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Power Spectral Density of UWB PSM Signal

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Abstract

In order to satisfy the Federal Communications Commission (FCC) indoor and outdoor limit spectral masks, a good understanding of power spectral density (PSD) of ultra wideband (UWB) signal and how it is influenced by modulation is necessary. In this paper, the PSD of UWB signal using pulse shape modulation (PSM) without and with time hopping (TH) is analyzed. An orthogonal pair of modulated Gaussian waveforms, which satisfy the UWB signal definition and FCC indoor and outdoor limit spectral masks, are considered and demonstrated. The capability of PSM with TH, that suppresses the discrete component is discussed.

Keyword: ultra wideband (UWB), pulse shape modulation (PSM), orthogonal waveform and spectral mask.

1. Introduction

Almost all communication systems employ a sinusoid as a basic waveform on which information is mapped via modulation. The result is that the power spectral density (PSD) of a signal is well concentrated in a specific frequency band, which easily suppresses the noise and interference by using a bandpass filter. Unfortunately, the narrowband system is sensitive to fading. Furthermore, the frequency spectrum is divided into many narrow frequency bands causing a deficient spectrum for new communication systems.

An ultra wideband (UWB) refers to a technology, which makes use of signal waveforms occupying a very large bandwidth. The Federal Communications Commission (FCC) in US defines the UWB signal, which is any signal where the fractional bandwidth is equal to or greater than 0.20, or the occupied bandwidth is equal to or greater than 0.50 GHz. The fractional and occupied bandwidth are defined as [1]:

$$\text{Fractional bandwidth} = \frac{2(f_H - f_L)}{f_H + f_L}, \quad (1)$$

$$\text{Occupied bandwidth} = f_H - f_L, \quad (2)$$

where f_L and f_H are the lowest and highest frequencies at the -10 dB points, respectively.

The main concern about UWB communications is that they occupy a portion of spectrum where other narrowband communications already operate, so a regulation is necessary in order to avoid co-existent interference problems. Therefore, the FCC regulates the indoor and outdoor spectral masks to limit the maximum emission of unlicensed UWB signals to guarantee protection to the already existent and planed radio services. The UWB communication regulations specify that the FCC indoor and outdoor spectral masks be undetectable by other communication systems and have the PSD below the noise limit. Furthermore, UWB radio technology is an ideal candidate that can be utilized for commercial, short range, low power, low cost, indoor and outdoor communication systems such as wireless personal area networks (WPANs) [2] - [5].

Numerous UWB waveforms have been proposed [6]. The waveform designs are reviewed, but not considered for the UWB signal definition and spectral masks specified by the FCC. The signal processing and numerical techniques are used to design the UWB waveform [7]-[14]. Although the waveform has very highly effective spectra in the designed frequency range, these algorithms are complex. Therefore, simple waveforms for UWB communications are proposed [15]. After that, orthogonal pairs of simple UWB waveforms are developed for a pulse shape modulation (PSM) scheme [16]. Although, these waveforms have closed form expressions in both time and frequency domains, they are considered only the PSD of one UWB waveform. There is no consideration about the PSD of a pulse train of a UWB signal using a modulation scheme.

In this paper, the PSD of a UWB signal using a modulation scheme is analyzed. The modulation scheme is focused on the PSM without and with time hopping (TH) [17]. An orthogonal pair of modulated Gaussian waveforms, which satisfy the UWB signal definition and FCC indoor and outdoor limit spectral masks [16], are considered and demonstrated. The PSD of UWB signal consists of the continuous and discrete components. The discrete component presents greater interference to narrowband communication systems than the continuous component. The PSD of UWB signal using PSM without and with TH is analyzed and shown. The capability of PSM with TH that suppresses the discrete component is discussed in the conclusion.

This paper is organized as follows. Section 2, the PSD of UWB signal using PSM is briefly described. Next, the PSD analysis results are illustrated in Section 3. Finally, the conclusions are drawn in Section 4.

2. PSD of UWB Signal Using PSM

In this section, we will first introduce the UWB waveform model, which is an orthogonal pair of modulated Gaussian waveforms. After that, we will investigate the PSD expressions of UWB signal using PSM without and with TH.

2.1 UWB Waveform Model

PSM is the modulation scheme that uses orthogonal waveforms to represent the bits '0' and '1'. The PSM can be applied with pulse amplitude modulation (PAM) or pulse position modulation (PPM) for increasing data rate. The definition of orthogonal waveforms is given by:

$$\int_{-T_s/2}^{T_s/2} f_i(t)\cdot f_j^*(t)dt = \begin{cases} k & i=j \\ 0 & i\neq j \end{cases}, \qquad (3)$$

where $*$ is the complex conjugate operator and k is a nonzero constant.

The UWB waveforms that are used for the PSM scheme are an orthogonal pair of modulated Gaussian waveforms. The orthogonal pair of modulated Gaussian waveforms in time domain, f_1 and f_2, and their spectral density functions, F_1 and F_2, are given by [16]:

$$f_0(t) = A_0 e^{-(t/d)^2}\sin(2\pi f_c t) \qquad (4)$$

$$f_1(t) = A_1 e^{-(t/d)^2}\cos(2\pi f_c t) \qquad (5)$$

$$F_0(f) = \frac{A_0 d\sqrt{\pi}}{j2}\left[e^{-\pi^2 d^2 (f-f_c)^2} - e^{-\pi^2 d^2 (f+f_c)^2}\right] \qquad (6)$$

$$F_1(f) = \frac{A_1 d\sqrt{\pi}}{2}\left[e^{-\pi^2 d^2 (f-f_c)^2} + e^{-\pi^2 d^2 (f+f_c)^2}\right] \qquad (7)$$

where f_c is the carrier frequency, d is the $1/e$ characteristic decay time, A_0 and A_1 are the maximum amplitudes of waveform envelopes f_0 and f_1, respectively.

2.2 PSD of UWB Signal Using PSM without TH

The UWB signal using PSM without TH can be presented as [17]

$$s(t) = \sum_{n=-\infty}^{\infty} [(1-d_n)f_0(t-nT_s) + d_n f_1(t-nT_s)] \qquad (8)$$

where d_n is the digital data in sequence of n, T_s is the time interval of bit data, f_0 and f_1 are the waveforms representing bits '0' and '1', respectively.

The probability distribution function (PDF) of d_n is:

$$P\{d_n\} = \begin{cases} p & d_n = 1 \\ 1-p & d_n = 0 \end{cases} \qquad (9)$$

where p is the probability of d_n, and is the bit '1'.

The PSD of the transmitted signal can be estimated by using:

$$S_T(f) = \lim_{T\to\infty} \frac{1}{RT} |S(f)|^2 \qquad (10)$$

where R is the internal circuit impedance and S is the spectral density of transmitted signal, which can be calculated by using the Fourier transform of the UWB signal:

$$S(f) = \int_{-\infty}^{\infty} s(t) e^{-j2\pi ft} dt. \qquad (11)$$

For considering radiated PSD, the transmitter antenna is assumed to be an isotropic antenna. The internal circuit and transmitter antenna impedances are assumed to be the same real value R. That is the ideal with maximum radiated PSD. In this paper, the path loss and measurement system are not considered. In this case, the radiated voltage signal is half of the transmitted voltage signal. Therefore, the radiated PSD is $1/4$ of the transmitted PSD. By using the linearity and time shifting characteristics of Fourier transform [18], the radiated PSD of UWB signal using PSM without TH can be derived as:

$$S_R(f) = \lim_{N\to\infty} \frac{1}{4RNT_s} \left| \sum_{n=-N/2}^{N/2} \begin{bmatrix} (1-d_n)F_0(f) \\ +d_n F_1(f) \end{bmatrix} e^{-j2n\pi fT_s} \right|^2 \qquad (12)$$

where N is the bit number.

2.3 PSD of UWB Signal Using PSM with TH

TH is a method of transmitting signals by adding the delayed time of each bit T_n. Practically, T_n is the pseudorandom code, which is known by both transmitter and receiver. By using TH, the period of each bit is not certain. Therefore, the discrete component of PSD is suppressed by the continuous component. This results to reducing the level of PSD.

The PDF of T_n is the uniform distribution in the range of $-T_s/2$ to $T_s/2$, which can be written as:

$$P(T_n) = \begin{cases} \frac{1}{T_s} & -\frac{T_s}{2} \le T_n \le \frac{T_s}{2}, \\ 0 & \text{elsewhere} \end{cases} \qquad (13)$$

The PSM with TH is used to suppress the discrete component of PSD. The UWB signal using PSM with TH can be presented as [17]:

$$s(t) = \sum_{n=-\infty}^{\infty} \begin{Bmatrix} (1-d_n) f_0(t-nT_s+T_n) \\ +d_n f_1(t-nT_s+T_n) \end{Bmatrix} \qquad (14)$$

The radiated PSD of UWB signal using PSM with TH is considered in the same way of that without TH, which can be derived as:

$$S_R(f) = \lim_{N\to\infty} \frac{1}{4RNT_s} \left| \sum_{n=-N/2}^{N/2} \begin{bmatrix} (1-d_n)F_0(f) \\ +d_n F_1(f) \end{bmatrix} e^{-j2\pi f(nT_s+T_n)} \right|^2 \qquad (15)$$

3. PSD Analysis Result

An orthogonal pair of modulated Gaussian waveforms is used as the UWB signal for representing bits '0' and '1'. The waveform parameters, which are obtained from the maximum amplitude and average power optimizations [16], are considered for both FCC indoor and outdoor limit spectral masks. The parameters R and N are set to be 50 Ω and 1,000,000 bits, respectively. The bit rate is assumed to be 110 Mbps, therefore T_s is equal to 9.09 ns.

For the FCC indoor limit spectral mask, the waveform parameters are $A_0 = A_1 = 3.76$ V, $d = 0.11$ ns and $f_c = 7.34$ GHz. The time domain waveforms and their PSD compared with the FCC indoor limit spectral mask are shown in Figures 1 and 2, respectively. The fractional bandwidth, occupied bandwidth and average power of these waveforms are 0.84, 6.20 GHz and -62.75 dBm, respectively

For the FCC outdoor limit spectral mask, the waveform parameters are $A_0 = A_1 = 3.18$ V,

$d = 0.13$ ns and $f_c = 6.85$ GHz. Figures 3 and 4 show the time domain waveforms and their PSD compared with the FCC outdoor limit spectral mask, respectively. The fractional bandwidth, occupied bandwidth and average power of these waveforms are 0.77, 5.24 GHz and -63.25 dBm, respectively. The PSD of each waveform is the same for both cases.

For analyzing PSD of UWB signal using PSM without and with TH, two cases of p are considered for the FCC indoor and outdoor limit

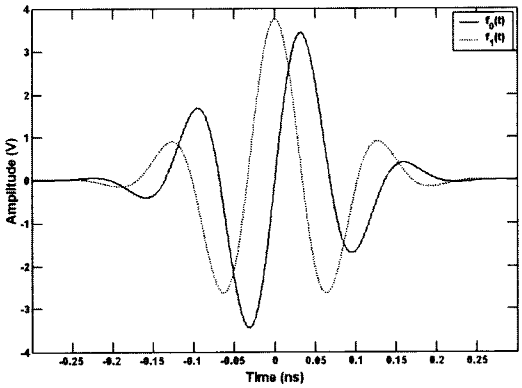

Fig. 1 Orthogonal pair of modulated Gaussian waveforms satisfying the FCC indoor spectral mask.

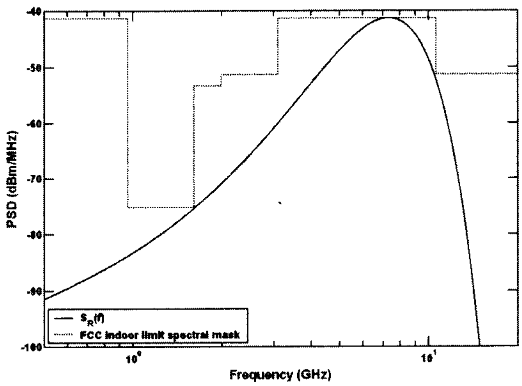

Fig. 2 PSD of orthogonal pair of modulated Gaussian waveforms compared with the FCC indoor spectral mask.

spectral masks. For the first case, the parameter p is set to be 0.0 or 1.0, which all bits are '0' or '1'. For the other case, the parameter p is set to be 0.5, which the bits '0' and '1' are equal.

Figures 5 and 6 show the PSD of the UWB signal using PSM without TH compared with the FCC indoor and outdoor limit spectral masks, respectively. The continuous and discrete component characteristics of PSD for the FCC indoor and outdoor limit spectral masks are the same. The PSD of $p = 0.0$ or 1.0 is more than the FCC indoor and outdoor limit spectral masks up to 59.99 dB, while that of $p = 0.5$ is more than the FCC indoor and outdoor limit spectral masks up to 56.98 dB. The value at about 60 dB for $p = 0.0$ or 1.0 is a direct consequence of using 1,000,000 bits. The spectrum components are added in (12) to be 10^6 times and then are squared

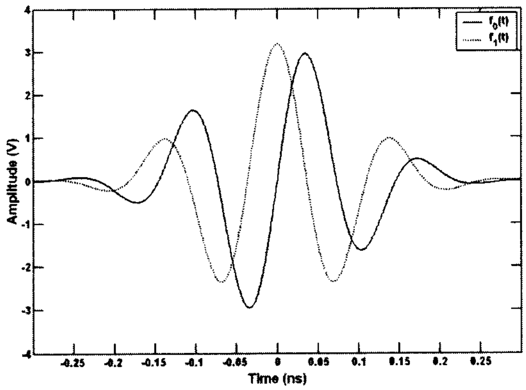

Fig. 3 Orthogonal pair of modulated Gaussian waveforms satisfying the FCC outdoor spectral mask.

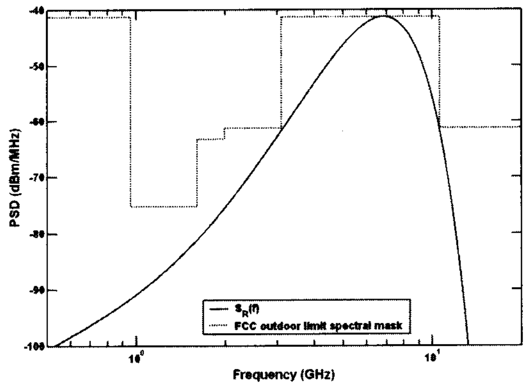

Fig. 4 PSD of orthogonal pair of modulated Gaussian waveforms compared with the they FCC outdoor spectral mask.

before they are divided by 10^6, yielding 10^6 times (60 dB) eventually. For $p = 0.5$, half the spectrum components are added up in phase, hence the reduction by 3 dB. Although this orthogonal pair of modulated Gaussian waveforms is well designed to satisfy the FCC indoor and outdoor limit spectral masks, their PSD using PSM without TH very much exceeds the FCC indoor and outdoor limit spectral masks so, a technique that is used to suppress the discrete component of PSD is necessary.

In this paper, the PSD of UWB signal using PSM with TH is considered to suppress the discrete component. The PSD of UWB signal using PSM with TH, compared with the FCC indoor and outdoor limit spectral masks, are shown in Figures 7 and 8, respectively. The continuous and discrete component characteristics of PSD for the FCC indoor and outdoor limit

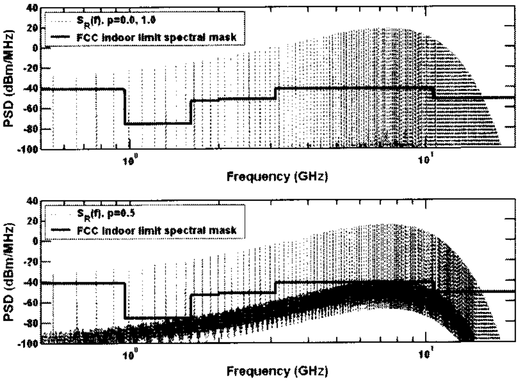

Fig. 5 PSD of UWB signal using PSM without TH compared with the FCC indoor limit spectral mask.

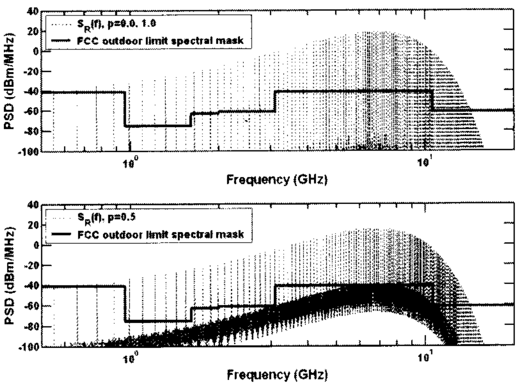

Fig. 6 PSD of UWB signal using PSM without TH compared with the FCC outdoor limit spectral mask.

spectral masks have little difference. The PSD of $p = 0.0$ or 1.0 is more than the FCC indoor and outdoor limit spectral masks up to 8.64 and 9.01 dB, respectively. For $p = 0.5$, the PSD is more than the FCC indoor and outdoor limit spectral mask up to 9.01 and 8.34 dB, respectively. In this case, the parameter p does not have any effect on PSD suppression. The discrete component of UWB signal using PSM with TH is less than that without TH (about 51 dB for $p = 0.0$ or 1.0, and 48 dB for $p = 0.5$). Although the PSD of UWB signal using PSM with TH is extremely reduced compared with that of without TH, their PSD still exceeds the FCC indoor and outdoor limit spectral masks. Therefore, the peak power of UWB signal must decrease to satisfy the FCC indoor and outdoor limit spectral masks.

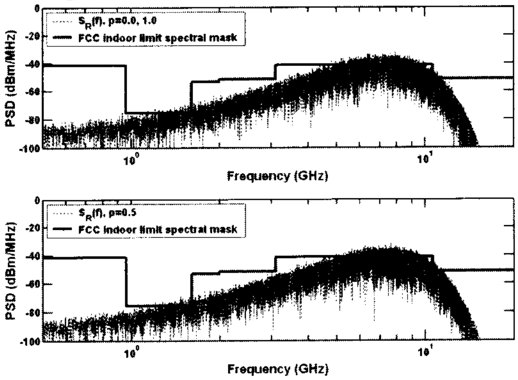

Fig. 7 PSD of UWB signal using PSM with TH compared with the FCC indoor limit spectral mask.

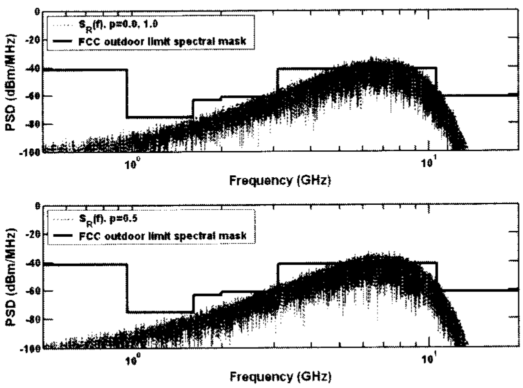

Fig. 8 PSD of UWB signal using PSM with TH compared with the FCC outdoor limit spectral mask.

The 10 dB peak power decrement of UWB signal is demonstrated to satisfy the FCC spectral mask. Figure 9 shows the PSD of UWB signal using PSM with TH, which is 10 dB peak power, compared with the FCC indoor limit spectral mask. We can see that the PSD satisfies the FCC indoor spectrum for both $p = 0.0$ or 1.0 and $p = 0.5$ cases.

4. Conclusion

In this paper, the PSD of UWB signal using PSM without and with TH is analyzed. The orthogonal pair of modulated Gaussian waveforms, which satisfy the UWB signal definition and FCC indoor and outdoor limit spectral masks, are considered. From the results, we can see that the PSD characteristics of UWB signal for the FCC indoor and outdoor limit

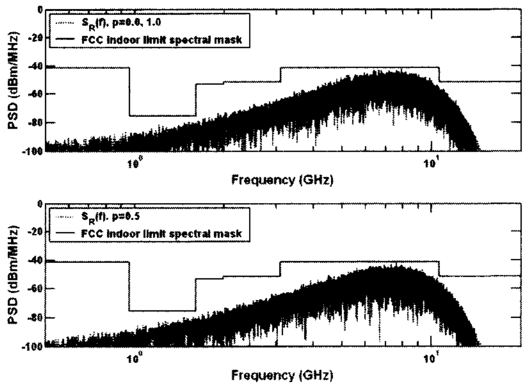

Fig. 9 PSD of UWB signal using PSM with TH, which is decreased 10 dB peak power, compared with the FCC indoor limit spectral mask.

spectral masks are almost the same. For a bit number of 1,000,000 bits, the PSM with TH can be suppress the discrete component of the PSD (about 50 dB), but this is not sufficient. The peak power of UWB signal must decrease about 10 dB to satisfy the FCC indoor and outdoor limit spectral masks.

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