ANALYSIS OF JAMMING ON DS-UWB SYSTEM

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ABSTRACT

This paper presents ultra wideband (UWB) jamming studies in additive white Gaussian noise (AWGN) channel. Analytical approach for UWB system performance in the presence of partial band jamming (or interference), whose special case is tone jamming, is presented. In UWB case, most of the jamming (interference) could be seen as partial band jamming due to the extremely large inherent bandwidth of the desired signal. The given modifications for the existing formulas, which originally have applied for wideband system with narrowband interference, are verified with the corresponding simulated results in UWB context. The study has focused on direct sequence (DS) based single-band UWB system that uses binary pulse amplitude modulation (BPAM) as a data modulation scheme. Jamming (interference) is assumed to be band limited and Gaussian distributed, and the presented analytical expressions allow freely spacing and arbitrary bandwidth for the interfering signal. It has been noticed that the general bit error rate (BER) formulas for wideband systems can also be applied to UWB to calculate the upper bounds for the performances using real UWB system parameters in very simply way through spectral characteristics.

INTRODUCTION

Due to the low transmission power and extremely wide occupied bandwidth, ultra wideband technology could provide new approach to tactical and secure communications. Inherent signal structure provides low probability of interception and detection (LPI/LPD) which are essential, especially, in military applications. UWB signal's -10 dB bandwidth could be from 500 MHz to 7.5 GHz according to the existing FCC regulations [1]. This extremely large bandwidth exposes UWB transmission to severe (un)intentional interference and jamming that will decrease the performance of the desired system.

Currently, there are two competing approaches for UWB; single-band direct sequence [2] and multiband-OFDM[1] [3] based UWB techniques. The UWB standardization process led by the IEEE 802.15.3 [4] was unable to select one or the other proposals for a final standard. However, both technologies have their pros and cons, and have their own supporting groups. Single-band approach allows cheap implementation but is mostly limited by the maximum data rate while multiband approach that is already utilized, e.g., in wireless local area networks (WLAN) and digital video broadcasting (DVB), could offer much higher data rates but with increasing implementation complexity. Single-band approach can also be based on non-coherent detection which makes the transceiver quite simple. However, non-coherent systems are more vulnerable to interference than the corresponding coherent systems. This phenomenon is further emphasized in military applications.

This paper is focused on single-band 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, the baseband bipolar UWB pulse train obeying the polarities of the binary spreading code is used to create one data symbol. DS-UWB has been selected for the detailed study because of its better resistance against interference, see e.g. [6]. The generated pulse stream is then transmitted without frequency up-conversion stages thus we are dealing with the baseband communication. All the studied signals fulfill requirements given for UWB signal by the FCC [1].

Due to the extremely large occupied bandwidth, UWB receiver captures lot of signal energy coming from the other radio systems than only the desired one. Radio channel generates also several multipath components that are worsening the reception. Jamming and interference degrade the performance of the desired communication link, and its effects should be taken into account in advance as much as possible when designing a communication system. To predict the performance of UWB system, simple tools for analyzing the performance when jamming exists is therefore needed. Then, the possible need for, e.g., interference suppression methods could be clarified early enough and could be taken into account in the system design.

[1] OFDM = orthogonal frequency division multiplexing

This paper is organized as follows. Chapter 2 introduces the UWB system model used. In Chapter 3, the analytical approaches for bit-error-rate (BER) calculations are given. In Chapter 4, the results are shown and verified with the simulated results. Finally, Chapter 5 concludes the paper.

SYSTEM MODEL

In DS-UWB system, one data bit is spread over multiple pulses using pseudo random (PR) code, which in our simulations is maximum length code (m-sequence [7]). This multi-pulse transmission per symbol is also seen at the receiver side as a processing gain G, having value $G = 10\log_{10}(N_p)$, where N_p is the length of the spreading code that in our case equals the number of transmitted pulses per data symbol. In the studied DS-UWB transmission, pulse width T_p equals to T_c which is the chip length, and the transmission is continuous. Silent periods could be introduced if $T_p < T_c$ when also the average power spectral density is decreased if the energy of the single pulse remains the same.

The used signal model follows the typical approach used in the radio communications studies. In a transmission media, there exist different kinds of interference coming from the other radio transmitters. By the desired link, this external signal energy, called $n_j(t)$, can be seen as interference, or in military applications, as intentional jamming. In addition, thermal noise $n(t)$, having one-sided power spectral density (psd) N_0, is always present. Therefore, the received signal $r(t)$ can be presented as

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

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

The UWB pulse waveforms used in this study are based on the Gaussian pulse and its higher derivatives. The general zero mean Gaussian pulse can be express by [7]

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

where t and σ denote time and standard deviation, respectively, and σ is defined as $\sigma \approx T_p/2\pi$. The higher (n^{th}) derivatives of the Gaussian pulse are calculating from (2) by differentiating it n times (n presents the order of the derivative).

BER IN THE PRESENCE OF JAMMING

In this chapter, different approaches to calculate BER for DS-UWB in the presence of partial band jamming are introduced and compared. A barrage jamming (full-band jamming) in the UWB context is not the most interesting case, and it can be seen (in most of the cases) based on the multi-user interference due to the large inherent bandwidth by the system of interest.

If only a fraction of the desired spectrum (bandwidth is W) is jammed, we are dealing with partial band jamming, and the jammer bandwidth is denoted by $W_j < W$, as shown in Figure 1.

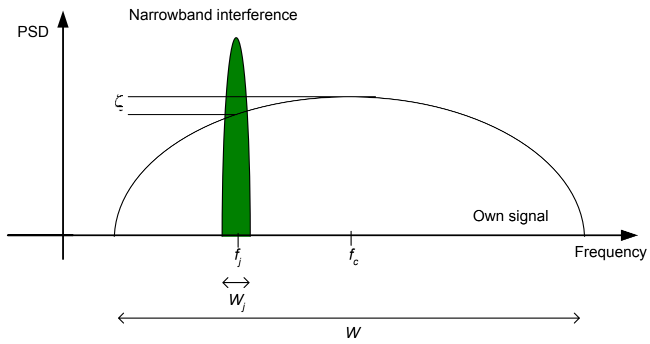

Figure 1. Power spectral densities presented for the desired UWB and jamming signals.

The parameter ζ presents the ratio between the UWB signal level at the center frequency of the jammed band and the maximum level of the desired signal's psd. Mathematically this ratio is

$$\zeta = \frac{S_{UWB}(f_j)}{S_{UWB}(f_c)}, \tag{3}$$

where S_{UWB}, f_j and f_c are UWB (desired) power spectral density and center frequencies of jamming and UWB signals, respectively, as presented in Figure 1. In Gaussian waveform based UWB systems, the center frequency is nominal due to the asymmetric spectrum and is pointing out the frequency having the maximum power level.

A special case of the partial band jamming is tone jamming when $W_j << W$, later referred as narrowband (NB). Typically, in the case of UWB transmission, the bandwidth of the jamming signal is much smaller than the one of the desired signal which justifies the partial band, or even tone jamming, approach.

In the following, neither nonlinearity nor saturation effects from the real receiver are taken into account. The formulations are given for the perfectly synchronized DS-UWB system.

Partial band jamming

The following analysis is based on the co-existence study derived originally for wideband spread spectrum signals in [8] where it was assumed that both noise processes in (1) are narrowband if compared to the carrier frequency of the desired band-pass signal. In barrage jamming case, the psd of the jamming signal is $N_j = J/W$, where N_j and J denote one-sided power spectral density of the jammer and jamming power, respectively. The overlapping fraction of the partial band jamming can then be given by $N_j^{'} = J/W_j$ [8]. The error probability P_b for the BPSK and BPAM modulated signal can now be calculated as

$$P_b = Q\left(\sqrt{\frac{E_b}{(N_0/2)+\zeta\cdot S(f_j)}}\right), \tag{4}$$

where E_b and N_0 are bit energy and one-sided noise power spectral density, respectively, and $S(f_j)$ is the contribution of the jammer energy which impair the performance of the desired system. When calculating the impact of jamming on the desired UWB system performance in (4), the weighting is done using the psd of the desired signal on the band of interference presented as

$$S(f_j) = \frac{N_j^{'}}{W}\int_{f_j-½W_j}^{f_j+½W_j}\frac{(2\pi f\sigma)^2\exp\left[-(2\pi f\sigma)^2\right]}{n^n\exp(-n)}df\,, \tag{5}$$

where n defines the number of differentiations of the Gaussian pulse from (2).

Narrowband jamming

If $W_j << W$, (4) can be presented in a simpler way, and the power scaling factor ζ is utilized to improve the accuracy of (4) as presented by

$$P_b = Q\left(\sqrt{\frac{2}{\frac{RN_0}{P}+2\zeta\frac{J}{P}\frac{R}{W}}}\right) \tag{6}$$

where R and P are data rate and signal power, respectively. Except the variable ζ, the equations (4) and (6) are similar than presented in [8] where, however, the n and n_j in (1) were assumed to be narrowband if compared to the desired signal, as earlier stated. In the following chapter, we will show that this assumption could also be extended to systems where the desired signal is UWB.

RESULTS

In this Chapter, the analytical formulas are firstly verified with the simulations. Then, using the formulas, use-case performances examples will be given. Gaussian pulse waveforms having order between 1 and 8 with a fixed pulse width $T_p = 0.5$ ns were used in the verification phase. 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 consisted of 32 consecutive pulses and the achievable data rate is 62.5 Mbps. Increasing the pulse width, data rate is decreasing if G remains the same. In the simulations, a correlation receiver is used all the time.

Verification

The analytical notations are verified with the corresponding simulation results as shown in the following paragraphs. The tested cases were narrowband (NB) approach from (6) with and without (w, wo) the scaling factor ζ, and two partial band approaches both also with and without scaling; original formula (4) like presented in [8] where the weighting is calculated different way at the intermediate frequency. This approach is named as PB(B). The modified version with the weighting by the own pulse spectrum from (5) is called as PB(U).

The curves in Figure 2 represent the difference between the simulated and analytical E_b/N_0 to reach BER = 10^{-3}, as $\Delta E_b/N_0 = (E_b/N_0)_{sim} - (E_b/N_0)_{an}$. Positive value indicates that the simulations give pessimistic estimation for the link quality if compared to the analytical calculations. The results show that the proposed analytical approaches; weighted versions of (4) using (5), and (6) fit well with the simulations. The difference is less than 0.5 dB if the pulse waveform is higher or equal than the 3rd derivative of the Gaussian pulse. Lower order pulses differs more but being less than 1 dB. In every case, (6) without psd-scaling gives the worst result and the deviation is about 1 dB, or more. The required E_b/N_0 for different approaches is 8 dB ± 0.5 dB. In the example of Figure 2, the interference is located at $f_j = 0.8*f_c$. The x-axis reflects to the order of the Gaussian derivative. In the figure, two interference bandwidths were used, namely W_j = 20 MHz (solid line) and W_j = 200 kHz (dotted line). Signal-to-interference ratio (SIR) is -5 dB.

If f_j is close to f_c, all the analytical results are close to each others, independently of the bandwidth of the interfering signal. The difference between the different approaches is less than 0.1 dB and the deviation from the simulations is 0.6 dB at the maximum. The results also indicated that the weighted analytical approached NB and PB(U) give more accurate results if the interference is located at the rising edge of the UWB spectrum.

If one studies the situation from Figure 3, where $f_j = 1.4*f_c$ and W_j = 200 kHz, one can notice that when increasing the order of the Gaussian pulse, the deviation from the simulation results decreases. Also, the difference between the partial band approaches and weighted narrowband estimation will converge.

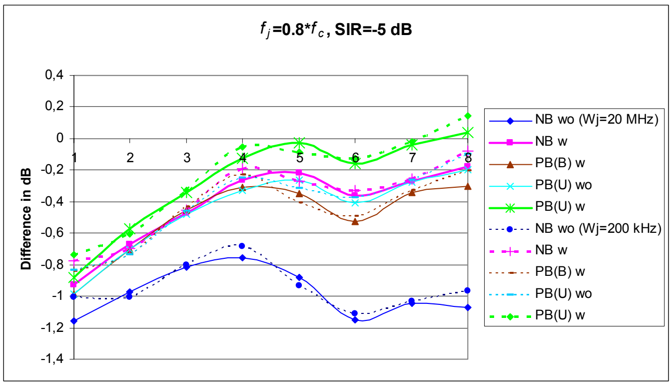

Figure 2. Difference between the simulated and analytical results, $f_j = 0.8 * f_c$. x-axis reflects to the order of the Gaussian pulse. Solid line and dashed line indicate $W_j = 20$ MHz and 200 kHz, respectively, SIR = -5 dB.

However, also in this case, NB without weighting gives the worst estimations elsewhere but the lowest pulses. If using the Gaussian 1st and 2nd pulses, NB without scaling gives, however, the most accurate result. It's deviation from the simulated results increases with the higher order pulses.

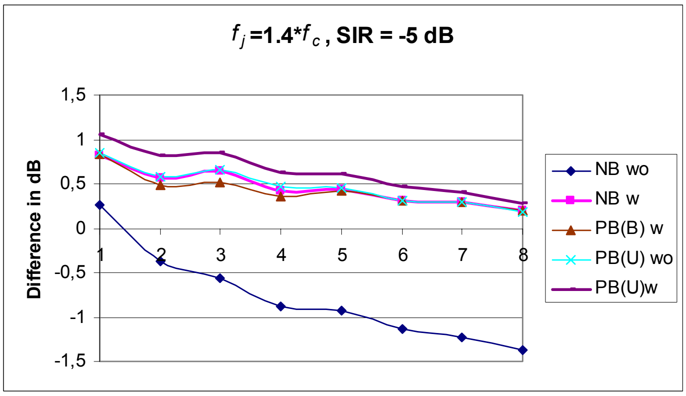

Figure 3. Difference between the simulated and analytical results, $f_j = 1.4 * f_c$. x-axis reflects to the order of the Gaussian pulse.

Utilization of the formulas

In this Section, the modified weighted formulas are applied to calculate bit error rates for several use-cases. In Figure 4, BER is presented for UWB signal using the 7th derivative of a Gaussian pulse with $T_p = 0.5$ ns as a transmitted waveform. Now, the nominal center frequency is 5.4 GHz and the signal's -20 dB bandwidth $W = 5.9$ GHz. Markers and dotted-lines represent simulated and analytical results, respectively. Five different jamming frequencies are studied (f_j = 2.5, 4.14, 5.38, 6 and 9 GHz), each having W_j = 100 MHz and analytical scaled results PB(U) from (4) are compared to the simulated results. SIR is set to -3 dB. As the figure show, the analytical results are fitting well with the simulated results. However, if the interference is close to the nominal center frequency of the desired signal at the lowering edge of the spectrum, analytical method estimates too optimistic performance for UWB.

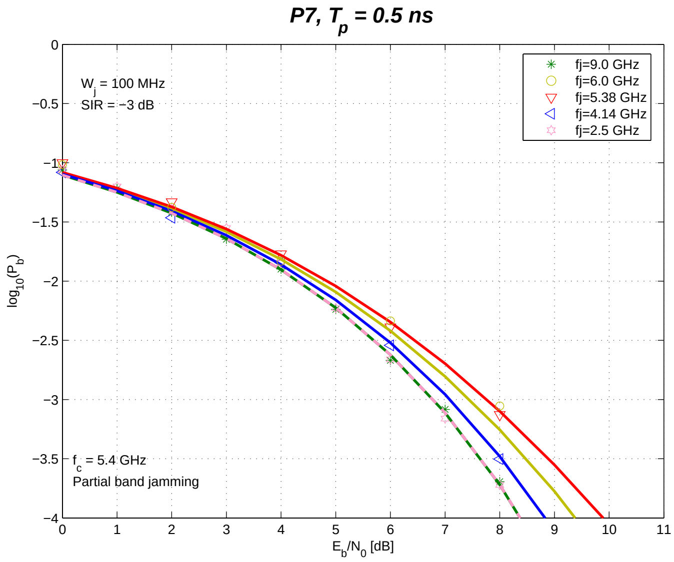

Figure 4. BER for different jamming frequencies; simulations (markers) vs. partial band (lines) calculations.

Corresponding results when using narrowband approach from (6) are presented in Figure 5. The latter approach gives exact results if $f_j = f_c$. In general, the matching of the analytical results is good. One reason for the deviation between the simulated and analytical results is that the side lobes of the interference signal that are present in the simulations are excluded in the analytical derivations. Side lobes are based on the filtering effect when matching the interference in the specified frequency band. Thus being in quite low level, side lobes still carry additional energy that increases the cumulative interference at the reception.

In Figure 6, BER is studied as a function of $\rho = W_j/W$ around three jamming center frequencies (f_j = 200, 300 and 400 MHz) using two sets of UWB system parameters; Gaussian pulses 1 and 2, having pulse widths of 3.2 ns and 4.8 ns, respectively. Due to these assumptions, UWB transmission is located at the frequency band suitable for military applications at VHF/UHF band. As can be seen, the impact of jamming is the highest when ρ is less than about 0.2. When ρ increases from that and the total energy is kept the same, the level of the power spectral density of the interference is reduced, and therefore the interfered UWB system performance will improve. Results from Figure 6 also showed that the impact of jamming is the most efficient if the nominal center frequency of the victim system is jammed, or interference in general is overlapping the center frequency.

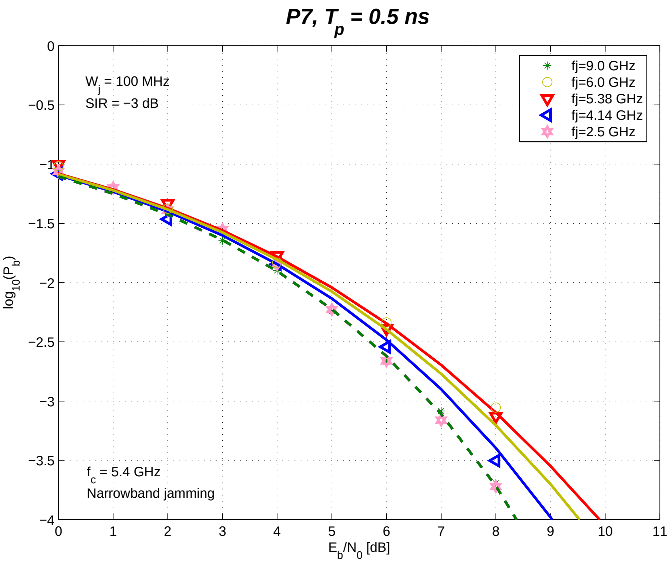

Figure 5. BER for different jamming frequencies; simulations (markers) vs. narrowband (lines) calculations.

The anomaly in the solid green line (f_j = 5 GHz) is due to the spectrum properties. The spectrum of the interferer is more than two times larger than the nominal center frequency of the UWB signal when ρ > 0.8. Therefore, the interference is spread also to "negative frequencies" and the calculation is not accurate anymore.

Similar results than are given for the lower band UWB signal in Figure 6 are presented for the FCC compliant signal in Figure 7, still as a function of ρ. Generated UWB signal is locating at f_c = 5.38 GHz (Gaussian 7th pulse), and three different center frequencies for the interferer have been used (f_j = 5, 6 and 7 GHz). Again, the impact of the interference will decrease when ρ gets larger values. However, the impact remains harmful longer than in the case of Figure 6. One should remember that the UWB spectrum is wider in the latter case. Also, the psd of the UWB signal is lower due to the same signal energy assumption in the corresponding cases.

In Figure 8, BER is plotted against different SIR values using the 7th Gaussian pulse (T_p = 0.5 ns) with two E_b/N_0 values; 3 dB and 8 dB. Interference is located at 6 GHz having different bandwidths. Again, the simulated and calculated results are fitting well together. The analytical approach, as can be seen, also estimates the saturation level correctly for each E_b/N_0 values.

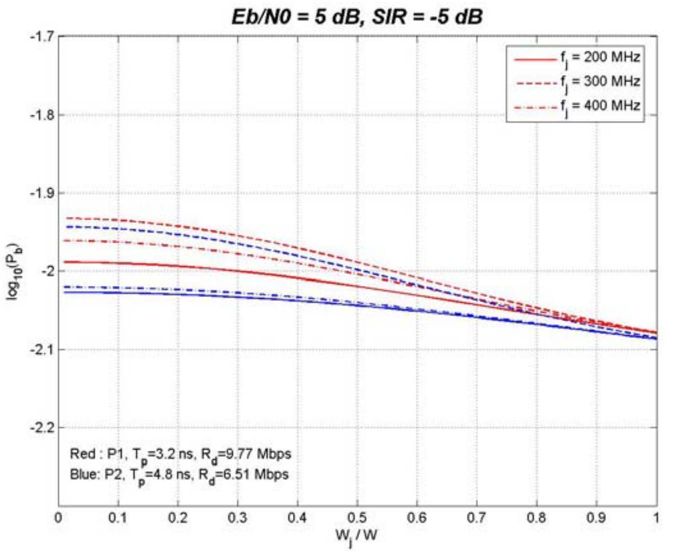

Figure 6. BER as a function of W_j/W for different jamming center frequencies.

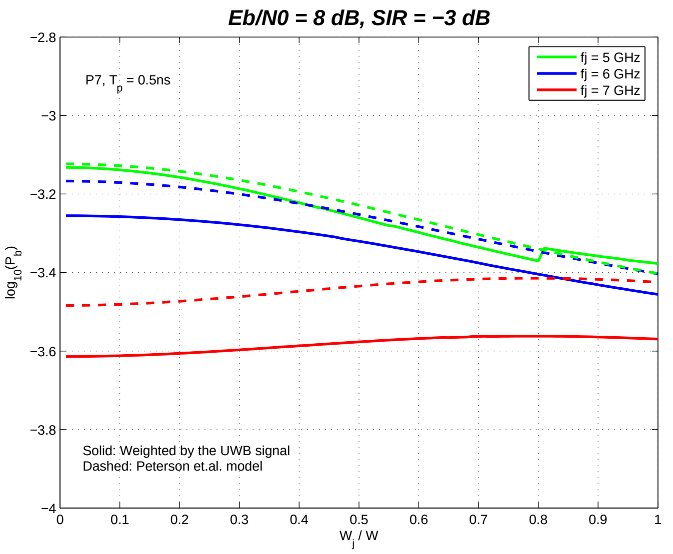

Figure 7. BER as a function of W_j/W for different jamming center frequencies for FCC compliant UWB signal.

In Figure 9, the corresponding BERs as a function of SIR are given for pulses P1 and P7 when the center frequency of the interference varies but the bandwidth is fixed to 20 MHz. The impact of the increased desired signal bandwidth on improved sensitivity against the interference can be easily seen from the curves. When P1 is used, ρ ≈ 4.6% but for P7, ρ ≈ 0.33% using Wj = 20 MHz.

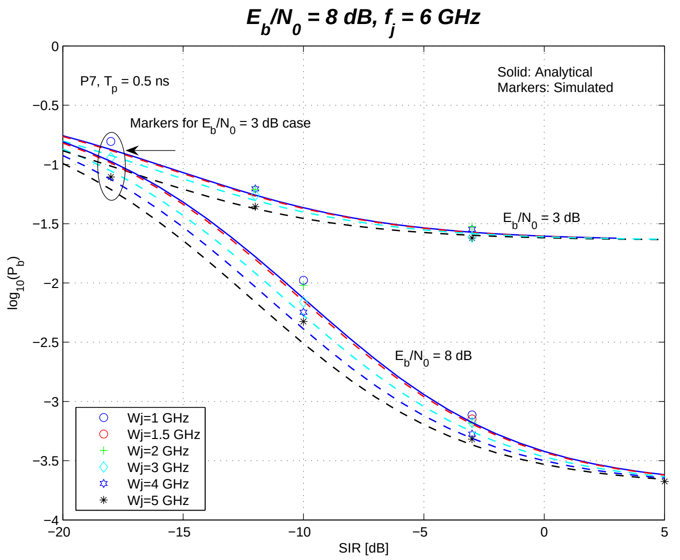

Figure 8. BER as a function of SIR for different W_j; the 7th Gaussian pulse, f_j = 6 GHz, E_b/N_0 = 3 dB and 8 dB.

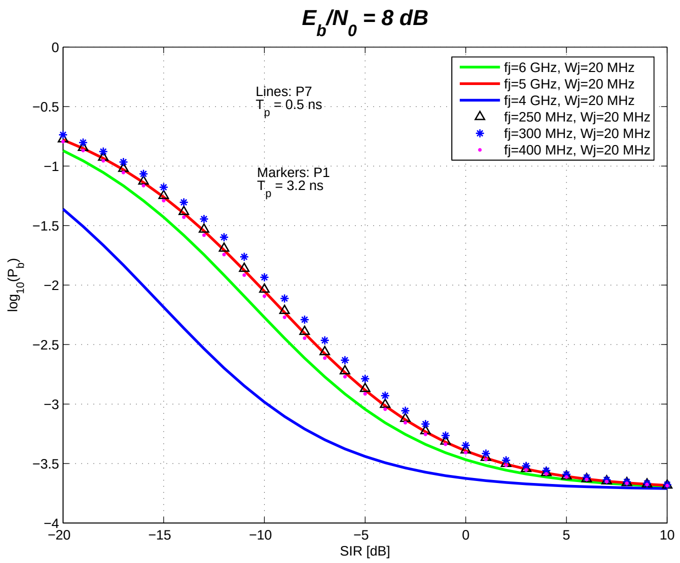

Figure 9. BER as a function of SIR. W_j is fixed to 320 MHz. Pulses P1 and P7.

The suitability of the modified formulas for UWB bit error rate calculations in AWGN channel in the presence of jamming (interference) has been proved and the modified formulations are general and very simple to use. However, more investigation on the generality of the approaches is needed to find exactly the cases, where the presented simple derivations loose the accuracy.

CONCLUSIONS

This paper discusses the analytical approach to calculate jamming impact on DS-UWB system in white Gaussian noise channel. An old analytical approach presented for wideband spread spectrum systems to calculate bit error rate in the presence of narrowband interference is modified to give reasonable good results also in the UWB bandwidths. Using the redefined formulation, example results for UWB signal interference tolerance are given using bit error rates a function of interference-to-signal bandwidth, signal-to-interference and signal-to-noise ratios as indicator. Formulation allows one to use real UWB and interference system parameters as inputs in formulas which make the calculation very convenient if compared to the existing published approaches that give closed-form presentation for same special case of interference and system scenarios.

Though focusing only on AWGN channel, the presented formulation is suitable for the system performance upper bound calculations because all the new receiver algorithms will be first tested in AWGN before applied to more realistic fading multipath channel.

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