Analysis of UWB Interference to MPSK Narrowband Receivers

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***Abstract*— This paper studies the in-band interference of time-hopping spread spectrum (TH-SS) ultra-wideband (UWB) signals to narrowband receivers. Based on the analysis of general power spectral density (PSD) of TH-SS UWB signal, the interference of UWB signal is partitioned into two parts: (1) additive white Gaussian noise interference, and (2) jamming tone interference. Following this framework, a novel analytical symbol error rate (SER) evaluation method for binary phase-shift keying (BPSK) and *M*-ary phase-shift keying (MPSK) signals subject to UWB interferences is proposed and corresponding simulation results are demonstrated. It is shown that as the number of in-band jamming tones increases, the UWB interference effect tends to be closer to the effect of the equivalent Gaussian noise. When there is only one UWB tone interferer within the narrowband receiver bandwidth, and when the signal-to-interference-and-noise ratio is higher than a certain value, the narrowband symbol error rate decreases as the relative tone power portion in the overall interference and noise power increases.**

***Index Terms*— Symbol Error Rate, UWB, Interference, Narrowband, BPSK, MPSK.**

I. Introduction

Ultra-wide bandwidth (UWB) technology is very promising for short-range high-speed wireless communications such as home entertainment, wireless video downloading, wireless USB connection, and so on, due to its ultra wide frequency bandwidth and low transmission power. However, the interference from UWB devices to existing narrowband devices, e.g., wireless phones, GPS (Global Positioning System) receivers, aeronautical communications, and wireless LAN, is one of the key issues which determine the possibility of wide deployment of UWB devices, and has drawn tremendous research attention recently. The interferences of UWB signals on GPS and Galileo receivers are studied in [1] and [2]. Ref. [3] and [4] investigates the interferences of different kinds of UWB signals on UMTS (Universal Mobile Telecommunications System), WCDMA (Wideband Code Division Multiple Access) and GSM (Global System for Mobile Communication) devices. The UWB Interferences on wireless LAN (Local Area Network), aeronautical and amateur radio devices are investigated in [5] to [8] respectively.

A general methodology for predicting the interference effects of pulsed UWB systems on the in-phase and quadrature (I/Q) outputs of narrowband receivers is proposed in [9] where the UWB interference effect is simply assumed to be equivalent to a certain amount of rise in the receiver noise level. Ref. [10] also models the UWB interference as additive white Gaussian noise within the bandwidth of the narrowband receivers. From the perspective of a single UWB pulse, the UWB pulse ideally has a flat energy spectrum, which looks like white Gaussian noise to a narrowband receiver. However, studies [11] and [12] show that the general power spectral density (PSD) of pulsed UWB signal has both continuous part and discrete lines. Both [9] and [10] only addressed the continuous part of UWB interference and missed the possible discrete line interference effect.

A novel analytical performance evaluation method of narrowband receivers, which models UWB interference as both additive white Gaussian noise and discrete jamming tones, was first reported in [13], where only BPSK performance degradation due to UWB interference is investigated. This paper expands the fundamental work laid out in [13] to include both BPSK and MPSK performance degradation due to UWB interference. Even though the semi-analytical simulation method in [14] also considered both tone and Gaussian noise effects of UWB interference, the differences between our method and the semi-analytical simulation method are: (1) the semi-analytical simulation method assumed that the probability distribution of combined jamming tones and Gaussian noise is still Gaussian noise, while our method doesn't make such assumption. Therefore, our method is more precise than the semi-analytical method in [14], and (2) Since the proposed method is an analytical method while the semi-analytical method is actually a simulation method, the proposed method is less time-consuming and more computation-efficient than the semi-analytical simulation method.

The rest of this paper is organized as follows. Section 2 analyzes the power spectrum of general UWB signals. Section 3 models the UWB interference as both additive white Gaussian noise and jamming tones, and derives a SER evaluation method for BPSK and MPSK narrowband receivers due to UWB Interference. Section 4 analyzes the simulation results for both BPSK and MPSK signals under both white Gaussian noise and tone interferences, and demonstrates the difference between the proposed method and the traditional semi-analytical simulation method. Finally, Section 5 summarizes the findings and concludes the paper.

II. UWB POWER SPECTRUM

The power spectrum of pulsed UWB signal is very important in analyzing the UWB interference to narrow band receivers. Generally speaking, the UWB PSD is calculated either by the average autocorrelation of the UWB waveform, e.g., in [11], [12] and [14], or by average change rate of UWB energy spectral density, e.g., in [14] and [15]. A PSD model for time-hopping spread spectrum UWB signals in the presence of random time jitter is derived in [16]. Even though the PSD derivation methods in the previous literature may vary one way or another, it is generally agreed upon that the PSD of UWB signals has both continuous and discrete components.

Following the notations used in [12] and [14], an individual UWB pulse is denoted by $p(t)$, and the transmitted data information $d(t)$ is embedded in a sequence of pulses with different amplitude a_k and/or variant time position T_k, i.e.,

$$d(t) = \sum_k a_k \delta(t - T_k),$$

where $\delta(t)$ is the delta function, i.e., $\delta(t) = \begin{cases} 1, & t = 0 \\ 0, & \text{otherwise} \end{cases}$. The general pulsed UWB signal $s(t)$ in time domain is expressed as

$$s(t) = p(t) \otimes \sum_k a_k \delta(t - T_k),$$

where notation $\otimes$ denotes the convolution operation. For fixed frame pulse position modulation (PPM) UWB signals, we have

$$T_k = kT + \varepsilon_k,$$

where T is the frame duration and ε_k is the pulse position perturbation. Now define a new variable $c_k(f)$ as

$$c_k(f) = a_k e^{-j2\pi f \varepsilon_k}.$$

Notations $\mu_c(f)$ and $\sigma_c^2(f)$ denote the mean and variance of $c_k(f)$ respectively. Following [13], the power spectral density $S_s(f)$ is expressed as:

$$S_s(f) = |P(f)|^2 \left\{ \frac{\sigma_c^2(f)}{T} + \frac{|\mu_c(f)|^2}{T^2} \sum_k \delta(f - \frac{k}{T}) \right\}.$$

It is worth noting that the power spectral density of UWB signal consists of two parts. The first part is the continuous term, i.e., $|P(f)|^2 \frac{\sigma_c^2(f)}{T}$, and the second part consists of the discrete lines, i.e., $|P(f)|^2 \frac{|\mu_c(f)|^2}{T^2} \sum_k \delta(f - \frac{k}{T})$. Since the variance $\sigma_c^2(f)$ is not equal to zero for any meaningful communication system, the continuous part always exists. However, the discrete lines in the power spectrum may disappear when the mean of $c_k(f)$, i.e., $\mu_c(f)$, is equal to zero.

In summary, the power spectral density of time-hopping UWB signals always has a continuous component, while the discrete components may be reduced by randomizing the position and/or amplitude modulation schemes.

III. NARROW-BAND RECEIVER PERFORMANCE DEGRADATION DUE TO UWB INTERFERENCE

A. BPSK Performance

Since the UWB power spectrum usually has both discrete lines and continuous part, and since the UWB bandwidth is much larger than the narrowband receiver bandwidth, the continuous part in the PSD of UWB signals can be reasonably assumed to be constant in the bandwidth of the narrowband receivers. The interference effect of the continuous part in the UWB PSD is equivalent to the effect of additive white Gaussian noise. The discrete lines in the UWB PSD become jamming tone interferences to the narrowband receiver. In a narrowband transceiver with BPSK modulation, the baseband equivalent of the received signal mixed with UWB interference can be expressed as

$$r = A_s b_i + \sum_{j=1}^{N} A_j \cos\theta_j + z, \tag{1}$$

where A_s = BPSK symbol amplitude;

A_j = UWB jamming tone amplitude;

θ_j = UWB jamming tone phase angle with respect to the desired signal carrier phase;
z = additive white Gaussian noise with 0 mean and σ_z^2 variance;
b_i = bipolar binary information bit, -1 or 1, and
N = number of discrete lines inside the receiving bandwidth.

The noise term z consists of both thermal noise, which is inherent in any narrowband receivers, and the additive white Gaussian noise from UWB interference. Notation N means there are totally N UWB jamming tones within the narrowband receiver intermediate frequency bandwidth. For each jamming tone, the tone phase is expressed as

$$\theta_j = 2\pi(f_j - f_c) + \theta_{j0}, \tag{2}$$

where f_j = the j-th jamming tone frequency;
f_c = narrowband receiver carrier frequency, and
θ_{j0} = the initial phase of the j-th jamming tone.

The difference between carrier frequency f_c and the jamming tone frequency f_j should be less than one half of symbol rate f_s, i.e., $|f_j - f_c| < f_s/2$. Otherwise, we can assume that the jamming tones are outside the receiving bandwidth and are significantly attenuated by the filters in the radio frequency, intermediate frequency, and baseband stages of the demodulation process in the receiver.

In general, the carrier frequency and the jamming tone frequency are not exactly the same, i.e., $f_j \neq f_c$, so the phase angle θ_j is assumed to be uniformly distributed in the interval $[-\pi, \pi)$. The probability density function (PDF) of θ_j is expressed as

$$f_\theta(\theta) = \begin{cases} \dfrac{1}{2\pi} & |\theta| < \pi \\ 0 & |\theta| > \pi \end{cases} \tag{3}$$

Let us define a new random variable y as $y = A_j \cos\theta_j$, which is the jamming tone term in (1). The probability density function of y [16] is

$$f_Y(y) = \begin{cases} \dfrac{1}{\pi\sqrt{A_j^2 - y^2}} & |y| < A_j \\ 0 & |y| \geq A_j \end{cases} \tag{4}$$

The characteristic function of $f_Y(y)$ is

$$\Psi_Y(w) = \int_{-A_j}^{A_j} \frac{1}{\pi\sqrt{A_j^2 - y^2}} \exp(jwy)dy = J_0(A_j w), \tag{5}$$

where function $J_0(\bullet)$ is the zero-order Bessel function of first kind.

The characteristic function of the white Gaussian noise z is

$$\Psi_Z(w) = \exp\left(-\frac{1}{2}w^2\sigma_z^2\right) \tag{6}$$

Now let a new random variable x denote the sum of y and z, i.e.,

$$x = y + z\,. \tag{7}$$

Variable x represents the overall interference and noise which includes UWB jamming tone interference, UWB additive white Gaussian interference, and narrowband receiver thermal noise. Since random variables y and z are independent, the probability density function of x is the convolution of the probability density functions of y and z, i.e.,

$$f_X(x) = \int_{-\infty}^{\infty} f_Z(x-y) f_Y(y)dy \tag{8}$$

After some manipulation, the probability density function of x becomes

$$f_X(x) = \int_{-A_j}^{A_j} \frac{1}{\sqrt{2\pi}\sigma_z} e^{-\frac{(x-y)^2}{2\sigma_z^2}} \frac{1}{\pi\sqrt{A_j^2 - y^2}} dy \tag{9}$$

This definite integral is quite clumsy to calculate, so we turn to the characteristic function of the probability density function $f_X(x)$. The characteristic function $\Psi_X(w)$ of $f_X(x)$ is equal to the product of the characteristic functions $\Psi_Y(w)$ and $\Psi_Z(w)$ of $f_Y(y)$ and $f_Z(z)$ respectively, i.e.,

$$\Psi_X(w) = \Psi_Y(w)\Psi_Z(w) \tag{10}$$

Now substituting (5) and (6) into (10), we get

$$\Psi_X(w) = \exp\left(-\frac{1}{2}w^2\sigma_z^2\right) J_0(A_j w) \tag{11}$$

According to Gil-Pelaez inversion theorem [18], the cumulative probability distribution function (CDF) of random variable x is

$$F_X(x) = \frac{1}{2} + \frac{1}{\pi}\int_0^{\infty} \frac{\sin(xw)}{w} \exp\left(-\frac{w^2\sigma_z^2}{2}\right) J_0(A_j w)dw \tag{12}$$

If there is only one jamming tone inside the receiving bandwidth, the symbol error probability turns out to be

$$P_2 = 1 - F_X(x) \tag{13}$$

After some manipulation, the symbol error probability of BPSK in the presence of a single UWB tone interferer and white Gaussian noise is derived as

$$P_2 = \frac{1}{2} - \frac{1}{\pi}\int_0^{\infty} \frac{\sin(A_s w)}{w} \exp\left(-\frac{w^2\sigma_z^2}{2}\right) J_0(A_j w)dw$$

Let us define γ_c as the square root of carrier-to-noise power ratio (CNR), i.e., $\gamma_c = \frac{A_s}{\sqrt{2}\sigma_z} = \frac{A_s}{\sigma_n} = \sqrt{CNR}$; and define γ_j as the square root of tone-to-noise power ratio (TNR), i.e., $\gamma_j = \frac{A_j}{\sigma_n} = \sqrt{TNR}$. For BPSK signals, the noise variance σ_z^2 is one half the overall receiver noise variance σ_n^2, i.e., $\sigma_z^2 = \sigma_n^2 / 2$. The SER of BPSK signal under signal tone and white Gaussian noise is

$$P_2 = \frac{1}{2} - \frac{1}{\pi}\int_0^\infty \frac{\sin(\gamma_c w)}{w} \exp\left(-\frac{w^2}{4}\right) J_0(\gamma_j w) dw \quad (14)$$

By the same logic, if there are N jamming tones inside the receiving bandwidth, the symbol error probability becomes

$$P_{2N} = \frac{1}{2} - \frac{1}{\pi}\int_0^\infty \frac{\sin(\gamma_c w)}{w} \exp\left(-\frac{w^2}{4}\right) \times \prod_{i=1}^{N} J_0(\gamma_{ji} w)\, dw \quad (15)$$

where γ_{ji} represents the tone-to-noise power ratio of the i-th jamming tone.

B. MPSK Performance

For M-ary Phase-Shift Keying (MPSK) narrowband receivers, the received signal vector corrupted with UWB interference is expressed as

$$\vec{r} = \vec{A}_s + a + j \times b . \quad (16)$$

Notation $\vec{A}_s$ is the ideal MPSK signal vector. Two new variables a and b are defined as $b = n_y + A_j \sin\theta$, and $a = n_x + A_j \cos\theta$. Notations n_x and n_y are white Gaussian noise with zero mean and $\sigma_n^2 / 2$ variance. Figure 1 shows a MPSK signal point under both random noise and tone interference. Since the ideal M-ary signal equally divides the constellation plane of 2π, the correct decision region of a received symbol is the region from $-\pi / M$ to π / M around the ideal symbol vector, i.e., between the two dashed lines in Figure 1.

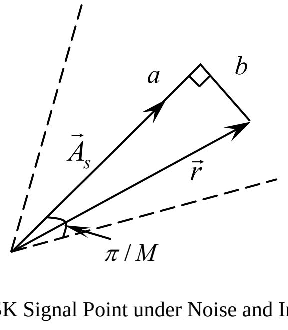

Figure 1. MPSK Signal Point under Noise and Interference

When the angle between the received signal $\vec{r}$ and the ideal signal vector $\vec{A}_s$ is less than π / M, the narrowband receiver will make a right decision about the received signal. The receiver will make an erroneous decision if the absolute angle between the received signal $\vec{r}$ and the ideal signal vector $\vec{A}_s$ is greater than π / M. The symbol error rate P_M of MPSK signals is the probability of the received signal lying outside the wedge between $-\pi / M$ and π / M around the ideal signal vector $\vec{A}_s$, i.e.,

$$P_M = \Pr\left\{\left|\arctan\left(\frac{b}{A_s + a}\right)\right| > \frac{\pi}{M}\right\}. \quad (17)$$

After some algebraic manipulation, (17) simplifies to

$$P_M = \Pr\left\{\left|z_e + A_j \sin\left(\theta - \frac{\pi}{M}\right)\right| > A_s \sin\left(\frac{\pi}{M}\right)\right\}, \quad (18)$$

where $z_e = n_y \cos\left(\frac{\pi}{M}\right) - n_x \sin\left(\frac{\pi}{M}\right)$.

Since both n_x and n_y are white Gaussian noise with zero mean and $\sigma_n^2 / 2$ variance, the combined equivalent noise z_e of $n_y \cos\left(\frac{\pi}{M}\right) - n_x \sin\left(\frac{\pi}{M}\right)$ is still white Gaussian with zero mean and $\sigma_n^2 / 2$ variance. The interference tone phase θ has a uniform distribution over $[-\pi, \pi)$ whose PDF is shown in (3). The term $A_j \sin\left(\theta - \frac{\pi}{M}\right)$ is similar to random variable y, and share the same PDF as in (4) and the same characteristic function as in (5). Following the logic of the above BPSK performance derivation, the symbol error probability P_M of MPSK signal under white Gaussian noise and single tone interference is

$$P_M = 1 - \frac{2}{\pi}\int_0^\infty \frac{\sin\left(w A_s \sin\left(\frac{\pi}{M}\right)\right)}{w} \exp\left(-\frac{w^2 {\sigma_n}^2}{4}\right) J_0\left(A_j w\right) dw \quad (19)$$

The SER of MPSK under single UWB tone interferer and white Gaussian noise can also be expressed as

$$P_M = 1 - \frac{2}{\pi}\int_0^\infty \frac{\sin\left(w \gamma_c \sin\left(\frac{\pi}{M}\right)\right)}{w} \exp\left(-\frac{w^2}{4}\right) J_0\left(\gamma_i w\right) dw \quad (20)$$

When there is no tone interferer, i.e., $A_j = 0$, from (18) the SER of MPSK signal under Gaussian noise is

$$P_M = 2Q\left(\sqrt{2}\,\frac{A_s \sin(\pi/M)}{\sigma_n}\right),$$

where $Q(x)$ is the right-tail probability function of a normal distributed random variable. It is worth noting that when there is only Gaussian noise in the receiver, our proposed method achieves the same MPSK SER approximation formula described in [19]. This SER formula is a very precise approximation of the theoretical MPSK SER performance [20], which is

$$P_M = \frac{1}{\pi}\int_0^{\pi-\pi/M} \exp\left(\frac{-\left(\frac{E_s}{N_0}\right)\sin^2\left(\frac{\pi}{M}\right)}{\sin^2\theta}\right)d\theta .$$

When there are multiple UWB interfering tones inside the frequency bandwidth of the narrowband receiver, similar to that of BPSK, the SER of MPSK signals is

$$P_{MN} = 1 - \frac{2}{\pi}\int_0^{\infty}\frac{\sin\left(w\gamma_c \sin\left(\frac{\pi}{M}\right)\right)}{w}\exp\left(-\frac{w^2}{4}\right)\prod_{j=1}^{N} J_0\left(\gamma_{ij} w\right)dw \quad (21)$$

IV. Simulation Study

A. BPSK Performance Simulation

The signal-to-interference-and-noise-ratio (SINR) is the ratio of signal power to the sum of multiple tone power and additive white Gaussian noise power. The interference tone-to-noise-ratio (TNR) is the power ratio of the in-band jamming tones to the additive white Gaussian noise from both UWB signals and the thermal noise inside the narrowband receiver. In the case where there is only one jamming tone within the receiver frequency bandwidth, the BPSK SER vs. SINR curves when TNR is 1 dB, 7 dB, 20 dB, and when there is only Gaussian noise, are plotted in Figure 2. As the TNR increases, the SER decreases when SINR is greater than 0 dB and increases when SINR is less than 0 dB. This is because the probability distribution $f_Y(y)$ of the tone interference does not have the long tails as the Gaussian distribution has.

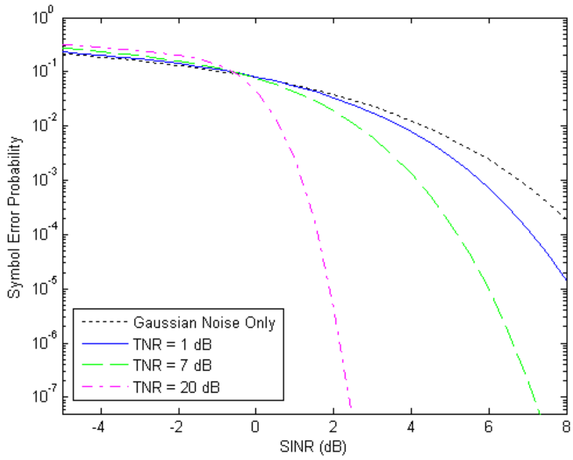

Figure 2. SER vs. SINR under Different TNRs

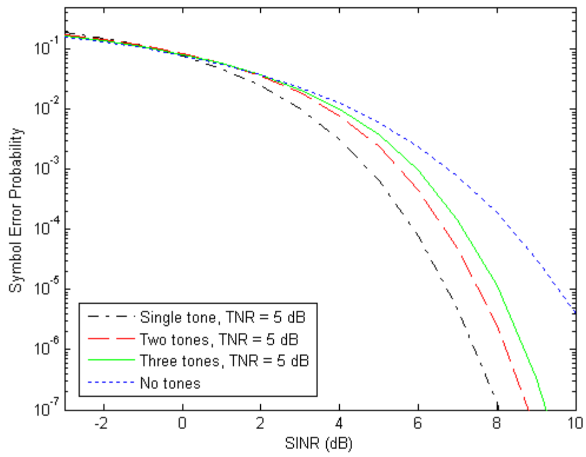

Figure 3. SER vs. SINR under Interference of Multiple Tones

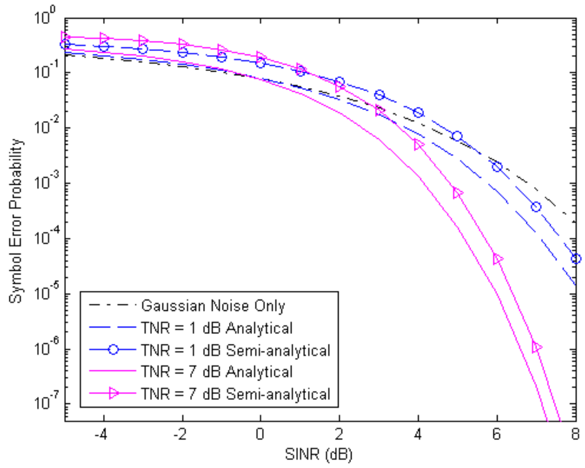

Figure 4. Comparison of Analytical and Semi-analytical Methods

When there are multiple UWB jamming tones within the frequency bandwidth of a victim receiver, and if the overall TNR is kept constant, the receiver SER approaches the SER under Gaussian noise with no jamming tones as the number of interfering tones increases. Figure 3 illustrates this case for constant TNR = 5 dB.

Even though the semi-analytical simulation method proposed in [14] achieves similar results, the semi-analytical simulation method usually overestimates the tone interference effects. When TNR is 1 dB and 7 dB, the SER curves of our analytical method is consistently less than the SER curves calculated using the semi-analytical simulation method, as shown in Figure 4. This is because that the semi-analytical method assumes the probability distribution of combined tone and Gaussian noise is still Gaussian distribution while our analytical method doesn't make such assumption. Therefore, our analytical method is more precise than the semi-analytical method. For completeness, the semi-analytical method is summarized in Appendix A.

B. MPSK Performance Simulation

When there is only one UWB tone interferer within the bandwidth of a narrowband receiver, the SER vs. E_b / N_0 curves for M = 4, 8, 16, and TNR = 0 dB, -3 dB, -10 dB, are demonstrated in Figure 5. As we can see from Figure 5 that the SER decreases as TNR decreases when E_b / N_0 is fixed.

When only a single UWB tone interferer falls within the MPSK receiver bandwidth, the SER vs. C/(T+N) performance curves for M = 4, 8, 16, and TNR = 0 dB, -3 dB, -10 dB are plotted in Figure 6. When C/(T+N) is fixed, the SER decreases as TNR increases for all M values.

When the overall TNR is fixed to 0 dB, and the tone power is split equally if there are multiple tones within the bandwidth of a narrowband receiver, the SER vs. C/(T+N) curves for M = 4, 8, and 16, under conditions that no tone, single tone, 3 tones and 5 tones fall within the receiver's bandwidth, are plotted in Figure 7. The solid lines in Figure 7 are the SER vs. C/(T+N) curves for M = 4, 8 and 16, when there are no tone interference. For the same C/(T+N), the SER with tone interference approaches to that of no tone interference as the number of interfering tones increases.

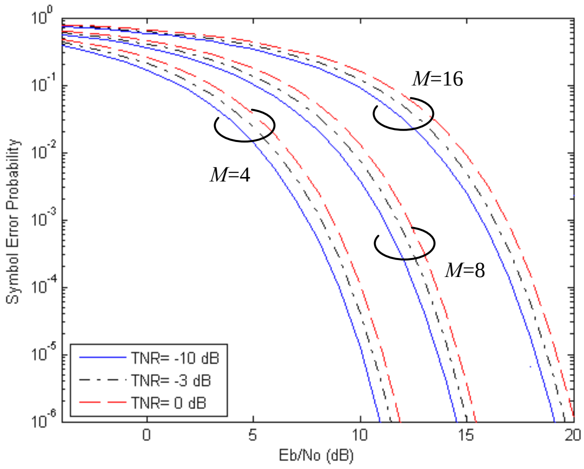

Figure 5. SER vs. E_b/No under Single Tone Interference

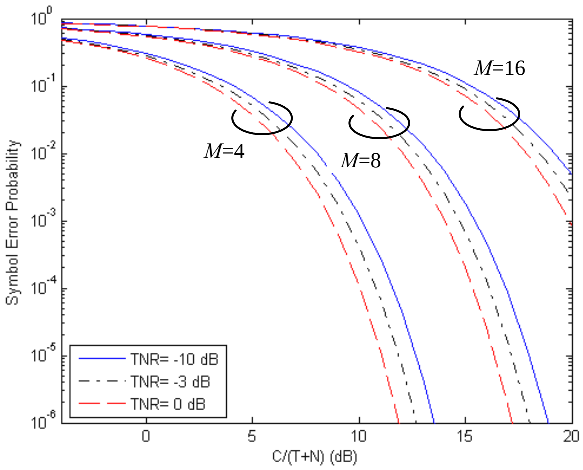

Figure 6. SER vs. C/(T+N) under Single Tone Interference

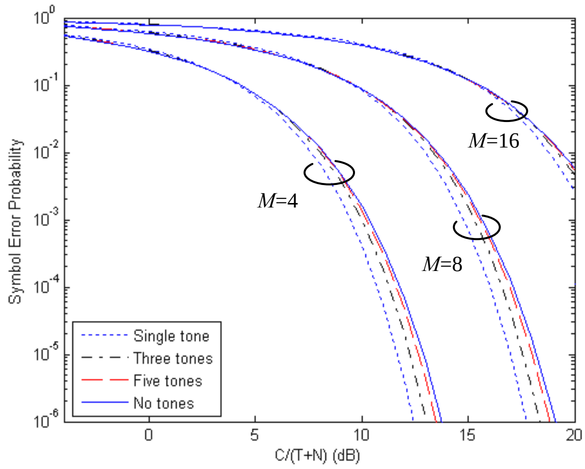

Figure 7. SER vs. C/(T+N) under Multiple Tones with the Same TNR = 0 dB

V. CONCLUSIONS

A novel analytical method of assessing the narrowband performance degradation due to UWB interferences is derived on the basis that the UWB interference is modeled as a composite signal of additive white Gaussian noise and jamming tones. Through the proposed analytical SER evaluation method, it was found that when SINR is greater than a certain value, the symbol error rates of both MPSK and BPSK receivers decrease as the power portion of jamming tones increases, and when SINR is less than a certain value, the symbol error rate of both MPSK and BPSK receivers increases as the power portion of jamming tones increases. Furthermore, as the number of in-band jamming tones increases, the UWB interference effect tends to be closer to the effect of equivalent Gaussian noise. The simulation results show that the semi-analytical simulation method [14] with the assumption that the PDF of combined tone and Gaussian noise is still a Gaussian distribution usually overestimates the SER. Our proposed analytical method doesn't make this assumption and therefore is more precise in evaluating UWB interference to narrow band receivers.

APPENDIX A SEMI-ANALYTICAL SIMULATION METHOD

According to UWB tone model in [13], the semi-analytical symbol error rate P_e of BPSK narrow band receiver under UWB interference is expressed as

$$P_e = \left\langle \frac{1}{2} Q\left(\sqrt{\frac{2E_b}{N_0}}(1+\delta)\right) + \frac{1}{2} Q\left(\sqrt{\frac{2E_b}{N_0}}(1-\delta)\right) \right\rangle$$

where notation $\langle \bullet \rangle$ denotes the time average operation, E_b is the energy per bit, N_0 is single band noise density, and δ is the interference perturbation factor, which is calculated as follows.

$$\delta = C / \sqrt{STR}$$

$$C = \frac{\sin[2\pi(f_j - f_c)T_s - \theta_0 + j2\pi f_j] + \sin[\theta_0 - j2\pi f_j]}{2\pi(f_j - f_c)T_s}$$

where STR is defined as the ratio of signal power over tone power, f_j is the tone frequency, f_c is the center frequency of narrow band receiver, T_s is the receiver sampling period, θ_0 is the initial phase of the jamming tone. The detail semi-analytical algorithms refer to [14].

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