Subsiding OOB Emission and ICI Power Using iPOWER Pulse in OFDM Systems

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***Abstract*—A novel family of Nyquist-I pulses called iPOWER is proposed with a new design parameter γ that provides an extra degree of freedom for a certain roll-off factor, α. The proposed pulse is examined and compared with other existing pulses in terms of out-of-band (OOB) power, intercarrier interference (ICI) power, signal-to-interference ratio (SIR) power, and bit-error-rate (BER) in orthogonal frequency division multiplexing (OFDM) systems. The BER was analyzed in the presence of carrier frequency offset (CFO), which introduces ICI in OFDM-based systems. Eye diagram tool is also used to visually analyze the performance of the proposed pulse. Simulation results show that the iPOWER pulse performs better in terms of OOB power, ICI power, SIR power, and improving BER in comparison to other existing pulses in OFDM-based systems.**

***Index Terms*—Doppler effect, filters, frequency response, OFDM, pulse shaping functions, wireless communication.**

I. INTRODUCTION

In the recent years, orthogonal frequency division multiplexing (OFDM) has been deployed over wireless channels that require high data rate transmission, such as IEEE 802.11a [1]. The combination of OFDM and various emergent multiple-input multiple-output (MIMO) standards, such as IEEE 802.11n, IEEE 802.20, and IEEE 802.22, as a single unit has been suggested [2-5]. OFDM is prominent due to high robustness against multi-path fading channels, converts a frequency selective fading channel into several flat fading channels with shorter delay spread and large symbol duration to achieve maximum spectral efficiency. Even though OFDM schemes have several advantages, there are some drawbacks that need to be addressed in its practical applications. It suffers out-of-band (OOB) radiation and high sensitivity to frequency offset, which eventually degrades the performance of the system [1].

In OFDM systems, high spectral side-lobes can introduce severe interference to users operating in the adjacent channels. In general, OOB power leakage occurs due to the large magnitude side-lobes of the data carriers in OFDM-based systems. A reduced tail size can reduce the OOB power. Several techniques have been proposed to minimize the OOB power in OFDM systems, including symbol optimization [6], combination of frequency and time domain approaches for side-lobes suppression [7]. However, high computational complexity is involved in the development of such schemes which may not be suitable for real time applications.

Frequency offset errors caused due to Doppler's effect, frequency mismatch among the transmitter and receiver oscillators, and disturbance in the channel [8-10]. Several impairments may occur due to carrier frequency offset (CFO), including attenuation, intercarrier interference (ICI), and rotation among the subcarriers; increasing the bit-error-rate (BER) of the system. Several methods have been used to minimize the ICI power in OFDM systems [11-22].

In this paper, a pulse shaping technique is used in OFDM systems to reduce the OOB emission [7], minimize ICI power [8], increase SIR power and diminish BER [23]. The objective is to use a waveform that has smaller magnitude side-lobes, which gives a smaller BER for an excess bandwidth. Several waveforms have been proposed with similar goals [7]. Recently, a new Nyquist-I pulse called POWER pulse [24] has been proposed with a tuning parameter β for a certain roll-off factor, α. It has been shown that the POWER pulse outperformed other existing pulses in terms of BER for particular values of β, referred as special cases of the POWER pulse. Recently, the design parameters of the POWER pulse were optimized for all the considered cases to minimize BER [25]. A novel pulse, which is an improved version of the POWER pulse, is proposed in this manuscript and called iPOWER. The proposed pulse is characterized with a new design parameter γ that provides an additional degree of freedom. Our investigation includes only special cases of the POWER pulse. However, the proposed pulse is found worth investigating in terms of OOB power reduction, diminishing ICI power, along with improvements in BER for OFDM-based systems. To the authors´ best knowledge, an enhanced version, explicitly for special cases of the POWER pulse, is being used in OFDM systems for the first time. In the same way, we are directing such waveforms for multicarrier systems, particularly for those where signal analysis is made in frequency domain. We compared the performance of the iPOWER pulse with the recently proposed polynomial pulses [26] i.e. Poly4, Poly5, and a linear combination of Poly4 and Poly5, denoted as LCP45 in terms of OOB power, ICI power, SIR power, and BER in OFDM systems. These polynomial pulses have already been evaluated, and outperformed other well-known pulses [8] i.e. “better than” raised cosine (BTRC), raised-cosine (RC) and rectangular (REC) for OFDM systems given in [26]. Therefore, we only evaluate and compare the performance of the proposed iPOWER pulse with the polynomial pulses

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i.e. Poly4, Poly5 and LCP45.

The remainder of the paper is organized as follows. A mathematical overview for OOB power, ICI power, SIR power, and BER is given in Section 2. We discuss the impulse response, frequency responses and eye diagram analysis of the iPOWER pulse in Section 3. Simulation results are given in detail in Section 4. Concluding remarks are presented in Section 5.

II. SYSTEM MODEL

We used a pulse shaping technique in OFDM systems to reduce OOB power and diminish BER. This approach has less computational complexity, is simple to process, and is effective [27] for practical OFDM applications in comparison with other approaches, such as pre-coding schemes, symbol mapping, and subcarrier weighting [7].

A. OOB Power in OFDM Systems

An OFDM symbol is the sum of N data symbols. These symbols are modulated using different schemes, such as M-PSK, or M-QAM, among others. A time limited waveform, $w(t)$ with-in an N-subcarrier OFDM system is defined as [8]

$$d(t) = \sum_{n=-N/2}^{N/2} d_n w(t) e^{j2\pi f_n t} \qquad (1)$$

where d_n represents data symbols, and f_n is the subcarrier frequency on the nth subcarrier. It is expected that the data is uncorrelated; symbols are assumed to be zero mean and unit variance. The '*' denotes the complex conjugate as follow

$$E(d_k d_l^*) = \begin{cases} 1, \rightarrow k = 1 \\ 0, \rightarrow k \neq 1 \end{cases} \qquad (2)$$

The waveform $w(t)$ should meet the criteria of subcarrier orthogonality for OFDM given in [14] and expressed as

$$\int w(t) e^{-j2\pi(f_k - f_m)t} dt = 0 \rightarrow k \neq m \qquad (3)$$

To ensure orthogonality, the following relationship is necessary

$$f_k - f_m = \frac{k-m}{T} \qquad (4)$$

where $1/T$ is the minimum frequency spacing required to satisfy orthogonality. The frequency response of the transmitted OFDM symbol given in (1) is defined as follows

$$D(f) = \sum_{n=-N/2}^{N/2-1} d_k W(f - \frac{n}{T}) \qquad (5)$$

where $W(f)$ is the frequency response of $w(t)$ given in (1). The average power spectral density (PSD) is represented by $P(f)$, where PSD is the average power of the frequency response of the transmitted symbol $d(t)$, and it is expressed as

$$P(f) = E\{|D(f)|^2\} \qquad (6)$$

The average PSD of an OFDM signal is given as [7]

$$P(f) = \sum_{n=-N/2}^{N/2-1} \left| W(f - \frac{n}{T}) \right|^2 \qquad (7)$$

B. ICI and BER Evaluation Metric

In general, carrier frequency offset introduces ICI that degrades the performance of an overall system. The performance of the OFDM system is determined in terms of ICI power, SIR power, and BER, in the presence of frequency offset, Δf. We implemented a BPSK-OFDM system to evaluate and compare the performance of the iPOWER pulse and other existing pulses over an additive complex Gaussian noise (AWGN) channel in terms of ICI power and SIR power, as it was done in [28-29]. Where the average ICI power depends on the frequency offset Δf. The average ICI power across different sequences is expressed as

$$\overline{\sigma_{ICI}^m} = \sum_{\substack{k=0, \\ k \neq m}}^{N-1} \left| W(\frac{k-m}{T} + \Delta f) \right|^2 \qquad (8)$$

The signal-to-interference power ratio (SIR) is defined in [28-29] as

$$SIR = \frac{|W(\Delta f)|^2}{\overline{\sigma_{ICI}^m}} \qquad (9)$$

Furthermore, the BER expressions given in [23] are used to evaluate the performance of different pulses over an AWGN channel. Details regarding the theoretical BER expressions, proposed for BER analysis of pulse shaping functions applied in OFDM systems with frequency offset are given in [23]. The BER expressions are given below as

$$\overline{BER_{OFDM}} = 1 - (1 - BER_{symbol})^N, \qquad (10)$$

$$BER_{symbol} = \frac{1}{2}(Q(\cos\theta[W(-\Delta f) + \sqrt{P_{ICI}}]\sqrt{2\gamma_b}) + Q(\cos\theta[W(-\Delta f) - \sqrt{P_{ICI}}]\sqrt{2\gamma_b})) \qquad (11)$$

where the average BER is given as a function of frequency offset Δf, phase noise θ, average ICI power P_{ICI}, the Fourier transform of the waveform $w(t)$ is represented as $W(f)$, N is the number of subcarriers, and $\gamma_b = E_b/N_o$.

III. DESIGN ASPECTS OF IPOWER PULSE

In this section, we give an overview of the POWER pulse, which was proposed and investigated in [24]. We consider only the special cases of the POWER pulse for different values of the constant β in our analysis and simulations. The time domain POWER pulse is given below as

$$w_{power}(t) = \begin{cases} 1, \rightarrow |t| \leq \dfrac{T(1-\alpha)}{2} \\ 1 - \dfrac{1}{2}\left[\dfrac{|t| - (1-\alpha)T}{2\alpha\beta}\right]^{\beta}, \rightarrow \dfrac{T(1-\alpha)}{2} \leq |t| < \dfrac{T}{2} \\ \dfrac{1}{2}\left[\dfrac{(1+\alpha)T - |t|}{2\alpha\beta}\right]^{\beta}, \rightarrow \dfrac{T}{2} < |t| \leq \dfrac{T(1+\alpha)}{2} \\ 0, \rightarrow \dfrac{T(1+\alpha)}{2} < |t| \end{cases} \qquad (12)$$

where α is the roll-off factor with range $0 \leq \alpha \leq 1$, and β (≥ 0) is the parameter is used to adjust the impulse and frequency response of the POWER pulse. Only the special cases of the POWER pulse for different values of β are studied in this work, which were investigated as ISI free pulses to diminish BER in the presence of timing errors [24].

TABLE I. SPECIAL CASES OF POWER PULSE

Name	**Waveform Functions**	
	b(f) = sin(πft)/πft	***β***
$W_0(f)$	b(f).cos(παft)	0
$W_1(f)$	b(f).sin(παft) / παft	1
$W_2(f)$	b(f).1-cos(παft) / ((παft)^2/2)	2
$W_3(f)$	b(f).3(παft – sin(παft)) / ((παft)^3/2)	3
$W_4(f)$	b(f).3(((παft)^2/2)-1+cos(παft)) / ((παft)^4/8)	4
$W_5(f)$	b(f).5(((παft)^3/2)-3παft+3sin(παft)) / ((παft)^5/8)	5

In this paper, we examined the special cases of the POWER pulse with further enhancement in performance with respect to OOB power, ICI power, SIR power, and BER in OFDM-based systems. The waveforms of the POWER pulse with different values of β are given in Table I. In general, the frequency response of the POWER pulse given in [24] is expressed as

$$W_{power}(f)=\frac{\sin(\pi ft)}{\pi ft}\left\{\begin{matrix}1-\dfrac{\pi^2\alpha^2f^2t^2}{2+3\beta+\beta^2}\\ \cdot{}_1F_2\left(1;\dfrac{3+\beta}{2},\dfrac{4+\beta}{2};\dfrac{-\pi^2\alpha^2f^2t^2}{4}\right)\end{matrix}\right\} \tag{13}$$

where the corresponding waveform is based on ${}_1F_2$ $(x;y_1,y_2;z)$, a hypergeometric function given below as

$${}_1F_2(x;y_1,y_2;z)=\sum_{n=0}^{\infty}\frac{(x)_n}{(y_1)_n(y_2)_n}.\frac{z^n}{n!} \tag{14}$$

where $(u)_o = 1$, and $(u)_n = u(u+1)\,(u+2)\dots\,(u+(n-1))$. In [24] it was concluded that small values of β reduce the pulse to much simpler waveforms. We only analyzed the special cases of the POWER pulse mentioned in Table I because the frequency response of the POWER pulse given in (13) becomes more complex in terms of computations due to the hypergeometric function. In-addition, such function gives infinite values. Moreover, it may not perform well for multicarrier systems due to the large number of subcarriers which increase the computation complexity of a system [25].

TABLE II. SPECIAL CASES OF IPOWER PULSE

Name	**Waveform Functions**	
	with, exp = $e^{-\gamma(fT)^2}$	***β***
$iW_0(f)$	exp. $W_0(f)$	0
$iW_1(f)$	exp. $W_1(f)$	1
$iW_2(f)$	exp. $W_2(f)$	2
$iW_3(f)$	exp. $W_3(f)$	3
$iW_4(f)$	exp. $W_4(f)$	4
$iW_5(f)$	exp. $W_5(f)$	5

In this manuscript, a novel family of Nyquist-I pulses called iPOWER pulse is proposed to minimize OOB power, reduce ICI power, increase SIR power and improve BER for OFDM systems. The proposed pulse has an exponential expression, which was first considered in [30]; providing a sufficient reduction in the magnitude of the two largest side-lobes of a pulse. The frequency functions of the iPOWER pulse for different values of β are given in Table II. In this work, we investigated the performance of the iPOWER pulse for a particular roll-off factor, α = 0.22. This is because the roll-off factor α = 0.22 was suggested by the 3rd Generation Partnership Project (3GPP) for the pulse shaping filter to be implemented at the transmitter and receiver side of the base station (BS) and user equipment (UE) [31-32].

The two design parameters in the iPOWER pulse i.e. β and γ are defined for all real number. The Nyquist-I criterion in the frequency domain applied in OFDM-based systems is given as follows

$$W(f)=\begin{cases}1,\rightarrow f=0\\ 0,\rightarrow f=\pm1/T,\pm2/T,\dots\end{cases} \tag{15}$$

In-order to verify that the iPOWER pulse given in Table II fulfills the frequency domain condition of the Nyquist-I criterion given in (15), the iPOWER pulse is evaluated for f = 0, and for any value of the parameters i.e. α, β, and γ, the iPOWER is always equal to one. Moreover, when the iPOWER pulse is evaluated for $f = \pm 1/T,\ \pm 2/T,\dots,$ and for any value of the parameters α, β, and γ, it will always be equal to zero. Therefore, the special cases of iPOWER pulse given in Table II fulfill Nyquist-I criterion. We analyze the performance of the iPOWER pulse and other existing pulses in time and frequency domain.

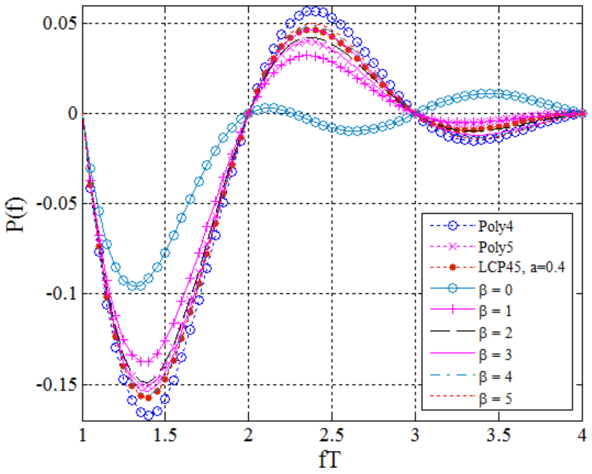

Figure 1. Frequency function of iPOWER for γ = 0.15, and other pulses at α = 0.22.

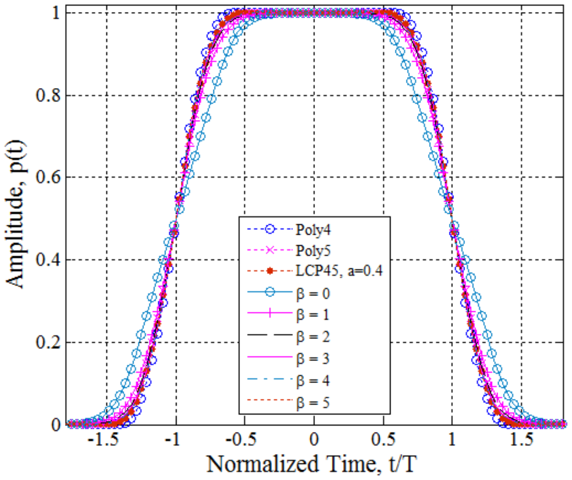

Figure 2. Time function of iPOWER for γ = 0.15, and other pulses at α = 0.22.

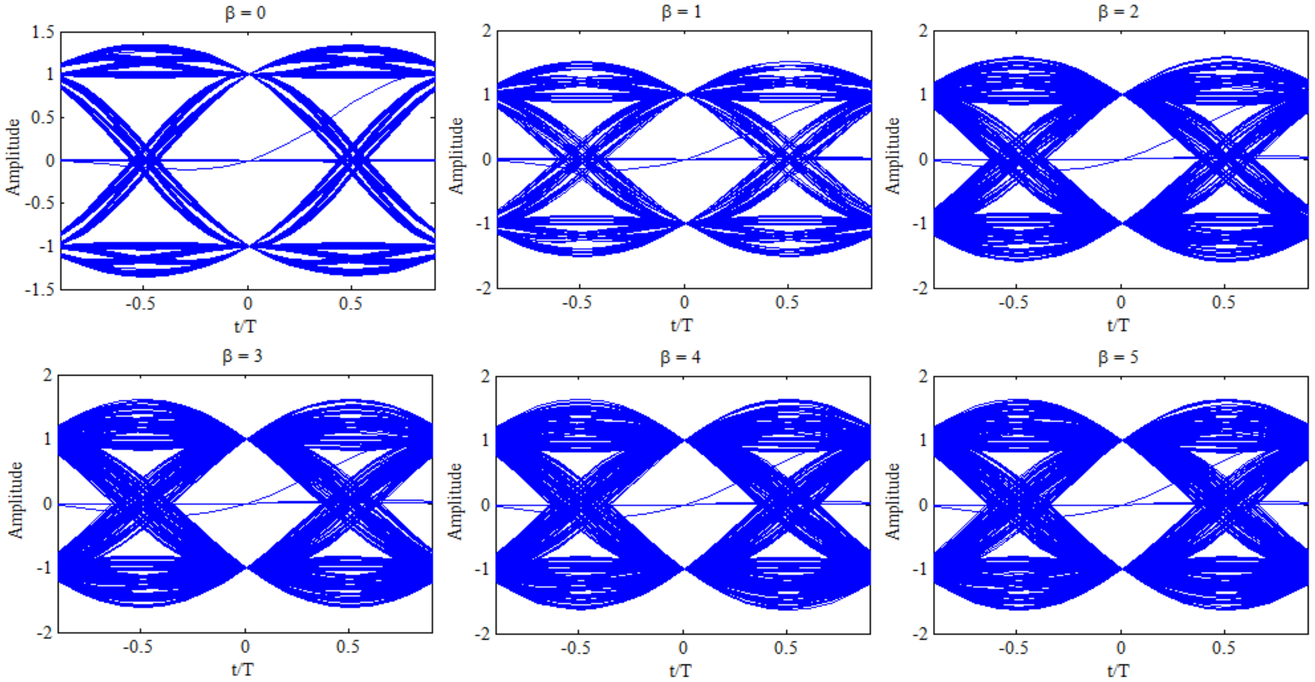

Figure 3. Eye diagram of iPOWER for $\gamma = 0.15$ and $\alpha = 0.22$.

Fig. 1 shows that the iPOWER pulse possesses smaller side-lobes for $\beta = 0$, 1 whereas polynomial pulses, including Poly4 and LCP45, have larger side-lobes. It is noticed that smaller values of β show sufficient suppression in tail size as given in [25]. In general, pulses for $\beta = 0$, 1, 2 and Poly5 show sufficient reduction in the magnitude of two largest side-lobes for $\alpha = 0.22$. The smaller side-lobes of a pulse can reduce the OOB in the OFDM systems [7]. All the comparison pulses show a rectangular behavior in the time domain, as shown in Fig. 2, which is very important in decreasing BER. In time domain analysis, a sharp rectangular behavior of a pulse ensures a low BER but it makes high amplitude side-lobes in frequency response of a pulse, which may lead to high OOB emission and increase ICI power [7-8], [11]. This is due to a tradeoff between the OOB power and the BER. Such concept can be verified from the Fig. 1 & 2. Where the Poly4 pulse shows large magnitude side-lobes with sharp rectangular behavior, and $\beta = 0$ shows small magnitude side-lobes with a less sharp rectangular behavior among the other evaluated pulses.

The iPOWER pulse introduces a new design parameter γ, which effectively handles the tradeoff between OOB power and BER. The sub-optimum value of the new design parameter $\gamma = 0.15$, is considered after running extensive computer simulations in terms of OOB power, ICI power, SIR power, and BER. We used $\gamma = 0.15$ throughout the manuscript, in our analysis and simulations.

Eye diagram tool is used to visually examine the vulnerability in the transmission systems due to inter-symbol interference (ISI) [33-34]. We generated 10^3 uniform random data points and used BPSK digital modulation to produce eye patterns by inserting two consecutive symbol periods. Additional zeros were inserted to up-sampled the transmitted sequence, where we convolved a pulse shaping function with the up-sampled transmitted sequences for visual investigation of the comparison pulses via eye diagram tool. Fig. 3 shows that small values of β possesses much wider eye opening compared to high values of β, which means that small values of β will yield lower BER values [33-34]. The purpose of the eye diagram is to show that the iPOWER pulse does not only perform well for OFDM-based systems, but it also diminishes ISI in baseband digital communication systems.

IV. SIMULATIONS AND RESULTS

In this section, we discussed the performance of the iPOWER pulse with respect to OOB power, ICI power, SIR power and BER. We compared the proposed pulse with Poly4, Poly5, and LCP45 pulses because these are the most recently proposed pulses and investigated in terms of OOB power and BER for OFDM-based systems [26]. Moreover, the polynomial pulses are characterized by an explicit frequency domain expression. We evaluate the performance of the iPOWER, Poly4, Poly5 and LCP45 pulses in terms of OOB power in two ways i.e. theoretical and numerical simulations. Firstly, the pulses are evaluated using (7) via theoretical simulations. Secondly, a real OFDM-based system is implemented. The simulation parameters given in Table III, are used to evaluate different pulses in terms OOB power, ICI power, and SIR power via numerical simulations.

We consider a BPSK-OFDM system over an AWGN channel to evaluate the ICI power and SIR power of different pulse shaping functions in the presence of frequency offset, Δf. A reduction in the ICI power and increase in the SIR power can be achieved by diminishing the magnitude of the two largest side-lobes of a pulse [28-29]. Moreover, the pulses are evaluated in terms of BER in a BPSK-OFDM system over an AWGN channel for a normalized frequency offset, $\Delta fT = 0.2$, $\theta = 30^{\circ}$ and $\alpha = 0.22$.

The sub-optimum value of γ with respect to OOB power reduction, minimizing ICI power, increase in SIR power, and lessening BER, is selected by running extensive computer simulations, separately for each special case of iPOWER pulse. We found that $\gamma = 0.15$ is a sub-optimum value of iPOWER pulse for $\alpha = 0.22$. Although for every roll-off factor and transmission scheme there is an optimal γ.

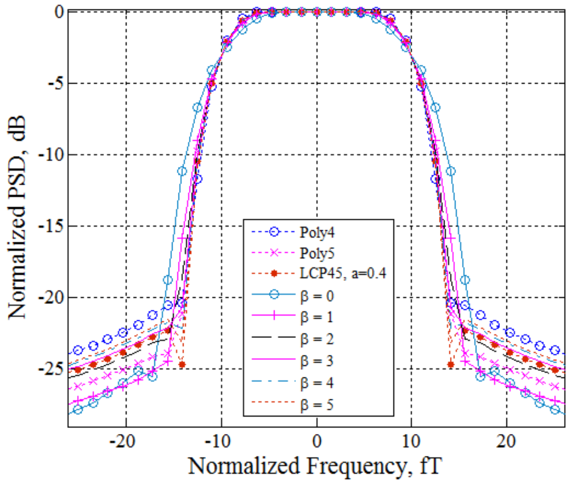

Figure 4. Theoretical OOB power of iPOWER, and other pulses for a 64 subcarriers OFDM system, for $\alpha = 0.22$.

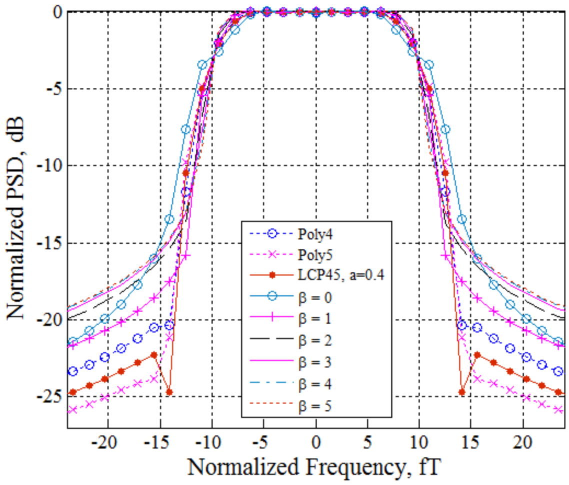

Figure 5. Theoretical OOB power of POWER, and other pulses for a 64 subcarriers OFDM system, for $\alpha = 0.22$.

Fig. 4 and Fig. 5, illustrate a theoretical comparison of the iPOWER and POWER pulses, respectively, with other existing pulses in terms of OOB power. In Fig. 4, it is observed that iPOWER at $\beta = 0$, 1 performed better than other pulses, whereas poly4 shows the worst performance. The difference between $\beta = 0$ and Poly4 is 5dB. The iPOWER pulse for $\beta = 5$ has the maximum OOB power among the iPOWER evaluated pulses.

TABLE III. PARAMETERS USED IN SIMULATIONS

Parameters	**Values**
Modulations	BPSK
Number of Symbols	100
Number of Subcarriers	64
Input Data Block Size	52
Block Oversampling	10
Roll-off factor, α	0.22

A comparison of the Poly4, Poly5 and LCP45 is made with the conventional POWER pulse to show the difference in performance of the proposed iPOWER and the conventional POWER pulse. Polynomial pulses performed better than the POWER pulse. However, $\beta = 4$, 5 shows worst performance in terms of OOB power among the evaluated pulses, as shown in Fig. 5.

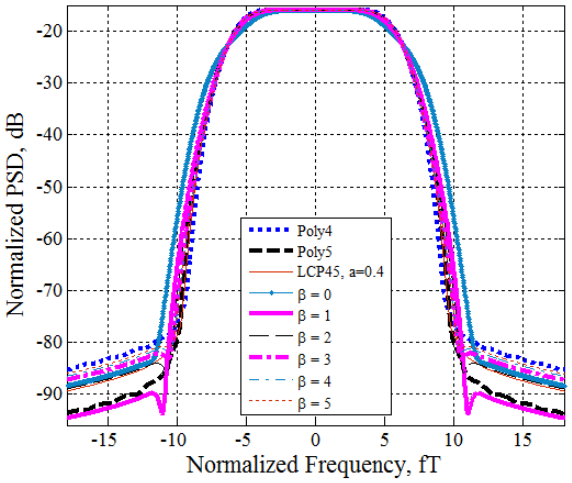

Figure 6. Comparison of OOB power of iPOWER, and other pulses applied in a 64 subcarriers OFDM system, for $\alpha = 0.22$.

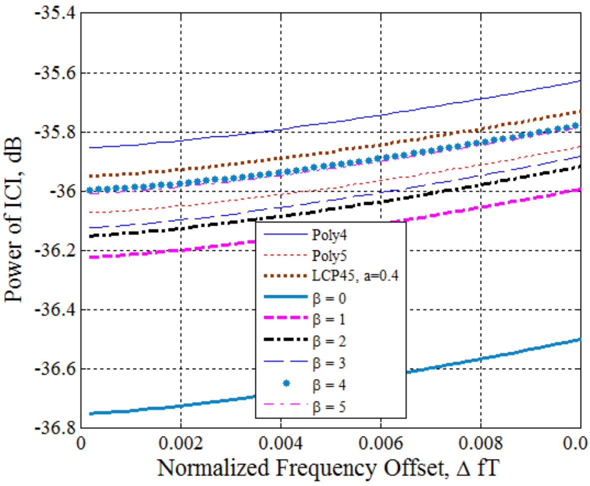

Figure 7. Comparison of ICI power of different pulses applied in a 64 subcarriers OFDM system, and $\alpha = 0.22$.

The comparison of iPOWER and polynomial pulses is conducted in terms of OOB power in a 64-subcarrier BPSK-OFDM system via numerical simulations, as shown in Fig. 6. Interesting results were obtained by applying iPOWER, Poly4, Poly5 and LCP45 in a real OFDM system. A reduction of 9dB is obtained at $\beta = 1$ for iPOWER pulses compared to the Poly4 pulse. The $\beta = 1$ value of iPOWER shows best performance among the evaluated pulses. However, $\beta = 5$ obtained the maximum OOB power among other β values for iPOWER pulse. However, Poly4 has the worst performance in comparison with other pulses. The iPOWER pulse shows sufficient reduction in OOB power compared to the POWER pulse and the most recently proposed polynomial pulses [26].

Fig. 7 illustrates the comparison of iPOWER and other existing pulses in terms of ICI power. The iPOWER pulse shows better performance for all the values of β except for $\beta = 4$, 5 which performed worse than Poly5 pulse. Hence, it is verified that pulses with small magnitude side-lobes provide sufficient reduction in ICI power, particularly for the cases of $\beta = 0$, 1, as shown in Fig. 1. In-addition, Poly4 shows the worst performance in terms of ICI power reduction because it has large magnitude side-lobes, as depicted in Fig. 1.

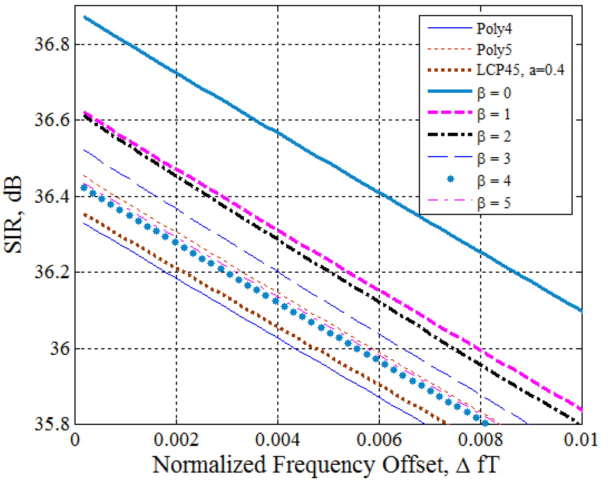

Figure 8. Comparison of SIR power of different pulses applied in a 64 subcarriers OFDM system, and $\alpha = 0.22$.

In the recent literature, the Poly4, Poly5 and LCP45 pulses are considered the pulses with the best time and frequency responses for OFDM-based systems [26]. Therefore, it was important to evaluate and compare the proposed pulses with those pulses to fully validate the performance of the iPOWER pulse. The proposed pulse shows low ICI power for both the small and high normalized frequency offset, ΔfT. We only showed low values of ΔfT in-order to make the curve visible and easily recognizable.

Fig. 8 depicts that iPOWER pulse performed well for most of the values of β, whereas Poly4 and LCP45 have the worst performance in terms of SIR power. The SIR power analysis was required with respect pulse shaping functions particularly when we are dealing with interference issues in wireless communications systems.

TABLE IV. SIR POWER IN DECIBELS

Pulses	SIR Power (dB)	ΔfT
Poly4	24.082	0.15
Poly5	24.107	
LCP45	24.100	
β = 0	24.388	
β = 1	24.217	
β = 2	24.134	
β = 3	24.097	
β = 4	24.108	
β = 5	24.101	
Poly4	17.33	0.3
Poly5	17.39	
LCP45	17.40	
β = 0	17.70	
β = 1	17.48	
β = 2	17.45	
β = 3	17.41	
β = 4	17.38	
β = 5	17.39	

Table IV illustrates the numerical values of different pulse shaping functions that were obtained during the simulations. In-order to verify the performances of the evaluated pulses for low and high normalized frequency offset those values were observed at normalized frequency offsets, $\Delta fT = 0.15$, 0.3 for different pulse shaping functions.

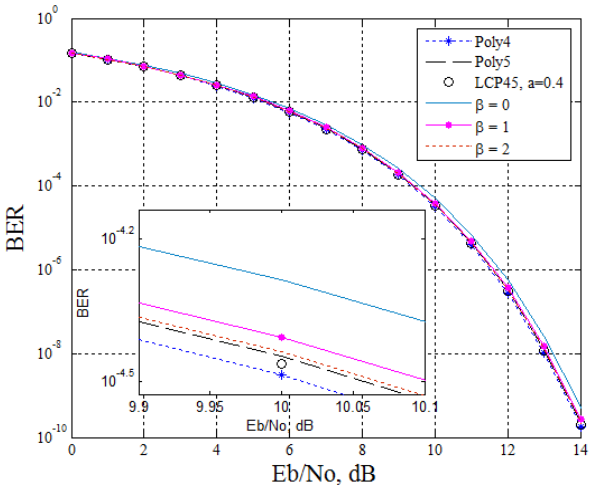

Figure 9. BER of iPOWER and other pulses applied in a 64 subcarriers OFDM system, $\alpha = 0.22$, $\Delta fT = 0.2$, $\theta = 30^{\circ}$.

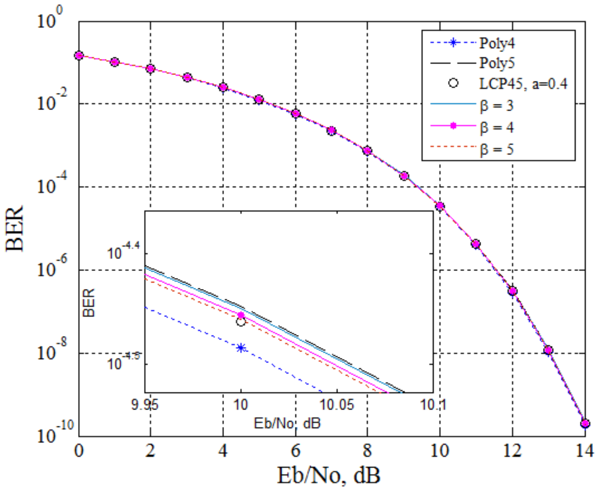

Figure 10. BER of iPOWER and other pulses applied in a 64 subcarriers OFDM system, $\alpha = 0.22$, $\Delta fT = 0.2$, $\theta = 30^{\circ}$.

Fig. 9 and Fig. 10, illustrate the BER comparative analysis for special cases of iPOWER and other pulses, including Poly4, Poly5 and LCP45 for normalized frequency offset, $\Delta fT = 0.2$, at $\theta = 30^{\circ}$, and $\alpha = 0.22$. Fig. 9 depicts that $\beta = 0$ obtains higher BER values among all other pulses, whereas $\beta = 2$ and Poly5 are very close in performance in terms of BER. However, $\beta = 3$, 4, 5 show lower BER values than Poly5, whereas $\beta = 5$ performed almost similar to LCP 45, as shown in Fig. 10. In general, Poly4 has the best performance among the evaluated pulses in terms of BER, but does not perform well in terms of OOB power, ICI power and SIR power due to high magnitude side-lobes.

In-addition, there is a tradeoff between the OOB power and BER. When the OOB power is reduced, the BER of the system is increased [7]. The sub-optimum iPOWER pulse was obtained to achieve a balance in terms of OOB power and BER reduction for OFDM-based systems. Moreover, extensive computer simulations were considered for the selection of a sub-optimum value of γ with respect to OOB power, ICI power, SIR power and BER. The iPOWER pulse shows superiority in performance over other comparison pulse in terms of OOB, ICI power and SIR power for $\beta = 0$, 1. It is observed that $\beta = 0$ has the worst BER, but it has achieved the best performance in terms of ICI power. The $\beta = 5$ has the lowest BER among other β values of iPOWER pulse, but unable to perform well in the other two scenarios. However, the Poly4 outperformed other comparison pulses in terms of BER, whereas the LCP45 pulse performed similarly to the $\beta = 4, 5$. The $\beta = 3, 4$ and 5 for iPOWER pulse performed better in terms of BER compared to the Poly5. In general, the iPOWER pulse performed better than polynomial pulses [26] including Poly4, Poly5, and LCP45 in terms of OOB power, ICI power and SIR power, as well as achieving lower BER values than Poly5 and LCP45.

V. CONCLUSION

A novel family of Nyquist-I pulses called iPOWER pulse is proposed and compared with the polynomial pulses, including Poly4, Poly5, and LCP45 in terms of OOB power, ICI power, SIR power and BER for OFDM-based systems. The proposed pulse is an enhanced version of the POWER pulse, and it is characterized by having an additional design parameter γ, which provides a tradeoff between OOB power and BER. This is because OOB power is reduced with side-lobes suppression, but at the expense of a poor BER. Therefore, after running extensive computer simulations in terms of OOB power, ICI power, SIR power, and BER in OFDM-based systems, it was found that the sub-optimum iPOWER pulse is given for $\gamma = 0.15$ and $\alpha = 0.22$. However, we only considered special cases of the iPOWER pulse in our analysis. Simulation results show that the proposed pulse performed better than other existing pulses in terms of OOB power, ICI power and SIR power, along with a sufficient improvement in BER.

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