Channel Models for Ultra-Wideband Communications: an Overview

Aawatif Menouni Hayar* and Giorgio M. Vitetta**
*Eurecom Institute, Sophia Antipolis, France - **CNIT, University of Modena and Reggio Emilia, Italy

E-mail: aawatif.menouni@eurecom.fr, giorgio.vitetta@unimo.it

***Abstract* - This paper presents an overview of *ultra-wideband* (UWB) channel modeling. After outlining the enormous potentialities of UWB systems and the benefits in terms of capacity and flexibility coming from their large bandwidth, we illustrate the state of the art on UWB channel models based on both empirical and statistical approaches. Finally, we underline the need of further research work and measurement campaigns in this area; this should aim at capturing the specificity of UWB propagation, leading to the derivation of more accurate channels models to be employed in both system design and performance optimization.**

***Index Terms* - UWB channel modeling, empirical models, statistical models.**

I. INTRODUCTION

U*LTRA-wideband* (UWB) signaling techniques [1] are currently being considered for indoor short-range radio links operating at high data rate and overlaying with other existing wireless systems. In particular, substantial attention to these techniques has been paid in the standardization process of the IEEE 802.15 *Wireless Personal Area Networks* (WPAN) proposal. Following the FCC's "Report and Order" [2], more than 7.5 GHz can be exploited for unlicensed UWB applications in the US spectrum. This large bandwidth represents a high potential in terms of capacity and flexibility and makes UWB systems attractive for applications such as localization, security systems, emerging automotive and home based "location awareness" systems.

UWB communications are expected not to have an observable impact over more conventional (narrowband) systems. This result should be achieved keeping their transmission power at very low levels. Unavoidably, this constraint limits the range of UWB wireless links to values typically not exceeding 20 m, making such systems suitable to short range indoor applications. This explains why most of the research work on the characterization and on the modeling of UWB channels has focused on *indoor environments* with both *line-of-sight* (LOS) and *non*-LOS (NLOS) settings.

In this paper an overview of the most important results offered by the recent literature on UWB channel models is provided. First, sounding techniques commonly employed in measurement campaigns for UWB channels are illustrated. Then, we comment on some significant results extracted from such campaigns, considering, in particular, some relevant parameters, like the path loss, the delay spread and the degrees of freedom of UWB channels. Finally, a statistical description of UWB channels is given, taking into consideration the stochastic properties of their *channel impulse response* (CIR) and offering some brief information about their description in the frequency domain.

This paper is organized as follows. Sounding techniques for UWB channels are summarized in Section II. Overviews of empirical and statistical channel models are provided in Sections III and IV, respectively, Finally, Section V offers some conclusions.

II. MEASUREMENT TECHNIQUES

In this Section measurement scenarios and sounding techniques for UWB channels are briefly described.

A. Measurements scenarios

Recent measurements campaigns for UWB systems have aimed at analyzing electromagnetic propagation over the bandwidth approved by the FCC [2] and for short ranges (typically from 1 m to 20 m) [3]-[9]. In the cited references, characterizations of UWB communication channels in offices, laboratory rooms or corridors are available; further results concerning specific areas, like hospitals or industrial halls, can be also found in the technical literature [10].

B. Time domain sounding

In time domain techniques for UWB channel sounding, the channel is generally excited by a short pulse, and a receiver records samples of the channel response captured by its antenna. The main advantages offered by this approach are the immediate availability of CIR realizations in the time domain, and the possibility of easily assessing time variations in a propagation scenario. Time domain sounding, however, requires the generation of ultra-short pulses, and is impaired by the use of non-ideal transmit pulses, distorting the observed impulse response. For this reason, the use of *deconvolution*

This work has been developed in the framework of the IST Network of Excellence "NEWCOM" (507325), funded by the European Community in its VI Framework Programme.

techniques for extracting the real CIR from measured data, for a given transmit pulse, has been proposed in [6], [11].

C. Frequency domain sounding

A common approach to frequency domain sounding of UWB channels is based on the use of a *vector network analyzer* (VNA), recording the channel frequency response for fixed transmitter-receiver locations. The allowed maximum distance of the UWB link, however, is limited by the used RF-cables, since in the measurement equipment the transmitting and receiving ports are connected to the same device. Recently, an advanced technique for channel sounding in the frequency domain, dubbed *modified* VNA (see Fig. 1), has been proposed [7]. In this case, independent locations for the transmitter and receiver ends can be selected; for this reason, the VNA can be employed as a receiver just like in a conventional VNA sounder. The novelty of the proposed approach is mainly due to the use of an external signal generator as a transmitter. The transmitter and the receiver are kept synchronized together using a specific radio link; this is exploited to send a triggering signal that starts the frequency sweep in the transmitter, as shown in Fig. 1. The main drawback of this sounding technique is the fact that the exact phase response of UWB channels cannot be acquired, because the phase of the frequency sweep in the transmitter cannot be controlled; moreover, like in other methods for channel sounding in the frequency domain, time variations of the communication channel cannot be recorded.

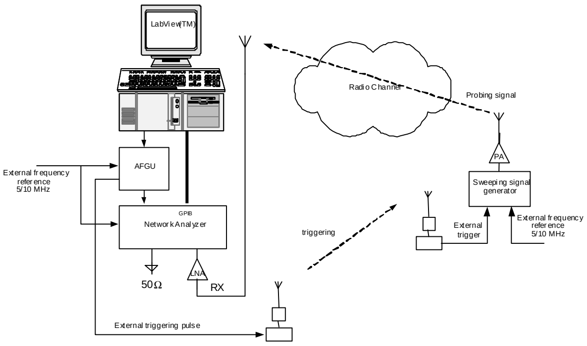

Fig. 1 - Modified frequency domain channel sounder [7].

III. ULTRA WIDE BAND INDOOR CHANNELS: EMPIRICAL MODELS

In this Section some considerations about the empirical results acquired on significant parameters of UWB channels are illustrated.

1) Path loss models

Path loss models describe the average power loss encountered in radio propagation at a given distance of the receiver from the transmitter. In UWB communications, a *log-distance model* [12], [13] is commonly adopted, so that the *average path loss* $\overline{PL}_{\mathrm{dB}}(d)$ in dB at a distance d of the receiver from the wireless transmitter is given by

$$\overline{PL}_{\mathrm{dB}}(d) = \overline{PL}_{\mathrm{dB}}\left(d_0\right) + 10\,n\log_{10}\left(d/d_0\right) \qquad (1)$$

where $\overline{PL}_{\mathrm{dB}}\left(d_0\right)$ is the *mean path loss* (in dB) at a *reference distance* d_0 and *n* represent the environment-specific *path loss decay exponent*. In practice, the path loss $\overline{PL}_{\mathrm{dB}}\left(d\right)$ can be evaluated processing a set of values of the channel frequency response $H(d,f)$ measured at a distance d from the transmitter. In particular, if the samples $\{H(d,f_{\mathrm{i}}),\ i=1,2,...,N\}$ of $H(d,f)$, taken at N equally spaced frequencies $\left\{f_{\mathrm{i}}\right\}$, are available, $\overline{PL}_{\mathrm{dB}}\left(d\right)$ can be estimated as

$$\overline{PL}_{\mathrm{dB}}\left(d\right) \approx 10\log_{10}\left(\frac{1}{N}\sum_{i=1}^{N}\left|H(d,f_{\mathrm{i}})\right|^2\right). \qquad (2)$$

Measurements at different carrier frequencies have evidenced that the decay exponent *n* varies from 1 to 2 in LOS scenarios and from 3 to 4 in NLOS ones [10]. Decaying exponents ranging between 1 and 1.43 in LOS environments and between 3.17 and 3.85 in NLOS ones has been experimentally assessed in [14].

2) Power delay profile

Measurement results about the so-called *average power delay profile* (APDP) in UWB channels have evidenced (a) the presence of several distinct clusters of scatterers, (b) an exponential decay with cluster dependent decaying constants, and (c) an high number of resolvable paths [4], [8], [15], [16].

A typical measured APDP of a LOS UWB channel is shown in Fig. 2.

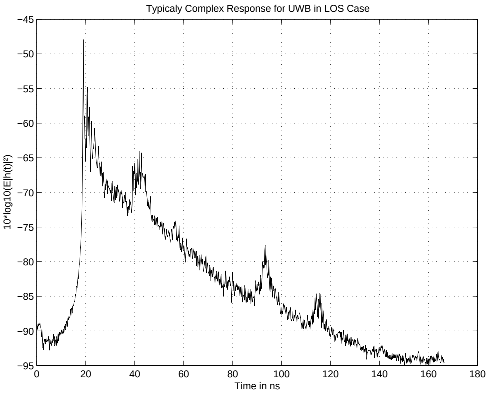

Fig. 2 - Average power delay profile of a LOS UWB channel.

3) Delay spread

Root mean square (RMS) *delay spread* is a time domain parameter providing an indication of the time dispersion due to channel multipath [17]. It can be computed from the measured channel *power delay profile* (PDP). Typical values of the RMS delay spread assessed in UWB indoor environments are listed in Table II.

Recent measurements for high-rise apartment environments [18] have evidenced a mean RMS delay spread ranging from 10.41 to 42.70 ns (from 10.36 ns to 45.55 ns) and to an excess delay ranging from 0.98 to 16.19 ns (from 10.36 to 45.55 ns) in 3-bedrooms apartments (4-bedrooms apartments).

Table II: Typical delay spreads for UWB indoor channels.

	RMS delay (ns)			Excess delay (ns)	
Ref.	LOS	NLOS	Extreme NLOS		Env.
[11]	5.28	14.28	25	5.05-14.18	CM1-CM4
[15]	28-31	34-40	40	-	Industrial
[14]	14-21	18-21	21	-	Office-corridor

4) *Channel degrees of freedom*

The number of significant degrees of freedom of UWB channels has been investigated in [8], applying empirical subspace analysis to experimental data acquired at 3-9 GHz in indoor environments (laboratory rooms) with a separation distance of 6 m. This work has evidenced (a) a saturation of the number of *degrees of freedom* (DoF, defined as the minimum number of significant eigenvalues capturing at least 98% of the overall energy) starting from some critical bandwidth for both LOS and NLOS scenarios (see Fig. 3), and (b) a statistical dependence between distinct resolvable paths.

These results provide some insight in the capacity of UWB channels. In fact, they show that (a) it is not always necessary to exploit the whole bandwidth in order to benefit from the maximum channel capacity and that (b) transmission rates are not expected to increase linearly with the allocated bandwidth.

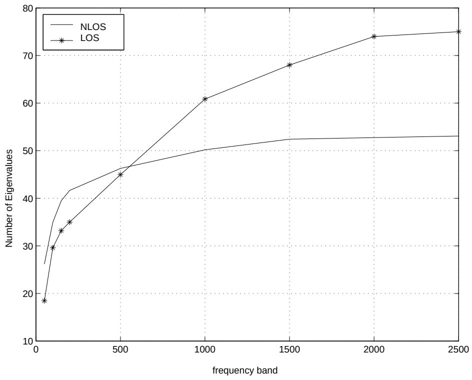

Fig. 3 - Channel degrees of freedom versus transmission bandwidth in UWB channels.

IV. ULTRA WIDE BAND INDOOR CHANNELS: STATISTICAL MODELS

This Section provides an overview of some relevant results about statistical channel models for UWB channels. Both large scale and small scale fading models are considered.

1) *Large-Scale Fading*

The path loss model usually employed in a statistical analysis of UWB systems is the *log-distance model with lognormal shadowing* [5]. This means that the path loss $PL_{\text{dB}}(d)$ in dB at a distance d of the receiver from the wireless transmitter is expressed as

$$P_{\text{dB}}(d) = \overline{PL}_{\text{dB}}(d) + X_{\sigma} \tag{3}$$

where $\overline{PL}_{\text{dB}}(d)$, the average path loss in dB at a distance d, is given by (1) and X_{σ} is a Gaussian random variable having zero mean (in dB) and standard deviation σ (in dB also). Various measurement campaigns, performed in commercial and residential buildings, have evidenced that both the parameters n and σ in UWB channels usually take on lower values than those estimated in narrowband systems [5], [19]-[21]. In [5], a *dual slope* model providing a better approximation of the path loss has been also developed.

2) *Small-Scale Fading*

a) *Channel impulse response model*

A small-scale representation of a multipath fading channel is provided by its time varying CIR $h(t,\tau)$. A *tapped-delay line model with clusters* is commonly adopted for the CIR of a UWB channel [20], [22]. This means that, if a *static* channel is assumed over a given observation interval, the CIR is expressed as

$$h(t) = \sum_{l=0}^{L-1} \sum_{k=0}^{K-1} a_{kl} \exp\left(j\theta_{kl}\right) \delta\left(t - T_l - \tau_{kl}\right) \tag{4}$$

where L is the number of *clusters* of scatterers, K is the number of echoes in each cluster, a_{kl} and θ_{kl} are the amplitude and phase shift of the k-th echo in the l-th cluster, respectively, T_l and τ_{kl} are the arrival instant of the l-th cluster and the arrival delay of the k-th echo with respect to the beginning of the l-th cluster, respectively ($T_0 = \tau_{0l} = 0$), and $\delta(t)$ is the Dirac impulse.

Given (4), a *complete* stochastic model of a UWB channel is provided, when a full *statistical* description of the amplitudes, phases and delays of its distinct paths is given.

b) *Statistics of channel delays*

Two significant models for the delays of the multiple echoes have been proposed in the technical literature: the $\Delta - K$ model and by the *Neyman-Scott* model [23].

The $\Delta - K$ model is a two state Markov model. In its first state S_1 and in its second one S_2 the arrival average frequencies of channel echoes are $\lambda_0(t)$ and $K\lambda_0(t)$, respectively. The initial state of the process is assumed to be S_1. If at the instant t a signal echo arrives, the process state becomes S_2. If at the end of the interval $[t, t+\Delta)$ no new signal echo has appeared, the process state changes again, returning to S_1.

The Neyman-Scott model (also dubbed $S-V$ model since Saleh and Valenzuela applied it to the description of a radio channel for the first time in [20]) assumes that the both the scattering clusters of a UWB channel and the scatterers belonging to the same cluster are described by Poisson distributions; the latter, however, are characterized by an arrival average frequency depending on the cluster itself.

Despite the $\Delta - K$ and $S - V$ models are in good agreement with experimental data, their parameters cannot be easily evaluated, so that simpler stochastic models are very useful. For instance, a simplified version of $S - V$ model is the so-called *split-Poisson* model [24]. This assumes the existence of two clusters only, each with a different arrival frequency.

c) Statistics of phases and amplitudes of channel taps

Measurement campaigns for UWB systems have evidenced that, with the exception of few cases [25], the statistical distributions of the tap amplitudes of (4) can differ significantly from the well-known Rayleigh and Rice models. For this reason, other distributions have been adopted to approximate experimental data more accurately. These include the *Nakagami* [5], [23], [26], the *log-normal* [26] and the so-called *POCA–NAZU* distributions [14].

A uniform distribution over $[0, 2\pi)$ is commonly adopted to model the phase of channel echoes. In some cases, however, the two possible (and equiprobable) $\{0, \pi\}$ (rad) phase shifts for each multipath component are assumed [26]. This is equivalent to handling only the polarity of the received signal components.

d) Power delay profile statistics

If the channel model takes into account a clustering effect in the arrival times of the multipath components (like the $S - V$ model), the power delay profile of a UWB channel is usually approximated as a *double exponential*, so that the average power associated with the k-th echo in the l-th cluster of (4) is given by

$$E\left\{a_{kl}^2\right\} = \Omega_0 \exp\left(-T / \Gamma_l\right) \exp\left(-\tau_{kl} / \gamma\right) \tag{5}$$

Here Ω_0 is the average power of the first[1] multipath component, and Γ and γ are the *decay constants* of the clusters and of the echoes inside the clusters, respectively.

Eq. (5) does not provide information about the fast fluctuations of the received power due to fading. In fact, it describes the so-called *average power delay profile* (APDP) of a UWB channel (also dubbed *small-scale averaged power delay profile*, SSA-PDP), evaluated as a spatial or a temporal average of multiple power profiles. A statistical description of the *local power delay profile* (also called *multipath intensity profile*, MIP) requires the introduction of a stochastic process expressing the deviation of the received power from its average [27].

e) Arrival angle of multipath components

Research activities on UWB channels have often aimed at assessing the delays associated with the distinct multipath components in the received signal, without taking into consideration their *angle of arrival* (AOA). In many applications, angular information are unrelevant, but in those involving *multiple input – multiple output* (MIMO) systems, they are absolutely necessary for an accurate description of the channel behavior. A statistical description of the AOA in UWB systems has been proposed in [28], where statistical independence about arrival instants and angles is assumed.

f) Time variance of UWB channels

A realistic description of a UWB channel should account for the time variations of a given propagation scenario. The time variance in a radio channel is usually due to two distinct factors [29]: (1) the relative motion between the transmitter and the receiver; (2) the motion of the scatterers. A small-scale statistical description for the relative motion between the transmitter and the receiver can be derived under the assumption of *wide sense stationary uncorrelated scattering* (WSS-US) channel. Modeling the motion of different scattering points, however, is substantially more complicated, since, in this case, the WSS-US assumption is no more realistic. Channel stationarity does not hold, for instance, when an object having a large angular section, like a person, obstructs the direct path between the transmitter and the receiver, producing an appreciable variation in the geometry of the channel (which would change from LOS to NLOS) [29].

g) Auto-regressive models for UWB channels

The main disadvantage of channel models based on the description of the CIR (4) is that they involve a large number of parameters, when a satisfactory description of a given UWB propagation scenario is required. In [30] it is shown that a second order auto-regressive model in the frequency domain can provide a channel description closely matching experimental data. Therefore, this approach leads to an accurate modeling of the channel frequency response of a UWB channel, even if a small number of parameters is required.

V. CONCLUSIONS

In this paper an overview of the sounding techniques, of the significant empirical data and of the statistical models for UWB channels has been provided. Most of the mentioned experimental results have been acquired in measurement campaigns using frequency domain channel sounding. Time domain sounding, however, should be also exploited in the future in order to characterize the time variability of UWB scenarios. Experimental efforts in this area should also aim at developing common measurement databases containing a large number of channel realizations; this would allow to extract statistical properties of UWB channels in an accurate fashion and to assess the presence of specific propagation phenomena. This would also lead to the development of more accurate UWB channel models and of more realistic channel simulators for system design and performance optimization.

---

[1] The parameter Ω_0 can also represent the average power of the second multipath component; this occurs if the first one is very strong and its power diverges from the profile followed by the other components.

REFERENCES

[1] R. A Scholtz, "Multiple Access with Time-hopping Impulse Modulation", *Proc. of the IEEE Military Communications Conference 1993* (MILCOM '93), vol. 2, pp. 447-450, Oct. 1993.

[2] ***FCC***, “Revision of Part 15 if the Commission’s Rules Regarding Ultra-Wideband Transmission Systems”, ET Docket 98-153, released on April 22 2002, available at *http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-02-48A1.pdf*.

[3] M. Z. Win, R. A. Scholtz, and M. A. Barnes, “Ultra-wide bandwidth signal propagation for indoor wireless communications”, *Proc. of the IEEE Int. Conf. on Commun. 1997* (ICC’97), vol. 1, pp. 56–60, Montréal, Canada, June 1997.

[4] J. Kunisch and J. Pamp, “Measurement results and modeling aspects for UWB radio channel”, *Proc. of the 2002 IEEE Conf. on Ultra Wideband Systems and Technologies 2002* (*UWBST 2002*), pp. 19 – 23, Baltimore, USA, May 2002.

[5] D. Cassioli, M. Z. Win and A. F. Molisch, “The Ultra-Wide Bandwidth Indoor Channel: From Statistical Model to Simulations”, *IEEE J. Sel. Areas Commun.*, vol. 20, no. 6, pp. 1247-1257, Aug. 2002.

[6] J. Keignart and N. Daniele, “Subnanosecond UWB Channel Sounding in Frequency and Temporal Domain,” *Proc. of the 2002 IEEE Conf. on Ultra Wideband Systems and Technologies* (*UWBST 2002*), pp. 25–30, Baltimore, USA, May 2002.

[7] M. Hämäläinen, L. Hentilä, J. Pihlaja and P. Nissinaho, “Modified frequency domain radio channel measurement system for ultra wideband studies”, *Proc. of the Finnish Wireless Communications Workshop 2003* (*FWCW2003*), Oulu, Finland, 2003.

[8] A. Menouni Hayar, R. Knopp and R. Saadane, “Empirical eigenanalysis of indoor UWB propagation channels”, *EURASIP Journal on applied signal processing, special issue on UWB*, 2004.

[9] Z. Irahhauten, H. Nikookar and G. J. M. Janssen, “ An Overview of Ultra Wide Band Indoor Channel Measurements and Modeling”, IEEE Microwave and Wireless Components Letters, vol. 14, no. 8, pp. 386-388, Aug. 2004.

[10] D. Cassioli, W. Ciccognani and A. Durantini, “UWB Channel Model Report”, *ULTRAWAVES (*IST-2001-35189), Document D3.

[11] J. R. Foerster, M. Pendergrass and A. F. Molisch, “A UWB Channel Model for Ultra Wideband Indoor Communications”, *Proc. of the International Symposium on Wireless Personal Multimedia Communications 2003* (WPMC 2003), October 2003.

[12] D. Cassioli, A. Molisch and M. Z. Win, “A Statistical Model for UWB Indoor Channel”, *Proc. of the IEEE 53rd Vehicular Technology Conference* (VTC Spring 2001), vol. 2, pp. 1159-1163, Rhodes, May 2001.

[13] K. Siwiak and A. Petroff, “A Path Link Model for Ultra Wide Band Pulse Transmissions”, *Proc. of the IEEE 53rd Vehicular Technology Conference* (VTC Spring 2001), vol. 2, pp. 1173 - 1175, Rhodes, May 2001.

[14] L. Hentilä, V. Hovinen and M. Hämäläinen, “Sub-band analysis in UWB radio channel modeling”, *Proc. of the Finnish Wireless Communications Workshop 2004* (*FWCW2004*), Oulu, Finland.

[15] J. Karedal, S. Wyne, P. Almers, F. Tufvesson and A. F. Molisch, “UWB channel measurements in an industrial environment”, *Proc. of the IEEE* Global Telecommunications Conference 2004. (GLOBECOM '04), vol. 6, pp. 3511 – 3516, Atlanta, USA Nov.\ Dec. 2004.

[16] S. S. Ghassemzadeh, L. J. Greenstein, A. Kavcic, T. Sveinsson and V. Tarokh, “UWB Indoor Delay Profile Model for Residential and Commercial Environments”, *Proc. of the IEEE 58th Vehicular Technology Conference* (VTC Fall 2003), vol. 5, pp. 3120-3125, Oct. 2003.

[17] D. C. Cox, R. P. Leck “Distributions of Multipath Delay Spread and Average Excess Delay for 910 MHz Urban Mobile Radio Paths”, *IEEE Trans. Ant. and Prop.*, vol. 23, pp. 206-213, March 1975.

[18] C. Chong, Y. Kim and S. Lee, “UWB Indoor Propagation Channel Measurements and Data Analysis in Various Types of High-Rise Apartments”, *Proc. of the IEEE 58th Vehicular Technology Conference* (VTC Fall 2004), Sept. 2004.

[19] S. S. Ghassemzadeh, L. J. Greenstein, A. Kavcic, T. Sveinsson and V. Tarokh, “UWB Indoor Path Loss Model for Residential and Commercial Buildings”, *Proc. of the IEEE 58th Vehicular Technology Conference* (VTC Fall 2003), vol. 5, pp. 3115-3119, Oct. 2003.

[20] A. Saleh and R. Valenzuela, “A Statistical Model for Indoor Multipath Propagation”, *IEEE J. Sel. Areas Commun.*, vol. 5, no. 2, pp. 128-137, Feb. 1987.

[21] Z. Irahhauten, H. Nikookar and G. J. Janssen, “An Overview of Ultra Wide Band Indoor Channel Measurements and Modeling”, *IEEE Microwave and Wireless Components Letters*, vol. 14, no. 8, pp. 386-388, Aug. 2004.

[22] J. Foerster, “Channel Modeling Sub-comittee Report Final,” IEEE P802.15 WG for WPANs Technical Report, no. 02/490r0-SG3a, 2002.

[23] H. Hashemi, “The Indoor Radio Propagation Channel”, *IEEE Proc.*, vol. 81, no. 7, pp. 943-968, July 1993.

[24] S. Venkatesh, J. Ibrahim and R. M. Buehrer, “A new 2 cluster Model for Indoor UWB Channel Measurements ”, *Proc. of the IEEE International Symposium on Antennas and Propagation*, vol. 1, pp. 946-949, June 2004.

[25] R. J. Cramer, R. A. Scholtz and M. Z. Win, “Evaluation of an Ultra-Wideband Propagation Channel”, *IEEE Trans. Ant. and Prop.*, vol. 50, no. 5, pp. 561-570, May 2002.

[26] A. F. Molisch, J. R. Foerster and M. Pendergrass, “Channel Models for Ultrawideband Personal Area Networks”, *IEEE Wireless Commun.*, vol. 10, no. 6, pp. 14-21, Dec. 2003.

[27] H. Zhang, T. Udagawa, T. Arita and M. Nakagawa, “A Statistical Model for the Small-Scale Multipath Fading Characteristics of Ultra Wideband Indoor Channel”, *Proc. of the IEEE Conference on Ultra Wideband Systems and Technologies 2002* (*UWBST 2002*), pp. 81-85, May 2002.

[28] D. R. McKinstry and R. M. Buehrer, “UWB Small Scale Channel Modeling and System Performance”, *Proc. of the IEEE 58th Vehicular Technology Conference* (*VTC Fall 2003*), vol. 1, pp. 6-10, Oct. 2003.

[29] A. F. Molisch, “Time Variance for UWB Wireless Channel”, *IEEE P802.15 Working Group for Wireless Personal Area Networks*, Nov. 2002.

[30] W. Turin, R. Jana, S. Ghassemzadeh, C. W. Rice and V. Tarokh, “Autoregressive Modeling of an Indoor UWB Channel”, *Proc. of the IEEE Conference on Ultra Wideband Systems and Technologies* (*UWBST 2002*), pp. 71-74, May 2002.