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Transmitter Pulse Shaping to Reduce OOB Power and ICI in OFDM Systems

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Abstract The goal of waveform shaping techniques in orthogonal frequency division multiplexing systems is reduction in out of band (OOB) transmit power as well as reduction in inter-carrier interference (ICI) generated by carrier frequency offset at the receiver. We propose waveform shaping using a linear combination of time-limited polynomial pulses having spectral decay rates of $1/f^4$ and $1/f^5$. The resultant pulses can be optimized with respect to OOB power and bit error rate caused by ICI.

Keywords Carrier frequency offset · Orthogonal frequency division multiplexing · Out of band power · Power spectral density

1 Introduction

Two major issues with respect to signal design in orthogonal frequency division multiplexing (OFDM) systems are out of band (OOB) transmit power and inter carrier interference (ICI) due to carrier frequency offset (CFO) at the receiver. Most of the time limited Nyquist pulse shaping techniques proposed in the literature have either addressed the reduction in OOB power [1, 2, 6] or else the reduction in ICI power due to CFO [3, 5, 8–11]. Although there is no direct relation between these two criteria, there is a need for considering them together because both depend on the pulse shaping used in the transmitter. This becomes all the more important in view of an observation (refer Sect. 3) that has been found to hold for four different pulses: higher the spectral decay rate worse is the ICI. One possible reason why the two criteria have not been addressed simultaneously earlier is because of the difficulty in arriving at an approach which can appropriately

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combine both of them. In this paper we make a beginning in this direction by first selecting the most natural candidate for reduction in OOB power and then proposing a simple method so that it can be made to provide a reasonable ICI performance as well. The main contributions of this paper are:

- The best candidate for reducing OOB power in OFDM systems is a pulse family reported in [12].
- A linear combination of two polynomial pulses of appropriate degree provide a flexible and useful solution from the viewpoint of both the factors mentioned above.

Rest of the paper is organized as follows. In Sect. 2 we first select two polynomial pulses of different degrees and then analyze their OOB performance in OFDM systems. In Sect. 3 we evaluate the BER performance of the chosen pulses due to CFO and in Sect. 4 we propose a linear combination of the two pulses and then evaluate their performance with respect to OOB power and CFO. Conclusion are drawn in Sect. 5.

2 Polynomial Pulses and their OOB Spectrum in OFDM Systems

The time domain expression of a N subcarrier OFDM symbol with time limited pulse shaping g(t) is given by [16]

$$s(t) = \sum_{n=-N/2}^{N/2-1} b_n exp(j2\pi f_n t) g(t) \tag{1}$$

where b_n denotes data symbols on the nth subcarrier and f_n is subcarrier frequency of the nth subcarrier. Pulse shaping function g(t) will also satisfy the subcarrier orthogonality criteria for OFDM [9]; i.e.,

$$\int g(t) e^{-j2\pi(f_k - f_m)t} dt = 0 \quad \text{for} \quad k \neq m$$

where

$$f_k - f_m = \frac{k-m}{T}$$

and $\frac{1}{T}$ is minimum subcarrier frequency spacing required.

The frequency spectrum of the transmitted OFDM signal given in (1) can be written as

$$S(f) = \sum_{n=-N/2}^{N/2-1} b_k G\left(f - \frac{n}{T}\right) \tag{2}$$

where G(f) is frequency domain response of g(t). Hence the average power spectral density (PSD) of the transmitted signal s(t) is

$$P(f) = \mathbb{E}\left\{ |S(f)|^2 \right\} \tag{3}$$

The data symbols are assumed to be zero mean and of unit variance. Also assume that data is uncorrelated; i.e.,

$$\mathbb{E}(b_k b_l^*) = \begin{cases} 1, & \text{for k} = 1 \\ 0, & \text{for k} \neq 1 \end{cases}$$

where '*' represents the complex conjugate operator.

The average Power Spectral Density (PSD) of an OFDM signal is given by [13]

$$P(f) = \sum_{n=-N/2}^{N/2-1} \left| G\left(f - \frac{n}{T}\right) \right|^2 \tag{4}$$

For pulses having a spectral decay rate of $1/f^k$, the OOB power decays as $1/f^{2k}$. Hence pulses with high spectral decay rates are desired for less OOB power. The spectra of some pulses with good ICI performance eg. [8, 9, 14, 16] have a decay rate of $1/f^2$. The most commonly used pulse Raised Cosine (RC) [4, 6, 19] has a decay rate of $1/f^3$. Nyquist pulses discussed in [15] can achieve a decay rate of $1/f^n$ for odd values of n but they do not have a closed form expression. However, polynomial pulses proposed in [12] can provide a decay rate of $1/f^k$ for any integer value of k and have a closed form expression as well. Hence, they are natural candidates for providing any desired decay rate and thereby minimizing OOB power in OFDM systems. However, to the best of our knowledge they have not yet been proposed in the literature for this purpose.

To design a polynomial pulse with a decay rate $1/f^k$, we follow the procedure given in [12]. The time domain expression, in general, is given by

$$g_{Poly}(t) = \begin{cases} \frac{1}{T}, & |t| < \frac{T(1-\alpha)}{2} \\ \frac{1}{T} x\left[\frac{|t| - T(1-\alpha)/2}{\alpha T}\right], & \frac{T(1-\alpha)}{2} \leq |t| < \frac{T}{2} \\ \frac{1}{T}\left\{1 - x\left[\frac{T(1+\alpha)/2 - |t|}{\alpha T}\right]\right\}, & \frac{T}{2} \leq |t| \leq \frac{T(1+\alpha)}{2} \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where $x(t) = \sum_{i=0}^{n} a_i t^i$ is a polynomial of degree n.

In this paper we will consider polynomial pulses having decay rates of $1/f^4$ and $1/f^5$. First, we consider a degree 4 polynomial with coefficients [12] satisfying the constraints $x(0) = 1, x(1/2) = 1/2, x^{(1)}(0) = 0, x^{(2)}(0) = 0, x^{(2)}(1/2) = 0, x^{(3)}(0) \neq 0$. The resulting coefficient values [12] are $\{a_0, a_1, a_2, a_3.a_5\} = \{1, 0, 0, -8, 8\}$. Using these values of a_i's we get

$$x_{\text{Poly4}}(t) = 1 - 8t^3 + 8t^4.$$

This pulse has a decay rate of $1/f^4$ and we refer to it as Poly4 pulse. The time domain expression of Poly4, $g_{\text{Poly4}}(t)$ is obtained by substituting $x_{\text{Poly4}}(t)$ in (5) while its frequency domain expression is given by

$$G_{\text{Poly4}}(f) = 3\sin(2\pi Tf)\frac{(\text{sinc}^2(\alpha\text{Tf}) - \text{sinc}(2\alpha\text{Tf}))}{(2\pi Tf)(\pi\alpha Tf)^2} \tag{6}$$

Next, we consider a polynomial pulse having a decay rate of $1/f^5$ and call this pulse as Poly5. We consider a degree 5 polynomial with coefficients [12] satisfying the constraints $x(0) = 1, x(1/2) = 1/2, x^{(1)}(0) = 0, x^{(2)}(0) = 0, x^{(2)}(1/2) = 0,$ and $x^{(3)}(0) = 0$. These constraints lead to the parameters $\{a_0, a_1, a_2, a_3, a_4, a_5\} = \{1, 0, 0, 0, -20, 24\}$ which also satisfy $x^{(4)}(0) \neq 0$ [12]. Using these values of a_i's we get

$$x_{\mathrm{Poly5}}(t) = 1 - 20t^4 + 24t^5.$$

The time domain expression of Poly5, $g_{\mathrm{Poly5}}(t)$ is obtained by substituting $x_{\mathrm{Poly5}}(t)$ in (5) while its frequency domain expression is given by

$$\begin{aligned} G_{Poly5}(f) = & \frac{4}{\alpha^4 (4\pi Tf)^5} (480 \sin(2\pi Tf) \cos(2\pi\alpha Tf) + 960 \sin(2\pi Tf)) \\ & - \frac{4}{\alpha^5 (4\pi Tf)^6} (2880 \sin(2\pi Tf) \sin(2\pi\alpha Tf)) \end{aligned} \tag{7}$$

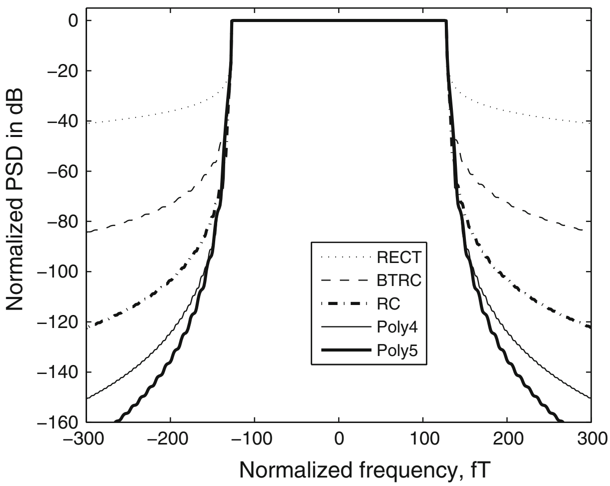
PSD plots of OFDM systems with different pulses can be obtained using (4). Taking the number of subcarriers N = 256 and roll off factor $\alpha = 0.1$, in Fig. 1 we show the PSD of OFDM systems employing Poly4 and Poly5 pulses along with RC and BTRC pulses. The expressions for RC and BTRC pulses have been taken from [Eqs.(11), (12) [16]].

It can be observed that, as expected, Poly5 pulse achieves the best OOB performance. Poly5 pulses experiences nearly 28 and 65 dB less OOB power compared to RC and BTRC pulses respectively at $B/4$ distance from the band edge where $B = \frac{N}{T}$ is the bandwidth of the OFDM signal. Because of its higher decay rate, Poly5 pulse has better OOB performance than Poly4 pulse also. Clearly, polynomial family of pulses offer a very good design choice from the view point of OOB power criterion.

It may be noted that in this work we are discussing only the basic pulse shapes and not the precoding techniques that can be combined with the basic pulses to further improve upon the OOB performance. Thus the decay at the band edges can be substantially improved near the band edges by combining the polynomial pulses with the precoding techniques discussed in [4, 17, 18] or guardband optimization method as discussed in [4].

In the next section, we study the effect of decay rate on the Bit Error Rate (BER) performance of polynomial pulses in the presence of CFO.

Fig. 1 Comparison of PSD of polynomial pulses with BTRC and RC pulses for alpha = 0.1



3 BER Performance of OFDM Systems in the Presence of CFO

CFO introduces intercarrier interference leading to BER degradation in OFDM systems. In this section, we analyze the average bit error rate (BER) performance of an uncoded BPSK OFDM system with polynomial pulses.

The received baseband OFDM signal can be written as

$$r(t) = e^{j2\pi\delta ft} \sum_{n=-N/2}^{N/2-1} b_n exp(j2\pi f_n t)g(t) + n(t) \tag{8}$$

where δf denotes CFO value and n(t) complex AWGN noise with zero mean and of variance $\sigma^2 = N_0/2$. The decision variable for transmitted symbol b_m is obtained from the mth subcarrier correlation demodulator as follows [9]

$$\begin{aligned} \widehat{b}_m &= \int_{-\infty}^{\infty} r(t)e^{j2\pi f_m t}dt \\ &= b_m \int_{-\infty}^{\infty} g(t)e^{j2\pi\delta ft}dt \\ &\quad + \sum_{k=-N/2,k\neq m}^{N/2-1} \int_{-\infty}^{\infty} g(t)e^{j2\pi(f_k-f_m+\delta f)t}dt + N_m \end{aligned} \tag{9}$$

where first term contains the signal term and second term is interference term. The N_m denotes the independent complex Gaussian random variable with zero mean and of variance σ^2 for both real and imaginary parts.

For the case of uncoded BPSK case, the data symbols b_m are chosen from values $\{-\sqrt{E_b}, \sqrt{Eb}\}$ independently and equiprobability. The E_b denotes bit energy. The decision statistics for b_m data symbols on mth subcarrier can be expressed as

$$\widehat{b}_m = b_m c_0 + \sum_{k=-N/2,k\neq m}^{N/2-1} b_k c_{k-m} + N_m \tag{10}$$

where

$$c_{k-m} = G\left(\frac{k-m+\epsilon}{T}\right)$$

and $\varepsilon = \delta f \cdot T$ denotes normalized values of CFO.

To calculate the average BER from decision statistics given by (10), one can proceed in the same way as given in [16] and obtain the BER of the mth subcarrier that is given by

$$\begin{aligned} P_b(m) = \frac{1}{2} - \int_0^{\infty} \frac{\sin\left(\sqrt{E_b}\omega c_0\right)}{\pi\omega} e^{\left(-\frac{1}{2}\omega^2\sigma^2\right)} \\ \times \prod_{k=-N/2,k\neq m}^{N/2-1} \cos\left(\sqrt{E_b}\omega c_{k-m}\right) d\omega \end{aligned} \tag{11}$$

Hence, the average BER is given by

Table 1 Average BER for different pulses at SNR = 15 dB

α	ε	Poly5	Poly4	RC
0.1	±0.05	6.0173e−12	5.4478e−12	4.8438e−12
	±0.1	1.0779e−08	9.0107e−09	7.2867e−09
	±0.2	2.6963e−03	2.4306e−03	2.1310e−03
0.2	±0.05	1.7117e−13	1.4385e−13	1.1800e−13
	±0.1	1.1774e−09	8.7951e−10	4.9938e−10
	±0.2	1.6849e−03	1.3157e−03	9.6448e−04
0.35	±0.05	2.7475e−14	1.8236e−14	1.0497e−14
	±0.1	1.4171e−10	8.4264e−11	4.7366e−11
	±0.2	2.5350e−03	1.7851e−03	1.1548e−03

Table 2 Average BER for different pulses at $\varepsilon = \pm 0.15$

α	SNR (dB)	Poly5	Poly4	RC
0.1	15	2.1022e−05	1.7711e−05	1.4394e−05
	10	2.3741e−03	2.2965e−03	2.2052e−03
	5	3.1529e−02	3.1334e−02	3.1096e−02
0.2	15	3.7708e−06	2.5922e−06	1.6650e−06
	10	1.7903e−03	1.6726e−03	1.5430e−03
	5	1.6718e−03	1.5384e−03	1.3961e−03
0.35	15	1.3821e−06	7.8320e−07	4.0994e−07
	10	1.7228e−03	1.5494e−03	1.3723e−03
	5	3.2209e−02	3.1839e−02	3.1404e−02

$$P_b = \frac{1}{N}\sum_{m=0}^{N-1} P_b(m) \tag{12}$$

Table 1 provides the BER values for different α and ε for RC, Poly4 and Poly5 pulses for 15 dB SNR where SNR $= E_b/N_0$. Table 2 provides the BER values for $\epsilon = \pm 0.15$ and different values of α and SNR. The number of subcarriers is taken to be 256. From Tables 1 and 2, it can be observed that RC pulses have the best BER performance and Poly5 have the worst. The BTRC and polynomial pulses with $1/f^2$ decay rate have better BER performance [16] but given their significantly inferior OOB performance than RC, Poly4 and Poly5 pulses we have not included them here. Clearly improvement in OOB performance of Poly4 and Poly5 pulses comes at the cost of BER performance degradation. Also, given the fact that BTRC has a spectral decay rate of $1/f^2$ and RC has a spectral decay rate of $1/f^3$, it is clear that within these four pulses higher the spectral decay rate worse is the BER performance.

The numerical and simulated BER values for different pulses for $\alpha = 0.25$ and normalized CFO $\delta fT = 0.2$ is plotted in Fig. 2. It can be seen that the theoretical results and the simulation results are perfectly matched.

The BTRC and polynomial pulses with $1/f^2$ decay rate have better BER performance [16] but given their significantly inferior OOB performance than RC, POLY4 and POLY5 pulses we have not included them here.

The improvement in OOB performance of POLY4 and POLY5 pulses comes finally at the cost of BER performance degradation. Also, it is clear that within these four pulses higher the spectral decay rate worse is the BER performance. In the next section, we apply

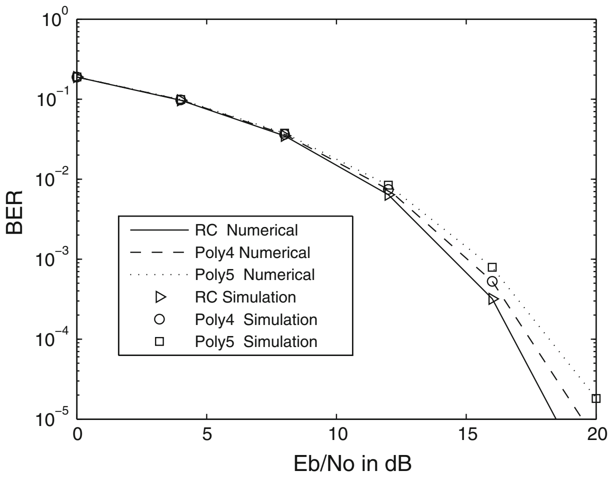


Fig. 2 Average BER plots for different pulses with $\alpha = 0.25$ and normalized CFO $= 0.2$

linear combination of Poly4 and Poly5 to improve the average BER performance in the presence of CFO.

4 Linear Combination of Two Polynomial Pulses

Drawing inspiration from the linear combination idea which was initially proposed in [20], albeit in a different context, we obtain the following pulse as a linear combination of Poly4 and Poly5 pulses and call it the 'LC' pulse:

$$G_{LC}(f) = aG_{Poly4}(f) + (1 - a)G_{Poly5}(f) \tag{13}$$

where the parameter a can taken real values and both the pulses have the same α. The idea is to vary a in small steps, evaluate the performance of the resulting pulse for every a and thus obtain an appropriate value of a such that the resulting pulse has better BER performance than both Poly4 and Poly5 pulses.

The average BER of uncoded BPSK OFDM systems using LC pulses in an AWGN channel has been evaluated for different values of a, ε and SNR. Table 3 provides the BER values obtained for 15 dB SNR and $\alpha = 0.1$.

It can be seen that for $a = 1.7$, LC pulse achieves less BER than Poly5 pulse but higher than that of RC pulse. For $a = 5$, LC pulse achieves less BER compared to both Poly5 and RC pulses while for $a = 15$, LC pulse has higher BER than both Poly5 and RC pulses. From this we can infer that there exists a range of a in which LC pulse achieves better BER performance than both Poly5 and RC pulses. In general, there is an a for every α, ε and SNR at which we get a local minima of BER i.e. BER increases for any increase or decrease in a.

Now let us examine how the OOB power of the LC pulse varies as a function of the parameter a. From (13) it can be seen that for $a = 0$ the LC pulse reduces to Poly5 and hence will give excellent OOB power performance. As the value of a increases, the component of Poly4 increases and hence the OOB power also increases. This is corroborated by Fig. 3 which shows the PSD plots for LC pulses for different values of a. Thus the improvement in BER comes at the cost of some degradation in OOB performance. From this it can be inferred that the parameter a can serve as a tuning parameter for

Table 3 Comparison of average BER for different pulses at SNR = 15dB and $\alpha = 0.1$

Pulses	$\epsilon = \pm 0.1$	$\epsilon = \pm 0.15$	$\epsilon = \pm 0.2$
RC	7.2867e−09	1.4394e−05	2.1310e−03
Poly5	1.0779e−08	2.1022e−05	2.6963e−03
LC (a = 1.7)	8.0623e−09	1.5902e−05	2.2727e−03
LC (a = 5)	5.7345e−09	1.1279e−05	1.7985e−03
LC (a = 15)	1.4272e−08	2.4225e−05	2.5143e−03

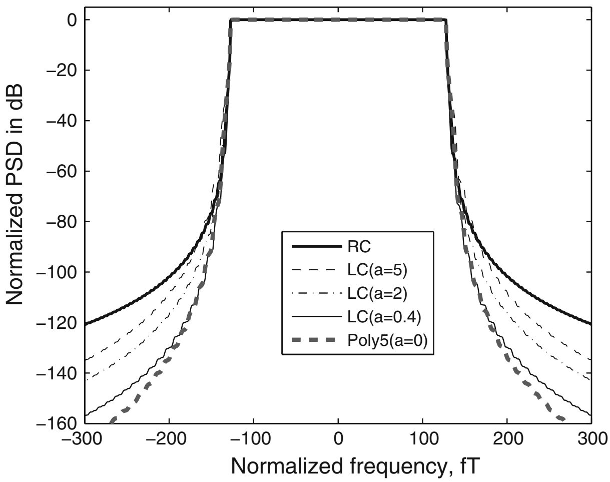


Fig. 3 PSD of OFDM systems with LC pulses for different values of parameter ‘a’ and $\alpha = 0.1$

LC pulses. Depending on the required performance of OOB power and BER, it can be adjusted to approach the desired performance as much as feasible. Let us illustrate this with an example.

Suppose it is desired that the OOB power of the LC pulse is at least 10dB less than that of the RC pulse at $B/4$ distance from the band edge where $B = N.1/T$ is transmission bandwidth of the OFDM system. Simultaneously the BER because of CFO is also at least 1 % less than of the RC pulse. The upper limit of the range of a of the LC pulse will be decided by the OOB criteria while the lower limit will be decided by the BER criteria. Table 4 provides a range of a that satisfies these OOB power and BER criteria simultaneously for $\alpha = 0.1, N = 256$, three different values of ε, and two different values of SNRs.

We also find the range of ‘a’ for 4-QAM and 16-QAM uncoded modulations using the same criteria as described above. The BER expressions for 4-QAM and 16-QAM can be obtained in the same way as for uncoded BPSK systems. The BER for the mth subcarrier for 4-QAM moulation is found using the following expression [16]

$$P_b(m) = \frac{1}{2} - \int_0^{\infty} \frac{\sin\left(\sqrt{E_b}\omega c_0^I\right)\cos\left(\sqrt{E_b}\omega c_0^Q\right)}{\pi\omega} e^{\left(-\frac{1}{2}\omega^2\sigma^2\right)} \times \prod_{k=-N/2, k\neq m}^{N/2-1} \cos\left(\sqrt{E_b}\omega c_{k-m}^I\right)\cos\left(\sqrt{E_b}\omega c_{k-m}^Q\right) d\omega \tag{14}$$

where

Table 4 Range of parameter a for different values of SNR, α and ε

α	SNR (dB)	Range of a		
		$\varepsilon = \pm 0.1$	$\varepsilon = \pm 0.15$	$\varepsilon = \pm 0.2$
0.1	15	[2.3,3.25]	[2.34,3.25]	[2.45,3.25]
	10	[2.33,3.25]	[2.28,3.25]	[2.31,3.25]
0.2	15	[2.40,5.6]	[2.44,5.6]	[2.46,5.6]
	10	[2.41,5.6]	[2.39,5.6]	[2.36,5.6]
0.35	15	[2.3,7.5]	[2.25,7.5]	[2.68,7.5]
	10	[2.40,7.5]	[2.29,7.5]	[2.53,7.5]

$$c^I_{k-m} = G\left(\frac{k-m+\epsilon}{T}\right)\cos\left(2\pi\frac{k-m+\epsilon}{T}\right)$$
$$c^Q_{k-m} = G\left(\frac{k-m+\epsilon}{T}\right)\sin\left(2\pi\frac{k-m+\epsilon}{T}\right)$$

The average BER can be found by averaging the BER over all the subcarriers using (15). In the case of 16-QAM modulation, the average BER is given by [16]

$$P_b = \frac{1}{2N}\sum_{m=0}^{N-1}[P_{b1}(m) + P_{b2}(m)] \tag{15}$$

where

$$P_{b1}(m) = \frac{1}{2} - \int_0^\infty \frac{e^{\left(-\frac{1}{2}\omega^2\sigma^2\right)}}{\pi\omega}\sin\left(2d\omega c^I_0\right)\cos\left(2d\omega c^Q_0\right)\cos\left(d\omega c^Q_0\right)\cos\left(d\omega c^I_0\right) \times \prod_{k=-N/2,k\neq m}^{N/2-1}\cos\left(d\omega c^I_{k-m}\right)\cos\left(d\omega c^Q_{k-m}\right)\cos\left(2d\omega c^I_{k-m}\right)\cos\left(2d\omega c^Q_{k-m}\right)d\omega \tag{16}$$

$$P_{b2}(m) = \frac{1}{2} - \int_0^\infty \frac{e^{\left(-\frac{1}{2}\omega^2\sigma^2\right)}}{\pi\omega}2\sin(2d\omega)\sin\left(2d\omega c^I_0\right)\cos\left(d\omega c^Q_0\right)\cos\left(2d\omega c^Q_0\right)\sin\left(d\omega c^I_0\right) \times \prod_{k=-N/2,k\neq m}^{N/2-1}\cos\left(d\omega c^I_{k-m}\right)\cos\left(d\omega c^Q_{k-m}\right)\cos\left(2d\omega c^I_{k-m}\right)\cos\left(2d\omega c^Q_{k-m}\right)d\omega \tag{17}$$

and

$$d = \sqrt{(E_b/2.5)}.$$

Table 5 provides ranges of a that simultaneously satisfy the OOB power and BER criteria used above, for $N = 64$ for 4-QAM and 16-QAM modulation schemes. Just like the case of BPSK, here also the value of a can be used to provide a trade-off between OOB and BER.

There is nothing sacrosanct about the criteria used in the above example. One can come up with any number of such criteria. It has been used merely to illustrate the point that with

Table 5 Range of a for SNR = 10dB, $\alpha = 0.2$ and $\varepsilon = 0.1$ for 4-QAM and 16-QAM modulations

Modulation scheme	Range of 'a'
4-QAM	[2.39,5.6]
16-QAM	[2.41,5.38]

the aid of the tuning parameter a an LC pulse can be designed to simultaneously satisfy any feasible pair of OOB power and BER criteria. Another good thing is that one can achieve OOB power and BER values that cannot be achieved by either the polynomial pulse alone or the RC pulse alone. While in principle, one can try linear combinations of Poly5 with any other pulse viz. RC or BTRC, we chose Poly4 so that a good OOB performance is guaranteed and then used the linear combination idea to improve the BER performance by tolerating a slightly increased OOB power.

5 Conclusions and Future Work

A linear combination of the polynomial pulses of degree four and five presents a very good choice for spectral shaping in OFDM systems. It provides a good out of band power performance as well as a good BER performance in the presence of carrier frequency offset. Further, it provides a tuning parameter which can be used to tailor the pulse for any feasible combination of out of band power and BER. As is true for the other pulses, the out of band power of this pulse can also be improved near the band edge by using the available precoding techniques, deactivation of subcarriers etc. Given the observation that for several pulses higher the spectral decay rate worse is the BER performance, there seems to be some underlying relation between these two seemingly unrelated metrics. Although this is not surprising since both depend on the pulse shape used, there is a need to explore this relation.

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