Design of a family of ISI free pulses for very high data rate UWB Wireless Systems

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***Abstract*— In this paper we propose modified raised cosine pulses and a family of modified ISI free and bandlimited polynomial pulses for UWB communication systems which could provide very high data rates not possible by the conventional pulses and other proposed pulse design algorithms. The power spectrum of these proposed pulses fits the FCC spectral mask even for very high data rates and data rates gets quantized for various levels depending upon the shift frequency. Using this scheme and with a certain choice of design variables it is possible to design orthogonal pulses which could be used for multiuser data communication after truncating them for the same time interval.**

I. Introduction

Ultra-wideband (UWB) communication techniques[1] have attracted a great interest in both academia and industry in the past few years for applications in short-range wireless mobile systems. This is due to the potential advantages of UWB transmissions such as low power, high data rate, immunity to multipath propagation, less complex transceiver hardware, and low interference. However, tremendous R&D efforts are required to face various technical challenges in developing UWB wireless systems, including UWB channel characterization, transceiver design, coexistence with other narrowband wireless systems, and optimum pulse design for UWB transmission since the stringent requirements has been introduced by the FCC on the spectral mask.

In this paper we will first briefly discuss the typical waveforms like Gaussian and Hermite pulses[4] and a pulse design algorithm[2] for the generation of UWB pulses. Further, we have proposed modified raised cosine UWB pulses and a family of modified ISI free bandlimited polynomial pulses for UWB communication system which could be used to provide very high data rates not possible by the conventional pulses and pulses obtained by the pulse design algorithm[2]. The power spectrum of these pulses fits the FCC spectral mask and they could also be designed to fit any spectral mask. These proposed pulses have potential to give very high data rates, quantized with various levels depending upon the shift frequency. These pulses perform much better than the typical waveforms and the pulse design algorithm[2] with a choice on a number of design variables. Using this proposed scheme and an efficient choice of design variables it is also possible to design orthogonal pulses which could be used for multiuser data communication after truncating them for the same time interval.

II. Typical Waveforms

As a UWB signal has to transmit data at a very high data rate so the first constraint that is imposed on a UWB pulse is that it should be a short pulse in time domain. Generally speaking, the extremely short pulses with fast rise and fall times have a very broad spectrum and very small energy content. Before the advent of UWB in real life several non-damped waveforms were proposed for UWB systems such as Gaussian, Rayleigh, Laplacian, cubic and modified Hermitian pulses (MHP)[4]. All these waveforms tried to obtain a nearly flat frequency domain spectrum of the transmitted signal over the bandwidth of the pulse and to avoid a DC component. When FCC introduced the spectral mask for real life UWB transmission, new technological challenges were faced by the designers and engineers. A very narrow approach was to design new filters which will satisfy the FCC mask and to pass UWB signals from such a filter before transmission. Such an approach requires extra circuitry as well as it rejects a usable amount of energy.

A. Gaussian and Hermite Pulses

The Gaussian pulses[4] are not orthogonal and they do not satisfy the FCC spectral mask. Hermite pulses[4] although are orthogonal but they still do not satisfy the FCC mask. Therefore these pulses have to be shifted to the center frequency of the FCC mask in order to satisfy the FCC mask. In addition to this they have to be passed through appropriate filters to eliminate the available energy outside the mask before transmission. Filtering results in a loss of usable signal energy which is another disadvantage of the Gaussian and Hermite pulses.

B. Pulse Design Algorithm

A more technically sound algorithm was proposed in [2] to numerically generate UWB pulses that not only have a short time duration for multiple access, but also meet the power spectral constraint of FCC UWB mask. Such an algorithm

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could be used to design multiple orthogonal pulses that are compliant. This algorithm presents a flexible and systematic method for generating UWB pulses that have many advantages over traditional non damped waveforms. However, we observed that as we go on reducing the product $2WT$ [2] for higher data rate pulses for single user communication, this algorithm fails after a certain maximum possible data rate. Simulation results show that this limit is between 3 to 4 Gb/s for these pulses (with more than 99% power lying inside the band). So for a single user data communication the need arises for pulses with potential of even higher data rates.

C. Mask Fitting Criterion

In all the simulations that we have performed, the criterion to justify whether the power spectral density (PSD) of a pulse fits the FCC mask is either one or both of the following conditions.

1) If the maxima of the PSD of the pulse lies within the 3.1 to 10.6 GHz band then the maximum of the PSD is matched with the peak of the mask within the band, otherwise peak of the PSD is maximized with the peak of the mask in the corresponding range. If both these methods fail to fit the PSD within the mask then the power of the pulse is sufficiently reduced but we have to compromise with the performance.
2) The power concentrated within the 3.1 to 10.6 GHz band should be more than some predefined limit. Typical choice could be between 95% to 99% of total power.

III. Nyquist Criterion and ISI free Pulses

In any data transmission system the goal at the receiver is to sample the received signal at an optimal point in the pulse interval to maximize the probability of an accurate binary decision. This implies that the fundamental shapes of the pulses be such that they do not interfere with one another at the optimal sampling point. Such pulses have to satisfy Nyquist Criterion [5] for distortionless baseband transmission in absence of noise. Typical ISI free pulses are raised cosine pulses[5]. A family of polynomial ISI free pulses was proposed in [3] which have low equivalent bandwidth than conventional ISI free pulses by having higher decay rates. If an ISI free pulse is shifted in frequency domain in a way such that the overall pulse still satisfies the Nyquist criterion then that pulse could be used as an ISI free pulse for UWB communication.

IV. Modified Raised Cosine Pulse

In order to satisfy the Nyquist criterion [5], the frequency function $P(f)$ of the pulse with bandwidth W and roll-off factor α must satisfy the following condition

$$P(f)+P(f-2W)+P(f+2W) = \frac{1}{2W}, -W \leq f \leq W \quad (1)$$

Maximum possible data rate for this pulse is $2W$. If this pulse is shifted to a center frequency f_c, then the condition $2nW = f_c$ must hold so that the shifted pulse also satisfies the Nyquist criterion.

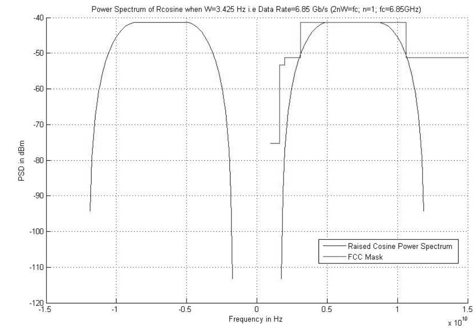


Fig. 1. Power Spectrum of modified raised cosine UWB pulse

If the shift frequency is chosen to be the center of the mask i.e $f_c = 6.85$ GHz then data rates are allowed only for integer values of n. The highest data rate possible is for $n = 1$ i.e 6.85 Gb/s followed by 3.425 Gb/s for $n = 2$ and so on. Therefore the data rate gets quantized with the choice of shift frequency. The frequency limits now become $[f_c-(2W-f_1), f_c+(2W-f_1)]$ which further reduces to $[W(2n-(1+\alpha)), W(2n+(1+\alpha))]$.

A. Simulation Results

A modified raised cosine pulse for UWB communication is given by

$$p(t) = \cos(2\pi f_c t)(\text{sinc}(2Wt))\left(\frac{\cos(2\pi\alpha Wt)}{1-16\alpha^2W^2t^2}\right) \quad (2)$$

The simulation is performed with parameters $f_c = 6.85$ GHz, $\alpha = 0.50$, $n = 1$ and so $W = 3.425$ GHz. This ensures $2W = f_c$ and hence data rate is maximum i.e. 6.85 Gb/s. The frequency range in this case is $[1.7125, 11.9875]$ GHz. This could satisfy the FCC mask either by lowering the power or by matching the peak and simulation shows that this indeed satisfies the mask. Almost 98.77% power lies within the 3.1 to 10.6 GHz band. Figure 1 shows that the power spectrum of this pulse clearly fits the desired FCC mask.

It could easily be observed that for lower data rates the pulses obtained would satisfy the FCC mask even more strictly. This is so because the bandwidth of raised cosine pulse i.e. $2W - f_1$ shrinks even more for an average choice of roll-off factor α.

V. Family of ISI free polynomial pulses for UWB wireless systems

The intuitive idea is the same as for the raised cosine pulses. Polynomial pulse of a desired Asymptotic Decay Rate (ADR) of t^{-k} is designed as in [3] and shifted in frequency domain for a desired center frequency. We found that for a single user communication, polynomial pulses could be designed which are not only ISI free but could also provide very high data rate and with sufficient decay rate not possible with the previous algorithm [2]. In this case too, data rate gets quantized with the choice of shift frequency as given by the condition $2nW = f_c$. Frequency limits are $[f_c - (2W - f_1), f_c + (2W - f_1)]$ which further reduces to $[W(2n - (1+\alpha)), W(2n + (1+\alpha))]$.

A. Illustrations

We will now show some test cases for UWB pulses having different ADRs, n, α and data rates with shift frequency f_c as the center of mask i.e 6.85 GHz. We first demonstrate bandlimited UWB ISI free pulses of various ADRs possible from a 4^{th} degree polynomial $G(f)$ as defined in [3]. Using the expression $k = \lfloor \frac{2n+5}{3} \rfloor$ given in [3], the maximum achievable ADR for a 4^{th} degree polynomial $G(f)$ is t^{-4}.

To get the maximum possible ADR of t^{-4}, we impose the constraints $G(0) = 1$, $G(1/2) = 1/2$, $G^{(1)}(0) = 0$, $G^{(2)}(0) = 0$ and $G^{(2)}(1/2) = 0$ given in [3]. These constraints give a unique solution $\{a_0, a_1, a_2, a_3, a_4\} = \{1, 0, 0, -8, 8\}$ which also satisfies $G^{(3)}(0) \neq 0$ and the time domain expression is

$$p(t) = \cos(2\pi f_c t) \left(3\,\mathrm{sinc}(2Wt) \frac{(\mathrm{sinc}^2(\alpha Wt) - \mathrm{sinc}(2\alpha Wt))}{(\pi\alpha Wt)^2} \right)$$

Other parameters are chosen as $W = 3.425$ GHz, $\alpha = 0.5$ and $f_c = 6.85$ GHz. Figures 2(a) and 2(b) shows the time domain and PSD for this pulse.

We could have more test cases with more number of design variables for the same or different ADRs and different data rates. For a given decay rate, any desired number of design variables can be obtained by properly choosing the degree of the polynomial $G(f)$. As an example, for an ADR of t^{-4}, a 12^{th} degree polynomial $G(f)$ would have eight design variables. It is worth emphasizing that the bandwidth does not depend on the choice of the design variables.

VI. Orthogonal Solutions

Another important utility of generalized ISI free polynomial pulses[3] is that it is possible to find ISI free pulses which are orthogonal to each other. So if two or more pulses have a very high decay rate then we could truncate them and use them as normal orthogonal pulses. Consider two ISI free Polynomial Pulses $P_1(f)$ and $P_2(f)$. Let $G_1(f$ and $G_2(f)$ be the corresponding polynomial functions. $P_1(f)$ and $P_2(f)$ would be orthogonal if and only if the following condition holds.

$$\int_{-\infty}^{\infty} P_1(f) P_2(f)\, df = 0 \qquad (3)$$

With $P_i(f)$ being an even function limited to $[-(2W - f_1), 2W - f_1]$ and assuming same value of roll off factor α and data rate $2W$, (3) reduces to

$$\int_{0}^{2W-f_1} P_1(f) P_2(f)\, df = 0 \qquad (4)$$

which further reduces to

$$\int_{0}^{\frac{1}{2}} [G_1(f) + G_2(f) - 2G_1(f)G_2(f)]\, df = \frac{1}{2\alpha} \qquad (5)$$

A. Obtaining Orthogonal Polynomial Pulses

Let $G(f)$ be a n^{th} degree polynomial and the desired ADR be t^{-k}. The number of constraints n_k imposed on $G(f)$ for $p(t)$ to have an ADR of t^{-k} are given in [3]. The maximum ADR t^{-k} achievable for an n^{th} degree $G(f)$ is for $k = \lfloor \frac{2n+5}{3} \rfloor$ and the minimum degree n_{min} of the polynomial required $= \lfloor \frac{3k-4}{2} \rfloor$.

For an even k, $n_{min} = \frac{3k-4}{2}$. Therefore there are $n_{min} + 1$ total variables i.e. $\frac{3k-2}{2}$ variables. Number of constraints initially used is equal to $(k - 2 + 1)$ i.e. $(k - 1)$ to find out $(k-1)$ variables. Number of remaining variables to be solved $= \frac{3k-2}{2} - (k - 1) = \frac{k}{2}$. Number of equations available $= \frac{k}{2} = \left(\frac{k-2}{2} + 1\right)$. So this could be solved completely to give a unique solution. If we take n equal to $n_{min} + 1$, we will have one lesser equation and that will give us a family of t^{-k} ADR pulses. So now if we want to find an orthogonal pulse to this pulse, we have to choose remaining one variable in the initial pulse. The remaining parameter of the second pulse could be found by the orthogonality equation (5). Similar results could be found out for an odd k. In general, number of orthogonal pulses $= i + 1$ if $n = n_{min} + i$, where $n_{min} = \lfloor \frac{3k-4}{2} \rfloor$.

B. Illustrations

For three orthogonal solution sets with an ADR of t^{-4}, $n_{min} = \lfloor \frac{3k-4}{2} \rfloor = 4$. So degree of polynomial required $= n_{min} + 2 = 6$. Using the $G(0) = 1$ and conditions in [3] the polynomial reduces to

$$G_1(f) = 1 + a_3 f^3 + a_4 f^4 + a_5 f^5 + a_6 f^6 \qquad (6)$$

Number of remaining equations are 2 i.e. $G_1(1/2) = \frac{1}{2}$ and $G_1^{(2)}(1/2) = \frac{1}{2}$ respectively. Let the other two polynomials be

$$G_2(f) = 1 + b_3 f^3 + b_4 f^4 + b_5 f^5 + b_6 f^6 \qquad (7)$$

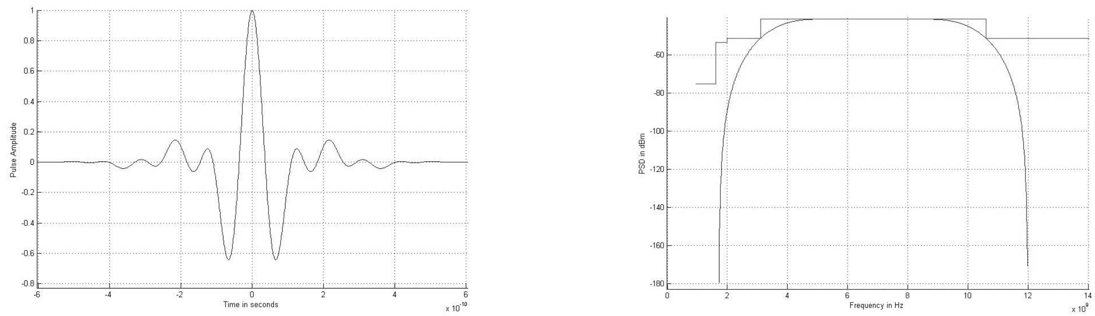
$$G_3(f) = 1 + c_3 f^3 + c_4 f^4 + c_5 f^5 + c_6 f^6 \qquad (8)$$

Methodology used is
$G_1(f) \rightarrow$ We choose two unknowns a_5 and a_6 and solve the remaining a_3 and a_4.
$G_2(f) \rightarrow$ We choose one unknown b_5 and solve the remaining using orthogonality equation (5) of $G_1(f)$ and $G_2(f)$.
$G_3(f) \rightarrow$ All variables could be solved by the orthogonality equations of $G_3(f)$ with $G_1(f)$ and $G_2(f)$ and the remaining equations of $G_3(f)$.

C. Simulation Results

Choosing $a_5 = a_6 = b_5 = 5$, one real orthogonal solution set of three functions is calculated with
$a_3 = -4.4583, a_4 = -2.8333, a_5 = 5, a_6 = 5$
$b_3 = -719.0721, b_4 = 1.9028103, b_5 = 5, b_6 = -1.9006103$
$c_3 = -6.5134103, c_4 = 4.4356104, c_5 = -9.7202104, c_6 = 6.9055104$

We can't go any further because if we have four polynomials then total number of equations would be 14 and number of unknowns would be 16. Similarly, orthogonal solutions could also be derived for $n = 7 = n_{min} + 3$.



(a) Modified ISI free pulse

(b) Power Spectrum

Fig. 2. Simulation results for Modified ISI free pulse

VII. Comparison and Results

As discussed earlier, the pulse design algorithm [2] fails to perform for very high data rates. Also the complexity of the algorithm increases further as pulses for higher data rates are desired for single user communication. Simulation shows that for data rates as high as 6.00 Gb/s, pulse obtained with the pulse design algorithm has only 91% of its power lying within the 3.1 to 10.6 GHz band and it also violates the FCC mask if power is quite high. So it is highly undesirable to use this pulse for single user data communication. On the other hand the ISI free polynomial pulse for UWB with an ADR t^{-4} fits the mask much better with an intelligent choice of design parameters. Simulation shows that for data rates higher than 6.00 Gb/s more than 99% power lies within 3.1 to 10.6 GHz band. We also observed that the designed pulse not only gives higher data rates compared to the pulse design algorithm but because of high ADR it could be truncated without causing much effect on the performance. It is interesting to notice that the modified ISI free UWB pulses could not only be used as ISI free pulses but the truncated pulses could also be used as normal pulses with significant data rates.

Comparing modified polynomial ISI free UWB pulses with modified raised cosine pulses we could see that the raised cosine pulse has an ADR of t^{-2} and once the roll off factor α is chosen, the shape of the pulse gets fixed. On the contrary, the polynomial pulse could be designed for any ADR with some design parameters. Also as shown earlier, orthogonal set of solutions could also be found for the polynomial pulses. Simulation shows that the raised cosine pulse oscillates for much longer time period compared to the polynomial pulse with ADR t^{-4}.

Gaussian and Hermite pulses, as discussed earlier, should be passed through appropriate filters before using them for real communication systems. Also the data rates obtained are quite low compared to both pulse design algorithm as well as modified ISI free pulses. For example, a Gaussian doublet could give data rates upto a maximum of 2.0 Gb/s.

As we go on increasing the number of orthogonal pulses for a certain modified ISI free polynomial pulses, net throughput of the system is also bound to increase depending on the number of pulses satisfying the FCC mask and also the width of the pulse in the time domain. Multiuser communication can be done by dividing the FCC mask into different multibands then designing pulses for these subsequent multibands.

VIII. Conclusion

We have proposed modified raised cosine UWB pulses and a family of ISI free and bandlimited polynomial pulses for UWB communication system which have the potential to provide very high data rates not possible by the conventional pulses and pulses obtained by the pulse design algorithm of [2]. These pulses could also be designed to fit any spectral mask. We saw that depending upon the shift frequency, data rates for these pulses gets quantized. We have also shown that one could choose any number of design variables for these polynomial pulses. Our proposed pulses have advantages over the commonly used Gaussian and Hermite pulses. Compared to recently proposed pulse design algorithm which fails after a certain data rate for single user data communication, modified polynomial ISI free UWB pulses continue to give higher data rates without affecting the performance and without violating the FCC mask. Also the pulse obtained from the pulse design algorithm suffered intersymbol interference. Finally, we have also shown that we could design orthogonal pulses with a certain choice of design variables and these orthogonal pulses could be used for multi user data communication after truncating them for the same time interval.

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