Experimental assessment of the UWB channel variability in a dynamic indoor environment

Pascal Pagani, Patrice Pajusco

EXPERIMENTAL ASSESSMENT OF THE UWB CHANNEL VARIABILITY IN A DYNAMIC INDOOR ENVIRONMENT

Pascal Pagani, Patrice Pajusco

France Telecom R&D/DMR/OIP, 6 av. des Usines, BP 382, Belfort Cedex, France
e-mail: { pascal.pagani; patrice.pajusco }@francetelecom.com

Abstract - Comprehensive modelling of the ultra-wide band (UWB) radio channel necessitates a good knowledge of its fading statistics. To evaluate the fluctuations of the UWB channel, a propagation experiment has been conducted in the 3.1 - 11 GHz frequency band, involving different antenna locations and moving people. The presented results emphasize the difference between the spatial and temporal channel variability, and provide a practical assessment of the UWB signal fading distribution in the case of a dynamic environment.

Keywords - Channel sounding, dynamic environment, radio propagation, ultra-wide bandwidth.

I. INTRODUCTION

The recent interest in UWB technology for high-rate indoor communication systems necessitates an accurate understanding of the different parameters characterizing the UWB propagation channel. Among these, the fading properties of the radio channel are of particular interest on a system point of view, since they influence the design of the radio interface.

Although a number of statistical studies of the fluctuations of UWB signals are available in the literature, the characterization of the fading properties in a UWB channel is a controversial issue. For instance, the small-scale statistics of the instantaneous received power magnitude have been reported to follow a Rayleigh distribution in [1], while other analyses concluded to a Nakagami [2] or Weibull [3] distribution. Most of these studies were based on experiments involving a measurements grid, resulting in series of channel realisations, with a spatial step length of a few cm. Examples of such an experimental design can be found in [1], [4] and [5].

It should be noted that this technique allows one to consider the *spatial* fluctuations of the signal, which would be experimented by a user with a mobile terminal. A number of applications of the UWB technology, however, will involve fixed access points and terminals, and the signal *temporal* fluctuations will mainly result from the movements of people in the close vicinity of the system. This will be the case for instance in the deployment of UWB-based WLANs in indoor office or residential environment [6].

A few studies regarding the impact of moving scatterers on a fixed wireless link are available in the literature. The experiment conducted in [7] reveals a substantial influence of moving persons on the main channel parameters, like the RMS delay spread or the K-factor. Measurements over a 600 MHz wide propagation channel are reported in [8], indicating a significant additional temporal fluctuation of the signal for some mutlipath components. This paper reports on an experiment designed to conjointly study both *spatial* and *temporal* fluctuations of the UWB signal in a typical indoor office environment. The proposed analysis of the small-scale amplitude distribution shows significant differences between the two concepts, and provides original results extending the available studies to the field of ultra-wideband signals.

II. THE UWB PROPAGATION EXPERIMENT

In order to get a precise idea of the signal fluctuations in a realistic indoor environment, a UWB propagation experiment was conducted in a fully furnished, typical conference room as presented in Fig. 1.

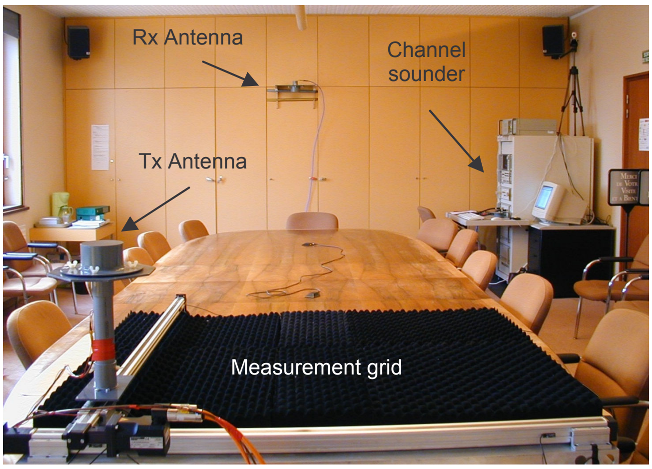


Fig. 1. Experimental setup.

A. Measurement setup

The measurement apparatus consisted of a Vector Network Analyser (VNA) HP8510C performing conventional S_{21} parameter measurements, the radio channel being the device under test. Using two omni-directional UWB antennas CMA 118/A, the channel response was sampled over 3955 equally spaced frequency tones between 3.1 and 11 GHz, thus covering the global FCC defined frequency band for UWB signals. To increase the signal gain, a power amplifier of 30 dB was inserted before the Tx antenna.

In order to evaluate the *spatial* fluctuations of the signal, up to 1841 measurements were performed over a 1 m² grid. The spacing between measurement points was of 14 mm in the central part of the grid and 28 mm at the periphery. This specific framework allows one to optimize the number of measurements while maintaining an adequate size of the sensor array available at each frequency for future DoA analyses. The automated motion of the antenna over the grid was fully synchronised with the VNA measurement procedure using a specifically developed Matlab® software.

B. Environment and measurement scenario

During the experiment, the 6 m × 9 m conference room was equipped with a central wooden table, about twenty chairs, some desks and shelves. The Tx antenna mounted on the measurement grid was situated on the central table, resulting in a height of 1.25 m. The Rx antenna was situated at 2.15 m from the floor in two configurations: one inside the room for LOS measurements and one in the nearby corridor for NLOS measurements.

For each configuration, the *spatial* fluctuations of the signal were assessed using the measurement grid in an empty room as explained above. To evaluate the *temporal* fluctuations of the signal, about 200 successive measurements were performed with a number of persons in the room varying between 1 and 10. Considering that a single measurement in the 3.1 – 11 GHz band lasts for several seconds, real-time measurement of the radio channel fluctuations is not technically feasible over a frequency band of several GHz. Instead, a *pseudo-dynamic* measurement technique was applied, where all persons in the room were keeping still for the measurement duration, and modified their position between measurements. As a result, a set of realistic realisations of the channel in an occupied conference room were obtained, which can be used for consistent statistical studies.

III. STATISTICAL ANALYSIS

A. Data processing

Each sampled frequency measurement obtained during the experiment was calibrated using a reference measurement, with the antenna feed cables directly connected. A Hanning window was applied to the resulting channel transfer function, and the base-band impulse response was obtained using an inverse Fourier transform.

As shown in Table 1, the number of measurements in each configuration was about 200. Regarding the static measurements over the 1 m² grid, all 1841 measurements were used to compute statistics about the total received power. For the sake of comparison, this data set was reduced to a sub-set of 225 measurements organised in a grid of 15 × 15 locations with 56 mm spacing for all other statistical studies. For this first analysis, LOS results only will be discussed in the following part of this paper.

Table 1
Number of measurements for each configuration.

LOS		*NLOS*	
1 person	200	1 person	200
4 persons	200	4 persons	200
10 persons	197	8 persons	175
Grid	1841 / 225	Grid	1841 / 225

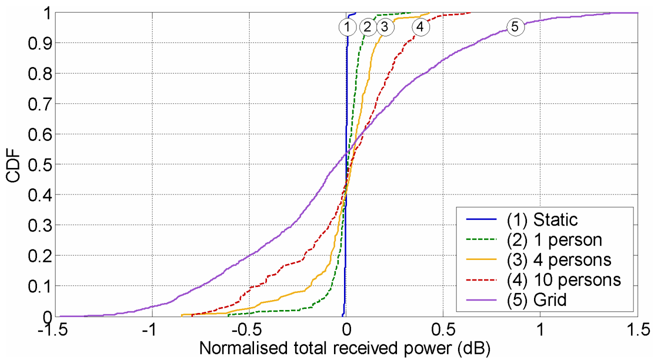


Fig. 2. Empirical CDF of the total received power.

B. Total received power

Our first analysis consisted in evaluating the fluctuations of the total received power. This corresponds to the fading statistics experienced by a receiver capable of extracting all the energy from the received waveform. A RAKE receiver with a high number of fingers is an example of such a device. Fig. 2 presents the CDF curves of the total received power for each configuration in the LOS case. A normalising factor has been applied to result in a mean received power equal to unity, and the power variations are represented in dB. The static curve (1) is obtained from a set of 200 successive measurements in a static configuration, and gives an idea of the power fluctuations inherent to the measurement process. One can note that an increasing number of moving persons in the conference room results in an increasing dispersion of the received power. The statistics observed for the measurement grid (i.e. for a *moving* terminal) seem to be an upper bound to the power fluctuations due to the motion of people. Our statistical study performed using a Kolmogorov-Smirnov (KS) testing procedure with a significance level $\alpha = 1\%$ indicates that the log-normal distribution is well-suited to represent the small-scale statistics of the total received power in both situations with 10 moving persons and with a measurement grid. Nevertheless, the grid of measurements should be taken as a worst case scenario, as the resulting standard deviation (σ = 0.53 dB) represents twice the one recorded with 10 moving persons (σ = 0.28 dB).

C. Evolution of the amplitude distribution

A further analysis consisted in deriving the multipath fading statistics experienced in each configuration at a given excess delay. For this purpose, we computed the CDF of the received signal envelope from a set of about 200 measurements at each delay τ of the impulse response h(τ). For the sake of clarity, we chose to represent only the CDF obtained at some demonstrative excess delays. We first selected the two main echoes of the measured Power Delay Profiles (PDP), then we studied the channel fluctuations in a region of dense multipath (τ = 68.9 ns). These three particular excess delays are marked on the PDP represented in Fig. 3, where the typical exponential decay of the UWB channel impulse responses is observable.

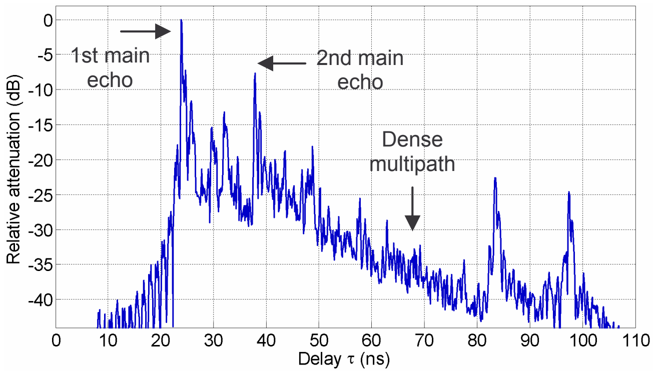
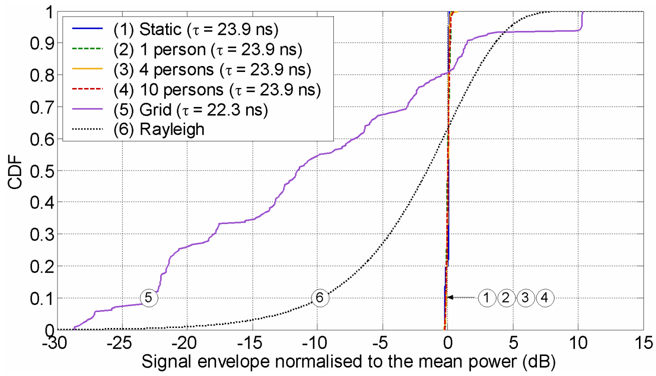


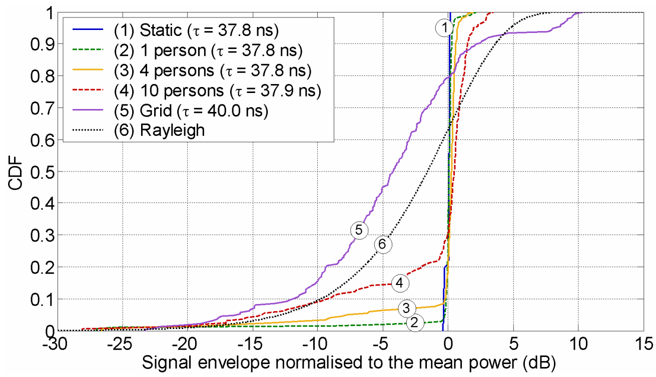
Fig. 3. Power Delay Profile (10 persons).

Correspondingly, Fig. 4 represents the empirical CDF curves of the signal envelope, for the measurement sets obtained with 1, 4 or 10 mobile persons in the vicinity of the radio system, and with a measurement grid of 225 emitter locations, in a LOS configuration. Again, the static curve corresponds to a fixed link in an empty room. One may note here that the delays selected for the two main echoes of the measurement grid are not exactly identical to the ones selected for the other data sets. This difference arises from the specific positioning of the measurement grid with respect to the Tx antenna location in the fixed link. The signal envelope has been normalised to result in an instantaneous power equal to unity, and converted in dB. For an easier comparison, the theoretical CDF curves corresponding to a Rayleigh distribution have been represented (dotted lines).

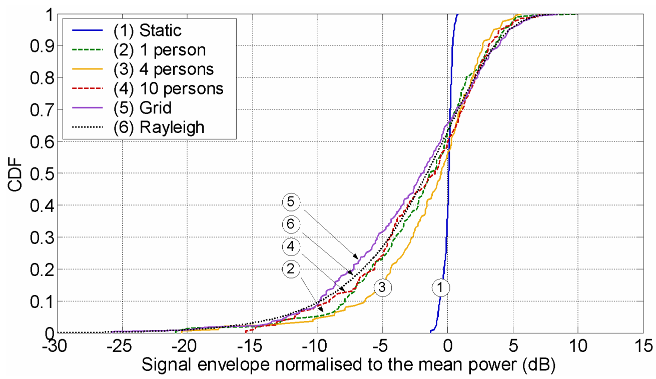
As explained above (section II.B), the curves corresponding to measurements with mobile persons are representative of the *temporal* fluctuations of the signal, while the measurement grid is characteristic of its *spatial* fluctuations. On the graphs corresponding to the two main echoes of the received waveform (a-b), a noteworthy difference between the two concepts is observable. The data sets related to the measurement grid are highly dispersed, with a standard deviation of the signal power in dB σ = 10.4 dB for the shortest path (a) and σ = 6.3 dB for the 2nd main echo (b).



(a)



(b)



(c)

Fig. 4. Empirical CDF of the signal envelope:
1st main echo (a), 2nd main echo (b) and cluster of dense multipath at τ = 68.9 ns (c).

These results can be explained by the high temporal resolution of UWB signals, implying a perceptible variation in the exact delay of the main echoes of the received waveform, when the antenna location is modified. The measurement method involving a grid of spatially distributed antenna locations, although often used, seems inappropriate to study the fading statistics experienced at a given excess delay. Thus, we will rather focus on the *temporal* variability of the UWB signal in the following paragraphs.

Regarding the main echo of the PDP (a), the CDF obtained for 1, 4 or 10 moving persons are almost superimposed on the static CDF. This suggests that the main echo of the received impulse response in a fixed UWB link is hardly affected by the motion of people in its neighbourhood. However, due to the room configuration, the direct path between the Tx and Rx antennas was rarely crossed during the experiment. A greater dispersion could be expected in another configuration.

When considering the excess delay of the 2nd main echo (b), the dispersion of the *temporal* variations of the signal seems now to increase with the number of persons in the room. The standard deviation of the signal power in dB increases from $\sigma = 2.7$ dB with 1 person to $\sigma = 3.6$ dB with 4 persons and $\sigma = 5.2$ dB with 10 persons. The signal paths corresponding to this excess delay are now possibly shadowed by moving people, and a greater number of mobile persons results in a higher dispersion of the received signal envelope.

Finally, the CDF curves corresponding to a region of dense multipath in the PDP are depicted in graph (c). Remarkably, in this situation, the signal fluctuations are similar in all configurations. The fading statistics experienced in both *spatial* and *temporal* domains actually approach the Rayleigh distribution quite closely. In clusters of dense multipath, the absence of predominant signal echo leads to a completely non-deterministic situation, which is equally affected by the environment variation and the antenna motion.

As suggested in [8], the results presented here confirm for a band of several GHz that the use of a grid of measurement is not a suitable approximation to properly evaluate the fading experienced in a fixed UWB communication system in a time-variant environment. However, this approximation still holds for regions of dense multipath in the PDP, where both *temporal* and *spatial* fluctuations of the UWB signal seem to be well represented using a Rayleigh distribution.

D. Distribution fit

In order to properly model the fading properties of the UWB propagation channel in both situations, we propose to fit the experimental statistics to a general distribution. Using a KS test with a significance level $\alpha = 1\%$, we compared the instantaneous distribution of the signal envelope for each collected measurement set in the LOS case (grid, 1 person, 4 persons and 10 persons) to the theoretical Rayleigh, Rice, Nakagami, Weibull and log-normal distributions. This test was repeated at each delay τ of the impulse response $h(\tau)$, provided that enough power was received (i.e. a maximum relative attenuation of the PDP of 45 dB). Table 2 presents the passing rates obtained for each distribution for all performed tests. As we can see, the Weibull distribution is characteristic of most of the data sets collected during the experiment. It has thus been selected to represent the studied distributions.

Table 2
Passing rate for the signal envelope distribution.

Distribution	Passing rate
Rayleigh	36.7 %
Rice	13.0 %
Nakagami	88.6 %
Weibull	91.4 %
Log-normal	73.7 %

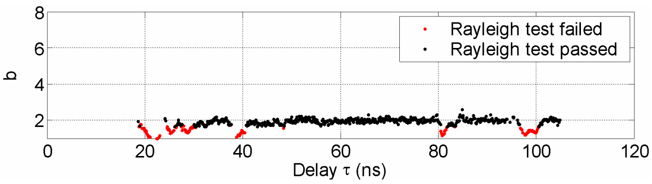
The Weibull PDF is defined as:

$$P_{a,b}(x) = a \cdot b \cdot x^{b-1} \cdot \exp\left(-a \cdot x^{b}\right),\ x \geq 0 \qquad (1)$$

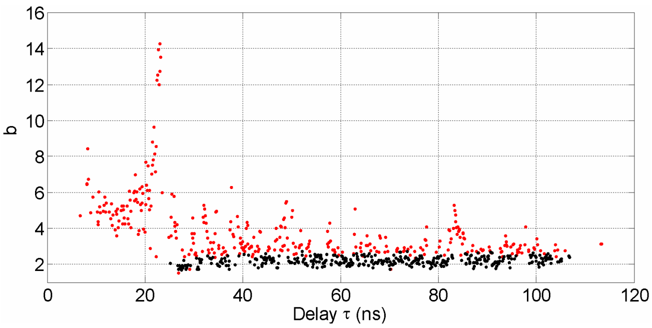
As parameter *a* is easily derived from parameter *b* and the distribution mean square value (corresponding to the mean signal power), the following discussion will focus on parameter *b* only. This latter parameter controls the spread of the distribution, a lower *b* parameter corresponding to a larger dispersion. One can note that the Rayleigh distribution can be derived from equation (2) by simply setting $b = 2$.

Fig. 5 presents the evolution of the Weibull *b* parameter along the delay for all data sets following this distribution, in the situations with a measurement grid (a), and with 10 to 1 moving persons (b-d). From the data obtained with a grid of measurement locations (a), one can note that the *spatial* fluctuations of the UWB signal follow a Rayleigh distribution over the whole impulse response, except for some specific delays corresponding to the main echoes (τ = 22 ns, 39 ns, 81 ns and 97 ns). Around these particular delays, the Weibull *b* parameter decreases from 2 to 1, hence denoting a widening of the distribution dispersion, arising from the measurement technique itself, as explained above.

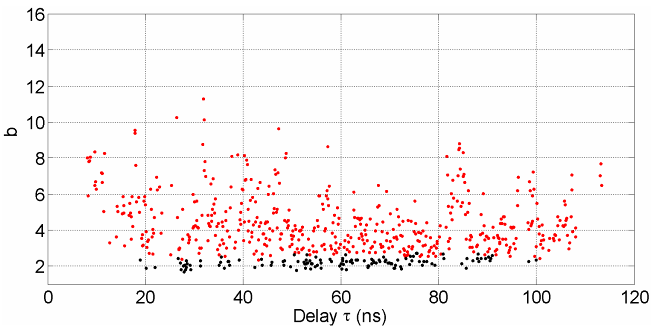
Again, the situation is notably different when considering *temporal* signal fluctuations due to the time-varying environment. With 10 moving persons in the vicinity of the radio system (b), a large part of the impulse response still follows a Rayleigh distribution, mainly in the clusters of dense multipath. However, regarding the main signal paths, the Weibull *b* parameter is now increasing from 2 up to 14 for the principal path. This indicates that the main echoes undergo less *temporal* variation. The measurements involving 4 (c) and 1 persons (d) correspond to more deterministic situations, and correspondingly an increase of the *b* parameter from 2 to 16 is noticeable. In particular, the measurement performed with 1 person represents a quasi-deterministic situation; hence the Weibull parameter is almost randomly distributed between 2 and 14 over the whole impulse response.



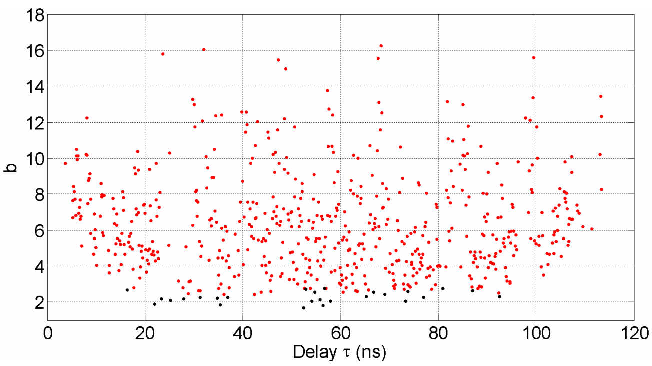
(a)



(b)



(c)



(d)

Fig. 5. Evolution of the Weibull *b* parameter: measurement grid (a), 10 persons (b), 4 persons (c) and 1 person (d).

IV. CONCLUSION

This paper presents a complete UWB channel sounding campaign designed in the 3.1 – 11 GHz band to conjointly study both *spatial* and *temporal* fluctuations experienced by an UWB link in a dynamic environment. For this purpose, measurements using a grid of antenna locations were first performed, then a set of measurement was realised with up to 10 mobile persons in the close vicinity of a fixed radio link. At first sight, these two concepts result in a similar variability of the channel, at least when considering the total received power. However, if we consider the small-scale fading statistics experienced at each delay of the received impulse response, the *spatial* variations of the signal significantly differ form the *temporal* variations, especially regarding the delays corresponding to arrival times of the signal main echoes. Hence the measurement technique involving a grid of spatially distributed antenna locations should not be used to properly estimate the *temporal* fluctuations of a fixed UWB link in a dynamic environment. Correspondingly, the *temporal* fading statistics of the UWB channel have been assessed by estimating the parameter of a general Weibull distribution. With a sufficiently high amount of mobile scatterers, one can clearly distinguish the clusters of dense multipath in the UWB impulse response, presenting a Rayleigh distribution of the signal envelope, from the main echoes of the received signal, subjected to a reduced dispersion. The analysis of further measurements, especially in the NLOS case, will complement our study and permit a consistent modeling of the UWB propagation channel in a time-varying environment.

REFERENCES

[1] R. J.-M. Cramer, R. A. Scholtz, M. Z. Win, "Evaluation of an Ultra-Wide-Band Propagation Channel", *IEEE Trans. on Antennas and Propag.*, vol. 50, no. 5, pp. 561-570, May 2002.

[2] D. Cassioli, M. Z. Win, A. F. Molisch, "The Ultra-Wide Bandwidth Indoor Channel: From Statistical Model to Simulations", *IEEE Journal On Selected Areas in Communications*, vol. 20, no. 6, pp. 1247-1257, Aug. 2002.

[3] A. Alvarez, G. Valera, M. Lobeira, R. Torres, J. L. Garcia, "Ultrawideband Channel Characterization and Modelling", in *Proc. Int. Workshop on Ultra Wideband Systems*, Oulu, Finland, June 2003.

[4] J. Kunisch, J. Pamp, "Measurement results and modelling aspects for the UWB radio channel", in *Proc. IEEE Conf. on Ultra Wide Band Systems and Tech.*, Baltimore, USA, pp. 19-23, May 2002.

[5] R. M. Buehrer, W. A. Davis, A. Safaai-Jazi, D. Sweeney, "Characterization of the Ultra-wideband Channel", in *Proc. IEEE Conf. on Ultra Wide Band Systems and Tech.*, Reston, USA, pp. 26-31, Nov. 2003.

[6] D. Porcino, W. Hirt, "Ultra-wideband radio technology: potential and challenges ahead", *IEEE Communications Magazine*, vol. 41, no 7, pp. 66-74, July 2003.

[7] P. Hafezi, A. Nix, M. A. Beach, "An Experimental Investigation of the Impact of human Shadowing on Temporal Variation of Broadband Indoor Radio Channel Characteristics and System Performance", in *Proc. IEEE 52nd Vehicular Tech. Conf.*, Boston, USA, vol. 1, pp. 37 - 42, Sept. 2000.

[8] R. Kattenbach, H. Früchting, "Investigation of the Impacts of Moving Scatterers by Wideband Measurements of Time-Variant Indoor Radio Channels", in *Proc. COST 273 Workshop*, Bologna, Italy, document TD(01)033, Oct. 2001.