Synthesis of UWB Pulse Following FCC mask

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ABSTRACT

We present an intuitive pulse synthesis technique for Ultra Wide Band communications (UWB). The synthesized pulse meets Federal Communications Commissions (FCC) spectral mask. The time-limited short duration pulse is synthesized from a band limited modified FCC mask. Features of the pulse have been compared with other reported UWB pulses.

I. INTRODUCTION

In the recent years, considerable interest has grown in the area of short distance wireless communications. One such area is Ultra Wide Band technology. UWB is aimed to provide wireless data communication at high rates (>100Mbps) over short distances (<10m) within the spectrum released by the FCC [1]. Some other attractive features of UWB include (a) the possibility of accurate position information and (b) potential low power implementation. In UWB technology the conventional analog waveform is a short duration time pulse. It is transmitted without up conversion. Hence UWB pulse shaping is very important to contain out of band interference.

Several techniques for generating short time wide band pulses have been reported in the literature [3-11]. In general the pulse generation techniques can be divided in two categories: (i) Single-Band (SB) based, employing one single transmission frequency band and (ii) Multi-Band (MB) based, employing two or more frequency bands, each with at least 500MHz bandwidth.

In the SB solution, the UWB signal is generated using very short base band electrical pulses with appropriate shape and duration. Due to the carrier-less characteristics these UWB systems are also referred to as carrier-free or impulse radio (IR-UWB) communication systems [2]. The MB UWB systems can be implemented carrier less or using carrier.

In the early development of UWB systems, Gaussian pulses were commonly used [3,6]. A general Gaussian pulse $x(t)$ is given by

$$x(t) = \frac{A}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{t^2}{2\sigma^2}\right) \tag{1}$$

where A is the amplitude, σ^2 is the variance and $-\infty < t < \infty$. Using the general Gaussian pulse in (1), its n-th derivative can be determined recursively from

$$x^{(n)}(t) = -\frac{(n-1)}{\sigma^2} x^{(n-2)}(t) - \frac{t}{\sigma^2} x^{(n-1)}(t) \tag{2}$$

where the superscript $^{(n)}$ denotes the n-th derivative, $x^{(n)}(t)$ is the n-th derivative of $x(t)$. The Fourier Transform of the n-th order derivative pulse $X_n(f)$ is

$$X_n(f) = A(j2\pi f)^n \exp\left(-\frac{(2\pi f\sigma)^2}{2}\right) \tag{3}$$

A Gaussian pulse so generated has the disadvantage that its their power spectral density (PSD) does not satisfy the FCC limits. However, higher order derivatives of such pulse are well suited to fulfill the mask requirements. Step Recovery Diodes (SRD) and CMOS transistors have been proposed for generating such pulses, but the efficiency is quite poor because as SRD consumes considerable power [7-9].

Another pulse described in [5] consists of sinusoidal wavelets. The frequencies are harmonics of a fundamental frequency. A good approximation to the FCC mask has been achieved resulting in a high-energy efficiency. The mathematical description of the time domain signal *u(t)* is

$$x(t) = rect\left(\frac{t}{t_o}\right)\left(k + 2\cos\left(\frac{2\phi t}{t_o}\right), \quad \omega_o = \frac{2\pi}{t_o} \tag{4}$$

$$u(t) = \hat{u}\ x(t)\cos(2\pi f_c t) \tag{5}$$

where ω_o is the first zero crossing of the spectral density and ϕ is the frequency shift. A very good shape results for k = √2 and $\phi = 1.25\pi$. Minor changes to design i.e., phase shifting the carrier frequency (f_c) by 90^0, offers the opportunity to simply produce a pair of orthogonal pulses. However, it requires four frequency multipliers.

Modified Hermite polynomials (MHP) have the properties of the orthogonality and not changing their pulse width [8].

$$h_n(t) = (-1)^n e^{\frac{t^2}{4}} \frac{d^n}{dt^n}\left(e^{\frac{-t^2}{2}}\right) \qquad (6)$$

where $h_n(t)$ is the n-th order MHP, $\frac{d}{dt}$ denotes differentiation, n= 1,2,… and $-\infty < t < \infty$. Pulse bandwidth significantly dependent on pulse order. But these pulses are more susceptible to jitter and infinite time response of the MHP is also the major drawback. The spectra of the pulses generated using Hermite polynomials of order 2 or higher contain multiple lobes of approximately equal amplitude requiring the use of a band pass filter. This filtering will result in a loss of usable signal energy.

Another pulse design algorithm has been reported utilizing ideas of prolate spheroidal wave functions and eigen vectors [4]. This can generate multiple orthogonal pulses that are FCC compliant. Similar concept has also been utilized in pulse design to suppress the narrow band interference at the desired frequency in [11]. Fig. 1. shows some of the UWB pulse reported so far.

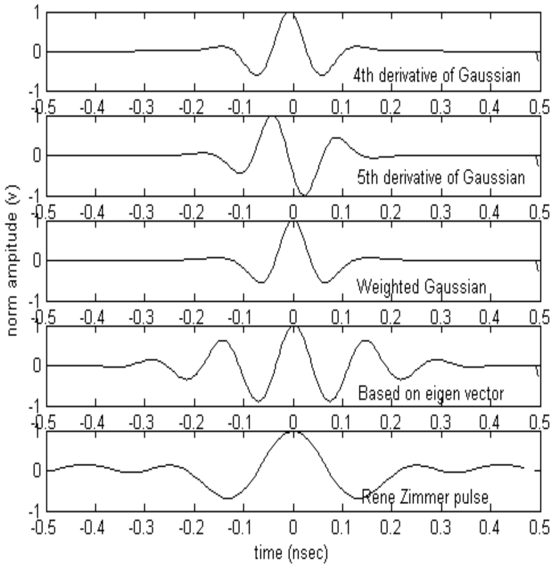

Fig. 1. Example for UWB pulses in time domain.

From the literature survey, we observe, that many of the pulses utilize different polynomials and Gaussian signals. However, the generated pulses are not time limited and their spectrum utilization efficiencies are moderate. Some pulses are not suited for multi-user environment (since Co-Channel Interference (CCI) exists). Fig. 2. shows a possible classification of UWB pulses reported so far.

The transmitter and receiver antenna perform high pass filtering (differentiation). Therefore, generated pulse at the transmitter undergoes twice differentiation [6]. Hence, the received pulse is not replica of the generated. This makes the matched filter receivers much complex. At the receive side, the antenna with wider bandwidth potentially produces less ISI, simplifying the receiver design. The antennae proposed [3,12] are wideband (1-18GHz) and provide 10dBi gain throughout the UWB band. Hence pulse differentiation, and distortion etc. should not occur during transmission and reception of the pulses with in the UWB band. The pulse that is transmitted should ideally be the same pulse that is received, so that correct decision can be employed at the receiver.

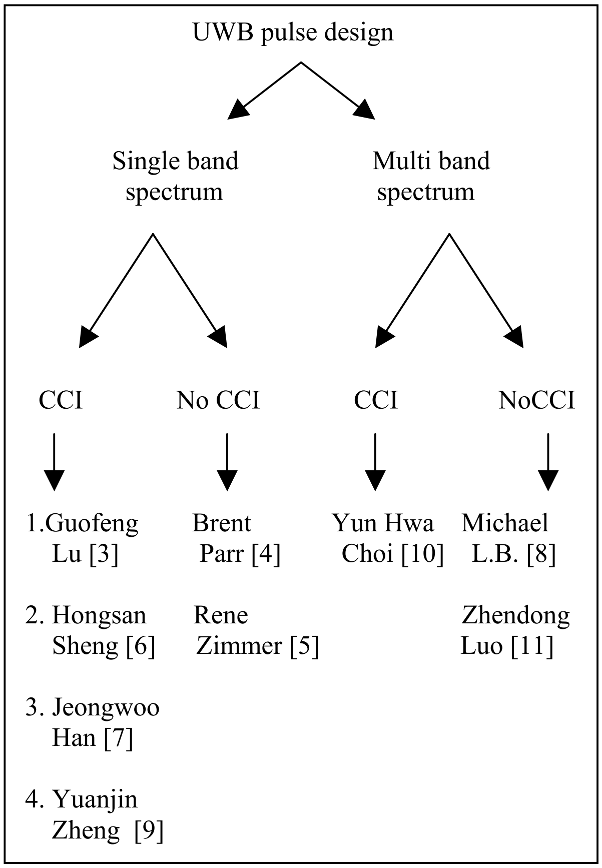

Fig. 2. Classification of the UWB pulse design research work so far.

In this paper we generate pulse shapes for Single-Band based UWB system. We focus on the efficient utilization of the FCC mask and try to generate orthogonal pulse shapes as much as possible. These pulses have very short duration in comparison with other pulses [3-9] and well suited for multi-user environment.

The rest of this paper is organized as follows. In Section II, the UWB pulse synthesis method based on Inverse Fourier Transform approach by modifying the FCC mask is introduced. In Section III, we describe generation of multiple orthogonal pulses and compare our pulse spectrum with other pulse spectra along with parameters such as spectrum utilization efficiency, 3dB bandwidth and pulse width.

II. PULSE SYNTHESIS METHOD

A good single band UWB pulse should exploit the FCC mask optimally. This would yield high allowable power. The ideal FCC pulse *fcc(t)*, can be found by applying inverse Fourier Transform on the normalized FCC mask amplitude response, *FCC(f)* or simply,

$$fcc(t) = \int_{f_l}^{f_h} FCC(f) e^{j2\pi ft} df \tag{7}$$

where f_l and f_h are lower and higher frequency limits of FCC mask. This FCC mask can be realized using a pulse that is a linear combination of *sinc* functions and is given as

$$fcc(t) = \sum_n a_n \sin c(t) \tag{8}$$

where *n* and a_n are appropriate constants to justify the FCC mask. But *fcc(t)* is difficult to generate in practice and it is not time-limited since it consists of *sinc* ($\frac{\sin(\pi x)}{\pi x}$) functions [3]. Hence, we modified the FCC mask as shown in Fig. 3. We call it as *S(f)* and *s(t)* as its time domain signal. Now, we describe construction of *S(f)* from *FCC(f)*. First, *FCC(f)* i.e., frequency ranges from f_l to f_h is divided into *M* sub-bands. The frequency range of each sub-band is not uniform.

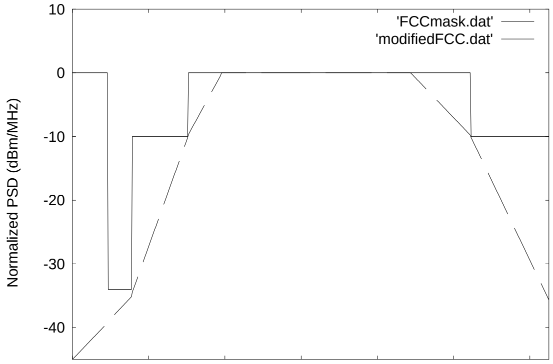

Fig. 3. Normalized FCC mask for indoor UWB communication modified FCC mask.

Our objective is to maximize the spectrum utilization efficiency in 3.1-10.6 GHz sub-band. Since it is difficult to get steep raise in power or voltage levels, hence we modify and represent in terms of simple first order equations. So, the modified FCC mask can be represented as linear summation of first order equations.

$$S(f) = \sum_{i=1}^{M} m_i f + c_i\,, \ f_l \le f \le f_h \tag{9}$$

where m_i and c_i are slope and constant calculated from the i^{th} sub-band corner points (f_i, p_i). Where f_i denotes frequency and p_i denotes the PSD values. So, our modified FCC mask passes through the corner points. Next, we make an assumption that a pulse has linear phase characteristic $\beta(f)$ in 3.1-10.6 GHz sub-band

$$\beta(f) = kf\,, \qquad 3.1 \le f \le 10.6 \tag{10}$$

where k is any fractional number. After inverse Fourier transformation applied on $S(f)e^{j\beta(f)}$, then *s(t)* is given as

$$s(t) = \int_{f_l}^{f_h} S(f) e^{j\beta(f)} e^{j2\pi ft} df \tag{11}$$

The normalized pulse *s(t)* is shown in Fig. 4.

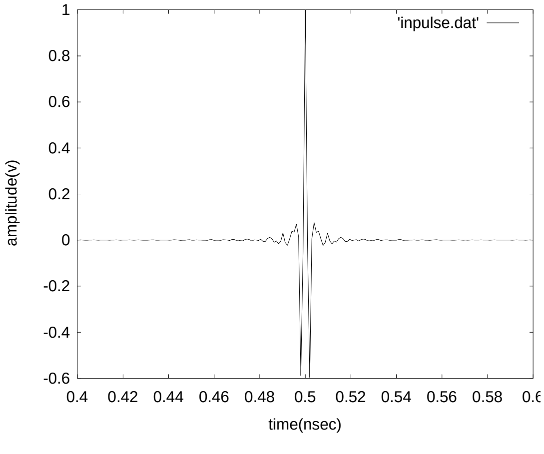

Fig. 4. Synthesized UWB pulse in time domain.

III. RESULTS AND OBSERVATIONS

In this section, we explain some important values used for simulation and performance comparison in terms of spectrum utilization efficiency (η), 3dB bandwidth (B_{3dB}) and pulse width T_p. The spectrum utilization efficiency can be measured by the normalized effective signal power, is given as

$$\eta = \frac{\int_{f_1}^{f_2} S(f)\,df}{\int_{f_1}^{f_2} FCC(f)\,df} X\ 100\% \qquad (12)$$

A high value of η yields maximum value of received signal power, hence high SNR. We evaluate η in the frequency ranges from (f_1, f_2) = (1.6GHz, 12.0GHz). B_{3dB} is the 3dB bandwidth obtained from the considered frequency response. Here, we define the pulse width, as the interval in which 99.9% of the energy of the pulse contained. We summarize the above parameters in Table I.

Orthogonality:

In UWB, all users share the same spectrum, hence Co-Channel Interference (CCI) exists. By using orthogonal pulses CCI can be effectively countered. Orthogonal pulses can be transmitted simultaneously without interfering with each other. We use the Gram-Schmidt orthogonalization procedure to generate orthogonal signals $\phi_i(t)$ from the linearly independent set { $s_i(t)$ } [13]. The $s_i(t)$'s are generated from $s(t)$(eq. (11)) as given by

$$s_i(t) = s(t - t_s) \qquad i = 1,2,\ldots N$$

if and only if $\int_0^T s(t)s_i(t-t_s)dt < C$ (13)

where C is a very small fractional number chosen to generate a set of N pulses, t_s is the time shift between 0 and T (o<t_s<T), T is the time duration of $s(t)$ and condition for orthogonality is

$$\int_0^T \phi_i(t)\phi_j(t)\,dt = \begin{cases} 1, & if\, i = j \\ 0, & if\, i \neq j \end{cases} \qquad (14)$$

By controlling C, we generate the desired number of energy signals in set { $s_i(t)$ }. For example: if C=0.001%, we are able to generate four orthogonal pulses from the set of four energy signals. These pulses have zero average value and very short duration.

For simulation purpose, we assume a modified FCC mask passing through the corner points (0Hz, -45.0dB), (1.6GHz, -34.0dB), (3.1, -10.0), (4.0, 0.0), (9.0, 0.0), (10.6,

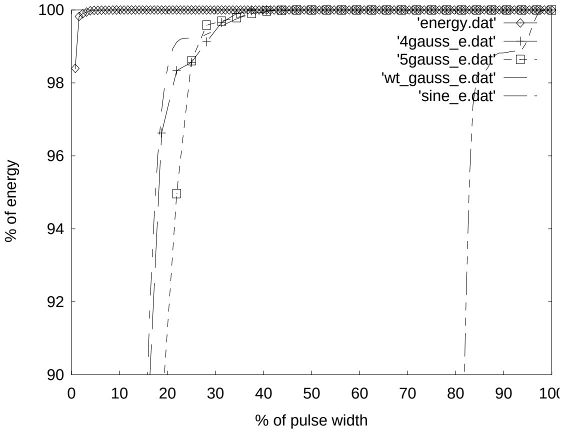

Fig. 5. Comparison of % of total energy Vs % of pulse width for various pulses.

Table I: Comparison of several UWB pulses with proposed pulses.

#	Pulse proposed by	η (%)	B_{3dB} (GHz)	T_p (ps)
1	Brent Parr [4]	38.67	2.55	990
2	Hongsan Sheng [6]	58.31	3.93	470
3	Hongsan Sheng [6]	54.21	3.67	510
4	Guofeng Lu [3]	72.32	4.41	460
5	Rene Zimmer [5]	74.04	5.53	550
6	Using modified FCC mask [1] (proposed)	78.68	5.40	100
7	[1] shifted inward by 10%	72.55	4.40	120
8	[1] shifted out-ward by 10%	85.55	6.40	80

0.0) and (13.0, -40.0) for M=6 and f_l=0, f_h=13.0GHz. The time domain pulse $s(t)$ is calculated by using Inverse Discrete Fourier Transform (IDFT) of length of N = 1024, which results in sampling frequency $(f_s = \frac{(f_h - f_l)}{N})$ of 12.69MHz and assumed phase values $\beta(f)$ vary between ($-\pi$, π). We observe that to generate 16 orthogonal pulses it requires C=0.0042%.

From the Table I, it is may be noted that a pulse synthesized from modified FCC mask performs better than other proposed pulses [3-9]. It uses the allocated spectrum effectively and has a pulse width of only 100 psec. The 7th and 8th entries in table I show the, modified FCC mask shifted inward and outward by 10% (with in the 3.1 – 10.6GHz band only). When compared with other pulses, our pulse reaches 99.9% energy very quickly [Fig. 5.].

IV. CONCLUSION

A method has been proposed to generate orthogonal UWB pulses, satisfying the FCC spectral mask. The pulses effectively eliminate Co-Channel Interference. These pulses are well suited for multi-user environment. We have also shown that our proposed pulses have the high utilization of FCC mask, and very narrow width.

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