Performance Comparison Between Various UWB Signals in AWGN Channel in Presence of Multitone Interference at the GSM Downlink Band

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Abstract

This paper studies the performances of carrierless ultra wideband (UWB) systems in AWGN channel with the presence of narrowband multitone jamming at the GSM downlink band. System models are based on time hopping and direct sequence concepts. The systems are studied in single UWB user case, whereas the interference model consists of multiple narrowband interference sources. Performance measure is bit error rate as a function of signal-to-noise ratio. Both of the UWB concepts spread one information bit to the numerous consecutive narrow pulses. The radiated UWB pulse waveforms (i.e. the waveforms in the channel) are modeled using the 1st and the 3rd derivatives of a generic Gaussian pulse. Data modulation is based on the binary baseband modulation scheme. The results showed that the UWB system based on the time hopping concept performs slightly better than corresponding direct sequence based system. Also, the pulse waveform based on the 3rd derivative of Gaussian pulse leads usually better performance than the pulse based on the 1st derivative of Gaussian pulse.

Key words

Ultra wideband, time hopping, direct sequence, spread spectrum, bit error rate, narrowband, multitone, interference.

1. Introduction

Ultra wideband (UWB) technology is a promising technique for future data communication systems, high accuracy (indoor) geolocation devices, sensor applications, etc. UWB systems utilize carrierless transmission with very low power spectral density. UWB techniques are based on the transmission of nanosecond level short pulses that generate extremely wide spectrum. This results in a covert noise-like signal in a radio channel. UWB technology can be comprehended as a time hopping spread spectrum technique, although there is no pseudo random code used for spectral spreading. The narrow pulse waveform spreads the signal energy over the large frequency band. In a conventional direct sequence spread spectrum system the spectrum is spread by increased chip rate. Sub-nanosecond pulse yields a -10 dB bandwidth of several GHz. This paper discusses about two types of UWB concepts.

In a time hopping (TH) UWB system, a pseudo random (PR) code is used to indicate the transmission instant of the pulses. In TH-UWB each user has their own PR code, which is used not only to separate the users, but also to smooth the spectrum [1]. Pulse repetition interval is randomized, which suppresses of the fixed line spectral components.

Another method to generate UWB signal is to utilize direct sequence (DS) spread spectrum concept with a chip waveform of a very narrow pulse [2]. Also in the DS-UWB each user has an individual PR code for user separation and spectrum smoothing.

At the moment, the equipments based on the ultra wideband technology are not allowed to be used commercially. The governmental authorities in the USA (FCC) and in Europe (CEPT) are making regulations and standards for the technology. This regulatory work will direct also the final applications that are going to benefit this technology. In ideal case the same equipment can be used for high data rate communication as well as for geolocation.

2. System model

Figure 1 introduces the basic ideas of the TH-UWB and the DS-UWB concepts covered in this paper. The two UWB concepts represent each transmitted data bit using a number of individual pulses, in this example $N = 4$. At the reception, one can achieve processing gain due to the pulse repetition (cf. repetition coding) by $G_N = 10\log_{10}(4) = 6$ dB, in both concepts. Additional processing gain in TH-UWB is brought in by the low duty cycle. Duty cycle is the ratio of the pulse repetition interval T_f and the pulse width T_p, expressed by $G_d = 10\log_{10}(T_f/T_p)$ dB. Total processing gain in the TH-UWB concept is therefore $G_t = G_N + G_d$ [dB].

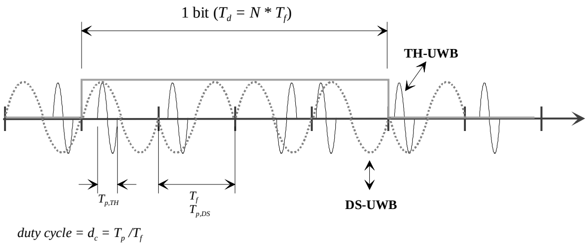

Figure 1: UWB system based on time hopping and direct sequence techniques

In our study, data modulation scheme is baseband binary pulse amplitude modulation (BPAM), where pulse or its amplitude reversed version is sent. In other words, because the UWB systems do not have carrier frequency, modulation can be seen as a baseband bipolar modulation. The other modulation scheme generally used in UWB applications is pulse position modulations (PPM) [1], but it is excluded from this study.

The information signal $s(t)$ for the m^{th} user in the TH-UWB can be mathematically presented as

$$s^{(m)}(t)=\sum_{k=-\infty}^{\infty}\sum_{j=1}^{N}w\left(t-kT_d-jT_f-\left(c_w\right)_j^{(m)}T_c\right)d_k^{(m)}\ , \tag{1}$$

and in the DS-UWB the corresponding form is

$$s^{(m)}(t)=\sum_{k=-\infty}^{\infty}\sum_{j=1}^{N}w\left(t-kT_d-jT_c\right)\left(c_p\right)_j^{(m)}d_k^{(m)}, \tag{2}$$

where $w(t)$ is the pulse waveform in time, d_k is the k^{th} data bit, N presents the number of pulses to transmit one data bit, $(c_p)_j$ is the j^{th} chip of a PR code and $(c_w)_j$ is the j^{th} code phase defined by the spreading code, T_d present the length of a data bit, respectively. T_f and T_p remains the same as earlier noted.

Both of the UWB concepts utilize two different kinds of radiated pulse waveforms. A generic pulse waveform $w(t)$ is a Gaussian pulse defined by

$$w(t)=\frac{\exp\left(-0.5\left(\frac{t-m}{\sigma}\right)^2\right)}{\sigma\sqrt{2\pi}}, \tag{3}$$

where t = time, m = mean value and σ = standard deviation of the Gaussian distribution. The pulse width T_p in Eq. 3 is related to the standard deviation via $\sigma = T_p/2\pi$.

The transmitting and receiving antennas are modeled as differentiation (derivative) operations [3]. In other words, the pulse waveforms in the channel and at the receiver are higher derivatives of the generated Gaussian pulse.

In our case the radiated pulse waveforms (i.e., the waveforms in the channel) are the 1^{st} and the 3^{rd} derivatives of the Gaussian pulse. The radiated waveforms and their spectra are presented in Figures 2 and 3, respectively. In Figure 3 there is also marked the GSM900 downlink band [4] to show where the interfering signal is located. In the figures, the pulse energies are equalized.

Figure 4 shows the pulse at the receiver end, where a derivative operation is applied to simulate the RX-antenna. Then the received waveforms for the radiated 1^{st} and the 3^{rd} derivative of the Gaussian pulse are the 2^{nd} and the 4^{th} derivative, respectively. Later in the text, the 1^{st} derivative of Gaussian pulse is called Gaussian 1^{st} derivative, and correspondingly the Gaussian 3^{rd} derivative means the 3^{rd} derivative of Gaussian pulse.

Conventionally, spread spectrum systems use long spreading codes to achieve processing gain against narrowband interference. This is done by using high chip rates. If one likes to obtain higher data rates R_d with the same bandwidth one has to use a lower processing gain G. Because the DS spread spectrum system is based on superheterodyne tranceiver the center frequency can be selected independently of the chip rate. In UWB systems the pulse width fixes both the center frequency and the bandwidth of the transmission.

UWB spectrum depends on both the pulse width and the pulse waveform. A narrow pulse generates wide spectrum whose bandwidth is inversely proportional to the pulse width. The frequency band (location of the main lobe of the spectrum

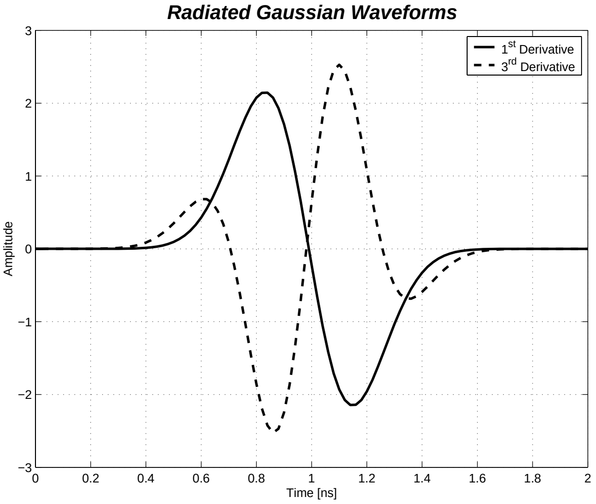

Figure 2: The radiated pulse waveforms

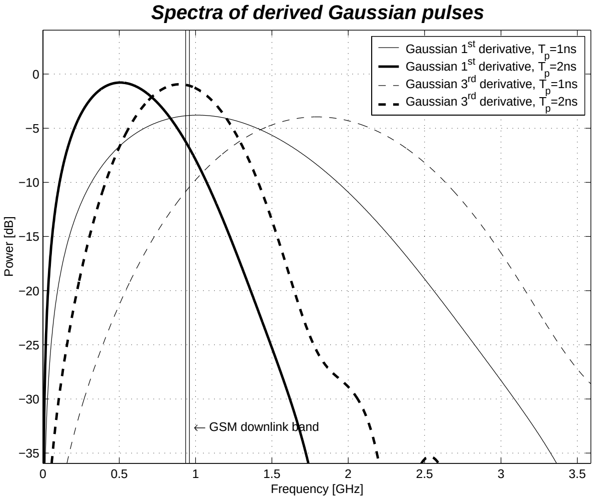

Figure 3: Transmitted UWB spectra

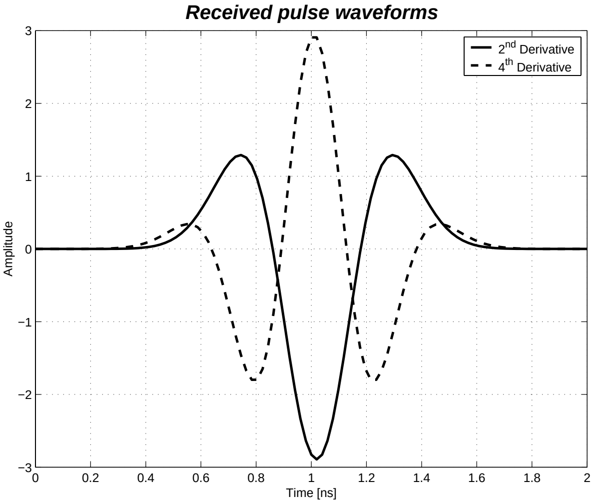

Figure 4: The received pulse waveforms

envelope) depends on the pulse waveform. The Gaussian 1st derivative has a center frequency at $f_c \approx 1/T_p$ and the -10 dB bandwidth $B_{-10\mathrm{dB}} \approx 2/T_p$. The Gaussian 3rd derivative has a center frequency at $f_c \approx 1.73/T_i$ and $B_{-10\mathrm{dB}} \approx 2.1/T_p$. The center frequency of a UWB spectrum is defined as a frequency having a maximum power level. As can be noticed from Figure 3 spectra of both the both waveforms are asymmetric about f_c. The spectral properties of the pulse waveforms with lengths of T_p = 1 ns and T_p = 2 ns are presented in Table 1.

Table 1: f_c and B_{-10dB} for the Gaussian 1st and the Gaussian 3rd derivatives [GHz] with T_p = 1 ns and T_p = 2 ns

Waveform	T_p = 1 ns		T_p = 2 ns	
	f_c	**B_{-10dB}**	**f_c**	**B_{-10dB}**
1st deriv.	1	2	0.5	1
3rd deriv.	1.73	2.1	0.865	1.05

Data rate R_d in UWB system can be calculated as $R_d = 1/(NT_f)$, where N is the number of transmitted pulses/data bit, and T_f defines the pulse repetition interval. At the receiver, N consecutive pulses are coherently combined before the bit decision. From the receiver's point of view this is seen as a pulse integration.

The DS-UWB has a duty cycle $d_c = T_p/T_f$ = 100%, and the total processing gain (G_t) comes solely from the pulse integration (N), i.e., $G_t = G_N = N$. In the TH-UWB, the duty cycle is less than unity, which introduces silent periods into the transmission. Because the nominal transmission instants are randomized by the PR code, also the allocations and the lengths of the silent periods are randomized. G_t comes from the pulse integration as well as from the duty cycle $G_t = NT_f/T_p = G_N G_d$, where $G_d = T_f/T_p$ is the processing gain contributed by the duty cycle.

Data rate of a TH system is

$$R_{d,TH} = 1/(NT_f) = 1/(NT_pG_d) = 1/(T_pG_t), \tag{4a}$$

and in DS system the corresponding data rate is

$$R_{d,TH} = 1/(NT_f) = 1/(NT_p) = 1/(T_pG_t). \tag{4b}$$

The assumption of the constant processing gain produces similar spectrum and the same R_d for both the UWB concepts having the same T_p but the number of transmitted pulses per data bit differs, i.e. in TH-UWB the number of pulses per data bit is scaled down by G_d. Keeping the average energy over one data bit the same, gain lost in smaller pulse integration is regained by increasing pulse peak power respectively. The cost is the increasing interference caused to the other radio systems. Table 2 summaries the data rates of the UWB systems for the different pulse widths. The values are calculated using (4) and setting the total processing gain G_t = 20 dB.

Table 2: Data rates for simulated pulse widths, $[T_p]$ = ns and $[R_d]$ = Mbps

T_p	0.5	0.75	1.0	1.5	2.0	5.0
R_d	20	13.3	10	6.67	5	2

The radio channel is assumed to be additive white Gaussian noise channel (AWGN). The narrowband interference consists of ten GSM physical channels with a fully loaded frame structures. Because the channel bandwidth in GSM900 (BW_{GSM} = 0.2 MHz [4]) is a small fraction of the bandwidth of the UWB signal (typically BW_{UWB} > 500 MHz), the interference caused by GSM can be modeled using a multitone representation, where each channel is modeled by a tone. The received signal $r(t)$ for the m^{th} user can then be modeled by

$$r^{(m)}(t) = s^{(m)}(t) + n(t) + J(t), \tag{5}$$

where $n(t)$ and $J(t)$ presents noise and interference, respectively.

At the receiver the signal is detected in a correlator, whose template waveform corresponds to the signal waveforms presented in Figure 4. Correlation results are summed together, and the bit decision is made after N pulses has been received to form one data bit. Since we assume coherent reception, we achieve a processing gain G_N.

3. Simulation Assumptions

This chapter describes the procedure for the UWB system performance comparison simulations. Simulation environment has been built over Matlab®.

During the simulations a data sequence will be sent through the AWGN channel, where the interference signal is added to the propagating UWB signal. Total interfering narrowband signal power is evenly spread over ten randomly spaced carriers in the GSM900 downlink band (935 MHz – 960 MHz [4]). The GSM channel allocation is renewed each time the signal-to-noise ratio (SNR) is changed. The random phases of each of the jamming tone signals are updated when the data bit is changed. The GSM downlink channels 0 and 124 are always allocated but the rest of the channels are randomly selected with 200 kHz separation within the total downlink band. This selection maximizes the band occupation of the interference tones maintaining reasonable computational speed. Because the GSM uplink band occupies the frequency band 20 MHz below the GSM downlink band these results can, in some extend, to be applied for the uplink case as well.

Simulation limit per each SNR point is one million transmitted data bits or 100 incorrect bits, which ever comes first. Perfect synchronization in the UWB system is assumed at the receiver. The simulated pulse waveforms are shown in Figure 2.

As one can notice from Table 1, the spectra will be shifted to the higher frequencies when the degree of derivatives taken from the Gaussian pulse is increased (pulse waveform contains more zero crossings). Increasing T_p, the spectrum moves towards the lower frequencies. The fractional bandwidth B_f is defined by [5]

$$B_f = 2\frac{f_h - f_l}{f_h + f_l}, \tag{6}$$

where f_h and f_l are the higher and the lower band edge frequencies, respectively. [5] uses edge frequency of –3 dB below the center of spectrum, but also –10 dB band edge has been used by some authors. According to the definition of DARPA[1] signal is an UWB signal when B_f > 25%.

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[1] Defence Advanced Research Projects Agency

In this study G_t = 20 dB was used. Both the TH concept and the DS concept utilize maximum length code as a pseudo random code. In the DS-UWB this means that one data bit is sent using 100 pulses yielding the processing gain G_N.

In the TH-UWB a smaller number of pulses is generated, and the total G_t = 20 dB is maintained by increasing the pulsed energy. By this mechanism the lowered duty cycle comes to processing gain G_d. The level of interference caused to the other systems can be reduced by transmitting fewer pulses and taking advantage of the G_d at the UWB receiver end. However, the individual pulse energy increases when N decreases. In [6] the interference caused by different kinds of UWB signals to the GSM bands are studied as a function of pulse width.

4. Results

This chapter discusses the performances of various UWB systems in an AWGN channel with the presence of multitone jamming in GSM downlink band.

The simulation results are bit error rate (BER) curves as functions of both the desired UWB transmission signal to noise ratio and as functions of the total interfering multitone power. The reference curve in the following figures is the theoretical upper bound limit for BPAM modulated signal in AWGN channel, which is also the upper bound performance limit for BPSK. The theoretical upper bound limit P_e can be calculated using formula [7]

$$P_e = Q\left(\sqrt{2\frac{E_b}{N_0}}\right), \tag{7}$$

where E_b = bit energy and N_0 = noise energy.

Figure 5a and Figure 5b show the bit error rates for the 1st derivative of the Gaussian pulse in the TH-UWB and the DS-UWB systems, respectively. Performance curves are presented for several pulse widths suitable for high data rate UWB communication applications. Power of the UWB signal under interest is set to 0 dBm. The observed total interference power in a GSM downlink band at the receiver antenna is 15 dBm, in all cases. This yields a signal-to-jamming ratio (S/J) of -15 dB. Corresponding results for the Gaussian 3rd derivative are shown in Figure 6a and Figure 6b, respectively. The results show that the performance of the TH-UWB system is slightly better than the referred DS-UWB system. Our results express that the SNR difference between the concepts is about
0.5 dB … 1 dB to achieve the same performance.

Comparing Figure 5a and Figure 6a to see the effect of pulse waveform in the TH-UWB concept, one can notice that the Gaussian 3rd derivative leads to better performance than the Gaussian 1st derivative when $T_p < 2$ ns. Similar results for the DS-UWB can be noticed from Figure 5b and Figure 6b.

From Figure 3 one can notice that in the GSM downlink band the energy level of the UWB spectra of, e.g., the Gaussian 3rd derivative with T_p = 1 ns is about 9.6 dB lower than that of T_p = 2 ns. This might suggest that the former system tolerates 9.6 dB more interference power, still achieving the same system performance. Generalizing this comparison, we maintain that the results discussed here can be applied to a broad range of interference levels by calculating the jamming margin directly from the spectrum of the pulse. However, this topic needs some further evaluations. In general, the system performance decreases when the pulse width increases. This roots from the spectral shape of the UWB signal. Gaussian 1st derivative with T_p = 1 ns yields center frequency 1 GHz which is close to that of the interference source. Respectively, Gaussian 3rd derivative with T_p = 2 ns yields f_c = 865 MHz. Being a relatively narrowband interference around the vicinity of 950 MHz, the GSM downlink signal resembles a pulse whose width is matched close to the UWB signal.

These results of the pulse width matched interference can be seen in Figures 5a-b on curves for T_p = 1 ns, and in Figures 6a-b on curves for T_p = 2 ns. Setting T_p small enough the spectrum moves to higher frequencies and eventually out of the reach of the interfering frequency, as can be seen in Figure 3. This explains the improvement in the performance of the UWB system using narrow pulses. Without interference source, all curves in Figures 5-6 would fall on the theoretical performance curve. Changing the center frequency of the narrowband interference the performance results would be different.

Decreasing T_p or increasing the order of derivative of the radiated waveform will shift the power spectral density towards higher frequencies giving a larger jamming margin against GSM interference in both the TH-UWB and the DS-UWB systems.

When used in through-wall radar or indoor geolocation applications, longer pulses should be used to achieve reasonable penetration capabilities through the matter.

5. Conclusions

UWB communication system is able to combat narrowband interference with several ways. Pulse integration with coherent correlation receiver is the simplest method to achieve processing gain. The most powerful and at the same time the most demanding technique in combat against narrowband interference is pulse shaping, where UWB pulses are tailored to meet desired spectral properties.

The presented results show that, in the presence of the interference in GSM downlink band in AWGN channel, the time hopping UWB concept performs slightly better than the direct sequence based UWB concept. Also, according to the results the Gaussian 3rd derivative gives better perfomance compared to the Gaussian 1st derivative when pulse width is less than 2 ns.

6. Acknowledgements

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7. References

[1] Scholtz R.A., Win M.Z., ”Impulse Radio”, *Wireless Communications, TDMA versus CDMA* (Ed. S.Glisic, P.Leppänen), Kluwer Academic Publisher, London 1997, pp. 245-263.

[2] McCorkle J., *A Tutorial on Ultrawideband Technology*, doc: IEEE 802.15-00/082r0, Mar 2000.

[3] Ramirez-Mireles F., Scholtz R., “System Performance Analysis of Impulse Radio Modulation”, *Proceedings of the Radio and Wireless Conference (RAWCON1998),* Colorado Springs, CO, USA, 1998.

[4] Mouly M., Pautet M-B., *The GSM System for Mobile Communications*, Telecom Publishing, 1992.

[5] Taylor J.D. (Ed.), *Introduction to Ultra-Wideband Radar Systems*. CRC Press, Inc., Boca Raton, FL, USA, 1995.

[6] Hämäläinen M., Iinatti J., Latva-aho M., Hovinen V., "In-Band Interference of Three Kind of UWB Signals in GPS L1-Band and GSM900 Band", *Proceedings of the Personal, Indoor and Mobile Radio Communications Conference (PIMRC2001)*, San Diego, CA, USA.

[7] Couch II L.W., Digital and Analog Communication Systems. Macmillan Publishing Co., Inc., New York, 1983.

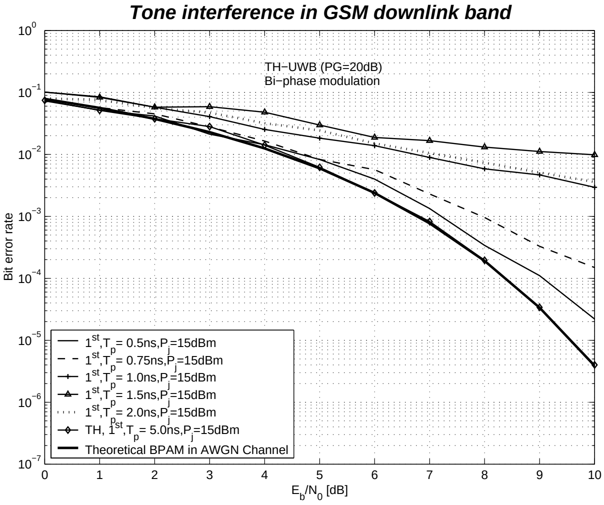

Figure 5a: Bit error rates for TH-UWB system utilizing the 1st derivative of Gaussian pulse with different pulse widths in the presence of multitone interference, interference power is 15 dBm

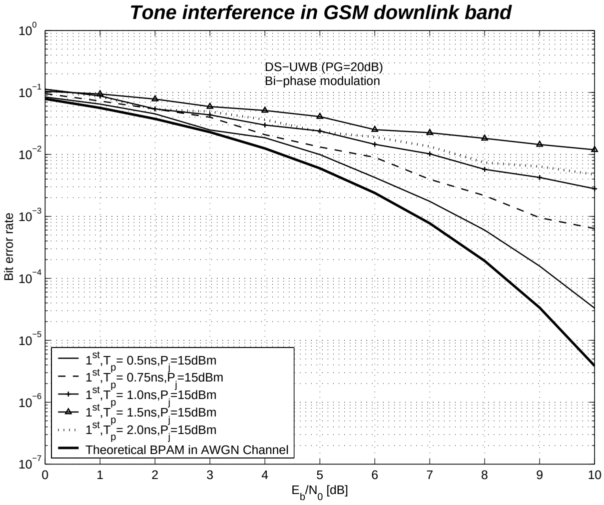

Figure 5b: Bit error rates for DS-UWB system utilizing the 1st derivative of Gaussian pulse with different pulse widths in the presence of multitone interference, interference power is 15 dBm

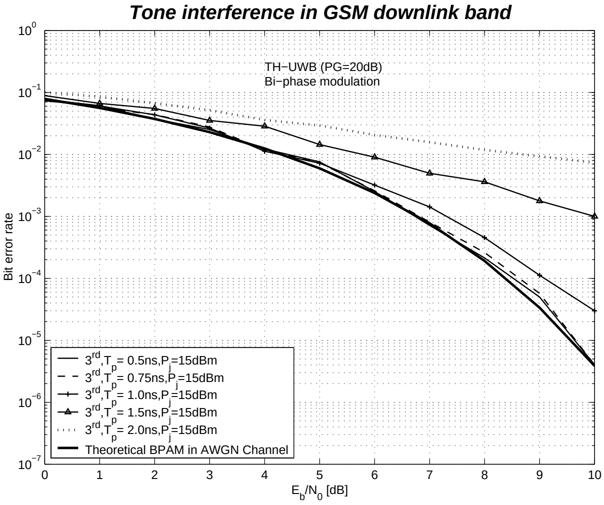

Figure 6a: Bit error rates for TH-UWB system utilizing the 3rd derivative of Gaussian pulse with different pulse widths in the presence of multitone interference, interference power is 15 dBm

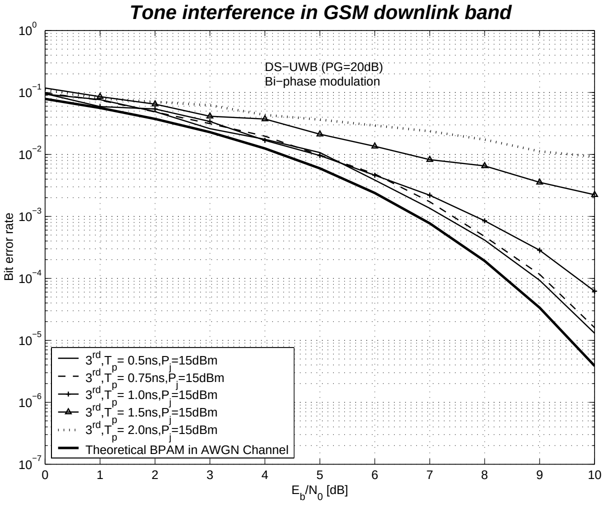

Figure 6b: Bit error rates for DS-UWB system utilizing the 3rd derivative of Gaussian pulse with different pulse widths in the presence of multitone interference, interference power is 15 dBm