In-Band Interference of Three Kind of UWB Signals in GPS L1 Band and GSM900 Uplink Band

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Abstract - **This paper studies in-band interference of different kind of ultra wideband (UWB) signals. UWB frequency spectra are produced by using several types of narrow pulse waveforms, all based on Gaussian pulse. Due to the extremely wide bandwidth these signals spread over the frequency bands allocated to the other radio systems. In-band interference power is calculated over the IF bandwidths of two victim receiver as a function of pulse width. Also, the signal attenuation with distance is presented. The victim systems under the study are GPS (L1-band) and GSM900. Based on the results the 3rd derivative of a Gaussian pulse seems to be best choice in the interference point of view among the waveforms included in this study. It will cause less interference than Gaussian pulse or Gaussian doublet if the pulse widths are shorter than 1 ns. The system utilizing direct sequence concept caused less in-band interference power than the system utilizing time hopping amongst all waveforms studied. The studied UWB systems are based on bi-phase baseband data modulation.**

I. INTRODUCTION

Ultra wideband (UWB) technology is one possible solution for the short range indoor communication applications. This technology has been introduced some decades ago but the applications have mostly been in ground penetrating radar systems [1]. UWB systems spread the signal energy over the extremely large frequency band and make the power spectral density very low. An easy pulse waveform to generate UWB spectrum is a narrow Gaussian pulse and some of it's modifications. The bandwidth of a Gaussian pulse is inversely proportional to the pulse width.

Due to the wide bandwidth of the UWB signal, the UWB energy will spread over the frequency bands allocated to the other radio systems, like GPS, cellular phones, broadcasting, etc. Currently, FCC in the USA is making regulations for UWB applications. In Europe this regulatory work has also been started by CEPT and ETSI. During the regulatory work some experimental field tests between the UWB transmitters and e.g. GPS receivers have been made [2,3]. The difference between this study and the other published studies is that this work considers different pulse waveforms under the same assumptions and conditions. This allows one to compare the interference levels in GPS and GSM frequencies caused by different UWB pulses. Corresponding study in the UMTS/WCDMA band can be found from [4].

In this paper, three pulse waveforms to generate UWB signal are studied. All waveforms are modifications of generic Gaussian pulse. The first waveform is the simplest one, a Gaussian pulse [5]. The second one is composed using two amplitude reversed Gaussian pulses with time gap between the pulses. It is called Gaussian doublet [6]. The third one is the 3rd derivative of a Gaussian pulse and this waveform resembles the wavelet presented in [7]. Some other waveforms to generate UWB signal are presented in [1] and [8] but they are not considered in this paper.

II. SYSTEM MODEL

A. *Time Domain Presentation*

Time domain presentations for the three narrow pulse waveforms to generate UWB signals used in this study are shown in Fig. 1. The effect of the UWB antenna in the transmitter is modelled as a derivative operation [9], so the waveform in time domain in the radio channel is the first derivative of the pulse waveform from Fig. 1.

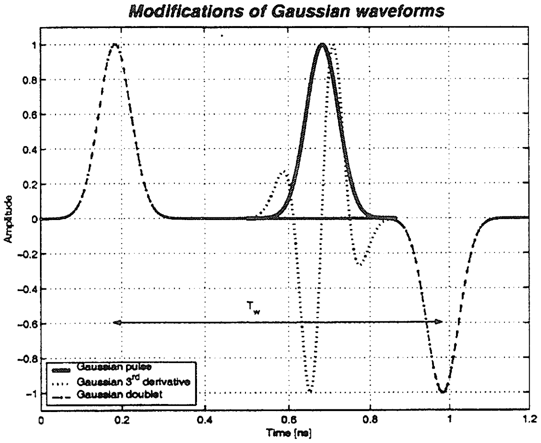

Fig. 1. Pulse waveforms used in this study.

In Fig. 1, the pulse width T_p of each waveform is equal to $T_p = 0.25$ ns. The Gaussian doublet consists of two amplitude reversed pulses with equal T_p transmitted with the time difference T_w. The data modulation technique used in the study is bi-phase baseband modulation. In time hopping mode (TH-UWB) the modulated information signal $s(t)$ for the m^{th} user can be presented as

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

and in direct sequence mode (DS-UWB)

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

where d_k is the k^{th} data bit, $(c_p)_j$ is the j^{th} chip of PR code and $(c_w)_j$ is the j^{th} code phase defined by the spreading code and $w(t)$ is the pulse waveform. N presents the number of pulses used to transmit one data bit, T_c is chip length and T_f is pulse repetition interval (frame length). Bit length $T_b = NT_c$ in DS and $T_b = NT_f$ in TH. In DS-UWB $T_c = T_p$ and in TH-UWB $T_f > T_p$ producing low duty cycle. Both the data and the code are bipolar ($d(t) \in \{-1,1\}$, $c(t) \in \{-1,1\}$).

B. Frequency Domain Presentation

The normalized spectra of different pulse waveforms used in the study are presented in Fig. 2. The pulse separation T_w inside a Gaussian doublet defines the spectral null spacing but the envelope of the spectrum is defined by the pulse waveform and pulse width. The effect of the pulse separation can be seen in Fig. 3 and it can be calculated using

$$f_{null} = 1/T_w\,. \tag{2}$$

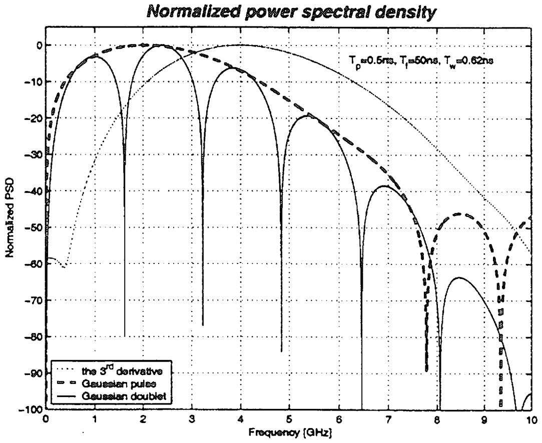

Fig. 2. Normalized power spectral densities for different pulse waveforms; T_p = 0.5 ns, T_w = 0.62 ns.

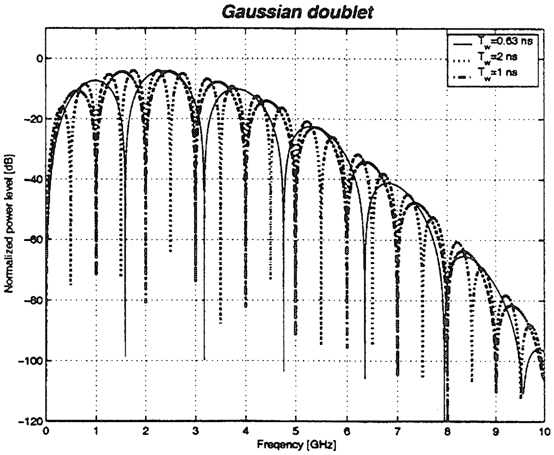

Fig. 3. Spectrum of the Gaussian doublet having different pulse separations, T_p = 0.5 ns.

Center frequency f_c (defined as the frequency having the maximum power level) is inversely proportional to the pulse width when the pulse waveform is Gaussian pulse or Gaussian doublet, $f_c \approx 1/T_p$. B_{-10dB} is about twice the center frequency. If the pulse waveform is the 3rd derivative of the Gaussian pulse $f_c \approx 2/T_p$. In the latter case the B_{-10dB} is about the same as the center frequency. In all cases the spectrum is asymmetric about f_c. Center frequencies as a function of pulse width for different waveforms are presented in Fig. 4.

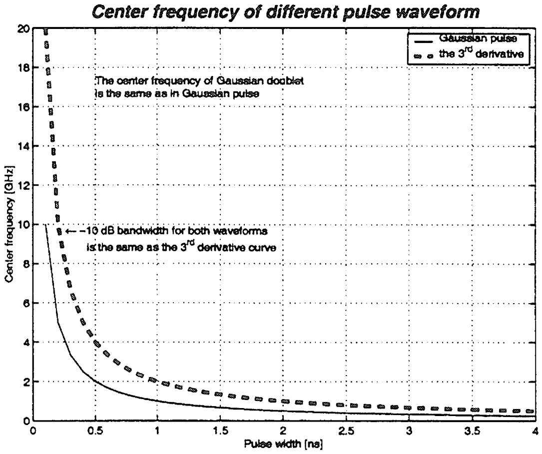

Fig. 4. Center frequency of a different pulse waveform as a function of pulse width.

C. Interference Calculation

When calculating the UWB signal power, one data bit was spread over N = 7 pulses, and the total transmitted power P_{TX} = 0.5 mW was assumed. The bandwidths of the interfering UWB signals (both in TH-UWB and DS-UWB mode) are equal if T_p remains the same. In Fig. 5, pulse power needed to satisfy certain symbol power assumption are presented as a function of N.

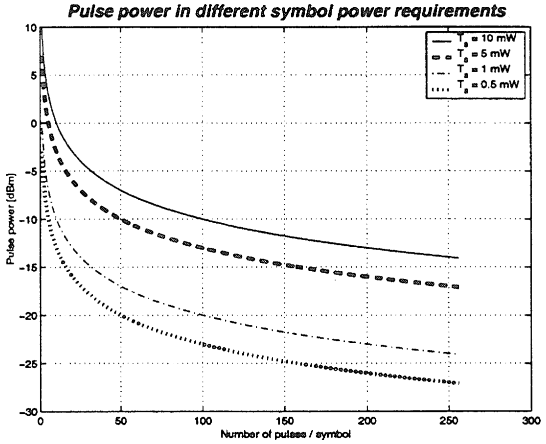

Fig. 5. Power decrease of a single pulse needed to satisfy symbol power requirement as a function of pulse spreading.

The in-band interference power P_I is calculated from the amplitude spectrum samples over the victim receiver's IF bandwidth, i.e.,

$$P_I = \sum_{i \in B_{IF}} |S_i(f)|^2 . \tag{3}$$

In the in-band interference power calculations different Gaussian pulse waveform modifications are used utilizing both the TH and DS concepts. In the power calculations antenna gains and system losses are omitted. The ideal probe in the channel was assumed.

The victim receiver's IF bandwidth is 20 MHz in GPS and 200 kHz in GSM system. Due to the relatively small IF bandwidth compared to the UWB signal band these victim IF bands under examinations can be assumed to be almost flat.

The FCC Part 15 emission limits for unlicenced *intentional* radiators allows 12 nW/MHz @ $f < 960$ MHz and 75 nW/MHz @ $f > 960$ MHz and for *unintentional* radiators the corresponding emission limits are 147 nW/MHz and 300 nW/MHz. Those limits result -19.2 dBm, -11.2 dBm, -8.3 dBm and -5.2 dBm over 1 GHz band, correspondingly.

III. UWB SYSTEM USING TIME HOPPING

Time hopping concept is generally imagined as, so called, impulse radio concept [5]. The idea of a simple TH-UWB concept is presented in Fig. 6, where the pulse width is expressed as T_p and pulse repetition interval (time hopping frame) as T_f. In our study, the exact transmission instant within each frame is evenly distributed over the frame. In general, time hopping instants depend on the pseudo random (PR) time hopping code. Time gaps between the consecutive pulses are also random due to the PR code. The use of PR code smooths the spectrum from the fixed line spectral components. The length of the PR code (M code phases) is independent on N. In TH mode the duty cycle $T_p/T_f < 100\%$. Data rate is inversely proportional to the number of pulses used to transmit one symbol and also inversely proportional to the frame length. Bit rate R_b of TH-UWB system can be defined by

$$R_b = 1/T_b = 1/NT_f . \tag{4}$$

In TH concept users are separated using different PR codes for each users. Inside a frame there are M possible transmission instants, so M users can be allocated into the system without aliasing.

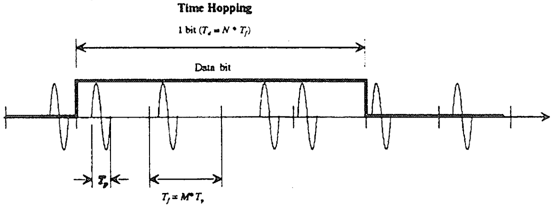

Fig. 6. The idea of time hopping system concept.

In the frequency domain presentation a line spectrum can be found if the transmission period is fixed. Random timing gets rid of the line spectrum components as can be noticed from Fig. 7. In the example, the transmission instants are evenly distributed over the frame. If the modulation technique is pulse position modulation the jitter caused by PPM smooths the spectrum more [5].

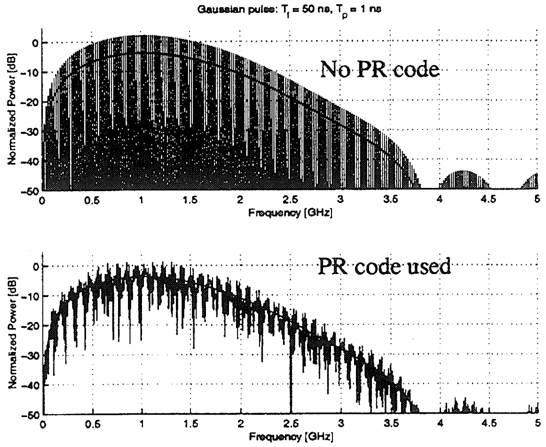

Fig. 7. Normalized spectra of a Gaussian pulse train without and with the pseudo random time hopping code. Reference curve is a spectrum of a single pulse.

IV. UWB SYSTEM USING DIRECT SEQUENCE

Another way to generate UWB signal is to utilize direct sequence spread spectrum concepts with chip waveforms of Fig. 1. We used maximum length code as a spreading code. The idea of DS-UWB is presented in Fig. 8. Duty cycle in DS-UWB is 100%. In DS-system pulse repetition interval equals the pulse width. The data rate in DS-UWB system can also be defined using (4) where N describes the length of a pseudo random code and $T_f = T_p$. Doublet waveform can be imagined as a pure DS concept if $T_w \approx T_p$.

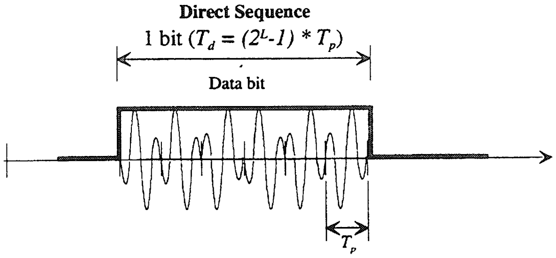

Fig. 8. The idea of UWB system based on direct sequence technique.

V. NUMERICAL RESULTS

In this chapter, some numerical in-band interference power calculation results are presented for different pulse waveforms as a function of pulse width. In Fig. 9 the transmitted pulse (before the antenna) is Gaussian pulse and the victim system is GPS (L1-band, f_c = 1.5 GHz, B = 20 MHz). In Fig. 10 the victim system is GSM (random channel in uplink band f_c = 902 MHz, B = 200 kHz). L1-band in GPS system is used to transmit the navigation message. In Fig. 9, the propagation loss is assumed to be inversely proportional to the squared distance that presents the worst case situation from the interference point of view. The used PR code in DS mode is maximum length code, length of seven chips. No additional pulse filtering is used during the calculations.

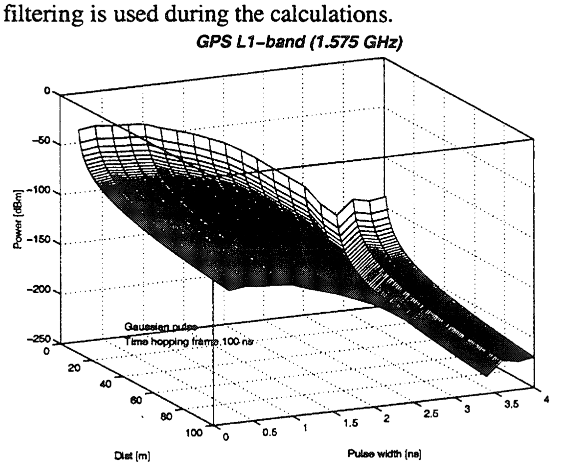

Fig. 9. In-band interference power in GPS L1 band in TH mode. Propagation loss is inversely proportional to squared distance and Gaussian pulse is used.

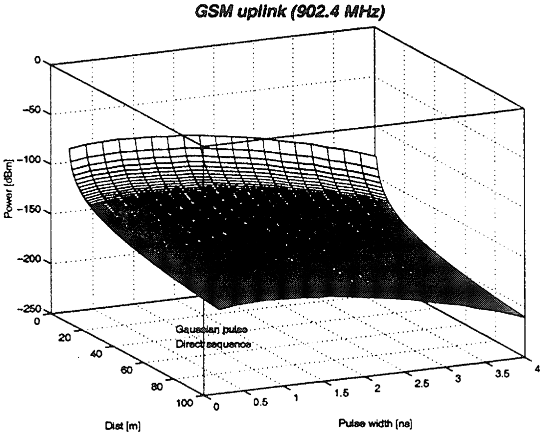

Fig. 10. In-band interference power in GSM uplink channel in TH mode. Propagation loss is inversely proportional to squared distance and Gaussian pulse is used.

In Fig. 11 in-band interference powers caused by three different pulse waveforms presented in Fig. 1 are considered in a GSM and GPS receivers' point of view.

When the pulse waveform is Gaussian pulse or Gaussian doublet with long pulse separation the in-band interference power is the same in DS mode. The pulse separation $T_w = 1.1$ ns creates a spectral null at a GSM band that can be seen from Fig. 11 (solid line with dots) as a reduced interference power. When the 3rd derivative of a Gaussian pulse is generated the spectrum overlaps frequencies below 1 GHz when $T_p > 2$ ns. In Fig. 12 the pulse separation in Gaussian doublet is optimized to create a spectral null in GPS band (solid line with dots, $T_w = 0.63$ ns) that also can be seen as a reduced interference power level. The difference between the total interference levels in GPS and GSM systems is caused by the different IF bandwidths. In GPS the interfering power is calculated over 20 MHz and in GSM the $B_{IF} = 200$ kHz. In the calculations the derivative operation of a transmitter antenna is taken into account but no propagation or system losses. The results represent the worst case situation where the UWB transmitter and victim receiver are altogether side by side with ideal coupling.

One can notice that it is possible to do spectral planning using pulse width and pulse separation (if doublet is used) as parameters to avoid some restricted frequency bands. The operating victim receiver adds noncoherently multiple impulses together during the receiver's integration time. The total in-band interference power in the decision statistics depends on the integration time of the victim receiver. A narrowband receiver will see UWB signal as an additive noise with quite flat power spectral density. If the UWB data rate is not critical one can use larger processing gain and reduced impulse power to minimize the interference.

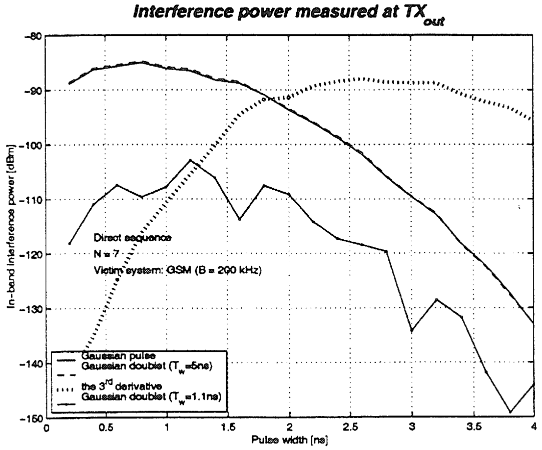

Fig. 11. In-band interference power as a function of pulse width in GSM900 uplink channel using DS-UWB.

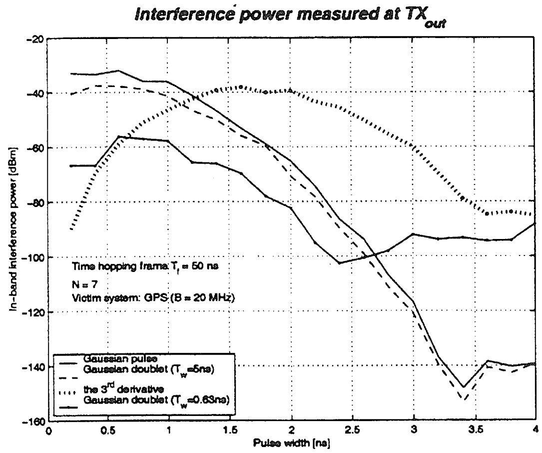

Fig. 12. In-band interference power as a function of pulse width in GPS L1-band using TH-UWB, $T_f = 50$ ns.

In impulse radio systems to achieve high data rates and accurate positioning capability the pulse widths should be ~1 ns, or less. To keep this in mind the 3rd derivative of the Gaussian pulse among the waveforms included in this study seems to be best choice from the interference point of view.

Figure 13 shows the difference between TH and DS concepts when interference power is calculated over the GPS L1-band. The number of pulses used to transmit one data symbol is the same in all cases. Time hopping frame in TH is $T_f = 50$ ns.

In all cases the DS concept is causing less in-band interference power than the TH concept. The line spectrum will appear in the interval that is related to code length and pulse repetition interval ($\Delta f = M/T_f$). In DS mode the pulse repetition interval is the same as the pulse width, as earlier stated. On the contrary, in TH mode the pulse repetition interval is much longer than in DS mode. The length of a time hopping frame depends on the data rate and the duty cycle. The longer the pulse repetition interval the smaller is the gap between the consecutive spectral lines. In DS mode the gap between consecutive spectral lines will increase when the pulse width decreases. In TH mode the spectral lines do not depend on the pulse width but the pulse repetition interval. Depending on the parameters chosen the spectral lines will or will not hit to the victim receivers RF-band. Receiver's sensitivity to fast impulses depends on the time constant of the receiver. If the pulse excitation is fast enough the pulse will not be noted in the integrator of the victim receiver. Additional randomness due to the code smooths also the spectrum and makes DS concept better than TH if one concider the interference caused to the other systems. Interference power can also be found when longer pulse widths are used. That is caused by the sidelobes of the spectrum. What matters in the interference point of view is the total number of pulses received during the integration time of a victim receiver.

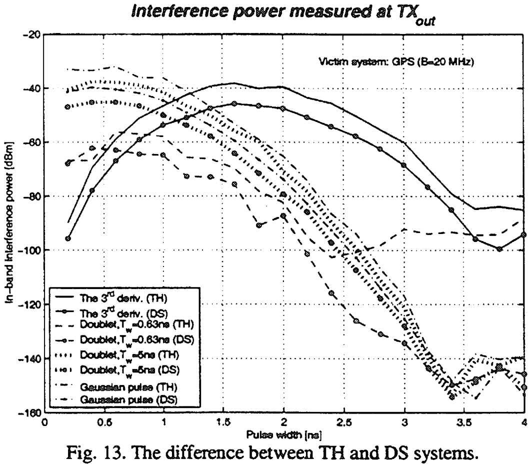

Fig. 13. The difference between TH and DS systems.

VI. CONCLUSIONS

In ultra wideband system design the pulse waveform and the pulse width are the main parameters in spectral allocation. The shape and location of the spectrum depends on the used pulse waveform. In UWB systems the power spectral density of the transmission is small. The interference against the other systems can be reduced by introducing spectral nulls, e.g., by using two separate narrow pulses to form a doublet. The distance between consecutive nulls in the spectrum is inversely dependent on the pulse separation inside a doublet. A pure Gaussian pulse generates the same spectrum envelope than the Gaussian doublet but the spectrum does not contain any nulls. Using the same pulse width as used with Gaussian pulse the spectrum of the 3rd derivative of the pulse goes twice as high in frequency domain. However, the latter pulse waveform is more complex to generate than the first ones.

If bipolar modulation and same number of pulses are used, the system utilizing direct sequence spread spectrum technique interferes less than the system based on time hopping. This is due to the line spectral components that will appear in the distance that are proportional to the code length and inversely proportional to the pulse width. In DS concept pulse repetition interval is smaller which increases the gap between the consecutive line spectral components.

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