between real symbols only, by using the offset by \( (T_0/2) \) to achieve the orthogonality in the real domain and get rid of the interference in the imaginary domain. and it has a better spectral efficiency than OFDM because it doesn’t need the cyclic prefix insertion. The structure of the FBMC/OQAM can show in figure.1 [14], we can show the PF is the first element in the system thereafter get the filters started here from this PF. Also, the transmitter consists of two main components, first, the OQAM pre-processing, second, the SFB (synthesis filter bank). Since the receiver side have the AFB (analysis filter bank), and the OQAM post processing. The delay value \( Z^{-D} \) will added to the output of the SFB in transmitter side and input of AFB in receiver side in order to adjust the phase for the down sampling process. \( D \) is depending on the length of the PF

\[
 l_p = KM + 1 - D \quad (5)
\]

If the length of filter is \( l_p = KM - 1 \) this mean the value of \( D \) will be 2 and the delay is \( Z^{-2} \). Where \( K \) is the overlapping factor.
2.1 FBMC/TRANSMITTER

In the transmitter side the pre-processing converts the complex input data $c_{m,n}$ to real symbol [2], and the imaginary components of $c_{m,n}$ are upsampled by 2.

$$c_{m,n}^R = \begin{cases} R\{Cm,n/2\} & n \text{ even} \\ 0 & \text{elsewhere} \end{cases} \quad (6)$$

$$c_{m,n}^I = \begin{cases} I\{Cm,n/2\} & n \text{ even} \\ 0 & \text{elsewhere} \end{cases} \quad (7)$$

Therefore, the transmitted symbol of $x_{m,n}$ will be a combination of real and imaginary components.

$$X_{m,n} = X_{m,n}^R + X_{m,n}^I \quad (8)$$

The transmitted symbol $x_{m,n}$ upsampled by a factor $M/2$ in the SFB.then the process of filtration applied to each subcarrier by shifted version of the $g_m[k]$ in order to obtain the transmitted signal.

$$s[k] = \sum_{n=-\infty}^{\infty} \sum_{m=0}^{M-1} x_{m,n} g_{m,k-nM/2} \quad (9)$$

and

$$g_m[k] = e^{j(2\pi/M)mk} g[k] \quad (10)$$

2.2 FBMC/RECEIVER

The demodulated symbol $y_{m,n}$ in the AFB can be obtained by the projection of the received signal $r[k]$ on the filter of receiver $g_m[k]$ like in eq.3

$$y_{m,n} = \sum_{k=-\infty}^{+\infty} r[k] g_m^*[k-nM/2] \quad (11)$$

And

$$g_m^*[k] = g_m^* [k] = e^{-j(2\pi/M)mk} g[k] \quad (12)$$

And the receiver signal can write as

$$y_{m,n} = x_{m,n} + j u_{m,n} \quad (13)$$
$u_{m,n}$ this interference represents the main or major interference (intrinsic interference), and it is the imaginary interference described in [2].

$$u_{m,n} = \sum_{(m,n) \neq (m,n)} x_{m,n} g_m \left[ k - \frac{nM}{2} \right] g_m \left[ k - \frac{nM}{2} \right]$$  \hspace{1cm} (14)

### 2.3 MATRIX-BASED SYSTEM MODEL

The representation matrix of the system model form simplicity in [21]. the PF can be expressed as $G \in C^{1 \times MN}$

$$G = \begin{bmatrix} g_{1,1} & \cdots & g_{1,M} & \cdots & g_{1,N} \\ \vdots & & \vdots & & \vdots \\ g_{M,1} & \cdots & g_{M,1} & \cdots & g_{M,N} \end{bmatrix}$$  \hspace{1cm} (15)

The transmitted symbols $x \in C^{MN+1}$

$$x = [x_{1,1}, x_{2,1}, \ldots, x_{M,1}, x_{1,2}, \ldots, x_{m,n}]^T $$  \hspace{1cm} (16)

And we can rewrite the transmitted signal $s(t)$ same as in equation (1)

$$s = GX $$  \hspace{1cm} (17)

In the same way like in eq. (15) the received sampled pulses $q_{m,n} \in C^{1 \times MN}$ it also can be written as

$$Q = \begin{bmatrix} q_{1,1} & \cdots & q_{1,M} & \cdots & q_{1,N} \\ \vdots & & \vdots & & \vdots \\ q_{M,1} & \cdots & q_{M,1} & \cdots & q_{M,N} \end{bmatrix}$$  \hspace{1cm} (18)

As we assume before if the fading channel, is AWGN then $Q = G$ and the $h[m, n]$ is the time-variant impulse response, where the $m_T$ is the delay in channel [21]. At last the convolution matrix can be written as

$$[H]_{i,j} = h[i - j, i] $$  \hspace{1cm} (19)

Therefore, the symbols in the receiver side can be rewritten as

$$y = Q^H r = Q^H H G x + n $$  \hspace{1cm} (20)

Where $r \in C^{N+1}$ is the received signal and $n - CN(0, P, Q^H Q)$ is the noise from the gaussian distribution. Where $P$, is the power of the time white gaussian noise. and we can neglect the interference from the channel because the interference is smaller than the noise in the highly under spreading channels, therefore, we can neglect all the elements of $Q^H H G$ matrix except the element in the diagonal of the matrix

$$y = diag(h) Q^H G x + n $$  \hspace{1cm} (21)
And from (21) the FBMC/OQAM keeps only the orthogonality in real domain, that leads to 
\[ R\{Q^H G\} = R\{G^H G\} = I_{NK} \]. Eliminate illusory interference and reduce it by several methods, 
including using the first or second order phase equalizer one tap or more and extracting the real only.

3. Filter design

The method that all researchers working on how to design a new pulse shape free of ISI and ICI, to 
satisfy this aim the value of the real points of intersection must be zero during the cycle of symbols 
and their multiples [22].

\[
x(kT) = \begin{cases} 
1, & k = 0 \\
0, & k = \pm 1, \pm 2, \pm 3, \pm 4, \ldots 
\end{cases} \quad (22) 
\]

where \( x(T) \) represent the pulse, and \( T \) represent the period of symbol. Therefore, the perfect sampling 
time for (22) is \( (kT) \) to maximize the output SNR of the filter, \( x(kT) \) will splits into two halve [23].
choose one filter in the transmitter and another one in the receiver side which work later as a match filter as below

\[
x(t) = h(t) \otimes h^*(t) \quad (23) 
\]

where \( h(t) \) and \( h^*(t) \) is the transmitter & receiver filter respectively, and the \( \otimes \) represent the convolution process. If \( h(t) \) is even symmetry and real function, then \( h^*(t) \) both filters are same. The rectangular pulse shape has petter shape in time domain but it contains a big side lobe when applied in OFDM. to reduce the spectra leakage, 10% of the bandwidth allocated was reserved as the guard band to overcome the interference in signals in (4G long term evolution in LTE) in the uplink channel this causes a loss of frequency resources. In addition, during the transmission process in the up-link channel in the system of the (LTE) each user transmits separately with a different timing, time offset and frequency, and thus a failure occurs in the process of forming a frequency-time link, and thus a deterioration in the work of the system occurs. Therefore, many developments were made on rectangular pulse. Recently, Hanning windowed or sinc and RRC were Studied and implemented to satisfy a short stopband attenuation in OFDM, the new pulse shape was called the filtered-OFDM [24]. In other studies, like [25]. In our s study, we will to make merge between two pulse, hanning pulse and extended rectangular pulse(SHAPE1) and between the PHYDYAS with quarter of the extended rectangular pulse (SHAPE2) to obtain anew pulse shape that outperform a rectangular pulse in term of spectrum characteristics and has a good IR behavior than the hanning or PHYDYAS pulse is the goal of the proposed pulse in order to become a candidate for the next generation waveform pulse shaping especially in the 5G when we do the analysis. In SHAPE1 we take a hanning pulse from (null-to-null) interval \( T_0 \) between [-To/2 to +To/2]

\[
w(t) = \begin{cases} 
0.5 - 0.5 \cos\left(\frac{2\pi t}{T_0}\right), & -\frac{T_0}{2} \leq t \leq \frac{T_0}{2} \\
0, & \text{otherwise} 
\end{cases} \quad (24) 
\]
to make a new filter function, we make a convolved between the hanning pulse and the inverse root time pulse (extended rectangular) with an interval of data symbol duration (t ≤ To/2) and we make the equation.

\[
m(t) = \begin{cases} \frac{1}{\sqrt{T_0}}, & -\frac{T_0}{2} \leq t \leq \frac{T_0}{2} \\ 0 & \text{otherwise} \end{cases} \quad (25)
\]

\[
n(t) = w(t) \otimes m(t) \quad (26)
\]

Where m(t) represent the inverse root time pulse to the same duration period and n(t) represent the function of the proposed filter. The new filter pulse shape (SHAPE1) convolution between the hanning and inverse root time pulse (Extended rectangular) characteristic in both time and frequency domain. Therefore, we have greater freedom and flexibility to obtain different pulse shapes, as depicted. In all pulses, the symbol interval can be taken T_0 as large as the first side lobe sway is F=1/T and therefore all pulses will have the same symbol level and the same bandwidth as in the rectangular pulse that employed in the OFDM. Figure 1-a Shows the impulse response of the Rectangular, PHYDYAS, RRC, Hermite. In the same way as the previous method, we will make a convolution between the pulse shape PHYDYAS with the pulse shape (EX. rectangular), where the equations are as follows:

\[
w(t) = \begin{cases} 1 + 2 \sum_{i=1}^{n-1} b_i \cos \left( \frac{2\pi t}{O\sqrt{T_0}} \right) & \text{if } -\frac{OT_0}{2} < t < \frac{OT_0}{2} \\ O\sqrt{T_0} & \text{else were} \end{cases} \quad (27)
\]

Where \( b_i \) is the coefficient that was calculated in the source [26], and O is the overlapping factor, so from [27] if we take the O=4 we have: \( b_1 = 0.97195983 \), \( b_2 = \sqrt{2/2} \), \( b_3 = 0.23514695 \quad (28) \)

Orthogonal: \( T = T_0, F = 2/T_0 \), \( TF = 2 \) \quad (29)

Localization: \( \sigma_t = 0.2745 T_0, \quad \sigma_f = 0.328 T_1 \) \quad (30)

\[
m(t) = \begin{cases} 0.25 \frac{1}{\sqrt{T_0}}, & -\frac{T_0}{2} \leq t \leq \frac{T_0}{2} \\ 0 & \text{otherwise} \end{cases} \quad (31)
\]

4. Results and discussion

We propose another pulse shape that we suggest the second new shape, which is a combination of a PHYDYAS shape with an extended rectangular shape to obtain a new shape that has specifications that combine the good specifications of the two shapes and lead to obtaining the best shape that gives the best performance. Despite the good performance of the pulse shape PHYDYAS, the combination
with the extended rectangular pulse shape of a quarter wavelength gives better performance than the two separate forms. And as shown in the figure 2-a from the comparison between figure 2-a and figure 2-b we can notice that the IR of the proposed pulses SHAPE1 don’t have any ripple in the shape that usually appear and have a minimum over shot and the shape give a better response in comparison with others pulses therefore the better characteristic it can be obtained in the new pulse shape that it is better than the rectangular pulse or the rest of the shapes used in the OFDM system. Therefore, if the new pulse is applied in OFDM scheme, the orthogonality between the sub-carrier will give the best result (optimum sample). The convolution process will be equal the summation of the two input signals used. And the SHAPE2 in figure 2-b have some ripple in the IR but it's have a good response in the frequency domain therefore the SHAPE2 will give a better performance than the PHYDYAS and the EX rectangular and from the figure 2-b the new IR interval for SHAPE1 and SHAPE2 is shorter, because it has a small side lob that ends quickly and completely after one or more symbol cycles. We use the MATLAB program 2019 and write the code that necessary to obtain the results that appears in figures.

Figure 2-a shows the impulse response of the commonly used pulse shapes like PHYDYAS, RRC, Hermite, Rectangular.

Figure 2-b shows the impulse response of shapes with the proposed pulse (SHAPE1α SHAPE2).
Fig.3-a spectra analysis of commonly used pulse shapes like Rectangular, RRC, Hermite, PHYDYAS.

Fig.3-b spectra of new proposed pulse shape (SHAPE1 & SHAPE2) with other pulses
From the comparison between the fig.3-b with fig.3-a we can see the proposed shape SHAPE1 has a better spectrum than Rectangular and the RRC but the Hermite and PHYDYAS has better spectral than the proposed pulse shape, therefore the proposed pulse will give a better response in time so the BER will be better, however, the proposed pulse is still giving a good result than other pulses. SHAPE2 from fig.3-b, we can notice it have a better spectrum than the rectangular and the RRC and the Hermite and it equal the PHYDYAS in the performance. Therefore, the proposed pulse will give a good result in the BER and SIR and PAPR. And it can be used as candidate wave form in the next generation.

In figure.4-a it is possible to observe the results taken from the source [28] that have been measured practically for the state of transmission from the outside to the inside when the frequency is 2.5 GHZ and also for the case of the transmission from the inside to the inside when the frequency is 60 GHZ[29] and by comparing the results between OFDM & FBMC we see that the two systems have the same error bit rate, which confirms the validity of the propagation approach but the FBMC has better spectral properties. therefore, when we inserted the proposed pulses design SHAPE1 & SHAPE2, fig.4-b we can note the performance of the FBMC has become better in term of the BER and the SIR (signal to interference ratio). this means that the proposed pulse shape gives more degree of freedom to FBMC to transmit and receive the signal and more reliability to the signal to aim the attenuation.

Fig.4-a real world-testbed measurement shows the FBMC and OFDM has the same bit error rate (BER) but the FBMC has the lower OOBE [28].
Fig.4-b real world-testbed measurement shows the result with the proposed pulse.

5. CONCLUSION

We conclude from the previous shapes and the analysis of the obtained shapes that it is possible to design several new and varied pulse shapes that can be used in the next generation of communications due to the good performance and good results provided by these forms compared to the rectangular shape used in the fourth generation of communications. What we obtained, we notice that the first SHAPE1 provides a good impulse response without any distortion in the signal and no side lobes appearing, which means an increase in the data transfer rate and a significant reduction of distortion and out of band emissions. In the second proposed figure, SHAPE2 the impulse response, despite the appearance of a small side lobe, it's very good compared to the other forms, except for Hermite. Its performance is better. However, the second form provides the best possible performance when dealing with the frequency analysis spectrum, and this means a reduction in error and interference, and increase the transmitted power rate, and achieving the best possible results and the best performance. It can be used SHAPE1&SHAPE2 in designing the shape of the pulse filters for the next generation of communications.

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