Interference and Distance Studies for DS-UWB

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ABSTRACT

This paper discusses ultra wideband (UWB) system bit error rate (BER) performance in additive white Gaussian noise (AWGN) channel in the presence of partial band interference. In most of the cases in UWB context, even narrowband interference approaches are reasonable. The study has focused on direct sequence (DS) based UWB system that utilizes binary pulse amplitude modulation (BPAM) as a data modulation scheme. Interference is assumed to be band limited and Gaussian distributed, and the presented analysis allows arbitrary interference allocations. Derived BER formulas are verified with the corresponding simulation results. It has been shown that the general BER formulas for wideband systems can also be applied to UWB to calculate the upper bound limit for the system performance in the presence of interference. Signal-to-noise and signal-to-interference (SNR and SIR, respectively) ratios providing the required BER can then be applied to calculate the minimum interference distance that satisfies the quality of service requirements.

1. INTRODUCTION

Ultra wideband technology can be used in overlay basis on the top of other existing radio systems due to the low transmission power and extremely wide occupied bandwidth. Because of the existing regulations [1], UWB signal's -10 dB bandwidth should be larger than 500 MHz.

The UWB standardization process led by the IEEE 802.15.3 [2] had two competing approaches for UWB; singleband DS-UWB [3] and multiband-OFDM [4] based techniques. However, one or the other proposals was not selected for the final standard and markets can select the surviving technique. The main difference between these two approaches are the following; singleband allows cheap implementation but is limited by the data rate while multiband (that is already utilized, e.g., in wireless local area networks (WLAN)) could offer much higher data rates but with the increasing complexity. Singleband approach can also be based on non-coherent energy collection detection which makes the receiver even simpler but more vulnerable to the intentional interference if compared to the corresponding coherent receiver.

This work is focused on singleband UWB approach which follows more the basic idea of the impulse radio, like presented, e.g., by Scholtz and Win in [5]. Though not utilizing time-hopping mechanism from [5], the baseband bipolar UWB pulse train modulated with the pseudo random spreading code is used to form one data symbol. The generated pulse stream is then transmitted without frequency up-conversion stages thus we are dealing with the baseband communications.

Due to the extremely large inherent bandwidth, there is also signal energy other than the desired one that the UWB receiver captures. In addition to that, radio channel generate several multipath components that disturb the received signal more. All (un)intentional interference causes performance degradation for the desired link. The effects should be taken into account in advance as much as possible when designing the communication system. To predict the performance of UWB system, tools for analyzing the performance when interference exists, are therefore needed. Typically, the published results are based on simulations, like in [6]. Some specific analytical studies have also been presented, e.g., for time-hopping UWB and DS-UWB in [7] and [8], respectively. However, the general utilization of the available closed form formulas is not so easy which makes it reasonable to find out a simpler formulation for the analytical calculations.

This paper is organized as follows: Chapter 2 introduces the used system model. In Chapter 3, the formulas for analytical BER calculations are given. In Chapter 4, the analytical results are verified with the simulated ones. Chapter 5 discusses the interference distance, and finally in Chapter 6, the conclusions are drawn.

2. SYSTEM MODEL

In DS-UWB system, one data bit is spread over the multiple pulses by using pseudo random (PRN) code. In our case, the code is maximum length code (m-sequence). Other spreading code, like Walsh-code [9] that has acceptable correlation properties can also be used. At the receiver, this multi-pulse per symbol transmission can be seen as a processing gain which has a value $G = 10\log_{10}(N_p)$, where N_p is the length of the spreading code that equals the number of transmitted pulses per data bit. In the studied DS-UWB transmission, pulse width T_p equals to the chip length T_c, and the transmission is continuous. Silent periods within the transmission is introduced if $T_p \leq T_c$. In this approach, the average power spectral density is decreased if the pulse energy remains the same due to the silent gaps within the transmission.

In radio channel, there exists different kind of interference coming from the other radio transmitters which is not favourable by the desired link. In addition to the (un)intentional interference $n_j(t)$, thermal noise $n(t)$ having one-sided power spectral density (psd) N_0 is always present. The received signal $r(t)$ can be presented as

$$r(t) = s(t) + n_j(t) + n(t), \tag{1}$$

where $s(t)$ denotes the transmitted signal.

The UWB pulse waveforms used in this study are based on the Gaussian pulse or its higher derivatives. Gaussian pulse can be expressed as [10]

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

where t and σ^2 are time and variance, respectively. Variance is linked to desired pulse width T_p by $\sigma \approx T_p / 2\pi$. The spectrum of the n^{th} derivative of the Gaussian pulse can be calculated from (2) by differentiating it n times and Fourier transforming it. The spectrum can be analytically presented as [12]

$$S_{UWB}(f) = \frac{(2\pi f\sigma)^2 \exp\{-(2\pi f\sigma)^2\}}{n^n \exp(-n)}. \tag{3}$$

3. BER IN THE PRESENCE OF INTERFERENCE

In this chapter, two approaches to calculate BER for DS-UWB in the presence of partial band interference are given.

If only a fraction of the desired spectrum, whose bandwidth is W, is interfered, we are dealing with partial band interference, and $W_j < W$, as denoted in Figure 1.

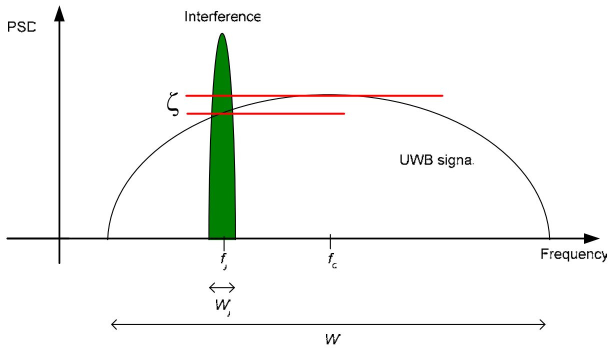

Figure 1. Power spectral densities presented for the desired UWB and interfering signals.

The parameter ζ presents the ratio between the psd levels at the interfered band and the maximum level of the desired signal. Mathematically this ratio can be presented as

$$\zeta = \frac{S_{UWB}(f_j)}{S_{UWB}(f_c)}, \tag{4}$$

where S_{UWB}, f_j and f_c represent UWB power spectral density (psd), centre frequencies of interference and UWB (nominal), respectively, as presented in Figure 1. A special case of the partial band interference is tone interference when $W_j << W$. Typically, in the case of UWB transmission, the bandwidth of the interfering signal is much smaller than the one of the desired signal which justifies the partial band or even tone interference approaches for analysis. Full-band interference, which can be seen as a multi-user interference in the case of UWB, is not touched in the following discussion.

Partial band interference

The following analysis is based on the study derived originally for wideband spread spectrum signal in [11]. In the barrage (full-band) interference case, the psd of the interfering signal is denoted by $N_j = J/W$, where N_j and J are one-sided power spectral density of the interference and interfering power, respectively. The overlapping fraction of the partial band interference can then be given by $N_j^{'} = J/W_j$ [11]. The error probability P_b for the binary phase shift keying (BPSK) and binary pulse amplitude modulation (BPAM) signal in the presence of interference can be modified to be

$$P_b = Q\left(\sqrt{\frac{E_b}{(N_0/2) + \zeta \cdot S(f_j)}}\right), \tag{5}$$

where E_b and N_0 are bit energy and one-sided noise power spectral density, respectively. $S(f_j)$ gives the contribution of the interfering energy in the decision variable which decreases the desired system's performance. In (5), the impact of interfering signal on the desired UWB system performance is further weighted by the psd of the own signal as

$$S(f_j) = \frac{N_j^{'}}{W} \int_{f_j - ½W_j}^{f_j + ½W_j} S_{UWB}(f)\,df . \tag{6}$$

The nominal centre frequency of the own signal in (3) is [12]

$$f_p^{(n)} = \sqrt{n} \Big/ 2\pi\sigma . \tag{7}$$

Tone interference

If $W_j << W$, (5) can be presented in a simpler form, and the power scaling factor ζ can be utilized to improve the accuracy of the original formula from [11] as presented by

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0 + 2N_j}}\right) = Q\left(\sqrt{\frac{2}{\frac{RN_0}{P} + 2\zeta\frac{J}{P}\frac{R_d}{W}}}\right), \tag{8}$$

where R_d and P are desired data rate and signal power, respectively.

Except the variable ζ, the equations (5) and (8) are similar as presented in [11] where, however, the noise components in (1) were assumed to be narrowband. In addition, the calculation of $S(f_j)$ is different.

4. BER RESULTS

In this Chapter, the analytical results are verified with the simulation results. Due to the simulation limitations, the processing gain of the studied system is kept rather low, G = 15 dB. This means that one data bit is conveyed using 32 consecutive pulses ($10\log_{10}(32) \approx 15$ dB) and data rate R_d = 62.5 Mbps.

In Figure 2, the different analytical approaches are compared with the simulated one. As can be seen, the narrowband approach without power scaling underestimates the UWB performance when the interfering signal does not overlap the nominal center frequency of the desired one. On the contrary, the scaled narrowband (NB) and partial band (PB) approaches give almost the same results. Comparison has been made for the 5^{th} derivative of the Gaussian pulse, T_p = 0.5 ns with centre frequency f_c = 4.5 GHz. Interfering signal is locating at f_j = 3 GHz, W_j = 10 MHz.

In Figure 3, BER is presented for UWB signal using the 7^{th} derivative of the Gaussian pulse with T_p = 0.5 ns. The analytical results are calculated using (5) and compared with the simulated results; Markers and dotted-lines represent simulated and analytical results, respectively. Nominal centre frequency of the desired signal is 5.4 GHz, and five different jamming frequencies are studied (each interferer has $W_j = 100$ MHz). As the curves showed, the analytical results are overlapping the simulated ones. However, if the interference is close to the nominal center frequency of the desired signal at the lowering edge of the spectrum, analytical method gives more optimistic result than simulations. Analytical results differ from the simulations because, e.g., sidelobes of the spectrum originated at the simulator are excluded. Thus being low level, the sidelobes still carry out-of-band energy which is detected at the simulator receiver.

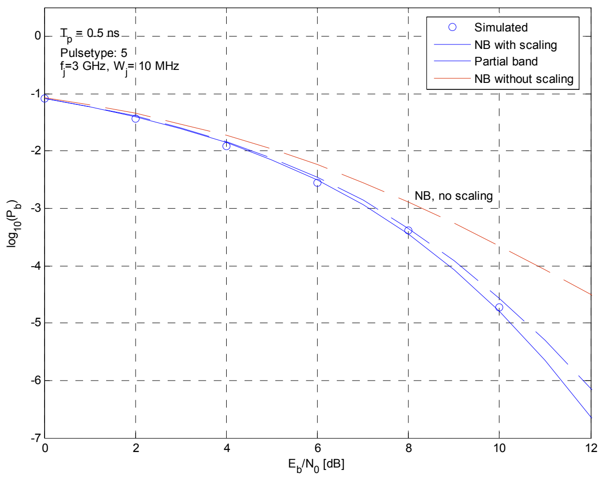

Figure 2. Comparison between the different approaches.

Corresponding results when using narrowband approach from (8) are presented in Figure 4. This approach gives reasonable good results when the scaling factor ζ is used. If ζ is omitted, the accuracy of the estimation decreases when the interference is shifted away from the nominal UWB center frequency. Non-scaled BER is presented with blue '+' marker in the figure, and it is overlapping the scaled and simulated curves when the UWB nominal center frequency and the interfering signal are the same.

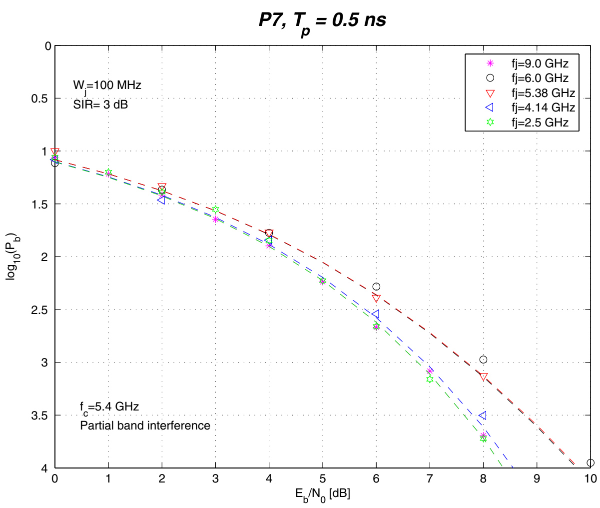

Figure 3. BER for different interfering frequencies; simulations (markers) vs. partial band (lines) calculations.

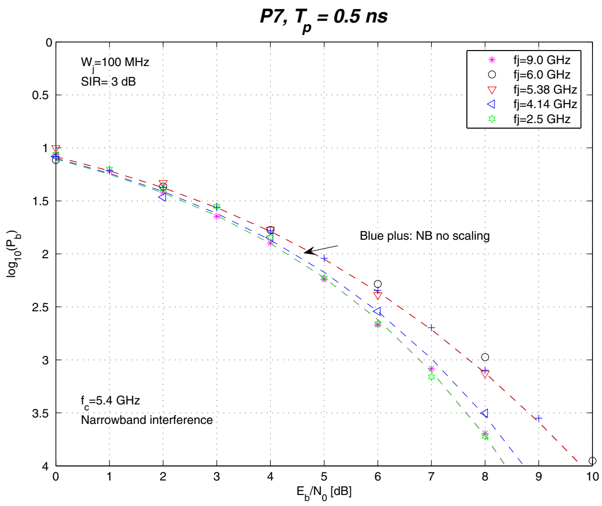

Figure 4. BER for different interfering frequencies; simulations (markers) vs. narrowband (lines) calculations.

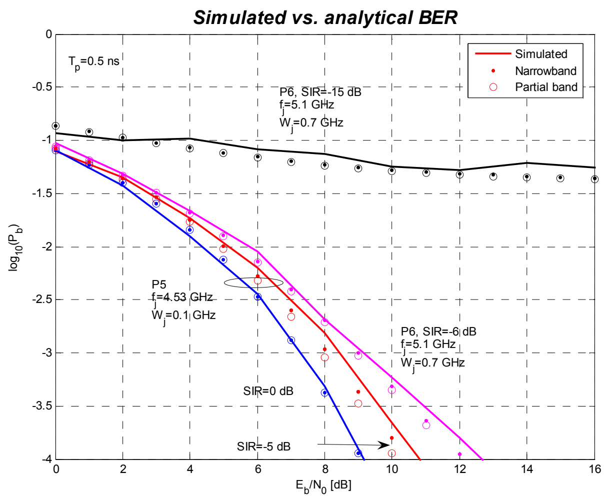

Figure 5. BER using different waveforms with different SIR.

In Figure 5, the used UWB pulses are both the 5th and the 6th derivative of the Gaussian pulse. Signal-to-interference ratio is varying from SIR = 0 dB … -15 dB. As can be seen, the analytical approaches (both scaled NB and PB) meet the simulated values even when the BER saturates due to the low SIR value. The results presented are used to demonstrate that the existing BER formulas that are created for wideband systems operating in the presence of narrowband interference can be adopted also in UWB context. The scaling factor ζ improves the accuracy of the formula. Further investigations on the generality of the approach are needed to find the cases, where the presented simple derivation looses the accuracy (for different interfering bandwidths, center frequencies, etc.) Exploitation ranges of the formulas are discussed in [13].

5. INTERFERENCE DISTANCE

The derived BER results can be utilized when calculating the minimum distance where the (un)intentional interference cause severe performance degradation to the desired link. If the minimum acceptable signal-to-noise ratio E_b/N_0 for the UWB receiver is marked as $\gamma_{\min}$, the minimum distance of the desired receiver from the interferer ($d_{\mathrm{int,min}}$) can be calculated by [14]

$$d_{\mathrm{int,min}} = d_{vic} \sqrt[\alpha]{\frac{\gamma_{\min} J}{P \cdot G}}, \qquad (9)$$

where d_{vic} is the distance of the desired link and α is the attenuation factor. In homogeneous propagation environment, like indoor office, it can be assumed that α is the same for both links; the desired and the interfering ones. However, the frequency diversity provided by the UWB system could make a difference between α_{UWB} and α of narrowband or wideband system.

In Figure 6, the minimum safety distances of the UWB receiver from the interference source are presented. The system parameters used in the example are the following: $P_{\mathrm{UWB}} = 0.5$ mW that is the maximum power level that fits the FCC mask [1] (-41.25 dBm/MHz * 7500 MHz ≈ 0.56 mW), $P_j = 100$ mW, $\gamma_{\min}$ is fixed to 5 dB or 10 dB. UWB system has typically smaller transmission power because the entire allowed spectrum is not used but only the fraction of it; allocated bandwidth is 500 MHz ≤ W ≤ 7.5 GHz. $P_j = 100$ mW corresponds the transmission power level used by the IEEE802.11a wireless LAN system. The path loss exponent α has values 1.7, 2 and 3.5. The channel measurement experiments carried out by CWC have proved that α = 1.7 is a reasonable estimation for indoor attenuation factor for UWB signal [15]. Processing gain G is fixed to 20 dB. Typical high data rate UWB link distance is below 10-15 meters. In that case, the minimum interference distance in the worst case, depending on the propagation loss, is from 17 m to 30 m @ 10 m UWB link distance for $\gamma_{\min} = 5$ dB. If the desired system is WLAN having transmission power of 100 mW and the interference is coming from UWB transmitter ($P_j = 0.5$ mW), the minimum separation to have $\gamma_{\min} = 5$ dB at the WLAN is below 0.5 m in typical propagation environments (see Figure 7).

Figure 8 shows the required safety distance as a function of UWB receiver's processing gain when the desired UWB link distance is 5 m, and the interference is coming from WLAN. When comparing the results to the corresponding ones but changing the interference and victim systems, the UWB system is seen to be much more sensitive to the interference coming from the WLAN than the other way around. This is based, of course, the large difference between the transmission powers.

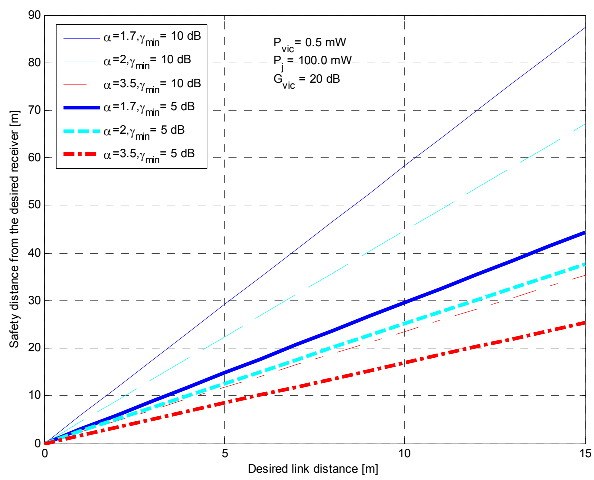

Figure 6. Minimum interference distance between WLAN and UWB; WLAN is interfering UWB.

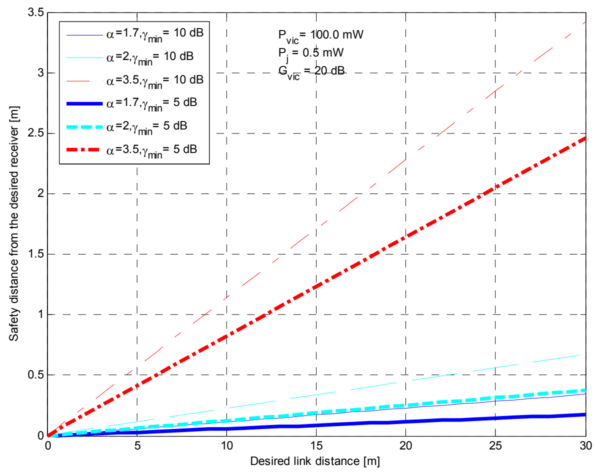

Figure 7. Minimum interference distance between WLAN and UWB; UWB is interfering WLAN.

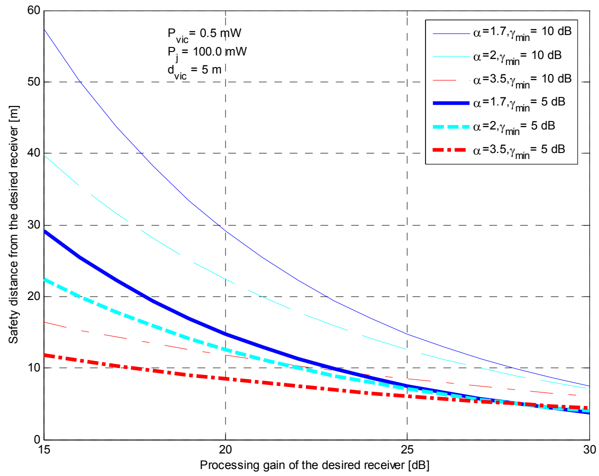

Figure 8. WLAN impact on UWB as a function of UWB processing gain. Desired link distance is 5 m.

6. CONCLUSIONS

This paper discussed the analytical approach to calculate the impact of interference on DS-UWB bit error performance and minimum interference distance. The presented formulation can be used when estimating the UWB system performance degradation in the presence of interference. The performance of the given formulas for UWB bit error rate calculations has been verified with the simulated results. Typically, the given closed form formulations are quite complicated when the effect of the interference is analytically taken into account. Using the approach presented in this paper, one can use the main UWB system parameters in the BER calculations which make the use of formulas very convenient. The calculated SNR for a given BER can then be used to find the minimum distance where the interfering signal cause degradation to the desired link. As can be seen from the results, the UWB system is more vulnerable to the WLAN interference than the other way around due to the big difference in the transmission powers.

7. ACKNOWLEDGEMENTS

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