1-2006

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***Abstract* – With 7.5 GHz of spectrum, Ultra Wide Band (UWB) is an ideal candidate for achieving high data rates over short distances with low cost and low power consumption. In this paper, we propose a simple pulse design method that uses a linear combination of two Gaussian derivatives to meet the FCC spectral mask requirements. With distance and data rate analysis, it is demonstrated that the proposed pulse design is efficient as compared to previously proposed standard Gaussian monocycles. In quest of making UWB a universal standard, the proposed pulse is shown to satisfy the ETSI proposed UWB spectral requirements.**

***Index Terms* – Ultra Wideband (UWB), Gaussian distributions, Pulse generation, Spectral performance analysis, Pulse amplitude modulation.**

I. INTRODUCTION

Ultra wideband (UWB) technology is an ideal candidate for a short range (10-20), low power, low cost, high data rate wireless communication systems. With wide spectrum and capability of achieving very high data rates, UWB has attracted significant interest in research institutions, standardization communities and industries. According to the Federal Communications Commission (FCC), UWB signal is defined as a signal having fractional bandwidth f_{BW} greater than 20% of the center frequency f_c or a signal that occupies bandwidth greater than 500 MHZ of the spectrum [1],

$$f_{BW} = \frac{2\,(f_H - f_L)}{(f_H + f_L)} \tag{1}$$

where f_c is the center frequency, f_H and f_L are the upper and lower frequency of the -10 dB emission point in the spectrum, respectively. UWB devices operate within frequency range of 3.1-10.6 GHz along with other existing narrowband communication systems. In order to reduce potential interference with existing narrowband communication systems and to make efficient use of already scarce spectrum, the FCC has proposed spectral masks for UWB indoor and outdoor systems, allowing a maximum transmitted spectral density of -41.3 dBm/MHz [1]. In past, several pulse designs have been proposed for UWB systems [2-4]. However, the standard Gaussian monocycles used in [2] and [3] do not meet the FCC spectral mask requirements and are not desirable for practical implementation [4]. Modified Hermite polynomial functions exhibit greater sensitivity to timing jitter and center frequency increases with increase in the pulse order [5]. These qualities make these functions unsuitable for UWB systems, where the transmission should be within a certain spectral mask [5]. However, the Gaussian fifth derivative, $\sigma = 51ps$, and the seventh derivative, $\sigma = 57ps$, satisfy the FCC indoor and outdoor spectral mask, respectively [4]. In order to generate fifth derivative Gaussian pulse, a Gaussian pulse is generated and then differentiated five times. Hence, this procedure is very complicated and is not suitable for a practical low cost, low power transceiver design.

A simple pulse design method is proposed in Section II. In particular, a linear combination of first derivative Gaussian pulses (LCFDGP) and a linear combination of third derivative Gaussian pulses (LCTDGP) satisfy the FCC issued spectral mask for indoor, and outdoor UWB communication system, respectively. Distance and data rate analysis of the proposed UWB pulse is also discussed in Section III.

II. NEW PULSE DESIGN

In this section we propose a new pulse design that meets FCC issued spectral mask for indoor and outdoor UWB communication systems. The proposed pulses are designed not only to possess ideal transmission power spectrum but also to achieve high data rate transmission over desirable short range distance. In the following discussion, we will consider LCFDGP for the FCC indoor spectral mask and the LCTDGP for the FCC outdoor spectral mask.

A. Linear Combination of First Derivative Gaussian Pulses

A general form of a linear modulated signal, $v(t)$, transmitted using PAM, with uniformly spaced pulses in time is given by [6, p.203],

$$v(t) = \sum_{n=-\infty}^{\infty} b_n\, s(t-nT) \tag{2}$$

The power spectrum of the transmitted signal, $v(t)$, can be computed as in [6, p.205],

$$\varphi_{vv}(f) = \frac{\sigma_b^2}{T}|S(f)|^2 + \frac{\mu_b^2}{T^2}\sum_{m=-\infty}^{\infty}\left|S\left(\frac{m}{T}\right)\right|^2 \delta\left(f - \frac{m}{T}\right) \qquad (3)$$

where $S(f)$ is a Fourier transform of the pulse waveform $s(t)$ and μ_b & σ_b^2 are the mean and variance, respectively, of the information symbols $\{b_n\}$. The discrete frequency components of the second term in (3) vanish when the information symbols have zero mean i.e. $\mu_b = 0$. This simplifies (3) to,

$$\varphi_{vv}(f) = \frac{\sigma_b^2}{T}|S(f)|^2 \qquad (4)$$

Now, consider the pulse waveform in (3) to be a Gaussian pulse given by [4],

$$s(t) = \frac{A}{\sqrt{2\pi}\sigma}\exp\left(\frac{-t^2}{2\sigma^2}\right) \qquad (5)$$

where A is the amplitude of the Gaussian pulse. According to [4], n-th Gaussian derivative can be given by [4, eq.6] and Fourier transform of n-th Gaussian derivative is given by [4, eq.8]. It is clear that the first derivative Gaussian pulse does not satisfy the FCC spectral mask for any value of T_p [4]. According to [4], the pulse width, T_p , that captures 99.99% of the energy for the first derivative Gaussian pulse is $T_p = 7\sigma$. As discussed earlier, though fifth derivative Gaussian pulse [4] satisfies the FCC indoor spectral mask, it not easy to it implement practically. We propose linear combination of two first derivative Gaussian pulses with different values of σ_{11} and σ_{12} . The general form of LCFDGP can be given by,

$$s_{Lc1}(t) = A_{11}s_{11}(t,\sigma_{11}) + A_{12}s_{12}(t,\sigma_{12}) \qquad (6)$$

$$s_{Lc1}(t) = \frac{-A_{11}t}{\sqrt{2\pi}\sigma_{11}^3}\exp\left(\frac{-t^2}{2\sigma_{11}^2}\right) + \frac{-A_{12}t}{\sqrt{2\pi}\sigma_{12}^3}\exp\left(\frac{-t^2}{2\sigma_{12}^2}\right) \qquad (7)$$

where A_{11} and A_{12} are the weight factors for $s_{11}(t)$ and $s_{12}(t)$, respectively. σ_{11}^2 and σ_{12}^2 are the variance of $s_{11}(t)$ and $s_{12}(t)$, respectively. The values of A_{11}, A_{12}, σ_{11} and σ_{12} can be chosen to satisfy the FCC spectral mask. Fig. 1 shows first derivative Gaussian pulses, $s_{11}(t)$ with $\sigma_{11} = 40ps$ and $s_{12}(t)$ with $\sigma_{12} = 47ps$ and their LCFDGP, $s_{Lc1}(t)$.

According to the FCC part 15 rules, only a peak value of -41.3 dBm/MHz is allowed in the band from 3.1 GHz to 10.6 GHz [1]. The PSD of the pulse waveform must meet the above constraint. The Fourier transform of LCFDGP, $s_{Lc1}(t)$, is given by,

$$S_{Lc1}(f) = A_{11}S_{11}(f,\sigma_{11}) + A_{12}S_{12}(f,\sigma_{12}) \qquad (8)$$

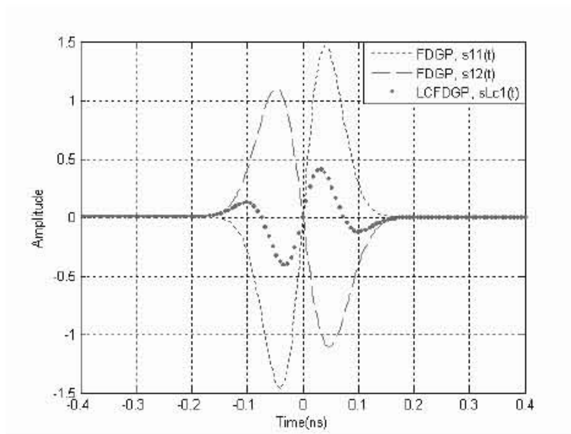
where, $$S_{11}(f,\sigma_{11}) = (j2\pi f)\exp\left(-\frac{(2\pi f\sigma_{11})^2}{2}\right) \qquad (9)$$

$$S_{12}(f,\sigma_{12}) = (j2\pi f)\exp\left(-\frac{(2\pi f\sigma_{12})^2}{2}\right) \qquad (10)$$

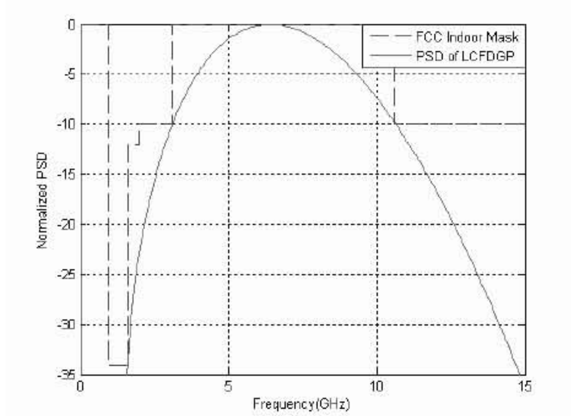
The normalized PSD, $|P_{Lc1}(f)|$, is expressed as,

$$|P_{Lc1}(f)| = \frac{|S_{Lc1}(f)|^2}{|S_{Lc1}(f_m)|^2} \qquad (11)$$

where $|S_{Lc1}(f_m)|$ is the maximum value of amplitude spectrum at the peak emission frequency f_m.



"Fig. 1." Linear combination of first derivative Gaussian pulses, $s_{Lc1}(t)$.



"Fig. 2." Normalized PSD for LCFDGP with the FCC indoor spectral mask.

In Fig. 2, the normalized PSD, $|P_{Lc1}(f)|$, is plotted with the FCC indoor spectral mask. It is evident from Fig. 2 that the proposed LCFDGP meets the FCC spectral requirements for UWB indoor communication systems. Performance of LCFDGP with respect to achievable distance and data rate is discussed in Section III.

B. Linear Combination of Third Derivative Gaussian Pulses

In this section, we propose a pulse that meets the FCC spectral requirements for outdoor UWB communication systems. According to [4] seventh derivative Gaussian pulse is best suited for UWB outdoor communication systems. In order to meet the FCC outdoor spectral mask, we consider a linear combination of two third derivative Gaussian pulses with different values of σ_{31} and σ_{32}. The LCTDGP is given by,

$$s_{Lc3}(t) = A_{31}s_{31}(t,\sigma_{31}) + A_{32}s_{32}(t,\sigma_{32}) \qquad (12)$$

$$s_{3n}(t,\sigma_{3n}) = \left[\left(\frac{3t}{\sqrt{2\pi}\sigma_{3n}^5}\right) - \left(\frac{t^3}{\sqrt{2\pi}\sigma_{3n}^7}\right)\right]\exp\left(\frac{-t^2}{2\sigma_{3n}^2}\right) \qquad (13)$$

$$n\varepsilon\{1,2\} \text{ and } \sigma_{31} = 48ps \ \& \ \sigma_{32} = 55ps$$

and its Fourier transform is given by,

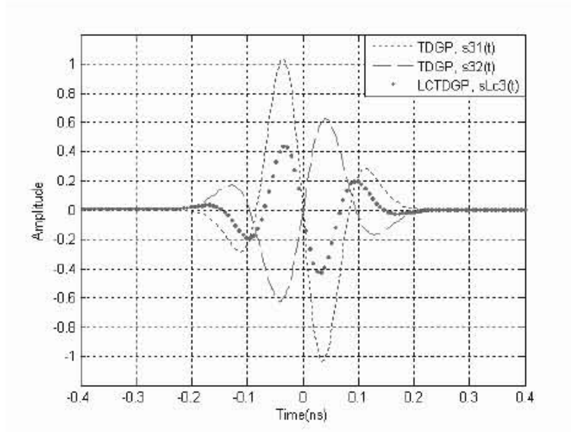
$$S_{Lc3}(f) = A_{31}S_{31}(f,\sigma_{31}) + A_{32}S_{32}(f,\sigma_{32}) \qquad (14)$$

$$S_{3n}(f,\sigma_{3n}) = (j2\pi f)^3 \exp\left(-\frac{(2\pi f\sigma_{3n})^2}{2}\right) \qquad (15)$$

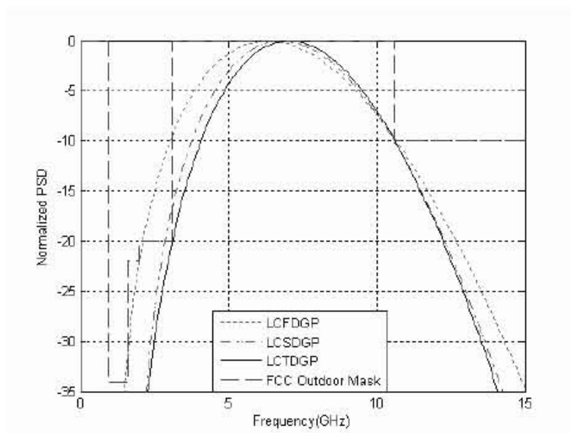
$$n\varepsilon\{1,2\}$$

Two third derivative Gaussian pulses with σ_{31} & σ_{32} and LCTDGP are shown in Fig. 3. In Fig. 4, normalized PSD of LCFDGP, LCSDGP (linear of combination second derivative Gaussian pulse) and LCTDGP are plotted along with the FCC outdoor spectral mask. From Fig. 4, it is clear that LCFDGP does not satisfy the FCC outdoor spectral mask. The LCSDGP closely meets the FCC outdoor spectral requirements with some violation in spectral mask. Compared to LCFDGP and LCSDGP, the LCTDGP is in compliance with the FCC outdoor spectral emission mask.

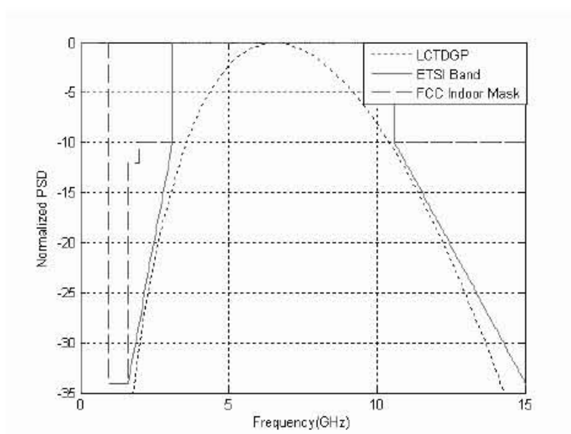
Recently European Telecommunication Standards Institute (ETSI) proposed a draft for UWB emission limits for indoor and portable communication systems in Europe. According to [9], the ETSI UWB emission limits are more stringent than the FCC UWB emission limits. Fig. 5 shows that LCTDGP meets the ETSI indoor spectral mask along with the FCC indoor spectral mask. Hence, the proposed pulse can be implemented in European UWB indoor communication systems and can be extended to meet UWB spectral requirements issued by different countries.



“Fig. 3.” Linear combination third derivative Gaussian pulse, $s_{Lc3}(t)$.



“Fig. 4.” Normalized PSD for LCFDGP, LCSDGP and LCTDGP with the FCC outdoor spectral mask.



“Fig. 5.” Normalized PSD for LCTDGP with the ETSI and the FCC indoor spectral mask.

III. Distance and Data Rate Analysis

With spectrum from 3.1 GHz to 10.6 GHz, UWB devices are expected to provide low power low cost solution with high data rates in realistic multipath environments. Expected data rates for a short distance range of 2 m (10 m) is 480 Mbps (110 Mbps). The relationship between distance, d , and data rate, R_b, can be given by [4, eq.22],

$$d = \frac{c}{4\pi}\sqrt{\frac{A_{\max} G_t G_r}{E_b / N_o \cdot R_b \cdot kT_o F \cdot LM}\int_{f_L}^{f_H}\frac{|P_{Lc1}(f)|}{f^2}df} \qquad (16)$$

where $|P_{Lc1}(f)|$ is the PSD of the LCFDGP, and other parameters values are same as in [4] i.e. $c = 3\times10^8 m/s$ $A_{\max} = -41\text{dBm/MHz}$, $k = 1.38\times10^{-23}$ Joules / K, $T_o = 300K$, $F = 6\text{dB}$ is the noise figure, $LM = 5\text{dB}$ is a link margin, and $G_t = G_r = 0\text{dB}i$ are the transmitter and receiver antenna gains, respectively.

To obtain desired spectral efficiency, a PAM UWB system is considered. The desired bit error rate is obtained as [6]

$$P_b = \frac{1}{\log_2(M)}\frac{2(M\text{-}1)}{M}\; Q\left(\sqrt{\frac{(6\log_2 M)}{(M^2-1)}\frac{E_b}{N_0}}\right) \qquad (17)$$

In Fig. 6, the performance of M-PAM system is evaluated with respect to distance as a function of data rate. It is clear that binary PAM can efficiently transmit data at a data rate of 100 Mbps over a distance of approximately 17 meters for BER = 10^{-3}. For the same data rate, fifth derivative Gaussian pulse can only support a distance of 13 meters [4]. Hence, with the LCFDGP high data rates are achievable for short distances compared to the fifth order derivative Gaussian pulse proposed in [4]. For BER = 10^{-6}, data rate of 100 Mbps can be achieved for distance of approximately 11 meters using binary PAM. From Fig. 6, it is clear that with the increase in the M value from 2 to 8, achievable data rate over the same distance decreases. This is expected as PAM is not a power efficient modulation technique [6]. Thus, LCFDGP is best suited to achieve high data rate over a short distance range for UWB communication systems.

IV. Conclusion

In this paper, a new pulse design has been proposed for UWB indoor and outdoor communication systems. We demonstrated that LCFDGP and LCTDGP meet the FCC spectral mask requirements for indoor and outdoor UWB communication systems, respectively. With distance and data rate analysis, it is clear that higher data rates are achievable with LCFDGP as compared to previously proposed Gaussian monocycles based on the higher order derivatives of Gaussian pulse. It is shown that the LCTDGP meets the ETSI as well as the FCC UWB spectral requirements for indoor communication systems. Moreover, the proposed pulses can be easily generated without much complexity by a slight modification of the pulse generator as proposed in [7-8] using CMOS technology. However, further performance analysis of the proposed pulses in multipath environments is needed.

References

[1] Federal Communications Commission, "Revision of Part 15 of the commission's rules regarding ultra-wideband transmission system, FIRST REPORT AND ORDER," *ET Docket 98-153, FCC 02-48*, pp. 1-118, February 14, 2002.

[2] J. Foerster, E. Green, S. Somayazulu, and D. Leeper, "Ultra-Wideband technology for short –or medium –range wireless communications," *Intel Technology Journal,* pp. 1-11, 2nd Quarter, 2001.

[3] L .Zho and A. M. Haimovich, "Capacity of M-ary PPM ultra-wideband communications over AWGN channels," *Proc. IEEE VTC*, vol.2, pp. 1191-1195, Fall 2001.

[4] H. Sheng, P. Orlik, A. M. Haimovich, L. J. Cimini and J. Zhang, " On the spectral and power requirements for ultra-wideband transmission," *IEEE Int. Conf. on communications*, vol. 1, pp. 738-742, March 2003.

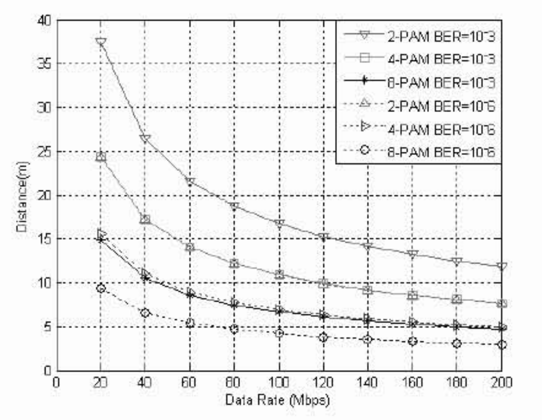
[5] B. Allen, S. Ghorashi, M. Ghavami, "A review of pulse design for impulse radio," *IEE ultrawideband workshop*, pp. 93-97, June 2004.

[6] J.G.Proakis, *Digital Communications*. Neywork: McGraw-Hill, 4th ed., 2001.

[7] L. Stoica, S.Tiuraniemi, A. Rabbachin and I. Oppermann, "An ultra wideband TAG circuit transceiver architecture," *IEEE Conf. on UltraWideband Sys. And Tech.*, pp. 258-262, May2004.

[8] H. Kim, D. Park and Y. Joo, "Design of Scholtz's monocycle pulse generator," *IEEE Conf. Ultra Wideband Sys. and Tech.*, pp. 81-85, Nov. 2003.

[9] B. Consult, "ETSI UWB Activities," *UWB Colloguium*, Jul. 23, 2002.



"Fig. 6." Plot of distance as function of data rate for M-PAM LCFDGP system with BER = 10^{-3} and 10^{-6}.