Questions of the Coexistence of the Ultra-Wideband Systems with the Conventional Radio Communication Systems

Ultra-Wideband Interference on a Non-UWB System

Ludwig Lubich[1]

Abstract – **The present article sets forth the effects, caused by UWB interference upon the conventional receivers.**

I. Introducion

Recently we witness an increased interest in the Ultra-wideband (UWB) communications and especially in the so-called impulse radio (IR). For carrying information it uses train of extremely short base-band pulses. The key concept is through the use of signal with very large bandwidth, respectively very low power spectral density, to reuse the spectrum, occupied by the already existing users without seriously lowering their performance [1,2]. An important area of research is the exploration of the effects, which will have the UWB-transmissions upon the non-UWB systems and vice versa, as well as the ways to avoid and suppress the mutual interference. Further in this article for the sake of brevity under "UWB system" we shall understand only UWB Impulse Radio.

II. UWB Signal Description

One of the general mathematical descriptions of a UWB signal is the following [3]:

$$s(t) = \sum_{l=-\infty}^{\infty} \frac{1}{\sqrt{R}} \sum_{i=0}^{R-1} A_l g_{pulse}(t - lT_S - iT_F - c_{(lR+i)_P} T_c - B_l T_{PPM}),$$

where $(lR+i)_P \equiv (lR+i) \mod P$ and g_{pulse} is the basic transmitted pulse, e.g., a monocycle. A_l and B_l represent the data modulation and they are constant in the frames of the symbol time T_S. A symbol is transmitted through R in number monocycles, where their average repetition time is T_F, and the exact position of each monocycle in its frame is determined by a pseudo-random time-hopping (dithering) sequence $\boldsymbol{c} = (c_0, c_1, ..., c_{P-1})$. The latter lowers the probability for catastrophic collisions of pulses, when operate more than one UWB transmitters and results in a more smooth power spectral density (PSD) of the UWB signal. The PSD is very important when considering the interference issues. The most important is, PSD to be if possible flat over the occupied bandwidth and what is most important not to have concentration of considerable power in discrete spectral lines. Many researchers have derived for PSD analytical expressions, proved by computer simulations [3-6]. It is characteristic that PSD is a sum of continuous component and a discrete component. In general, the shape of $PSD(f)$ is determined of PSD of the monocycle. If M, N is the smallest pair of integers, for which $N.R = M.P$, the discrete component of PSD is comprised of discrete spectral lines at frequencies $k/(NT_S)$. IF for $\forall l \neq l'$ the expectation $E_{l \neq l'}\{A_l A_{l'}\} = 0$, the discrete part vanishes [3,4]. This is valid in binary pulse-amplitude modulation (PAM), as well as in its combination with the pulse position modulation (PPM) (Fig. 1) .

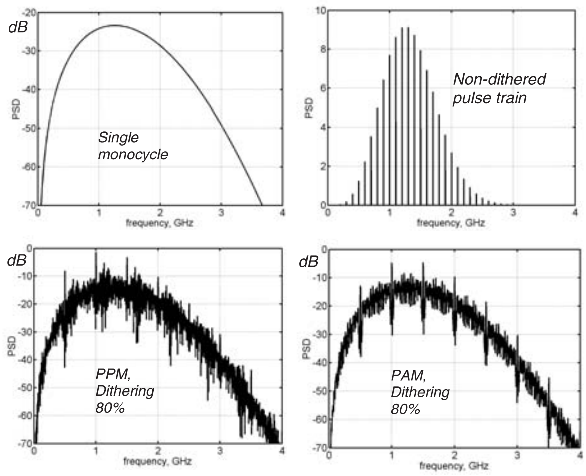

Fig. 1. UWB PSD examples

III. Influence of the UWB Emissions upon the Non-UWB Systems

This topic has been seriously researched, by both the regulatory authorities in respect to the necessity of creating regulations, treating the UWB devices, and the UWB proponents [7-14, etc.]. The greatest interest is the research of the level and the nature of the UWB interference at the IF- and the demodulator's output of a victim receiver, their dependence by the UWB signal parameters and the aggregate effect of multiple UWB emitters, especially in the expected proliferation of UWB devices. Based on these studies one can find appropriate UWB emission limits, UWB signal parameters and rules for operating of UWB devices, where the deleterious action upon the conventional receivers could be acceptable.

[1]L. Lubich is with the Faculty of Communication at Technical University - Sofia, E-mail:lvl@tu-sofia.bg

According to some early statements of UWB proponents, the influence of UWB signal upon a non-UWB receiver is similar to white gaussian noise. It turns out that this is not always the case. Generally, the level and the nature of the UWB interference at the output of a non-UWB receiver depend both by the parameters of the UWB signal, and by the receiver, especially by its IF bandwidth (IFBW). The most significant parameters of the UWB signal, affecting UWB waveform and power level at the receiver's IF output are the pulse repetition frequency (PRF = $1/T_F$), the pulse width T_m, use of time dithering/and/or gating of the UWB device and the type of the data modulation [8].

The power of a non dithered signal is concentrated in discrete spectral lines at frequencies divisible by PRF, where its potential to disturb the operation of the victim receivers is great, especially if any line of the UWB spectrum align with the non-UWB carrier. The experimental results [10] confirm this. And vice versa dithering results in a spectral smoothing, which is a prerequisite for getting at receiver's IF output more noise like waveform.

A. *Character of the UWB interference at the victim receiver IF output*

The ratio PRF/IFBW is decisive for the character of the waveform at receiver's IF output [8,15,16]. In practice, the response of the IF filter on each impulse, due to the very little Tm is equal to the impulse response of the IF filter. For $PRF < B_{IF}$, the responses, caused by the separate pulses remain distinguishable. The waveform at the receiver IF output will be pulse-like. For $PRF > B_{IF}$ the waveform will be similar to a continuous wave (CW), if the UWB signal is non-dithered, and noise-like in dithered UWB. The degree, to which receiver output response appears noise like, depends on the value of $c_{\max}T_c/T_F$ and the randomness of the dithering sequence. In [16] it is shown, that in PRF, several times bigger than BIF, at the demodulator output of a victim receiver in practice we receive Gaussian distribution of the signal, as it could be expected from the central limit theorem.

For a description of a time-domain characteristics and in particular for the evaluation of the degree, in which the waveform at the IF output is noise-like, is proposed the use of Amplitude probability distribution (APD) [7,10]. It is measurable, from it can be obtained some statistical values and can be used in receiver performance prediction. The APD express the probability that signal amplitude excess a threshold. The APD graph displays amplitude on the y-axis and probability on the x-axis. The probability is so scaled; that in gaussian noise APD becomes a straight line [10, Appendix E].

B. *UWB interference levels at the victim receiver IF output*

The dependency of the UWB interference level at the IF output is reviewed in several places [8,15]. The level depends basically on the IF bandwidth, PRF and on the presence or absence of dithering and/or gating. A simplified dependence is given in [17,18].

In [16] the same topic is also discussed, but some moments there are problematic. Probably the best notion about the problem could be acquired by [8,15], despite the rather more practical, than strictly scientific character of these two sources. Two cases are being discussed

Non-dithered signal: Its spectrum is built of discrete lines at frequencies spaced at $\Delta f = PRF$. When $\boldsymbol{IFBW < PRF}$, in the worst case one single spectral line will enter the IFBW. Then the *average power* P_{IAV} at the IF output would be independent by B_{IF}. In $B_{IF} > PRF$, P_{IAV} will be proportional to the number of UWB spectral lines, entering the IFBW, which is proportional to B_{IF}, therefore, P_{IAV}[dB] $= P_{AV0} + 10\log(B_{IF}/PRF)$, where P_{AV0} is the power in $B_{IF} < PRF$. *Peak power* P_{IP}: When $\boldsymbol{IFBW \ll PRF}$, the waveform at the IF output is CW-like. Then, obviously $P_{IP} \approx P_{IAV}$. In wider IFBW, waveform will be pulse-like. Then the ratio P_{IP}/P_{IAV} increases proportionally to B_{IF}. In the transitional area, when B_{IF} and PRF are from one and the same order, the dependence is more complex. But as a threshold we can accept $B_{IF} = 0.45PRF$, e.g. in $IFBW > 0.45PRF$ P_{IP}[dB] $= P_{AV0} + 20\log[B_{IF}/(0.45PRF)]$.

Dithered signal: In this case $PSD(f)$ is generally flat within the frames of IFBW of a conventional receiver, therefore P_{IAV} is proportional to IFBW, i.e. P_{IAV}[dB] $= P_{IAV}(B_{ref}) + 10\log(B_{IF}/B_{ref})$, B_{ref} is some IFBW, from which we know P_{IAV}. The dependence of P_{IP} by IFBW changes due to the dither percentage $c_{\max}T_c/T_F$. In a reasonable value of 50%, as a boundary value of IFBW one can accept with quite a good exactness $B_{IF} = 0.2PRF$: P_{IP}[dB] $= P(0.2PRF) + 20\log[B_{IF}/(0.2PRF)]$ when $B_{IF} > 0.2PRF$ and $P_{IP} \approx P_{IAV}$ when $B_{IF} < 0.2PRF$. These dependencies are shown on figure 2.

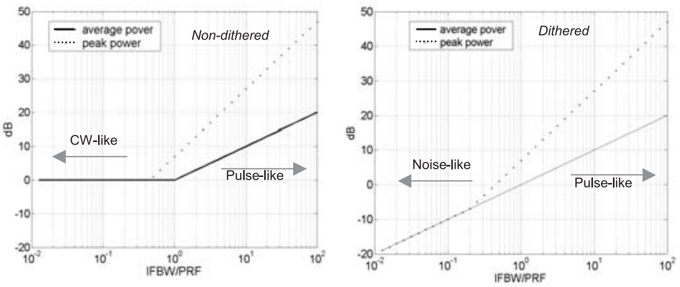

Fig. 2. UWB power at the receiver's IF output

They have been used by NTIA for the deriving of the so-called bandwidth correction factors (BWCF) [8,15], which allow to estimate average and peak power for various IFBW of the victim receiver from average power measurements made in a 1MHz reference bandwidth.

More often the answer to another question is much more: How the interference power at the IF output of a victim receiver depends on the UWB PRF (IFBW is fixed). In the literature I did not come across a thorough answer to this question. Let us review two cases:

Non-dithered UWB signal. The power of a non-dithered UWB signal is concentrated in discrete lines, spaced at $\Delta f = PRF$ one from another, and their number will be approximately $N_L = B_{UWB}/PRF$. Then the power in each line will be $P_L = P_{UWB}/N_L = PRF.P_{UWB}/B_{UWB} = PRF.PSD_{AV}$, where P_{UWB} is the power of the UWB signal, that falls on the input of the receiver, and $PSD_{AV} = P_{UWB}/B_{UWB}$ is average PSD of the UWB signal. The UWB power at IF output is proportional to the number of the spectral lines, that fall in the IFBW and the power of one spectral line, e.g. $P_{IAV} = a.(B_{IF}/PRF).PRF.PSD_{AV} = a.B_{IF}.PSD_{AV}$ in $PRF \ll B_{IF}$, where a is a given constant. In $PRF > B_{IF}$, in the worst case in IFBW will fall only one spectral line. Then $P_{IAV} = P_L = a.PRF.PSD_{AV}$, i.e. increase in PRF, the UWB signal becomes more deleterious.

Dithered UWB signal. In this case PSD is relatively even. Therefore $P_{IAV} = a.B_{IF}.PSD_{AV}$. For peak power could be expected $P_{IP} \approx P_{IAV}$ when $PRF \gg B_{IF}$ and increase in P_{IP} caused by the lowering of PRF in the transition area around $PRF = B_{IF}$ due to two factors: transition from noise/CW-like waveform to pulse-like and increased energy in one pulse, proportionally to $1/PRF$. When $PRF \ll B_{IF}$ the impulses are completely separated and only the latter factor is valid, therefore P_{IP} will increase proportionally to $1/PRF$.

In [8], Appendix D, the dependence is shown from PRF of a peak UWB power in a 50MHz bandwidth related to the average UWB power in a reference bandwidth of 1 MHz. It has been established to the considering of how to regulate the allowed peak power. A bandwidth of 50 MHz has been chosen, since it is comparable to the widest victim receiver IFBW. It can be determined that the setting of a limit for the maximum allowed P_{IP}/P_{IAV}, on behalf of the regulatory authorities, leads to the necessity to use PRF beyond a set limit. For example, if P_{IP}/P_{IAV} is limited to 20 dB, PRF $>$ 10 MHz for non-dithered UWB signal, and for dithered signal there is no value of PRF, that could satisfy the preset condition.

In [16] something more is done: analytical expression for the power caused by UWB interference has been given at the detector output of a victim receiver, but still in the article there are some dubious moments.

C. Victim receiver performance degradation

The victim receiver performance degradation is difficult to be foreseen exactly, because to a great extent it is dependent on the specific signal processing, used in the receiver. Many of the receivers are optimized to give the best performance, assuming that they work in conditions of white gaussian noise. Then in some cases, serious performance degradation can be expected, when UWB interference appear pulse-like at the IF output.

In [17,18] there is derived a simple expression for the signal/noise ratio and its use for determining of BER of the victim receiver is proposed. However, about the latter, it is necessary to know also the statistical properties of the UWB signal after its transition through the receiver's front-end. In [14] analysis is made about the influence of the UWB interference on a NB receiver and expression for BER has been found, which however, is difficult to apply. In [8], Appendix. E, is shown how easily from APD could predict bit error rate in non-coherent binary FSK.

Especially useful could be the gathered multiple results from simulations and measurements of the interference, caused by the UWB signals upon non-UWB receivers. [19,20,8,9,10]. In [19,20] mainly simulation results are presented. More interesting however are the given results from experiments conducted with GPS receivers [10]. In this article I have tried to summarize some of the more important results from [10]. Most informative appear to be the dependence of Reacquisition time (RQT) and pseudo-range (PSR) accuracy by the UWB power and the interference power at the break lock point (BL), measured in various UWB signal parameters. For a comparison measurements have been made with AWGN too. An interesting fact has been found out, that the deleterious influence of UWB interference is growing up with the increase of PRF. In the highest used PRF (20 MHz) the values for BL and RQT are almost the same as in AWGN, when the UWB signal is dithered, and considerably worse in non-dithered signal, as it was expected. It also interesting that in difference to the AWGN case, the PSR error does not change significantly in case of a change in UWB interference level and is about 2-3 times bigger than the error measured without additionally injected noise or UWB signal. Here also the non-dithered UWB signal is more deleterious especially in high PRF.

It is not exactly clear why the influence from the UWB signal gets bigger by the increase of PRF. The above described statements for the interference power at the IF output give partial explanation, since this phenomenon is witnessed in a dithered signal too. An explanation can be found in the presence of the non zero discrete component in the used in experiments UWB signals. In [16] an explanation is given, but with problematic correctness. Interesting is the article of [21], where based on the careful insight in the experimental data, one comes to the idea that significant role could have the participation of the nonlinearities in the victim receiver. Namely, a compressed receiver stage acts as a bandpass limiter, which is well known to help reduce the effects of pulsed interference. A lower PRF results in a higher peak power, which would be compressed in an earlier receiver stage and thus would produce less output interference. In general the question for the participation of the receiver's nonlinearities in the presence of UWB interference is interesting and poorly investigated.

IV. Aggregation Of Multiple UWB Signals

The issue has been discussed in many places [8,10,14,16,22]. Not until its answer the interference potential of the UWB systems will be fully and completely revealed. It is possible in urban areas hundreds, thousands or even more of UWB devices per square kilometer to be employed. The main questions are: how the power is accumulated from multiple UWB emitters and what is the nature of the resultant signal, and at the same time to have in mind the peculiarities of the radiopropagation. There are 2 opposite opinions: that decisive is the effect of the single nearest UWB-emitter and that there is no aggregate effect and vice versa.

In general for stationary, stochastic processes, average power from multiple sources do add linearly. It could be expected that the RMS UWB power also aids linearly. For the peak power things are more complex. Then amplitude statistics could be useful. In [8] experimental data are given, from combining of two UWB signals under various signal parameters. In practice upon turning on the second transmitter (having the same P_{AV}), P_{AVaggr} approximately doubles in size. Different are the results in [22], where a radiated measurement is carried out with measurement of SNR loss in a GPS receiver. Unfortunately not enough details are given about the conditions of the measurement. One can presume that the differences are caused by the effects in the radio propagation. Generally, the numerous experiments show that the average (RMS) power emitted by UWB devices is linearly additive in a receiver.

For evaluation of the possible interference, caused by the operation of a great number of UWB devices different models have been worked out: analytical and statistical. In [8] a comparison is made between the results, obtained using different models. More or less the results agree closely within 2 dB.

In NTIA is developed the "UWBrings" model, with which a number of experiments have been carried out [8]. The results can prove that:

Under given conditions some UWB emitter density exists, and above which aggregate interference begins significantly to exceed that from a single UWB emitter. Under different conditions, this emitter density is of few active emitters per square kilometer to greater than 1000.

The summation of numerous independent UWB signals must lead to a noise-like signal at the output of a narrow-band receiver. In [16] it is shown under what conditions aggregate UWB interference lead to Gaussian process at receiver's output.

As far as the aggregate UWB signal at receiver's input is concerned, in [14] is established analytically that the aggregate received signal is heavy-tailed.

The peculiarities of the radio propagation have a significant role for the aggregate interference. Factors such as obstructions due to terrain irregularities, foliage, buildings and UWB antenna directivity have also a very powerful influence [8]. It comes out that in urban environment; UWB emitters in a radius of 1 kilometer are decisive for the aggregate effect upon terrestrial victim receiver. In the experiment, described in [22] interesting effects have been witnessed, related probably to the reflections of near to the victim receiver objects. These effects could significantly increase the harmful effect of the UWB interference.

A great number of results from experiments and computations are given in [8,10]. In [10] the effect of various interference scenarios upon GPS receivers is given. In brief, the results presented, show that the influence of the aggregate UWB interference does not lead to results significantly worse than those in AWGN, except the case with the non-dithered signals. By increasing the number of the UWB emitters to more than 2, in fixed aggregate power, in practice the results cease to change with the number of the emitters and converge on these, received in AWGN, which agree with [16].

V. Conclusions

The mechanisms of influence of UWB signals on a non-UWB receiver were above exposed as well as some of the more important experimental results. It is obvious that it is a vast area for a research. For now on it has been studied as far as, it could give the right to accept the existence of the UWB technology, to find out appropriate UWB parameters, modulation schemes and regulations, so that the existing nowadays non-UWB systems could be adequately protected. Probably in future development of non-UWB receivers, when the proliferation of UWB transmitters will be a fact, methods for signal processing will be searched for purposeful suppression/mitigation of the UWB-interference. For that purpose a more serious clarification of the mechanisms of UWB signal's influence upon the non-UWB receivers will be needed.

References

[1] Win, M.Z., Scholtz, R., "Impulse Radio: How it Works", *IEEE Communications Letters*, Feb. 1998.

[2] Mitchell T., "Broad is the way", IEE REVIEW, January 2001

[3] Lehmann N., A. Haimovich, "New approach to control the power spectral density of a timehopping UWB signal", Conf. on Information Sciences and Systems, The Johns Hopkins University, March 12-14, 2003

[4] Romme J, L. Piazzo, "On the power spectral density of time-hopping impulse radio", *IEEE Conference on Ultra Wideband Systems and Technology*, 2002.

[5] Fontana R., "A note on Power Spectral Density Calculations for Jittered pulse trains", Multispectral solutions Inc., 2000.

[6] A. Alvarez, J. Garcia, "Improved Fast Fourier Transform Algorythm for the eastimation of the power spectral density of UWB signals", June 2002.

[7] Kissick, W.A., editor, "The Temporal and Spectral Characteristics of Ultrawideband Signals," NTIA Report 01-383, January 2001.

[8] Brunson, L.K. et al., "Assessment of Compatibility Between Ultrawideband Devices and Selected Federal Systems," NTIA Special Publication 01-43, January 2001.

[9] Anderson, D.S., E.F. Drocella, S.K. Jones and M.A. Settle, "Assessment of Compatibility between Ultrawideband (UWB) Systems and Global Positioning Systems (GPS) Receivers", NTIA Special Publication 01-45, February 2001.

[10] NTIA Report 01-384 Measurements to Determine Potential Interference to GPS receivers from Ultrawideband Transmission Systems, February 2001.

[11] RTCA Paper No. 086-01/PMC-139, "Second Interim Report to the Department of Transportation: Ultra-Wideband Technology Radio Frequency Interference Effects to Global Positioning System Receivers and Interference Encounter Scenario Development", RTCA Special Committee 159, March 27, 2001

[12] The Radiocommunications Agency (www.radio.gov.uk), "UWB Compatibility with TDAB and DVB-T. An RTCG Project Report", Project No 739, Date 22nd April 2002

[13] The Radiocommunications Agency (www.radio.gov.uk), "UWB interference to Bluetooth and GSM DCS 1800. An RTCG Project Report", Project No 639, Date 22nd April 2002

[14] Swami, A., Sadler, B., Turner, J., "On the Coexistence of Ultra-Wideband and Narrowband Radio Systems". *IEEE Military Communications Conference: Communications for Network-Centric Operations: Creating the Information Force*, 2001, vol. 1, pp. 16-19.

[15] Quincy E. A., "Victim Receiver Response To Ultrawideband Signals", *IEEE Military Communications Conference: Communications for Network-Centric Operations: Creating the Information Force*, 2001, vol. 1, pp. 20-24.

[16] Fontana, R., "An Insight into UWB Interference from a Shot Noise Perspective ". *IEEE Conference on Ultra Wideband Systems and Technology*, 2002.

[17] L. Piazzo, "Some basic facts about UWB EM compatibility and UWB spectrum", Internal report for the Whyless.com project, May 2001.

[18] L. Piazzo, "UWB EM compatibility and coexistence issues", IINFOCOM dept., University of Rome "La Sapienca", 2001.

[19] Hamalainen, M., Iinatti, J., Hovinen, V., Latva-aho, M., "In-Band Interference of Three Kind of UWB Signals in GPS L1 Band and GSM900 Uplink Band". *12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Sept. 2001, vol. 1, pp. 76-80.

[20] Hamalainen, M., Hovinen, V., Iinatti, J., Latva-aho, M., "In-Band Interference Power Caused by Different Kinds of UWB signals at UMTS/WCDMA Frequency Bands". *IEEE Radio and Wireless Conference*, 2001, pp. 97-100.

[21] R. D. Wilson, R. D. Weaver, M.-H. Chung And R. A. Scholtz, "Ultra Wideband Interference Effects On An Amateur Radio Receiver", *IEEE Conference on UWB Systems and Technologies*, Baltimore May 2002.

[22] Cummings, D.A., "Aggregate Ultra Wideband Impact on Global Positioning System Receivers". *IEEE Radio and Wireless Conference*, 2001, pp. 101-104.