Analysis of Interference on DS-UWB System in AWGN Channel

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***Abstract*—This paper discusses ultra wideband (UWB) system performance in additive white Gaussian noise (AWGN) channel in the presence of partial band interference, whose special case is tone interference. In UWB case, most of the interference can be seen as partial band interference due to the extremely large inherent bandwidth of the desired signal. The given redefined formulas are verified with the corresponding simulation results. Study has focused on direct sequence (DS) based UWB system that uses binary pulse amplitude modulation (BPAM) as a data modulation scheme. DS-UWB is selected due to its better performance when related to the corresponding time hopping system in the interfered environment. Interference is assumed to be band limited and Gaussian distributed, and the presented analysis allows freely spacing and arbitrary bandwidth for the interfering signal. It has been proved that the general bit-error-rate (BER) formulas for wideband systems can be applied also to UWB with some modifications to calculate the upper bound for the UWB performance. The given approaches are very simple and can benefit the real system parameters for the desired link.**

I. Introduction

Due to the low transmission power and extremely wide occupied bandwidth, ultra wideband (UWB) technology could be used in overlay basis on the top of other existing radio systems. The -10 dB bandwidth of UWB signal is limited between 500 MHz and 7.5 GHz according to the existing regulations [1].

Currently, there are two competing approaches for UWB; single-band DS-UWB [2] and multiband-OFDM [3] based techniques. The UWB standardization process led by the IEEE 802.15.3 [4] has not been able to select one or the other proposals for a final standard. Single-band approach allows cheap implementation but it is limited by the data rate, in short distances, while multiband approach that is already utilized, e.g., in wireless local area networks (WLAN) could offer much higher data rates with the increasing complexity also for UWB. Single-band approach can be based on non-coherent detection which makes the receiver even simpler. However, the non-coherent system is more vulnerable to intentional interference than the corresponding coherent system.

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This work is focused on the single-band UWB approach which follows more the basic idea of the impulse radio, like presented, e.g., by Scholtz and Win [5]. Though not utilizing time-hopping mechanism from [5], the baseband bipolar UWB pulse train obeying the spreading code polarities 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 communication.

Due to the extremely large inherent bandwidth, UWB receiver captures signal energy that is other than the desired one. Radio channel generates also several multipath components that disturb the received signal. Interference (or jamming in hostile environments) causes performance degradation for the desired communication link and its 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 analyze the performance when interference exists is therefore needed. Then, the possible need for interference suppression methods could be clarified. Typically, the published co-existence results are based on simulations, like in [6]. Some specific analytical results have also been presented, e.g., for time-hopping UWB and DS-UWB in [7] and [8], respectively. However, the utilization of the available closed form formulas is not very easy which makes it reasonable to find out a simple formulation for the analysis to estimate the upper bound for the UWB performance, i.e., lower bound for bit error rate (BER). The bound can be used as a reference when studying the performances of new algorithms or receiver structures. Typically they are first verified in AWGN channel which justifies our work.

This paper is organized as follows: Chapter 2 introduces the used system model. In Chapter 3, the formulas for the analytical bit error rate calculations are given. In Chapter 4, the analytical results are verified against the simulated ones and the exploitation range is discussed. Finally in Chapter 5, the conclusions are drawn.

II. System Model

In UWB systems, one data bit is spread over multiple pulses using pseudo random (PR) code, which in our case is maximum length code (m-sequence). This multi-pulse transmission per symbol could be seen, at the receiver side, as a processing gain, having 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

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bit. In the studied DS-UWB transmission, pulse width T_p equals to chip length T_c of the code, and the transmission is continuous. Silent periods within the transmission could, however, be introduced if $T_p \leq T_c$ when also the average power spectral density is decreased if individual pulse energy remains the same.

The used signal model follows the typical notation used in the radio communications. 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 in general way as

$$r(t) = s(t) + n_j(t) + n(t), \quad (1)$$

where $s(t)$ is the transmitted signal. Multipath components are now omitted but they can be seen as a weighted summation of the replicas of the transmitted signal as

$$s(t) = \sum_{i=1}^{L} \alpha_i s_i(t - \tau_i) \ , \quad (2)$$

where L is the number of multipath, α and τ are attenuation and delay of the corresponding multipath, respectively.

The UWB pulse waveforms used in this study are based on the Gaussian pulse and its higher derivatives. The general Gaussian pulse can be expressed by [9]

$$x(t) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[\frac{-t^2}{2\sigma^2}\right], \quad (3)$$

where t and σ are time and standard deviation, respectively. σ is defined as $\sigma \approx T_p / 2\pi$ where T_p is the desired pulse width. The n^{th} derivative of the Gaussian pulse can be calculated from (3) by differentiating it n times.

III. BER IN THE PRESENCE OF INTERFERENCE

In this chapter, different approaches to calculate bit error rate for DS-UWB in the presence of partial band interference are introduced. Full-band interference in the UWB context is not the most interested case and it can be seen (in most of the cases) based on the multi-user interference due to the extremely large bandwidth occupation by the desired signal.

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

The parameter ζ presents the ratio of the desired signal's power spectral density at the centre frequency of the interfering signal and at the maximum level of psd. Mathematically, this ratio can be presented as

$$\zeta = \frac{S_{UWB}(f_j)}{S_{UWB}(f_c)} \leq 1, \quad (4)$$

where S_{UWB}, f_j and f_c represent UWB power spectral density, centre frequency of interference and UWB (nominal), respectively, as depicted in Figure 1.

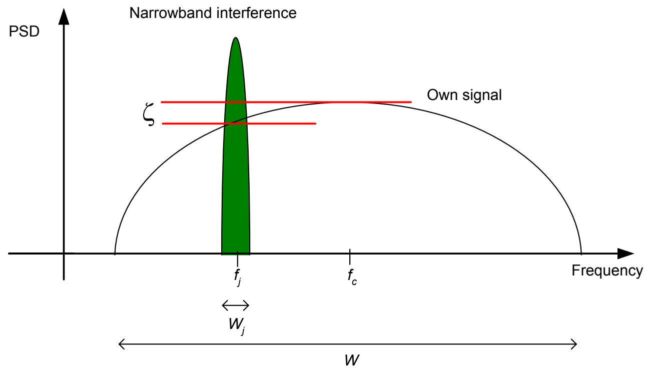

Figure 1. Power spectral densities presented for the desired UWB and jamming signals.

A special case of the partial band interference is tone interference; $W_j << W$. 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, approach. The rest of the study does not cover full-band interference, which can be seen as a multi-user interference as stated above, at all.

A. *Partial band interference*

The following analysis is based on the study derived originally for wideband spread spectrum signal in [10]. In the barrage (full-band) jamming 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 $N'_j = J/W_j$ [10]. The error probability P_b for the BPSK and BPAM modulated signal can be calculated by

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

where E_b is bit energy and $S(f_j)$ is 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 weighted by the psd of the own signal

$$S(f_j) = \frac{N'_j}{W} \int_{f_j - \frac{1}{2}W_j}^{f_j + \frac{1}{2}W_j} \frac{(2\pi f\sigma)^2 \exp\{-(2\pi f\sigma)^2\}}{n^n \exp(-n)} df \ , \quad (6)$$

where n defines the number of taken differentiations of the Gaussian pulse from (3). The nominal centre frequency of the own signal, e.g., in the integrand in (6), is $f_c^{(n)} = \frac{\sqrt{n}}{2\pi\sigma}$ for the n^{th} derivative [11].

B. 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 formula as presented by

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0 + 2N_j}}\right) = Q\left(\sqrt{\frac{2}{\frac{RN_0}{P} + 2\zeta \frac{J}{P}\frac{R}{W}}}\right) \tag{7}$$

where R and P are data rate and signal power, respectively. Except the variable ζ, the equations (5) and (7) are similar than presented in [10] where, however, n and n_j in (1) were assumed to be narrowband if compared to the desired signal. As showed in the following chapters, this limitation can be discarded and the weighted formula gives results that are close to the simulated ones even in UWB bandwidths. Simulations have been run till 100 errors or 10 million bits, which fulfilled first.

IV. RESULTS

In this Chapter, the analytical results are verified with the simulated 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 consisted of 32 consecutive pulses (10lg (32) ≈ 15 dB). The center frequencies of the used UWB signals in the channel are 4.5 GHz, 4.9 GHz and 5.4 GHz for 5th to 7th derivatives of Gaussian pulse, respectively.

A. Bit error rate

In Figure 2, the different analytical approaches are compared against the simulated one. As can be seen, the narrowband (NB) approach without power scaling underestimates the UWB performance when the interfering signal does not overlap the nominal center frequency of the desired one. The NB approach is the original one presented in [10]. On the contrary, the scaled narrowband and partial band approaches give almost the same results. Comparison has been made using the 5th derivative of the Gaussian pulse having T_p = 0.5 ns. Interfering signal is locating at f_j = 3 GHz, having W_j = 10 MHz and signal-to-interference ratio SIR = -5 dB.

In Figure 3, BER is presented for UWB signal using the 7th derivative of the Gaussian pulse with T_p = 0.5 ns. The analytical results are calculated using (5) with (6), and compared with the simulated results; Markers and dotted-lines represent simulated and analytical results, respectively. The UWB system has R = 62.5 Mbps when G = 15 dB. The nominal center frequency of the desired signal in the channel is 5.4 GHz and the five different jamming frequencies are studied (each interferer has W_j = 100 MHz). As the curves showed, the analytical results are well 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.

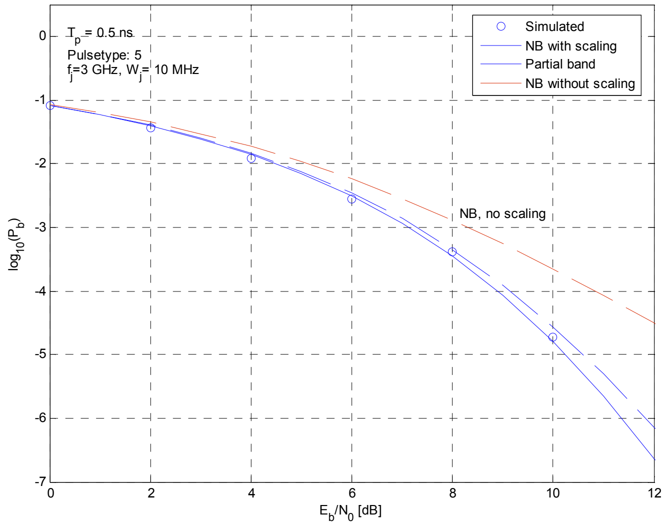

Figure 2. Comparison between the different approaches.

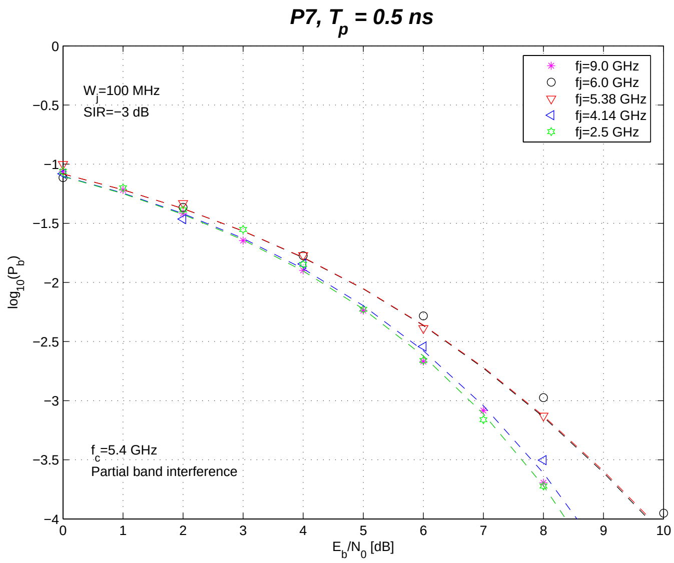

Figure 3. BER for different interfering frequencies; simulations (markers) vs. partial band (lines) calculations.

Corresponding results when using narrowband approach from (7) are presented in Figure 4. This approach gives reasonable good results when scaling factor ζ is used. If ζ is omitted, the accuracy of the estimation decreases when shifting the interference away from the nominal UWB centre 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.

In Figure 5 the used UWB pulse is either 5th or 6th derivative of the Gaussian pulse. Signal-to-interference ratio is varying from 0 dB to -15 dB. As can be seen from the results, the analytical approaches (both scaled NB and PB) meet the simulated values even if the BER saturates due to the low SIR value.

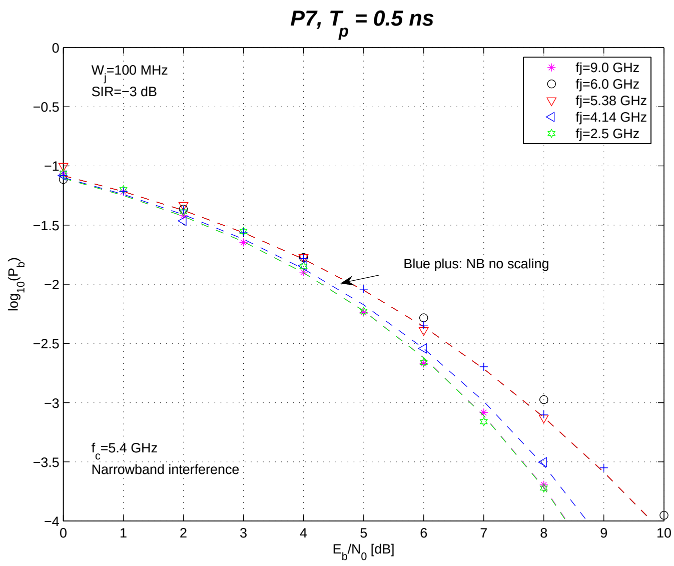

Figure 4. BER for different interfering frequencies; simulations (markers) vs. narrowband (lines) calculations.

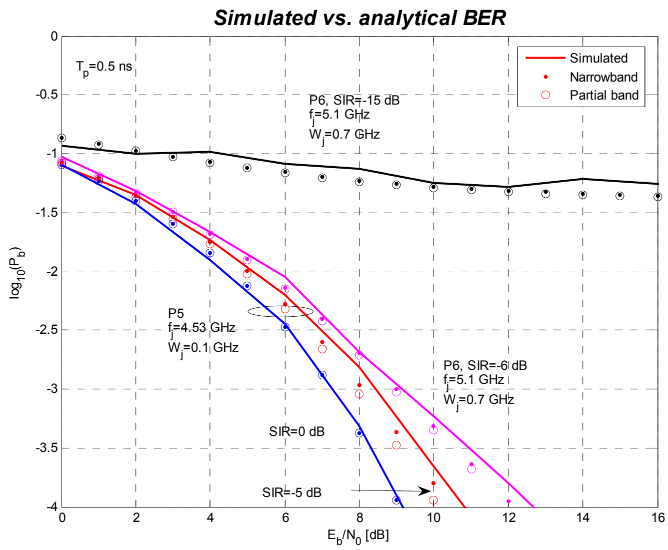

Figure 5. BER using different waveforms with different SIR.

The results presented above are used to prove that the existing BER formulas that are created for wideband systems in the presence of narrowband interference can be adopted also in UWB context. The accuracy of the formulas is improved by using the scaling factor that better takes into account the spectral properties of the UWB signal.

B. Exploitation

Despite that the analytical approach gives similar results than the corresponding simulated ones, there are some parameter ranges where the matching is better than elsewhere. This exploitation range is discussed next.

In Figure 6, the difference in E_b/N_0 between the simulated and analytically calculated results to reach BER = 10^{-3} is drawn as a function of the order of the Gaussian pulse. Positive value indicates that simulations give worse BER than the corresponding analytical approach. Interference is located at $f_j = 0.6f_c$ having W_j = 200 kHz and SIR = -5 dB. Corresponding results when the interference is above the nominal UWB centre frequency are given in Figure 7 using wider interference bandwidth; W_j = 200 MHz and 20 MHz. PB(B) and PB(U) depict the original partial band formula from [10] and modified formula from (5) with (6).

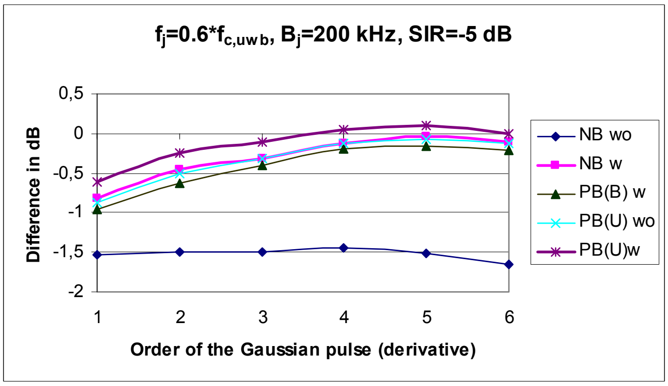

Figure 6. Difference between analytical and simulated results; $f_j = 0.6f_c$, W_j = 200 kHz, SIR = -5 dB.

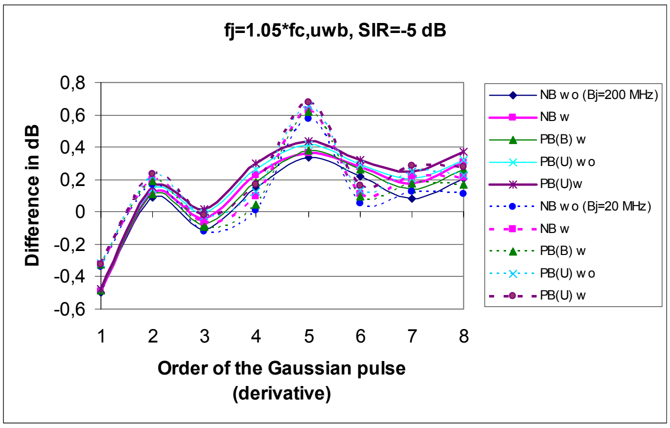

Figure 7.Difference between analytical and simulated results; $f_j = 1.05f_c$, W_j = 200 MHz and 20 MHz, SIR = -5 dB.

As can be seen form these figures, the difference between the analytical and the simulated results varies with the order of the used Gaussian pulse. If $f_j < f_c$, the weighted formulas of (5) and (7) are the closest to the corresponding simulated results. When the bandwidth of the interference signal increases, the differences between the analytical results come closer to each others, typically around 0.1 dB. The biggest difference between the results can be seen when W_j is small. Then, the narrowband formula without weighting does not match the simulations but the weighted approach is giving reasonable accurate estimation for the UWB system performance. In that case, the partial band approach from (5) with (6) gives the best estimation but the difference to (7) with weighting is only 0.2 dB, which is insignificant.

If studying the case when $f_j = 0.8f_c$ from Figure 8 it can be seen that the impact of the bandwidth of the interference is insignificant in the formulas when f_j is close to f_c. Now, the studied bandwidths are 200 kHz and 20 MHz. Again, the weighted partial band approach gives the best estimation to the UWB system performance and the narrowband approach is the second best. Using the narrowband formula without scaling differs about 1 dB from the simulated results.

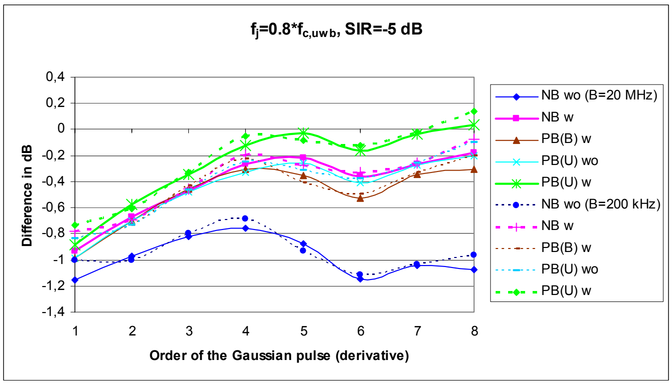

Figure 8. Difference between analytical and simulated results;

f_j = 0.8f_c, W_j = 200 MHz and 20 MHz, SIR = -5 dB.

The general trend is that the higher is the order of the Gaussian pulse, the bigger is the difference between the non-weighted narrowband approach to simulated results when the interference is shifting further from f_c. Partial band formula with weighting can, however, be used in all the cases.

C. *Numerical example*

Finally, the performance limits using specific system assumptions are given as a function of SIR. The calculations are made using the partial band formula discussed above.

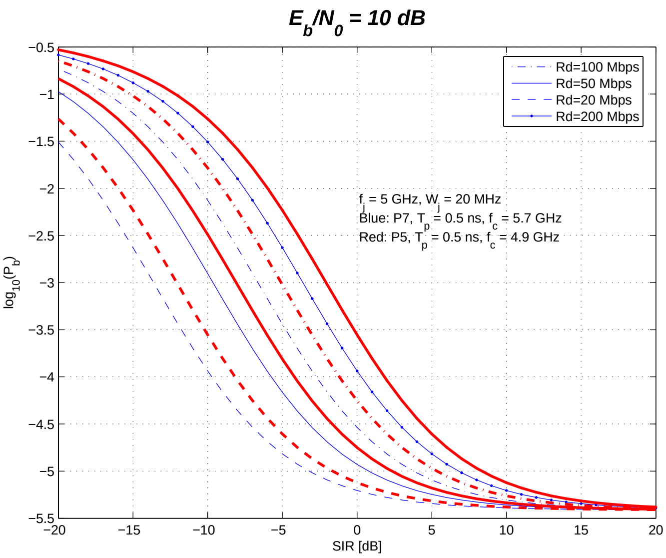

Figure 9. BER as a function of SIR for different UWB data rates.

In Figure 9, the UWB data rates vary from 20 Mbps to 200 Mbps. Interference is locating at 5 GHz and have 20 MHz bandwidth. UWB centre frequencies are 4.9 and 5.7 GHz. The UWB system performance is affected by the data rate but also by the pulse waveform due to the spectral allocation. As can be seen, the UWB system performance saturates at the level of $10^{-5.4}$ with increasing SIR when E_b/N_0 is fixed to 10 dB. 10^{-3} BER level could be achieved even with the SIR = -13.5 dB when the data rate is 20 Mbps (the 7th Gaussian pulse). If the required data rate is 200 Mbps, at least -3.6 dB SIR is required. The corresponding SIR limits for the 5th Gaussian pulse are -12 dB and -2 dB, respectively.

V. Conclusions

This paper discusses the analytical approach to calculate the impact of interference on DS-UWB bit error performance. The main contribution is the formulation which can be used when estimating the UWB system performance degradation in the presence of interference (or jamming in a hostile environment). 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 interference is taken into account. Using the approach presented in this paper, one can use the UWB system parameters in the BER calculations which make the use of formulas very convenient. It is shown that the given formulas follow the simulated results and are also able to estimate the saturation of the UWB system performance in the presence of interference.

The upper bound performance in additive white Gaussian noise channel is useful when studying, e.g., new receiver algorithms. The first reference of the usability is typically AGWN channel.

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