Dispersion and Pulse Interferences Investigation for UWB Signal Propagation

Robert URBAN, Stanislav ZVÁNOVEC

Dept. of Electromagnetic Field, Czech Technical University, Technicka 2, 166 27 Prague, Czech Republic

urbanr2@fel.cvut.cz, xzvanove@fel.cvut.cz

Abstract. *The Ultra WideBand (UWB) technology utilizing nanosecond pulses has been one of the main phenomena in communications and radar applications for several years. This paper discusses the basic measurement techniques of impulse systems, particularly focusing on the dispersion and pulse interferences of the UWB propagation channel. Propagation aspects of two-ray approach are investigated in depth, using both measurements and simulations.*

Keywords

UWB, Ultra Wideband, two-ray propagation model.

1. Introduction

Despite the current boom in short pulse-based wireless systems [1] [2], the history of Ultra-Wide Band (UWB) technology is over one hundred years old [3]. During the last several years, many books dealing with major aspects of UWB have been published (e.g. [3] [4]). This paper discusses specific features of UWB signal propagation based on measurements and simulations. It consists of two parts. The first part provides a brief outline introducing the two basic principles of UWB – orthogonal frequency division multiplex UWB (OFDM-UWB) and direct sequence UWB (DS-UWB). In the second part the results of time-domain (TD) measurements, with emphasis on propagation delay, are compared to the simulation results.

2. UWB Fundamentals

UWB has proved to be an extremely prospective technology. The wide frequency bandwidth allows the utilization of very high channel capacity. The well known Shannon's communication law (1) shows that it is obvious that the channel capacity C is linearly dependent on the frequency bandwidth B, but only logarithmically dependent on the signal-to-noise ratio (SNR).

$$C = B\log_2\left(1+SNR\right). \tag{1}$$

It is obvious that the use of a wide bandwidth and a lower SNR enables transmission of the same information capacity through a radio channel as a narrower bandwidth and higher SNR. This is the main advantage of UWB and it is powerful feature.

The basic definition of the UWB frequency spectrum is given by the FCC (Federal Communication Commission) [5]. This definition introduces the spectral mask, where the maximum Equivalent Isotropically Radiated Power (EIRP) is restricted to the level of -41.3 dBm/MHz in the 3.1 - 10.6 GHz frequency band (see Fig. 1). The European Commission (EC) published another spectral mask [6] several years after the FCC which is stricter and narrower; however developers and researchers usually prefer the FCCs spectral mask.

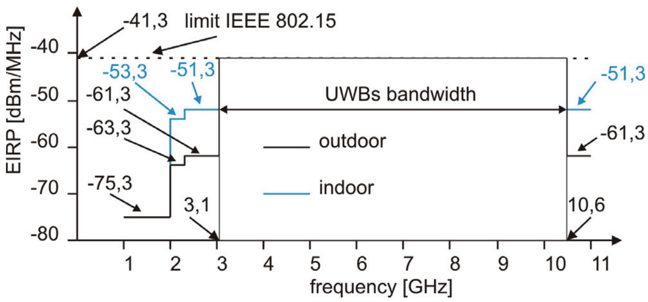

Fig. 1. FCC's power spectral mask for indoor and outdoor usage.

To satisfy this frequency-dependent power condition, specific signals (waveforms) are required. The UWB is therefore defined as pulse signals in the baseband without a carrier. According to this definition it is important to carefully select the types of signals which can be usefully implemented into the UWB system.

2.1 Signals for UWB

Just as other communication systems, Ultra-Wide Band systems utilize the orthogonality of signals. The most important categories of pulses within the UWB are of Gaussian pulses and Hermitian polynomial pulses, both of them having very similar shapes and properties. Gaussian pulses in time (t) are provided by the well-known equation:

$$y(t) = K_1 e^{-\left(\frac{t}{\tau}\right)^2} \tag{2}$$

where K_1 stands for an energy constant and τ represents a time constant [4].

The equation (2) can be further derived in order to reach other Gaussian waveforms – see the graphical interpretation both in the time domain (TD) and in the frequency domain (FD) in Fig. 2. The first derivation is known as a monocycle and the second one as a doublet.

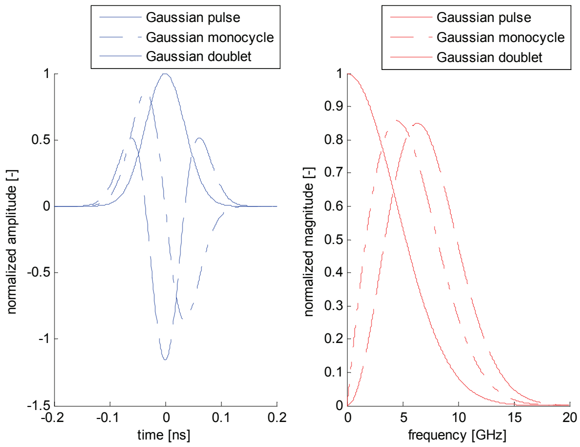

Fig. 2. An example of Gaussian pulses a) in the time domain, and b) in the frequency domain.

It has to be emphasized that the basic waveform of Gaussian pulses is not well suited to the UWB spectral mask particularly because its maximum lies in the zero frequency. The other Gaussian pulses are perfectly formed to accomplish the FCC rule.

The UWB technology has a range of possibilities how to form the frequency spectrum such as modulation, a combination of several different pulses etc. [3], [4]. It is also possible to shape pulses in the time domain to suit specific needs, for example for intelligent radio communications and communication systems like cognitive radio and software radio, respectively.

2.2 DS – UWB versus OFDM – UWB

There are two basic principles governing the efficient utilization of the UWB physical layer in communication systems. The first - Direct Sequence Ultra Wideband method (DS-UWB) - uses pulses, narrow in the time domain, which occupy a wide frequency spectrum. This principle is also referred to as the traditional UWB. High data rates (up to 1.5 Gbps) can be achieved using this technology. One of the basic modulation schemes, such as On-Off-Keying (OOK) or Binary Phase Shift Keying (BPSK), is mainly used for communications.

The second approach - Orthogonal Frequency Division Multiplex (OFDM) - has been an extremely popular multiplexing technique within convectional wireless systems for the last several years (WIFI, DVB and other). The UWB frequency band using OFDM is divided into several sub-bands (channels), which must satisfy the ultra-wideband definition [4]. This method is less frequency-consuming than DS-UWB, because it allows the disabling of some channels (frequency bands) where other narrowband services are allocated.

A comparison of Direct Sequence and OFDM based UWB for both the time and the frequency domain is depicted in Fig. 3.

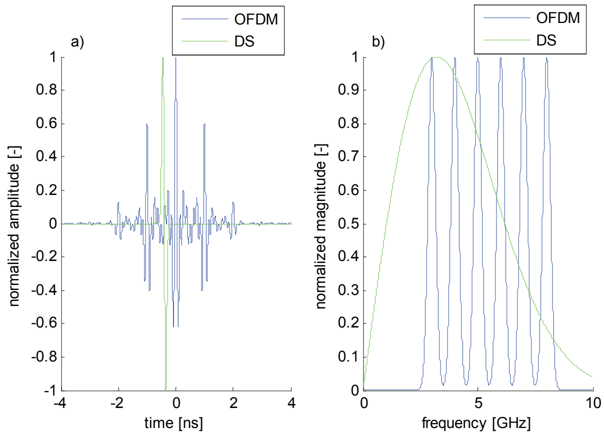

Fig. 3. A comparison of the time shifted DS (green) and OFDM (blue) based UWB a) in the time domain, and b) in the frequency domain.

It has to be mentioned that all the measurements and simulations discussed in this paper concern DS-UWB, especially because the utilization of a single pulse produces more illustrative results.

For communication purposes (mainly for a suppression of intersymbol interference) a guarded interval (GI) is used within the UWB [4]. The duration of the GI supplies immunity for multi-path signal distortion in a complex environment - nevertheless the longer the duration of the GI is, the less the information they may be transferred, i.e. a lower transmission rate can be guaranteed.

2.3 UWB Measurement Techniques

Wideband and ultra wideband signals can be measured either in the frequency or in the time domain. Both these techniques have their specific advantages and drawbacks. In the frequency domain, measurements of transition (s_{21} parameter) via a vector network analyzer are mostly utilized for discrete frequencies [7]. A subsequent Fourier transformation provides an easy conversion from the frequency to the time domain. The biggest drawback of this method is that it inevitably requires a stable frequency source. On the other hand, one of its advantages is for example the option of easily calibrating and suppressing of all cable and connector effects.

The time domain measurement is accomplished via a wideband sampling oscilloscope and a pulse generator. The use of these instruments allows us to directly measure the impulse response $h(t)$ of the system. This type of measurement is faster than measurements taken in the frequency domain. TD could be used in particular for antenna testing in an ordinary environment, i.e. without the need for an anechoic chamber. The disadvantage of the time domain measurements lies in data processing, which may require a slightly complicated hardware implementation.

The impulse response of the horn antenna measured in both time and frequency domains at the University of Karlsruhe during the European School of Antennas' UWB course [8] is depicted in Fig. 4.

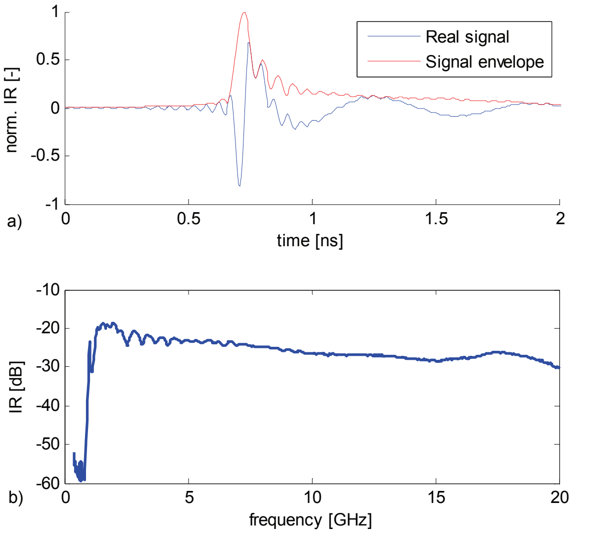

Fig. 4. Impulse response a) in TD and b) in FD (measured in the University of Karlsruhe during the ESOA UWB course [8]).

3. Specifics of UWB Signal Propagation

It is very difficult to describe the ultra-wideband wireless channel using standard equations for narrowband signal propagation [9]. Therefore the main part of this paper is devoted to a description and comparison of the measurements and simulations of UWB signal propagation. Results from time domain measurements using the Gaussian monocycle (the first derivation of the Gaussian pulse) modulator [10], specially designed UWB Vivaldi antennas [11] and an Agilent 86100C wideband sampling oscilloscope are introduced in this paper.

3.1 Path Loss in the UWB

One of the biggest advantages of the UWB propagation is a reduction of the signal fading. The absence of a carrier and proper pulse duration settings reduce the risk of sharp drops in received power at short distances - there are no interference regions - as can be observed in narrowband systems (Fig. 5).

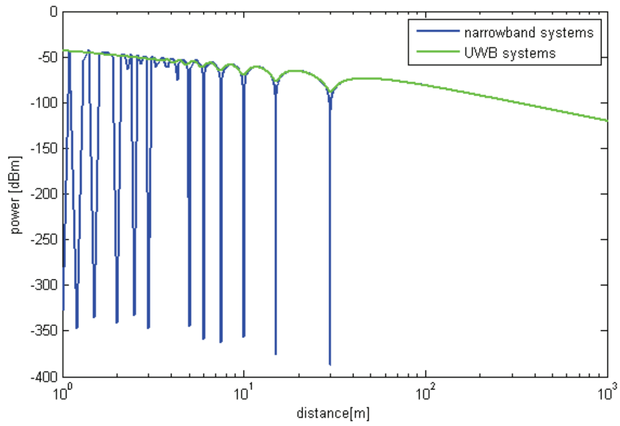

Fig. 5. Power profile.

In the literature frequency domain approaches to UWB propagation modeling prevail [3] [12-14], with ray tracing based methods for large amount of discrete frequencies. Nevertheless as was mentioned above the time domain provides useful tool for the investigation of path loss.

The path loss L in UWB may be defined as frequency and distance dependent [4] according to:

$$L(d,f) = L_0 + \gamma 10\log\left(\frac{d}{d_0}\right) + \nu 10\log\left(\frac{f}{f_0}\right) \qquad (3)$$

where L_0 represents the free space loss in the reference distance d_0 and f_0 is the central frequency. The coefficient γ stands for the distance dependence and ν introduces the frequency dependence, which is not taken into consideration in the case of narrowband systems. The main drawback of this empirical model is that it does not respect the pulse shape of the UWB waveform.

A measurement was performed to validate the above mentioned model (3). The basic measurement setup for the path loss measurement is depicted in Fig. 6; a vertical polarization of antennas was used. This setup represents multipath propagation in a real room. The same measurement was carried out in an anechoic chamber.

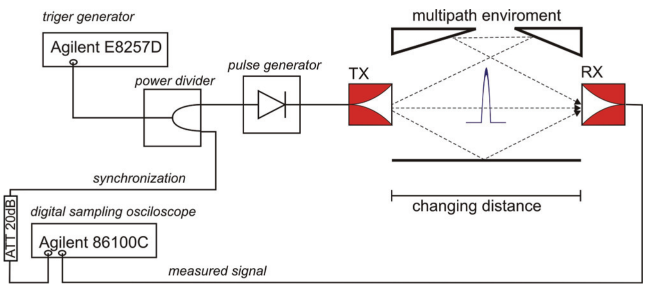

Fig. 6. Measurement setup for multipath propagation in a real environment.

It must be mentioned that in the time domain measurement it was only possible to determine the distance dependent coefficient γ. In particularly, the coefficient $\gamma = 1.85$ was derived from waveforms measured in the LOS scenario in a real room for distances in the range 0.5 to 2 meters.

3.2 Dispersion of the Gaussian Pulse

Dispersion is certainly the main factor for signal propagation in the time-invariant channel. In fact, one of common UWB received modes utilizes a comparison of the received signal with its replica (coherent detection using correlation). This reception mode is crucially dependent on the non-dispersive character of the pulse. Several measurements were performed to confirm or disprove such feature (see the measurement setup in Fig. 7). Very similar pulses to the Gaussian pulse were used in these measurements [10], [15]. These pulses were of Gaussian monocycle (the first derivation of Gaussian pulse) generated from the pulse generator with the trigger frequency set to 500 MHz (2 ns period of pulses). The pulse duration was of 1.28 ns in the time domain with amplitude 4 V and its 3 dB frequency spectrum bandwidth was of 3 GHz.

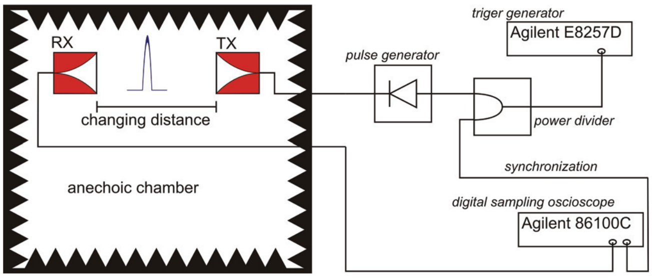

Fig. 7. Setup for measurements of signal dispersion in an anechoic chamber.

The signal distortion was investigated for several distances between antennas. The results were processed with MATLAB®, where the "peak-to-peak" method was implemented. This very simple function allows the recognition of exactly one measured Gaussian pulse from a measured sequence of pulses (pulse train). This method must be employed to compensate the dependence of the time delay between incident pulses (direct and reflected) with an increasing distance between these two paths. This time delay is clearly illustrated in Section 3.3 where two pulses, direct and reflected, are constructively/destructively added, based on the time and phase shift respectively.

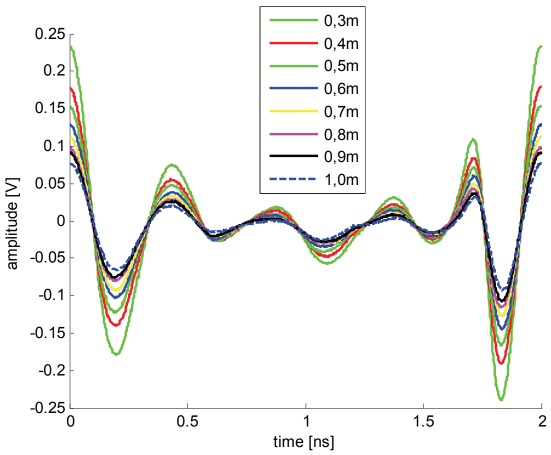

Fig. 8. Measurement of signal dispersion for different distances.

The "peak-to-peak" method allows a synchronization of the pulse in time, so at some point it should be possible to calculate the extension of the pulse. The output from the "peak-to-peak" synchronization (the time dependence of the voltage amplitude of the pulse from the sampling oscilloscope in Volts) can be seen in Fig. 8. It can be seen, that all pulses have the zero crossing in the same point. According to the results from Section 3.1, the path loss dependence is evident – the higher the distance, the lower amplitude of the pulse. It must also be emphasized that the same measurements were obtained from the real room and from the anechoic chamber – no dispersion of pulse was observed.

3.3 Prediction and Measurement of Reflected Pulses

A lack of interference of a direct and a reflected wave provides the basic insight into the difference between UWB signal propagation and narrowband systems. Therefore, a measurement campaign was accomplished with emphasis on the prediction and measurement of reflected pulse behavior. The basic simulation was made using the two-ray model [15]. Based on the precise prediction (confirmed by measurements) of the time arrival of pulses, it is possible to accommodate ray-tracing models in various complex environments [15], [16]. The ray-tracing models enable us to predict when some interference arises and whether this phenomenon will have a constructive or destructive influence on signal reception. Small differences between the direct pulse and the reflected pulse path cause interferences (overlapping) of these two signals. Over large distances some other pulses in the pulse train may be influenced, nevertheless a large distance, i.e. higher path loss, very often results in undetectable interference signals.

The basic principle of the simulation and measurement is demonstrated in Fig. 9. This setup was similar to the one depicted in Fig. 6, but in order to assure only the direct ray and the dominant reflected ray and to suppress the other undesirable reflected pulses, a conductive plane was placed on the floor between the antennas and the rest of the room was covered with an absorptive material. This approach enables us to extract only the dominant reflected ray.

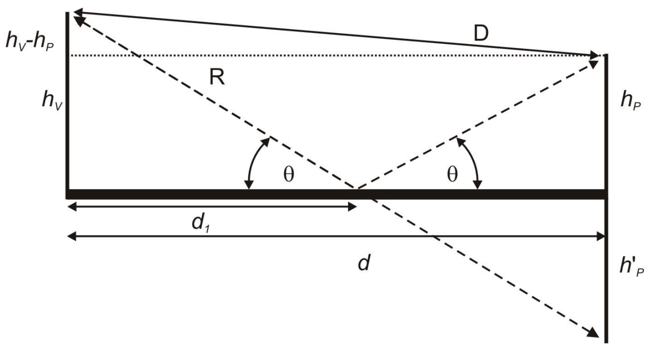

Fig. 9. Reflected and direct path.

Using the scheme from Fig. 9, two types of measurements were performed. In the first measurement both vertically polarized antennas were placed at a distance of 1 m and the height of antennas above the conductive ground was changed. Measurement results of the time delay between the direct and reflected pulses as compared to the simulations are depicted in Fig. 10. It can be clearly shown that the theoretically calculated values are similar to the measured values. The maximum deviation between the measured and theoretical values is 0.17 ns (i.e. 8.2% of the transmitted pulse duration) for antennas height of 1 m. This deviation could be partially caused by a slight difference between dielectric permittivity of gases in real scenario and our simulations and also by rounding of velocity of light.

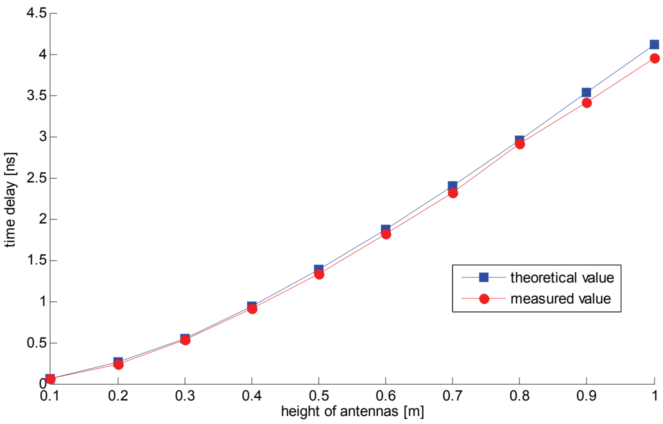

Fig. 10. Time delay between direct and reflected pulses.

During the processing of measured values the phase of the reflected pulse could be carefully treated. One could object that the phase is changed only during the reflection. In UWB measurements, the fact that the receiving antenna (when the same antennas are used) has the opposite space orientation, and that the phase is therefore "changed" again, should be taken into account. This phenomenon was proved by other UWB measurements, where the direct pulse and reflected pulse from a conducting ground having the same phase (one maximum peak and two minimum peaks) were observed – as depicted in Fig. 11.

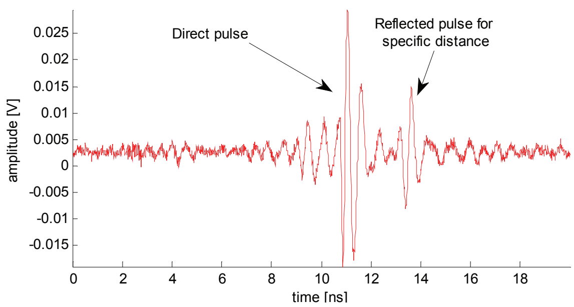

Fig. 11. Phase change for direct and reflected path.

In the second measurement, the distance between the antennas was increased in order to describe the overlapping of the pulses. Interpretation of this measurement is quite difficult (see in Fig. 12) since it creates the undesirable effect of a moving direct pulse on a timeline as in (4).

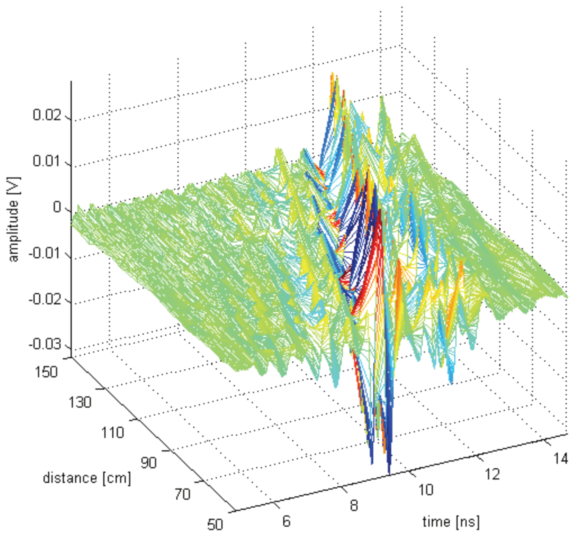

Fig. 12. Dependence of measured waveforms of the received signal on the distance between the antennas.

In Fig. 12 an overlapping of pulses can be distinguished, especially for longer distance. This effect corresponds to Fig. 10, because the time delay between the reflected and direct pulse must be greater than the time width of the pulse. From Fig. 8 we can derive that a width for used Gaussian pulse of about 2 ns and consequently from Fig. 10 it can be seen that this time delay can be obtained for antenna heights of over 60 cm, where the difference between the reflected and direct pulse path exceeds 0.18 m. This feature of UWB signal propagation was fully confirmed by the measurement campaign.

4. Conclusion

Several UWB propagation aspects were discussed in the paper. At first, the empirical path loss model for the LOS pulse propagation was compared with measured values.

A dispersion model for UWB pulses was investigated using measurements in an anechoic chamber. It was proved that for short distances (up to 2 meters) the UWB propagation channel can be treated as non-dispersive. This feature should be very important for communication systems.

The last part of the paper was focused on interference between the direct and the reflected pulses. The time delay of the reflected pulse was separated from measured data and the constructive and destructive interaction of direct and reflected pulses was determined and compared to the simulations. The measured waveforms tend to slightly different to those derived theoretically - the maximum deviation reached 8.2% (0.17 ns) of the transmitted pulse duration.

Acknowledgements

This work was supported in part by the Czech Ministry of Education, Youth and Sports within the framework of the MSM 6840770014 project (measurements) and in part by the Czech Science Foundation under Grant 102/08/H027 (simulations).

References

[1] GHARPUREY, R., KINGET, P. *Ultra Wideband Circuits, Transceivers and Systems*. New York: Springer, 2008.

[2] http://www.pulselink.net/technology/cwave_tech.htm

[3] SIWIAK, K., MCKEOWN, D. *Ultra-Wideband Radio Technology*. West Sussex: John Wiley & Sons, 2004.

[4] GHAVAMI, M., MICHAEL, L. B., KOHNO, R. *Ultra Wideband Signals and Systems in Communication Engineering*. West Sussex: John Wiley & Sons, Ltd, 2004.

[5] The Federal Communications Commission FCC, http://www.fcc.gov

[6] Decision of Commission of the European Communities of 21/II/2007, on allowing the use of the radio spectrum for equipment using ultra-wideband, http://ec.europa.eu

[7] HANEDA, K., TAKADA, J., KOBAYASHI, T. A parametric UWB propagation channel estimation and its performance validation in an anechoic chamber. *IEEE Transactions on Microwave Theory and Techniques*, 2006, vol. 54, no. 4 , Part 2, pp. 1802 – 1811.

[8] http://www.antennasvce.org/Community/Education/Courses/Locations

[9] PECHAC, P., KLEPAL, M., NOVOTNY, K. Novel approach to indoor propagation modeling. *Radioengineering*, 2000, vol. 9, no. 3, p. 12-16. ISSN 1210-2512.

[10] TESAR, R. *Generator for Ultra-wideband Applications*. Diploma thesis, Department of Electromagnetic Field, CTU in Prague, 2007 (in Czech).

[11] PIKSA, P., SOKOL, V. Small Vivaldi antenna for UWB. In *Proceedings of the Conference Radioelektronika*. Brno (Czech Republic), 2005, p. 490-493.

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

[13] CRAMER, R. J.-M., SCHOLTZ, R. A., WIN, M. Z. Evaluation of an ultra-wide-band propagation channel. *IEEE Transactions on Antennas and Propagation*, 2002, vol. 50, no. 5, pp. 561-570.

[14] MANTEUFFEL, D. Modeling and visualization of the communication link for UWB consumer applications. In *Loughborough International Conference on Antennas and Propagation,* 2007.

[15] URBAN, R. *Specifics of UWB Propagation in Nanocells*. Diploma thesis, Department of Electromagnetic Field, CTU in Prague, 2008 (in Czech).

[16] MÖNICH, U. J., STURM, C., BOCHE, H., WIESBECK, W. Empirical capacity and the fading characteristics of ultra-wideband indoor propagation channels. In *Radio and Wireless Symposium*, 2008 IEEE , pp.607-610, 2008.

About Authors …

ROBERT URBAN (*1984) received his M.Sc. degree from the Czech Technical University in Prague (CTU) in 2008. Now he is working on his Ph.D. thesis that is focused on electromagnetic wave propagation within new emerging wireless systems. His research interest is in ultra wideband propagation and cognitive systems. He is a member of IEEE.

STANISLAV ZVÁNOVEC (*1977) received his M.Sc. degree in electrical engineering from the Czech Technical University in Prague, Czech Republic, in 2002. He received his Ph.D. degree in 2006 and is now with the DEF of CTU. His current research and interests include electromagnetic wave propagation issues for millimeter wave band, quasioptical and optical systems and UWB radio propagation channel. He is a member of IEEE, Radioengineering Society and head of the Commission F of the Czech National URSI Committee.