ISI-free pulses for high-data-rate ultra-wideband wireless systems

Pulsations sans interférence intersymbole pour les systèmes sans fil ultra large bande à haut débit

Ziaul Hasan, Umesh Phuyal, V. Yadav, A.K. Chaturvedi, and Vijay K. Bhargava*

Modified intersymbol interference (ISI)–free pulses and ISI-free band-limited polynomial pulses for ultra-wideband (UWB) communication systems are proposed to provide the possibility of very high data rates not achievable by conventional pulses and the pulse design algorithms available in the literature. The power spectrum of the proposed pulses fits the Federal Communications Commission (FCC) spectral mask for very high data rates that have quantized values with various levels. Using this scheme and a particular choice of design variables, it is possible to design orthogonal pulses that could be used for multi-user data communication after they are truncated for the same time interval. Several possible improvements for these proposed pulses are considered for certain practical cases.

On propose de nouvelles pulsations sans interférence intersymbole et de nouvelles pulsations polynomiales à bande réduite sans interférence intersymbole pour les systèmes de communication ultra large bande (UWB) permettant des débits plus élevés que ceux publiés jusqu'à maintenant. Le spectre de puissance des pulsations proposées respecte le masque spectral de la *Federal Communications Commission* (FCC) pour des débits très élevés. On montre également comment construire des pulsations orthogonales pouvant être utilisées pour la communication de données à plusieurs usagers en les tronquant pour le même intervalle de temps. On décrit finalement comment améliorer les pulsations proposées pour quelques scénarios pratiques.

Keywords: high-data-rate system; ISI-free pulse; polynomial pulse; pulse design; ultra-wideband; UWB

I. Introduction

Ultra-wideband (UWB) communication techniques [1] have attracted 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 consumption, high data rate, immunity to multipath propagation, less complex transceiver hardware, and low interference. However, tremendous research and development efforts are required to deal with the various technical challenges of developing UWB wireless systems, including UWB channel characterization, transceiver design, coexistence with other narrowband wireless systems, and optimum pulse design for UWB transmission to meet stringent requirements for the spectral mask introduced by the Federal Communications Commission (FCC).

In this paper we briefly discuss typical waveforms like Gaussian and Hermite pulses [2], along with a pulse design algorithm [3] for the generation of UWB pulses. Further, we propose modified raised cosine (MRC) UWB pulses, other modified intersymbol interference (ISI)–free pulses, and a family of modified ISI-free band-limited polynomial pulses for UWB communication systems which could be used to provide very high data rates not possible with conventional pulses and pulses obtained by the pulse design algorithm [3]. The power spectrum of these pulses fits the FCC spectral mask and could be designed to fit any spectral mask. The proposed pulses provide the potential for very high data rates, quantized with various levels depending on the shift frequency. The pulses perform much better than typical waveforms and the pulse design algorithm [3], and they offer 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 multi-user data communication after they are truncated for the same time interval.

The rest of this paper is organized as follows. In Section II, we give a brief summary of the typical UWB waveforms. Section III states the Nyquist criterion for ISI-free pulses, proposes the idea of using them for UWB systems, and proposes MRC pulses and other modified ISI-free pulses for UWB. Section IV introduces a family of modified ISI-free polynomial pulses for UWB wireless systems. In Section V, we propose a method for obtaining orthogonal solutions for these pulses. A few practical considerations affecting the design of these UWB pulses are explained in Section VI. Comparison and results are presented in Section VII, and conclusions are drawn in Section VIII.

II. Typical waveforms

Since a UWB signal must transmit data at a very high data rate, the first constraint imposed on a UWB pulse is that it should be a short pulse in the time domain. Generally speaking, extremely short pulses with fast rise and fall times have a very broad spectrum and very low energy content. Before the advent of UWB in real-world applications, several non-damped waveforms, such as Gaussian, Rayleigh, Laplacian, cubic, and modified Hermite pulses (MHP), were proposed for UWB systems [2]. All these waveforms tried to achieve a nearly flat frequency-

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domain spectrum of the transmitted signal over the bandwidth of the pulse while avoiding a dc component. When the FCC introduced the spectral mask for UWB transmission, new technological challenges were faced by designers and engineers. A very narrow approach has been to pass UWB signals through filters designed to satisfy the FCC mask before transmission. However, such an approach requires extra circuitry. Moreover, it squanders a usable amount of energy.

A. Gaussian waveforms

The class of Gaussian waveforms is so named because their mathematical definition is similar to that of the Gaussian function [2]. The basis of these Gaussian waveforms is a Gaussian pulse represented by

$$y_{g1}(t) = k_1 e^{(t/\tau)^2}, \tag{1}$$

where $-\infty < t < \infty$, τ is the time-scaling factor, and k_1 is the constant. Higher-order waveforms can be obtained by high-pass-filtering this Gaussian pulse; this step is similar to taking derivatives of the Gaussian pulse. The choice of a particular Gaussian waveform is usually driven by system design and application requirements. For the case specific to UWB, the waveform should have a centre frequency between 3.1 and 10.6 GHz. One important characteristic of these waveforms is that they are almost uniformly distributed over their frequency spectrum and therefore are noise-like. The Gaussian pulses are not orthogonal and do not satisfy the FCC spectral mask. In order to shape waveforms for specific spectral masks, designers generally modulate Gaussian pulses to the centre frequency of the mask and pass them through specific filters. Multi-access capabilities can be achieved for these pulses by means of multi-band modulation techniques.

B. Orthogonal modified Hermite pulses

Orthogonal pulses have several additional advantages over non-orthogonal pulses, as they can be used to send multiple data streams at the same time. Hermite polynomials are not orthogonal in general, but they can be modified to become orthogonal [2]. The orthogonal modified Hermite pulse is given by

$$h_n(t) = k_n(-\tau)^n e^{t^2/4\tau^2} \frac{d^n}{dt^n}\left(e^{t^2/2\tau^2}\right), \tag{2}$$

where n is a positive integer, $-\infty < t < \infty$, τ is the time-scaling factor, and k_n is a constant determining the energy of the pulse. To gain more flexibility in the frequency domain, the time functions can be multiplied and modified by an arbitrary phase-shifted sinusoid as follows [2]:

$$p_n(t) = \sqrt{2} h_n(t) \cos(2\pi f_c t + \phi_r), \tag{3}$$

where f_c is the shifting frequency and ϕ_r is an arbitrary phase that can be zero without loss of generality. Hermite pulses do not satisfy the FCC mask even though they are orthogonal. As in the case of Gaussian pulses, these pulses must be shifted to the centre frequency of the FCC mask in order to satisfy the mask, and they are passed through appropriate filters to eliminate the energy outside the mask before transmission.

C. Pulse design algorithm

A more technically sound algorithm was proposed in [3] to numerically generate UWB pulses that not only have a short time duration for multiple access, but also meet the power spectral constraint of the FCC UWB mask. Such an algorithm could be used to design multiple orthogonal pulses that are FCC-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 the following issues with the pulse design algorithm:

1. Not all of the generated pulses completely satisfy the FCC mask criterion. Only the pulses corresponding to higher eigenvalues fit the FCC mask; i.e., the higher the eigenvalue corresponding to a pulse, the better it fits the mask.
2. The selection of pulse duration T is significant. The greater the value of T, the closer the frequency content of the pulse will be to that of the mask, and the greater will be the number of orthogonal pulses which fit the mask. However, as we increase T, the data rate goes down. Thus there is a tradeoff between the two variables.
3. As we reduce the product $2WT$ (where W is the bandwidth of the pulse) for higher-data-rate pulses for single-user communication [3], the algorithm fails after a certain maximum possible data rate. Simulation results show that this limit is between 3 and 4 Gb/s for these pulses (with more than 99% of the power lying inside the band).

Therefore, for single-user data communication, the need for pulses with potentially even higher data rates arises.

D. Other UWB pulse families

Recently, several other new pulse families and pulse shapers were proposed in [4]–[7], all of which have been shown to satisfy the FCC mask for UWB communication. A set of orthonormal pulses that comply with the FCC mask without additional frequency-shifting or bandpass filtering was derived in [4] from a parametric closed-form solution. In [5], the authors designed pulse-shaping finite-impulse-response filters for UWB using an optimization approach to tackle the problem of spectrum shaping for single-user communication systems through construction of a least-squares approximation. Similarly, the authors in [6] derived a pulse shaper that satisfies the FCC mask by using digital filter design methods. A subspace-based approach to pulse design that operates by making optimization of the maximum allowable transmit power (MATP) easier was introduced in [7] with application to UWB communications. In this paper we will be interested mainly in comparing our proposed pulses with more traditional Gaussian and Hermite pulses and the pulse design algorithm [3].

E. Mask-fitting criteria

Without loss of generality, we can normalize the power spectral density (PSD) of the pulse according to our need to fit the FCC mask; i.e., no part of the PSD curve should go above the FCC mask. It is desirable that (i) the maximum of the PSD curve match the FCC mask, and (ii) the power concentrated within the 3.1 to 10.6 GHz band be more than some predefined limit; a typical choice could be between 95% and 99% of total power. Then the following points are of interest:

1. If the maximum of the PSD of the pulse does not lie within 3.1 to 10.6 GHz, the pulse is very unlikely to satisfy condition (ii).
2. If the maximum of the PSD of the pulse lies within 3.1 to 10.6 GHz but does not match with the FCC mask, the MATP [7] of the UWB signal decreases with the increase in area under the mask and above the PSD curve. This area should be minimized for better bit error rate (BER) performance at high data rates.

III. Modified ISI-free pulses for UWB systems

A. 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 should be such that they do not interfere with one another at the optimal sampling point. Such pulses must satisfy the Nyquist criterion [8] for distortionless baseband transmission in the absence of noise. Typical ISI-free pulses are raised cosine pulses [8]. A family of polynomial ISI-free pulses that achieve lower equivalent bandwidth than conventional ISI-free pulses by having higher decay rates was proposed in [9].

If an ISI-free pulse is shifted in the frequency domain in such a way that the overall pulse still satisfies the Nyquist criterion, then the pulse can be used as an ISI-free pulse for UWB communication.

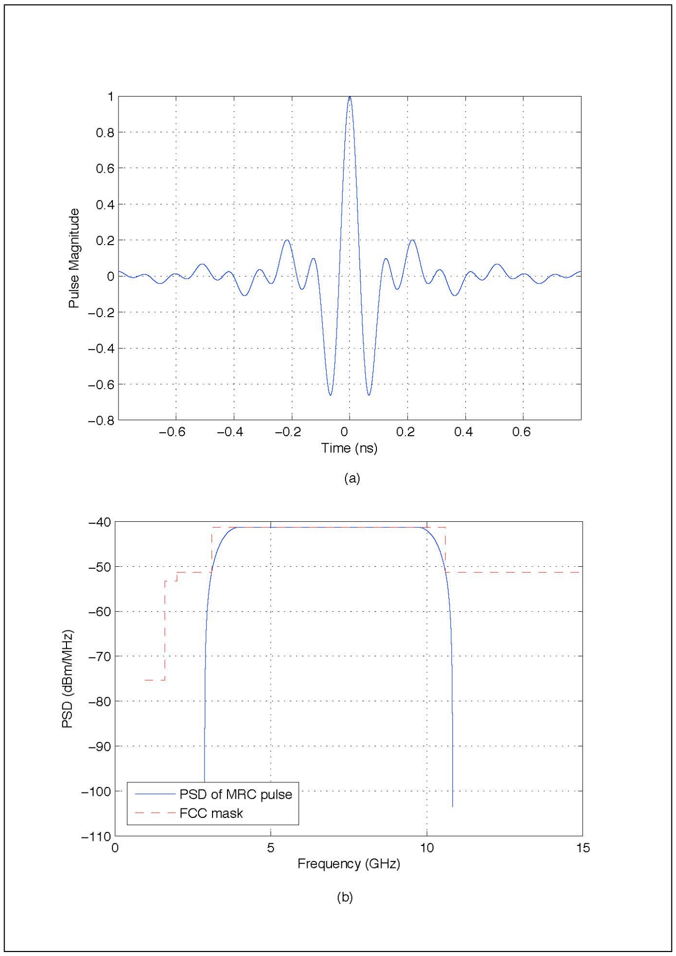

Figure 1: *MRC pulse for UWB with $W = 3.425$ GHz (maximum data rate is 6.85 Gb/s), $f_c = 6.85$ GHz, and $\alpha = 0.16$: (a) time domain, (b) PSD of the pulse.*

B. Modified raised cosine pulse for UWB

In order to satisfy the Nyquist criterion [8], the frequency response, $P(f)$, of a pulse with bandwidth W must satisfy the following condition within the band of interest $[-W, W]$:

$$P(f) + P(f - 2W) + P(f + 2W) = \frac{1}{2W}, \quad -W \leq f \leq W. \quad (4)$$

The maximum possible data rate for this pulse is $2W$. If the raised cosine pulse is shifted to a centre frequency f_c, then the condition $2nW = f_c$ must hold (for integer n) so that the shifted pulse also satisfies the Nyquist criterion.

If the shift frequency is chosen to be the centre of the FCC 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 is quantized with the choice of f_c. The transmission band of the MRC pulse with roll-off factor α will then be $[W(2n - (1 + \alpha)), W(2n + (1 + \alpha))]$.

1. Simulation results

The MRC pulse for UWB, obtained by frequency-shifting f_c as discussed above, is given by the time-domain function [8]

$$p(t) = \cos(2\pi f_c t)\,\mathrm{sinc}(2Wt)\left(\frac{\cos(2\pi\alpha Wt)}{1 - 16\alpha^2 W^2 t^2}\right). \quad (5)$$

The pulse is simulated by taking $f_c = 6.85$ GHz and $W = 3.425$ GHz (to ensure $2nW = f_c$ with $n = 1$, so that $p(t)$ is ISI-free) for different values of α. Thus the maximum data rate is 6.85 Gb/s. Fig. 1(a) shows the time-domain plot of the MRC pulse for UWB with $W = 3.425$ GHz (maximum data rate is 6.85 Gb/s), $f_c = 6.85$ GHz, and $\alpha = 0.16$. Fig. 1(b) shows the corresponding PSD. We see from Fig. 1(b) that the pulse satisfies the FCC mask and exactly matches the peaks for $\alpha = 0.16$. The frequency range of the pulse in this case is $[2.877, 10.823]$ GHz, and 99.78% of the transmission power lies within the 3.1 to 10.6 GHz band.

The MATP (without violating the FCC mask) for the pulse in this case is 91.13% of the ideal maximum transmit power (IMTP) for UWB in the 3.1 to 10.6 GHz band. It is observed that for $n = 2$ and above, the pulses obtained would satisfy the FCC mask even more strictly, allowing 100% of the transmission power to be within the 3.1 to 10.6 GHz range for any choice of roll-off factor α. This is due to the decrease in W by the factor of $2n$. However, these choices result in (i) lower maximum data rates (e.g., 3.425 Gb/s for $n = 2$), and (ii) significantly low MATP of the pulse (e.g., 45.67% of IMTP for $n = 2$ for any choice of α).

C. Other modified ISI-free pulses for UWB

A better-than-raised-cosine (BTRC) pulse was proposed in [10]. BTRC performs better than raised cosine (RC) in terms of ISI error probabilities in the presence of fixed timing errors, although BTRC decays with t^{-2}, compared to t^{-3} for RC. Several other ISI-free pulses with still better performance have been proposed in [11]. We can apply a procedure similar to that used to modify these pulses for UWB systems. All the conditions as discussed for MRC in the previous section are still valid for these modified pulses as well.

IV. ISI-free polynomial pulses for UWB wireless systems

The basic idea here is also the same as that for the MRC pulses. The polynomial pulse of a desired asymptotic decay rate (ADR) of t^{-k} is designed as in [9] and shifted in the frequency domain to the desired f_c. We found that for single-user communication, polynomial pulses could be designed which are not only ISI-free, but could also provide a very high data rate with sufficient decay rate, beyond what is possible with the algorithm given in [3]. In this case too, the data rate is quantized with the choice of f_c because of the condition $2nW = f_c$; and the transmission band of the pulse with roll-off factor α will be $[W(2n - (1 + \alpha)), W(2n + (1 + \alpha))]$.

We simulated the ISI-free polynomial UWB pulses with different ADRs and values of α and n (yielding different data rates) with $f_c = 6.85$ GHz (i.e., the centre of the FCC mask). As an example, we demonstrate here a band-limited ISI-free polynomial pulse for UWB with ADR of t^{-4}, which is the maximum ADR achievable from a fourth-degree polynomial $G(f)$ as defined in [9]. The time-domain expression of the pulse suggested in [9] is modified as

$$p(t) = 3\cos(2\pi f_c t)\,\mathrm{sinc}(2Wt)\frac{(\mathrm{sinc}^2(\alpha Wt) - \mathrm{sinc}(2\alpha Wt))}{(\pi\alpha Wt)^2}. \quad (6)$$

For very high data rate, we choose $n = 1$ and thus $W = 3.425$ GHz. We find that the pulse best fits the FCC mask for $\alpha = 0.5$. Figs. 2(a) and 2(b) show the time domain and PSD for this pulse respectively.

The frequency range of the pulse in this case is $[1.7125, 11.9875]$ GHz, and 99.23% of total power lies within the 3.1 to 10.6 GHz band. The MATP for the pulse in this case is 81.17% of the IMTP in the 3.1 to 10.6 GHz band. For $n = 2$ or more, a behaviour similar to that in MRC is observed.

V. Orthogonal solutions

Another important utility of generalized ISI-free polynomial pulses [9] is that it is possible to find ISI-free pulses which are orthogonal to each other. Thus, if two or more pulses have a very high decay rate, then

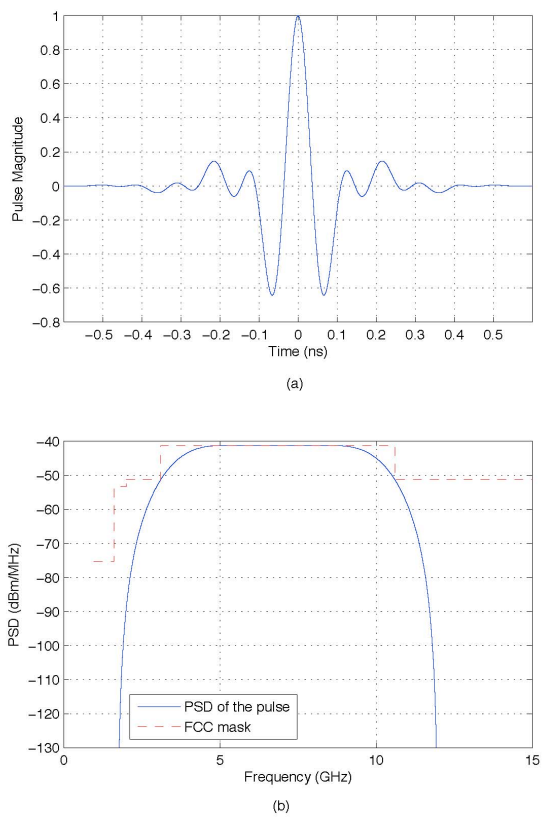

Figure 2: *Modified ISI-free polynomial pulse for UWB: (a) time domain, (b) PSD of the pulse.*

we could truncate them and use them as normal orthogonal pulses. Consider two ISI-free polynomial pulses $P_1(f)$ and $P_2(f)$ with $G_1(f)$ and $G_2(f)$ as their corresponding polynomial functions respectively, as defined in [9]. $P_1(f)$ and $P_2(f)$ will be orthogonal if the following condition holds:

$$\int_{-\infty}^{\infty} P_1(f)P_2(f)\,df = 0. \quad (7)$$

Since $P_i(f)$ is an even function limited to $[-(2W-f_1), 2W-f_1]$ (where $f_1 = W(1-\alpha)$), and if we assume same values of roll-off factor α and data rate $2W$, (7) is equivalent to

$$\int_{0}^{2W-f_1} P_1(f)P_2(f)\,df = 0. \quad (8)$$

Using the primary definition of polynomial pulse $P(f)$ as given in [9], (8) can be rewritten as

$$\int_0^{f_1} df + \int_{f_1}^{W} G_1\left(\frac{f-f_1}{2\alpha W}\right) G_2\left(\frac{f-f_1}{2\alpha W}\right) df + \int_{W}^{2W-f1}\left(1-G_1\left(\frac{2W-f-f_1}{2\alpha W}\right)\right) \times\left(1-G_2\left(\frac{2W-f-f_1}{2\alpha W}\right)\right) df = 0.$$

By changing the limits and after simplification, we can reduce this to

$$\int_0^{1/2}[G_1(f)+G_2(f)-2G_1(f)G_2(f)]\,df = \frac{1}{2\alpha}. \quad (9)$$

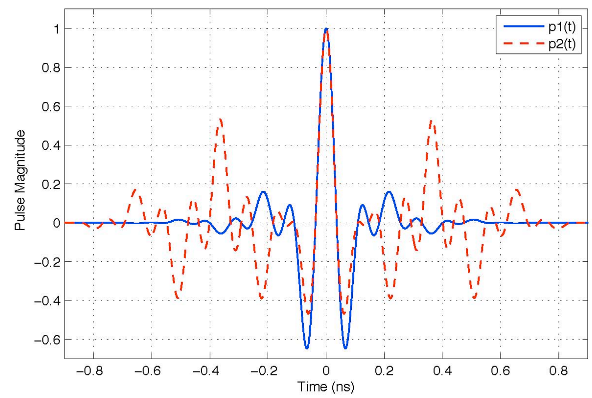

Figure 3: *Modified ISI-free polynomial UWB orthogonal pulses for ADR t^{-4}.*

A. Obtaining a set of orthogonal polynomial pulses

Let $G(f)$ be an m-th degree polynomial as defined in [9] and let the desired ADR be t^{-k}. The minimum degree of the polynomial required for an ADR of t^{-k} is $m_{\min} = \lfloor(3k-4)/2\rfloor$.

For an even k, $m_{\min} = (3k-4)/2$, and the polynomial of degree $m_{\min}$ can be uniquely solved for the desired ADR of t^{-k} [9], [12]. If we take $m = m_{\min}+1$, we will have a deficiency of one equation to uniquely solve, but we find a family of t^{-k} ADR pulses. Now, we can find a pair of orthogonal pulses by assuming the value of the remaining one variable in one pulse and solving the remaining variable of the other pulse by means of the orthogonality equation (9).

Similar results could be found for an odd k. In general, the number of orthogonal pulses in a set is equal to $i+1$ if $m = m_{\min}+i$, where $m_{\min} = \lfloor(3k-4)/2\rfloor$. In other words, to design a set of p orthogonal pulses with ADR of t^{-k}, the minimum order of polynomial required is $m_{\min}+p-1$.

B. Illustration

For a set of three orthogonal pulses with ADR of t^{-4}, the degree of polynomial required is $m_{\min}+3-1 = 6$. Using the constraints $G(0) = 0$ and $G^{(i)}(0) = 0$ for $1 \le i \le (k-2)$, as given in [9], we can reduce the sixth-order polynomials to

$$G_1(f) = 1 + a_3f^3 + a_4f^4 + a_5f^5 + a_6f^6, \quad (10)$$
$$G_2(f) = 1 + b_3f^3 + b_4f^4 + b_5f^5 + b_6f^6, \quad (11)$$
$$G_3(f) = 1 + c_3f^3 + c_4f^4 + c_5f^5 + c_6f^6. \quad (12)$$

We still have two constraints for each polynomial; namely, $G_j(1/2) = 1/2$ and $G_j^{(2)}(1/2) = 0$ for $j = 1,2,3$. We can use the following methodology to reach a solution:

- $G_1(f)$: We assume the values of two unknowns a_5 and a_6 and solve for a_3 and a_4 using the two constraints given above.
- $G_2(f)$: We assume the value of b_5 and solve for the remaining three variables using the two constraints given above and the orthogonality equation (9) of $G_1(f)$ and $G_2(f)$.
- $G_3(f)$: All variables could be solved by the orthogonality equations of $G_3(f)$ with $G_1(f)$ and $G_2(f)$ and the remaining constraints of $G_3(f)$.

C. Simulation results

Choosing $a_5 = a_6 = b_6 = 8$, we find one real orthogonal solution set of three functions to be

$$a_3 = -2.3333, \quad a_4 = -9.3333, \quad a_5 = 8, \quad a_6 = 8,$$
$$b_3 = -247.7383, \quad b_4 = 849.5841, \quad b_5 = -728.2149, \quad b_6 = 8,$$
$$c_3 = -11.1606, \quad c_4 = -3.0658 \times 10^3, \quad c_5 = 1.1096 \times 10^4,$$
$$c_6 = -9.8717 \times 10^3.$$

The time-domain function of pulses is calculated from the above results as suggested in [9], and the pulses are frequency-shifted as suggested in previous sections of this paper. The time-domain functions $p_1(t)$ and $p_2(t)$ corresponding to the polynomials in (10) and (11) respectively are illustrated in Fig. 3.

VI. Practical considerations

A. Truncation in time window

The ideal band-limited ISI-free pulses are inherently of infinite length. For real systems, the ideal pulses are truncated, such that sidelobes are introduced in the PSD. Through simulation, we see that the proposed ISI-free polynomial pulse for UWB satisfies the FCC mask even after the pulse has been truncated to as low as $\pm 2.5T$, where T represents the bit duration. In such a case, 95.20% of total transmission power still lies inside the 3.1 to $10.6\,\mathrm{GHz}$ band. Similar results are observed for MRC and other modified ISI-free pulses. These results show that the proposed pulses are robust against truncation error.

B. Sensitivity to synchronization errors

The timing error introduces ISI even though a pulse is ideally ISI-free. A linear combination of two ISI-free pulses with reduced sensitivity to timing errors was proposed in [13]. An optimum combination was obtained using the distribution of timing errors, and it was also shown that such pulses perform better than traditional ISI-free pulses for fixed as well as randomly distributed timing errors while having the same bandwidth [13]. We can apply a similar technique to the proposed UWB pulses to improve their timing sensitivity. Following the procedure given in [13], if we consider two ISI-free UWB pulses $p_1(t)$ and $p_2(t)$ to obtain a new pulse $p(t)$ as

$$p(t) = \beta p_1(t) + (1 - \beta) p_2(t), \tag{13}$$

then it is desirable to obtain the optimum value of β such that the expected value of ISI error probability is minimized. Since an analytical solution for β is not obvious, numerical solutions were suggested in [13], assuming some distribution of timing errors. It was also observed in [13] that the optimum value β_{opt} is unique for the cases observed. The bandwidth of the resultant pulse is bound by the larger of the two bandwidths of pulses $p_1(t)$ and $p_2(t)$.

C. Bit error rate

BER is an important performance criterion of the proposed ISI-free pulses for UWB systems. To determine the best pulse within certain system parameters, we can consider obtaining the BERs of the proposed pulses and determining the pulse which yields the lowest BER within those parameters.

VII. Comparison and results

As discussed earlier, the pulse design algorithm [3] fails to perform for very high data rates. Also, the complexity of the algorithm increases further as higher-data-rate pulses are pursued for single-user communication. Simulation shows that for data rates as high as $6.00\,\mathrm{Gb/s}$, a pulse obtained with the pulse design algorithm has only 91% of its power lying within the 3.1 to $10.6\,\mathrm{GHz}$ band. In addition, it violates the FCC mask if power is sufficiently high. Thus 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 of t^{-4} fits the mask much better with an intelligent choice of design parameters. Simulation shows that for data rates higher than $6.00\,\mathrm{Gb/s}$, more than 99% of the power lies within the 3.1 to $10.6\,\mathrm{GHz}$ band. We also observed that the designed pulse not only provides higher data rates compared to the pulse design algorithm, but because of high ADR it could be truncated without having much effect on the performance. It is interesting to note not only that the modified ISI-free UWB pulses could be used as ISI-free pulses, but also that the truncated pulses could be used as normal pulses with significant data rates.

Comparing modified polynomial ISI-free UWB pulses to MRC pulses, we can 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 is fixed. By contrast, the polynomial pulse could be designed for any ADR with some design parameters. Also, as shown earlier, an orthogonal set of solutions could be found for the polynomial pulses. Simulation shows that the raised cosine pulse oscillates for a much longer time period compared to the polynomial pulse with ADR of t^{-4}.

Gaussian and Hermite pulses, as discussed earlier, must be passed through appropriate filters before they are used for practical UWB communication systems. Filtering results in a loss of usable signal energy, which is another disadvantage of the Gaussian and Hermite pulses. Also, the data rates obtained are quite low compared to those of both the pulse design algorithm and modified ISI-free pulses. For example, a Gaussian doublet could deliver data rates of up to a maximum of $2.0\,\mathrm{Gb/s}$.

As we continue to increase the number of orthogonal pulses for a certain modified ISI-free polynomial pulse, the net throughput of the system also increases, depending on the number of pulses satisfying the FCC mask and also on the width of the pulse in the time domain. Multi-user communication can also be achieved by dividing the FCC mask into different multi-bands and then designing pulses for these multi-bands.

VIII. Conclusion

We proposed MRC UWB pulses, other modified ISI-free pulses, and a family of ISI-free and band-limited polynomial pulses for UWB communication systems. These pulses have the potential to provide very high data rates not achievable by conventional pulses and pulses obtained by the pulse design algorithm of [3]. They could be designed to fit any spectral mask. We saw that, depending upon the shift frequency, data rates for these pulses are quantized. We also showed that it is possible to 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 the pulse design algorithm [3], which not only results in pulses with ISI, but also fails after a certain data rate for single-user data communication, modified ISI-free polynomial pulses continue to provide higher data rates without affecting performance and without violating the FCC mask. The proposed pulses were found to be robust against the errors due to truncation in time. The design of orthogonal pulses with a certain choice of design variables was also demonstrated. Such orthogonal pulses could be used for multi-user data communication after being truncated for some time interval.

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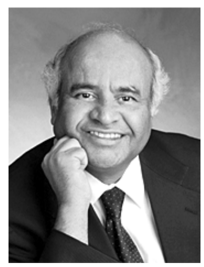

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