Multipath Propagation of UWB Through-Wall Radar and EMC Phenomena

Vladimír SCHEJBAL[1], *Dušan ČERMÁK*[1], *Zdeněk NĚMEC*[1], *Jan PIDANIČ*[1], *Jiří KONEČNÝ*[1], *Pavel BEZOUŠEK*[1], *Ondřej FIŠER*[2]

[1] University of Pardubice, Studentská 95, 532 10 Pardubice, Czech Republic
[2] Institute of Atmospheric Physics, Boční Street II/1401, 141 31 Prague 4, Czech Republic

vladimir.schejbal@upce.cz, dusan.cermak@upce.cz, zdenek.nemec@upce.cz, pavel.bezousek@upce.cz, ondrej@ufa.cas.cz

Abstract. *The UWB (ultra wide band) radar output signals can be substantially affected due to electromagnetic wave propagation through obstacles (such as walls) and multipath effects, too. Multipath effects are analyzed and simulated numerically for various cases with several antenna heights and distances. Delays (due to propagation through walls and various paths of direct and reflected rays) and the ringing (similar to UWB propagation through wall) can be clearly observed and analyzed. Moreover, frequency spectra analyses can demonstrate both UWB interferences and susceptibility from electromagnetic compatibility (EMC) viewpoint.*

Keywords

UWB propagation, multipath effects, UWB radars, electromagnetic compatibility (EMC).

1. Introduction

The UWB concept is very useful for radars and communications [1], [2], [3]. UWB devices are defined by FCC as any radio technology having a spectrum that occupies a -10 dB bandwidth greater than 20 percent of the center frequency or a -10 dB bandwidth of at least 500 MHz. UWB radar output signals are formed by both transmitters and antennas. Therefore UWB antenna should be considered as an integral part of the whole system. A UWB engineer needs to be familiar with both the time domain and frequency domain, able to switch from one domain to the other as the nature of problem demands. In many situations, harmonic functions offer a potentially misleading situation. For instance, any attempt to model an ideal step function using superposition of harmonic functions yields overshoot and ringing. Therefore, the utilization of Fourier transform (especially FFT, when aliasing can occur) should be considered very carefully.

When UWB radars are used, an important problem is presented by their electromagnetic compatibility with other electronic systems, because, in this case, the frequency diversity of other systems is practically impossible. The utilization of UWB signals creates quite different problems from EMC viewpoint. Many of these problems have been treated previously (such as [1], [2], [10] and [11]).

The output transmitted signal is usually formed according to UWB system requirements. That is why propagation analyses should be done for very wide frequency spectrum and simultaneously, the effect of various transmitted signal shapes (e.g. pulses) should be considered. The effect of various antenna receiving and transmitting responses as well as UWB signals (pulses) are analyzed in [4]–[6]. Various combinations of signals, transmitting or receiving antennas (small and aperture antennas) and wall structures as well as multipath propagation have been calculated and compared. The papers [4]–[9] study spectra and UWB signal propagation through walls.

This paper is mostly dealing with multipath effects in both time domain signal representation and frequency spectra. Frequency spectra analyses can demonstrate both UWB interferences and susceptibility from electromagnetic compatibility (EMC) viewpoint. The results of new numerical simulations are analyzed (some of these results can be only shown here).

2. Propagation through Walls

Antenna receiving and transmitting responses as well as UWB signals (pulses) are analyzed in [4], where spectra and their UWB signals are studied for several pulses, aperture and small antennas, both for transmitting and receiving antennas. Of course, the real antennas cannot work from DC to infinity and therefore, they form band-pass filters. Therefore, the real antennas do not exactly perform differentiation or integration and their responses are causal. The considered wall parameters are given [4] both for brick and concrete walls for various wall thickness t with wall electrical properties. The analyses and numerical simulations of parameters S_{11} and S_{21} for various cases of propagations through walls are shown in [4]. If the parameter S_{21}

is known (calculated), it is possible to obtain the output signal spectrum $b_2(\theta_0)$ for any point (θ_0 is the incident angle) both for TE and TM waves

$$b_2(\theta_0) = S_{21}(\theta_0)a_1(\theta_0) \tag{1}$$

where $a_1(\theta_0)$ is the input signal spectrum. The output signal spectra are not too illustrative (but they are certainly very important for various purposes such as EMC analyses). Therefore, it is much more convenient to use inverse Fourier transform (IFFT) and analyze the signal responses in the time domain. Several cases of propagation through walls have been analyzed. Some of them can be found in [4]–[7].

3. Multipath Effects

The multipath effects should be considered for UWB systems. The most common case is given in Fig. 1 where direct and reflected signals are shown. Usually, it is not possible to consider one reflection only and the other reflections from a ground, walls and nearby objects should be taken into account. To simplify the following analyses, one reflection is only considered here. Using the program [4] this case can be easily calculated. Both direct and reflected signals propagate through wall and they can be calculated directly by that program. The spectrum of reflected signal is modified (multiplied) by the reflection coefficient of ground (or possibly of another object)

$$b_{2r}(\theta_r) = S_{21}(\theta_r)a_1(\theta_r)\,\rho_S(\alpha), \tag{2}$$

where $\rho_S(\alpha)$ is the reflection coefficient at the given surface, which can be calculated as a reflection from a dielectric layer. Of course, surface properties at the related angle α should be considered. The other parameters are the same as for (1) but for the angle of θ_r. The reflection coefficient can be obtained by program [4], too. It is possible to use inverse Fourier transform (IFFT) and to analyze the signal responses in the time domain.

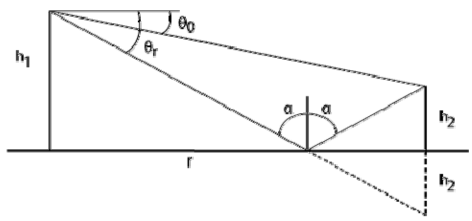

Fig. 1. Direct and reflected rays (the wall is not shown).

The special shaped pulses have been analyzed in [4]

$$s_n(t) = d_n(t)\cos\omega_0 t\,. \tag{3}$$

where $\omega_0 = 2\pi f_0$ and f_0 is the frequency. They were thoroughly used for multipath effect simulations. Even if the details can change substantially, the general conclusions are rather similar. Therefore, the following pulse (pulse 1) is only shown in this paper

$$\begin{aligned} d_1(t) &= 1 \quad for\ \ t \in \langle -\tau_0, +\tau_0 \rangle \\ &\ \ \ 0 \quad for\ \ t \notin \langle -\tau_0, +\tau_0 \rangle \end{aligned} \tag{4}$$

where f_0 = 1.5 GHz and τ_0 = 1 ns.

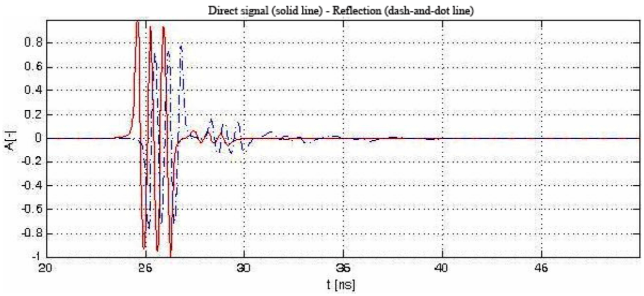

Fig. 2. Direct (solid line) and reflected (dot and dash line) signals for a small transmitting antenna, h_1 = 1.5 m, h_2 = 0.4 m and r = 7 m.

In this case, the delay between direct and reflected signals can be clearly seen. Various cases have been numerically simulated. Several heights h_1 and h_2 and distances r have been analyzed. Direct and reflected signals for small transmitting antenna and propagation through a wall with ε_r = 5.1 – j0.46 and thickness t=0.19 m are shown for TE waves in Fig. 2 to 5. The ground with ε_r = 5.1 – j0.46 and t=0.19 m has been considered. Numerical simulations for smaller distances r and the same pulse can be found in [8]. Numerical simulations for various distances r and the different pulse shapes can be found in [9]. Another two different examples are given in [4] and [7] to illustrate the described numerical simulation method.

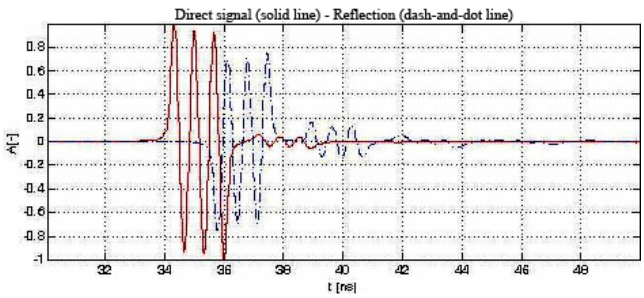

Fig. 3. Direct (solid line) and reflected (dot and dash line) signals for a small transmitting antenna, h_1 = 1.5 m, h_2 = 1.5 m and r = 10 m.

Various delays (due to propagation through a wall and various paths of direct and reflected rays) and the ringing (similar to UWB propagation through a wall) can be clearly seen. Certainly, these phenomena are much more pronounced for reflected rays.

On the other hand, the interference effects of multiple reflections and multipath effects are much smaller for UWB signals than for CW narrow-band applications as interference minima and maxima do not occur for the same frequencies. Moreover for very short pulses, the individual pulses are received at various times and can be distinguished more easily. Time delays between direct and reflected signals can be derived. That is shown in Fig. 6 for a small transmitting antenna, pulse 1, various r with $h_1 = 1.5$ m, $h_2 = 1.5$ m and $h_1 = 1.5$ m, $h_2 = 0.4$ m.

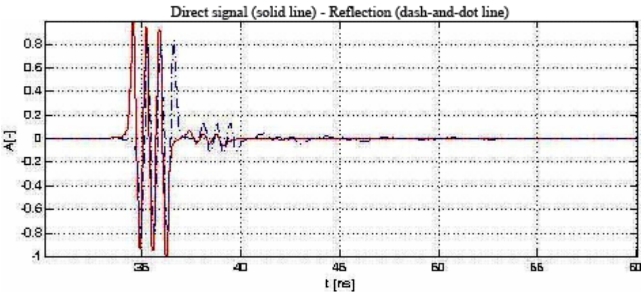

Fig. 4. Direct (solid line) and reflected (dot and dash line) signals for a small transmitting antenna, $h_1 = 1.5$ m, $h_2 = 0.4$ m and $r = 10$ m.

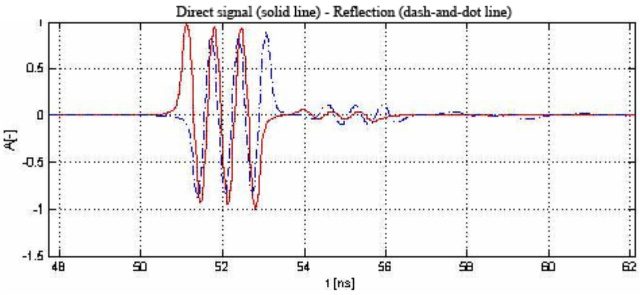

Fig. 5. Direct (solid line) and reflected (dot and dash line) signals for a small transmitting antenna, $h_1 = 1.5$ m, $h_2 = 0.4$ m and $r = 15$ m

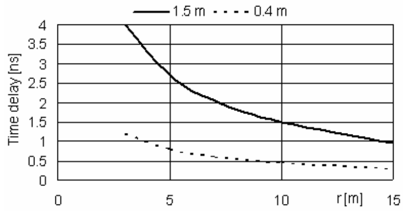

Fig. 6. Time delay between direct and reflected signals for a small transmitting antenna with $h_1 = 1.5$ m, $h_2 = 1.5$ m (solid line) and $h_1 = 1.5$ m, $h_2 = 0.4$ m (dot and dash line).

4. EMC Phenomena

When UWB radar operates jointly with conventional narrowband radar, only a slight portion of the UWB radar signal energy enters the frequency band of the narrowband radar receiver as the receiver channel can be considered as a linear filter with a transfer function $H_i(f)$. Then the output signal spectrum $Y_i(f)$ is given by the well-know equation

$$Y_i(f) = X_i(f) H_i(f) \tag{5}$$

where $X_i(f)$ is the input signal spectrum.

Alternatively, that can be derived also in the time domain. The time constant of the input circuit of a narrowband receiving device (τ_I=1/Δf), which determines the rise time of the input signal amplitude up to prescribed value, will be much longer than the pulse length of an UWB radar. The bandwidth of given UWB radar and that of the narrowband radar may differ by three order of magnitude (for pulse lengths of 1 ns and 1 μs). This means that jamming occurring in the narrowband radar receiver due to this UWB pulse has no time to reach a noticeable magnitude in the receiver. That is very advantageous property of narrowband system considering electromagnetic susceptibility (EMS).

Moreover, when both narrowband radar and UWB radar radiate equal powers, this UWB radar has the power spectral density (W/MHz), which is approximately by three orders of magnitude lower. This means that only about one-thousandth of the incident UWB signal power arrives at the narrowband radar detector. That follows from the well-known Parseval's energy theorem

$$\int_{-\infty}^{\infty} |x(t)|^2 dt = \int_{-\infty}^{\infty} |X(f)|^2 df \tag{6}$$

where $x(t)$ is the time-domain signal and $X(f)$ is the signal spectrum. That is very useful for a narrowband system from the electromagnetic interference (EMI) viewpoint. As a result, the UWB signal in the narrowband receiver is lower (about 60 dB), as compared with the effect of the signal of a similar narrowband radar on this receiver. Other measures may be provided (see [2]).

The above considerations can be demonstrated considering the narrowband radar for output received spectrum in Fig. 7 and output received signal in Fig. 8.

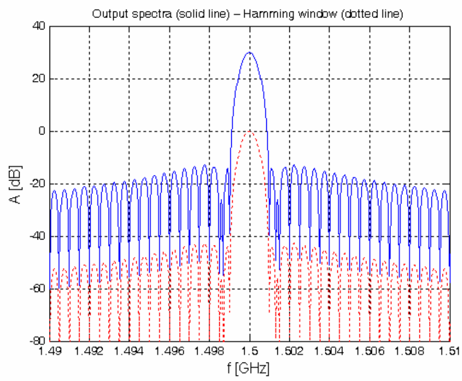

Fig. 7. Relative output spectra of a narrowband radar filter for a pulse with $f_0 = 1.5$ GHz and $\tau_0 = 1$ ns (solid line) and spectra of Hamming window (dotted line).

The radiated signal with $f_0 = 1.5$ GHz and $\tau_0 = 1$ ns according to (3) and (4) is observed. The Hamming window is considered for narrowband radar reception (in fact that is only a very rough approximation but various functions differ by various degrees of accuracy and their effects are not substantial). The center of Hamming window spectra (see Fig. 7) is 1.5 GHz with the highest sidelobe less than -40 dB and window pulse duration 2 μs (from –1 μs to 1 μs).

The relative output spectrum can be seen in Fig. 7. It is created according to (5), where $H_i(f)$ is the transfer function of Hamming window. The output signal is shown in Fig. 8, where various formats of axes are used. It can be observed that output signal amplitudes correspond to above analyses (it should be noted that the bandwidths are not the same as various waveforms are considered and therefore, the amplitude ratio is not exactly 1:1000). The other problem is energy ratio. For that purposes, Eq. (6) should be considered. Even if the attenuation is about 54 dB, the energy is only lowered by 28.5 dB because of very long pulse duration. That can be seen in Fig. 8.

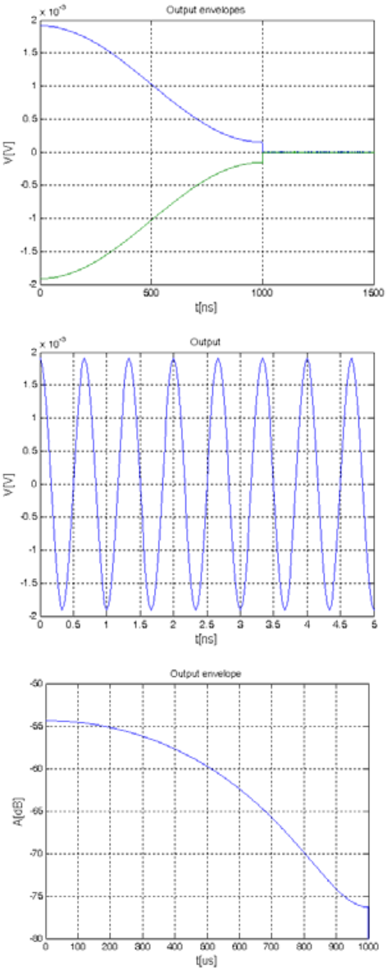

Fig. 8. Filter output signal of narrowband radar for pulse with $f_0 = 1.5$ GHz and $\tau_0 = 1$ ns. a) Envelope of output signal with linear scaling, b) Detailed view and c) Logarithmic scaling (dB) of output signal envelope

For UWB radar EMC analyses, when two UWB devices are considered, the radiated signal with $f_0 = 1.5$ GHz and $\tau_0 = 1$ ns according to (3) and (4) and a UWB radar reception with a filter corresponding to Hamming window is analyzed. The center of filter spectra is 1.5 GHz (see Fig. 9) with the highest sidelobes less than -40 dB and window duration of 2 ns (from -1 ns to 1 ns). The relative output spectrum can be seen in Fig. 9 and the output signal in Fig. 10. It can be seen that the UWB signal amplitudes in the UWB receiver are not substantially changed. On the other hand, the shape of the received signal is changed substantially as Hamming window is not matched filter for rectangular pulse.

When two or more UWB radars operate jointly, it is advisable to use the time division of the signals of stations. The interference of neighboring radar occupies a very small range section. When radars are mutually synchronized, this section can be blanked without adverse effects to target detection. Interference gating is possible in the radar computer after the estimation of the coordinates of an interfering station has been performed.

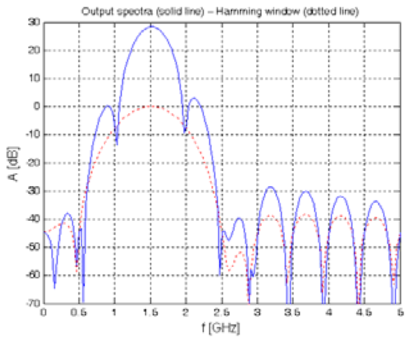

Fig. 9. Relative output spectra of a pulse with $f_0 = 1.5$ GHz and $\tau_0 = 1$ ns for UWB radar reception (solid line) and spectra of Hamming window (dotted line).

On the other hand, interference from narrowband systems is a major problem in UWB radar design. When narrowband radars interfere with UWB radars, one efficient jamming protection is the frequency rejection by cutting narrowband radar signals out of the UWB radar signal spectrum. This is usually done during signal processing. Several problems concerning moving target selection in the UWB radar and passive jamming protection are analyzed in [2]. The effect of UWB interference on the DCS-1800 and GSM-900 downlink is studied for different UWB power density in [10].

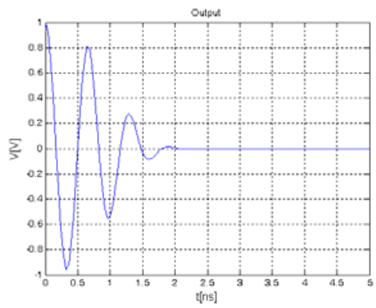

Fig. 10. Output signal of a pulse with $f_0 = 1.5$ GHz and $\tau_0 = 1$ ns and UWB radar reception with Hamming window.

Fig. 11 shows spectra for a small transmitting antenna, heights $h_1 = 1.5$ m and $h_2 = 0.4$ m and distance $r = 15$ m. Of course, it is clear that a reflected signal is much more disturbed than a direct signal. That could create problems in various situations and should be considered from signal processing points of view. It can be seen in this case that it is not possible to notice the time delay and ringing and from that point of view the output signal spectra are not too illustrative. However, they could be very important for various purposes such as EMC analyses from both EMI and EMS viewpoints. Even if the reflected signal is disturbed, it is clear that the EMC analyses would be similar to the case depicted in Fig. 9 and Fig. 10.

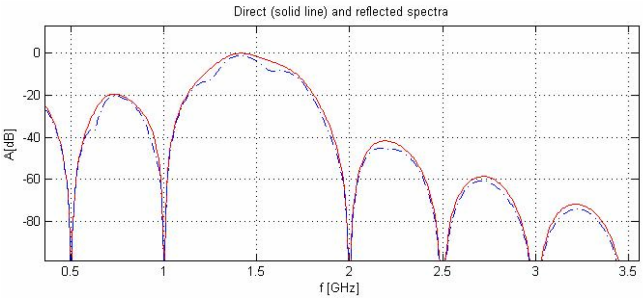

Fig. 11. Direct (solid line) and reflected spectra for a small transmitting antenna, heights $h_1 = 1.5$ m and $h_2 = 0.4$ m and distance $r = 15$ m.

The directional pattern of an antenna radiating or receiving the UWB signal becomes dependent on the signal waveform and duration. Therefore the directivity factor and gain factor of an antenna and the antenna effective cross-section become also dependent on the signal parameters. As a result, the directivity factor depends not only on the geometry of an antenna but also on matching the signal spectrum to the frequency response of an antenna. Therefore the calculation of the antenna directivity factor for the UWB signals presents great difficulties and it can be performed only for the simplest cases [2]. These phenomena form both the direct and reflected rays. That means that the analyses of multipath effects are very useful from viewpoint of delays and ringing but the detailed analyses of time or frequency responses cannot be done. On the other hand, general conclusions concerning EMC could be drawn as can be demonstrated in Fig. 11.

The capability to operate in a crowded RF environment without interfering with (or experiencing interference from) other narrowband communications systems or other similar devices is a key feature for UWB sensing and communication devices. The UWB communication devices will use a train of subnanosecond pulses, which may be separated by less than microseconds in some cases. To prevent these trains of pulses from interfering with narrowband communications, the timing of the pulse-coded signals will be varied with a pseudorandom code, which spreads the pulse train energy over a broad spectrum to avoid setting up any continuous-frequency signal that is detectable by narrowband sources. Many unique pseudorandom codes can be generated, based on the size of the pulse train and the number of unique spacings that can be obtained between pulses. The coding may be random to present interference in simple range sensors, or varied according to some known modulation scheme for communications. This type of coding permits a large number of devices to operate or communicate a large amount of information without mutual interference. As techniques are developed to better control the spacing of the pulses, the amount of information that can be communicated will increase. Also, the high pulse resolution provides a natural ability to reject multipath transmissions from cars, buildings, bridges, etc. Path differences of greater than 4 cm can be rejected with UWB sensor technology [2].

5. Conclusions

Several combinations of receiving and transmitting antennas and input signals have been calculated and compared, such as examples in [4] - [6]. It can be concluded that UWB radar output transmitted signals are formed both with transmitters and antennas. The transmitting transient responses of an ideal antenna are proportional to the time derivatives of the receiving transient responses of the same antenna. Therefore, UWB antennas should be considered as an integral part of the whole systems. Moreover, the output transmitted signals should be formed according to UWB system demands. That means that analyses should be done for very wide frequency spectrum and simultaneously, the effect of input signals (e.g. special shaped pulses) should be considered both for transmitting and receiving antennas.

The propagations of electromagnetic waves through obstacles have been analyzed [4] - [7], where wall parameters are given both for brick and concrete walls with various thicknesses, where S_{11} and S_{21} can be found for these cases. The responses (input and output signals calculated using IFFT) have been extensively analyzed as well. The ringing (due to boundary multiple reflections) can be clearly observed. Naturally, the interferences (disturbing) of multiple reflections are much smaller for very short pulses than for CW and narrow-band applications. Some preliminary measurements (in the frequency domain) can be found in [7]. The comparison of numerical simulations with time domain measurements and transformations into frequency domain is in [12].

The method [4] can be used for analyses of multipath propagation due to reflections (such as ground or wall reflections). Excessive numerical simulations (see Fig. 2 to 5 and [4], [7] to [9]) show delays (due to propagation through wall and various paths of direct and reflected rays) and the ringing (similar to UWB propagation through wall). Certainly, these phenomena are much more pronounced for reflected rays. On the other hand, the interference effects of multiple reflections and multipath effects are much smaller for UWB signals than for CW narrowband applications as interference minima and maxima do not occur for the same frequencies. Moreover for very short pulses, the individual pulses are received at various times and can be distinguished more easily. Time delays between direct and reflected signals for small transmitting antenna with $h_1 = 1.5$ m, $h_2 = 1.5$ m (solid line) and $h_1 = 1.5$ m, $h_2 = 0.4$ m are shown in Fig. 6. The obtained numerical simulation results can be very useful for UWB propagation analyses as well as for the design of signal processing methods.

When UWB radars are used, an important problem is presented by their electromagnetic compatibility with other electronic systems, because, in this case, the frequency diversity of other systems is practically impossible. The utilization of UWB signals creates quite different problems from EMC viewpoint. Many of these problems have been treated previously (such as [1], [2], [10] and [11]) and therefore, the special cases of mutual interferences of narrowband and UWB devices and two or more UWB devices are numerically simulated (see Fig. 7 to 11) and analyzed considering multipath propagation. The attenuation of the UWB signal in the narrowband receiver is about 60 dB, as compared with the influence of the signal of similar narrowband radar on this receiver. The energy is only lowered approximately by 30 dB because of very long pulse duration. When two or more UWB radars operate jointly, it is advisable to use the time division of the signals of stations. Interference gating is possible in the radar computer after the estimation of the coordinates of an interfering station has been performed. On the other hand, interference from narrowband systems is a major problem in UWB radar design. Some measures, which can be taken to diminish the narrowband interferences, can be found in [1] and [2]

It has been shown that the analyses of multipath effects are very useful from viewpoint of delays and ringing but the detailed analyses of time or frequency responses cannot be generally done. On the other hand, general conclusions concerning EMC could be drawn as can be demonstrated in Fig. 11.

Acknowledgements

This work was supported by the grant of UWB Technology for Radars FT-TA2/030. The project was realized using financial support of state budget assets by the Ministry of Industry and Trade of the Czech Republic.

References

[1] HEYMAN, E., MANDELBAUM, B., SHILOH, J. *Ultra-Wideband Short-Pulse Electromagnetics* 4. New York: Plenum Press, 1999.

[2] TAYLOR, J. D. *Ultra-Wideband Radar Technology.* N. York: CRC, 2001.

[3] BEZOUSEK, P., SCHEJBAL, V. Radar technology in the Czech Republic. *IEEE Aerospace & Electronic Systems Magazine.* 2004, vol. 19, no. 8, p. 27 - 34.

[4] SCHEJBAL, V. et al. UWB propagation through walls. *Radioengieering*. 2006, vol. 15, no. 1, p. 17 - 24.

[5] SCHEJBAL, V. et al. Electromagnetic wave propagation through obstacles. In *International Workshop on Microwaves, Radar and Remote Sensing MRRS 2005*. Kiev (Ukraine), 2005, p. 255 – 260.

[6] BEZOUSEK, P. et al. UWB signal propagation through walls. In *International Workshop on Microwaves, Radar and Remote Sensing MRRS 2005*. Kiev (Ukraine), 2005, p. 249 - 254.

[7] SCHEJBAL, V. et al. UWB radar signal propagation through walls and multipath effects. *IEEE Aerospace & Electronic Systems Magazine.* Submitted to publication.

[8] SCHEJBAL, V., CERMAK, D., NEMEC, Z., BEZOUSEK, P., FISER, O. Multipath propagation effects of UWB radars. In *MIKON – 2006*. Warszawa (Poland), 2006, p. 1188 – 1191.

[9] CERMAK, D., SCHEJBAL, V., NEMEC, Z., BEZOUSEK, P., FISER, O. UWB radar multipath propagation effects. In *Scientific Papers of the University of Pardubice*. Series B. The Jan Perner Transport Faculty 8 (2005).

[10] TAHA-AHMED, B., CALVO-RAMÓN, M., HARO-ARIET, L. Impact of UWB on macrocell downlink of DCS-1800 and GSM-900 systems. *Radioengineering.* 2005, vol. 14, no. 1, p. 51 -55.

[11] MOLISCH, A.F. Ultrawideband propagation channels-theory, measurement, and modeling. *IEEE Transactions on Vehicular Technology.* 2005, vol. 54, no. 5, p. 1528 – 1545.

[12] NEMEC, Z., MRKVICA, J., SCHEJBAL, V., CERMAK, D., BEZOUSEK, JERABEK, J., SIKL, R. UWB through-wall propagation measurements. Accepted for *The 1st European Conf. on Antennas and Propagation.* Nice, France, Nov. 6 – 10, 2006.

About Authors...

Vladimír SCHEJBAL (*1941) received his MS from the Czech Technical University(CTU) in Prague in 1970 and his PhD from the Slovak Academy of Sciences in Bratislava in 1980. He was with the Radio Research Inst. of Tesla Pardubice from 1969 till 1993. He has been with the University of Pardubice since 1994. He is interested in numerical methods, simulations, measurements, radar antennas and propagation.

Dušan ČERMÁK (*1974) received his MS from the CTU, Prague in 2003. He has been with the University of Pardubice since 2003. He is interested in propagation of electromagnetic waves.

Zdeněk NĚMEC (*1977) received MS degree from the Jan Perner Transport Faculty, University of Pardubice in 2000. He has been with the University of Pardubice since 2002. He is interested in signal and data processing.

Jan PIDANIČ (*1979) received MS degree from the Jan Perner Transport Faculty, University of Pardubice in 2005. He is interested in propagation of electromagnetic waves and in signal and data processing.

Jiří KONEČNÝ (*1944) received his MS degree from the Technical University in Brno in 1967 and his PhD degree from the CTU, Prague in 2002. He was with the Radio Research Inst. of Tesla Pardubice from 1967 till 1994. Since then he has been with the University of Pardubice, now at the Inst. of Electrical Engineering and Informatics. He is engaged in radar signal processing.

Pavel BEZOUŠEK (*1943) received his MS degree from the CTU, Prague in 1966 and his PhD degree from the same university in 1980. He was with the Radio Research Instit. of Tesla Pardubice from 1966 till 1994, where he was engaged in microwave circuits and systems design. Since then he has been with the University of Pardubice, now at the Inst. of Electrical Engineering and Informatics. Presently he is engaged in radar systems design.

Ondřej FIŠER (*1952) received his MS degree (1977) in electrical engineering and his PhD degree (1986) in electronics, both from the CTU, Prague. He works as a scientific researcher at the Inst. of Atmospheric Physics, Czech Academy focusing on radiowave propagation through the atmosphere and radar meteorology. He also teaches electrical engineering at the University of Pardubice.