EXPERIMENTAL ANALYSIS OF THE ULTRA WIDEBAND PROPAGATION CHANNEL OVER THE 3.1 GHZ - 10.6 GHZ FREQUENCY BAND

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ABSTRACT

In order to design communication systems fully exploiting the FCC-defined Ultra Wideband (UWB) spectrum, an accurate knowledge of the propagation mechanisms is necessary. This paper presents a comprehensive UWB channel measurement campaign designed in the office indoor environment to cover the 3.1 GHz - 10.6 GHz frequency band. From an extensive set of recorded Channel Impulse Responses (CIRs), statistical analyses permitted to extract the main UWB radio channel characteristics, such as the UWB path loss, delay spread and cluster and ray arrival rates. In particular, an alternative to the classical Saleh and Valenzuela approach is proposed for the description of UWB Power Delay Profiles (PDPs). Our experimental set of collected parameters may be used to build a realistic model for the UWB radio channel.

I. INTRODUCTION

The inherent characteristics of UWB systems, such as their potential for high transmission rates and their robustness to multipath fading, make this technology an attractive candidate for future high rate, short range communication links [1]. For the development of WLAN and WPAN applications in indoor environment, an accurate knowledge of the radio channel characteristics over the frequency band dedicated to UWB systems is necessary. Significant work was already performed in this field and a number of sounding experiments were designed to assess the properties of the UWB channel [2]. Within the IEEE Task Groups 802.15.3a and 802.15.4a, different analyzes were confronted to model the UWB propagation characteristics [3, 4].

In 2002, the FCC allocated the 3.1 GHz - 10.6 GHz frequency band to the use of UWB signals, imposing restrictions on the emitted signal [5]. It may be stressed that most of the reported measurement and analyzes covered this frequency band partially, with a few measurement campaigns only addressing the whole FCC spectrum [6–11]. This paper reports on a sounding campaign designed to assess the UWB channel over the 3.1 GHz - 10.6 GHz frequency band. Using a measurement technique in the frequency domain, an extensive set of experimental data was collected in the indoor office environment. The statistical analysis of the measurement results permitted to fully characterize the UWB channel. In particular, modifications to the classical approach of Saleh and Valenzuela are proposed to accurately describe our experimental observations. As a result, a complete set of radio parameters were extracted, which may be used for the modeling of the UWB indoor propagation channel.

II. UWB PROPAGATION EXPERIMENT

A. Experimental Setup

A UWB propagation sounding campaign was performed in a typical office indoor environment. The channel was probed using the frequency domain technique: a Vector Network Analyzer (VNA) HP8510C was used to perform classical S21 parameter measurements, the propagation channel being the device under test. 4005 frequency tones were probed between 3.1 GHz and 11.1 GHz. This configuration allows a maximum excess delay of about 500 ns for the measured CIRs. Monoclonal antennas CMA 118/A presenting an omni-directional pattern in the azimuth plane were connected at both transmitter (Tx) and receiver (Rx) sides of the link. In order to evaluate the spatial variations of the channel and perform local power averages, the Tx antenna was mounted on a rotating arm. For each measurement location, the channel was probed at 90 different positions along a circle of 40 cm in diameter. Depending on the Tx-Rx distance, up to 3 Low Noise Amplifiers were added in the measurement chain.

B. Measurement Plan

Figure 1 represents the office building were the sounding campaign took place. The Rx antenna emulated an access point.

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and was placed at two different locations: in a meeting room at a height of 2.19 m, and in a corridor at a height of 2.45 m. The Tx antenna was situated at a height of 1.5 m. About 120 different Tx locations were probed, leading to a collection of over 10 000 UWB CIRs. As can be seen on the measurement plan, both LOS and NLOS configurations were analyzed.

C. Antenna Effect and Calibration

The measured CIRs were calibrated using a reference measurement where the Tx and Rx ports were directly cable-connected. When considering UWB channel sounding, a specific attention must be given to the effect of antennas on the measured data. If the antenna pattern of the measurement antennas is almost omnidirectional in the azimuth plane, strong variations of the antenna gain were observed in the elevation plane. In addition, the global shape of the antenna pattern significantly varies when the operating frequency increases from 3.1 GHz to 11.1 GHz. Hence, the antennas need to be precisely characterized and experimental data must be corrected accordingly. For our analysis, the 3D radiation pattern of both Tx andRx antennas was measured every GHz. The recorded signal spectrum was then adjusted with respect to the antenna gain in the Tx-Rx direction. This method should be considered as an approximation, as the total power is not only received via the direct path, but also via multiple paths with different directions. However, it leads to a reasonable compensation of the antenna effect, as we observed in [12].

III. Path Loss Analysis

As a first analysis, Fig. 2 represents the attenuation of the power received over the 3.1 GHz - 10.6 GHz band as a function of the Tx-Rx distance $d$. Using a least squares procedure, we fitted the observed path loss $PL$ in dB to the theoretical expression:

$$PL(d) = PL(d_0) + 10N\log\left(\frac{d}{d_0}\right) + S(d) \quad (1)$$

where $N$ corresponds to the path loss exponent, $S$ represents the lognormal shadowing in dB with zero mean and standard deviation $\sigma_S$, and $d_0$ is a reference distance of 1 m.

In the LOS configuration, we observed a value of $N = 1.62$, with a standard deviation $\sigma_S = 1.7$ dB. In the NLOS configuration, the measurement plots are somewhat more dispersed with an exponent $N = 3.22$ and a standard deviation $\sigma_S = 5.7$ dB. The values of $PL(d_0)$ were respectively 53.7 dB and 50.4 dB. Note that we integrated the parameter $PL(d_0)$ in the least squares fitting procedure, while some authors use the theoretical value obtained in a free space configuration [7]. Table 1 compares our path loss results with other data available from measurements performed over the FCC frequency band.

IV. Large Scale Parameters

From each set of $M = 90$ CIRs $h_m(\tau)$ measured locally using the rotating arm, an average Power Delay Profile $P(\tau)$ was computed as follows:

$$P(\tau) = \frac{1}{M} \sum_{m=1}^{M} |h_m(\tau)|^2 \quad (2)$$

Figure 3 presents typical measured PDPs, for both LOS and NLOS configurations. Note that the delay on the $x$-axis was converted in path length in m for the sake of path interpretation. Different main echoes may be observed, followed by clusters of dense multipath. In the LOS case, objects or walls surrounding the radio link produce noteworthy echoes, which explains the presence of peaks 10 dB to 20 dB stronger than the following cluster.

A. Delay Spread

The delay spread $\tau_{RMS}$ was computed for each measured PDP over the whole 3.1 GHz - 10.6 GHz bandwidth, as follows:

$$\tau_{RMS} = \sqrt{\frac{\int_{-\infty}^{\infty} \tau^2 P(\tau) d\tau}{\int_{-\infty}^{\infty} P(\tau) d\tau} - \left(\frac{\int_{-\infty}^{\infty} \tau P(\tau) d\tau}{\int_{-\infty}^{\infty} P(\tau) d\tau}\right)^2} \quad (3)$$

In order to mitigate the effect of noise, we used a -20 dB threshold with respect to the PDP maximum.
In the LOS case, we observed a mean value $\tau_{RMS} = 4.1$ ns with a standard deviation $\sigma_{\tau} = 2.7$ ns. In the NLOS case, the mean delay spread was $\tau_{RMS} = 9.9$ ns with a standard deviation $\sigma_{\tau_{\text{RMS}}} = 5.0$ ns. These results are in accordance with other analyses of the UWB indoor channel [7, 13].

\subsection{PDP Power Decay}

Figure 3 shows that the received power is grouped in different clusters. This was first depicted by Saleh and Valenzuela, who proposed the following discrete representation of the CIR for indoor channels [14]:

$$h(t) = \sum_{l=1}^{L} \sum_{k=1}^{K_l} \beta_{k,l} e^{j\theta_{k,l}} \delta(t - T_l - \tau_{k,l})$$  \hspace{1cm} (4)

where $L$ denotes the number of clusters, $K_l$ the number of rays in the $l^{th}$ cluster, and $T_l$ the time of arrival of the $l^{th}$ cluster. The parameters $\beta_{k,l}, \theta_{k,l}$ et $\tau_{k,l}$ represent the magnitude, phase and the time of arrival of the $k^{th}$ ray within the $l^{th}$ cluster. In [14], it was assumed that the received power followed an exponential decay, at both cluster and ray scales. Hence, inter- and intra-cluster exponential decay constants, respectively noted $\Gamma$ and $\gamma$, were defined such that the ray magnitude followed the following law:

$$\beta_{k,l}^2 = \beta_{1,1}^2 e^{-\frac{T_l - \tau_{k,l} + T_1}{\tau_1}}$$  \hspace{1cm} (5)

To evaluate these parameters, we first identified the different clusters by visual inspection, as is performed in [15]. The coefficients $\Gamma$ and $\gamma$ were then extracted using a least squares method to fit the approximation given in Eq. (5). Figure 4 illustrates this procedure. Over the set of PDPs measured in a LOS configuration, we observed between 3 and 8 clusters (5.6 on average). The mean exponential decay constants were $\Gamma = 15.7$ ns and $\gamma = 7.5$ ns. In the NLOS configuration, the observed PDPs presented between 1 and 4 clusters (2.4 on average). The mean exponential decay constants were $\Gamma = 16.5$ ns and $\gamma = 12.0$ ns.

\subsubsection{Fitting to an Exponential Function}

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\subsubsection{Fitting to a Power Function}

By analyzing our measurement results using this classical approach, we observed that the exponential decay assumption was not totally satisfactory to model the PDP magnitude decay. Indeed, when the PDP is represented in a logarithmic scale, the whole PDP as well as each cluster should take a triangular shape, which is clearly not the case, e.g. in Fig. 4.

The attenuation between successive echoes of the main propagation path arises from two main reasons: (a) a longer propagation path induces a stronger power loss; and (b) delayed echoes undergo more propagation phenomena, such as reflection or diffraction. This physical approach in mind, we propose an adaptation to the Saleh and Valenzuela model, where the PDP attenuation follows a power function. This is already the case in the classical approximation of the path loss, as presented in Eq. (1). We hence suggest to replace the model given by Eq. (5) by the following:

$$\beta_{k,l}^2 = \beta_{1,1}^2 \left(\frac{T_1}{T_l}\right)^{-\Omega} \left(\frac{T_l + \tau_{k,l}}{T_1}\right)^{-\omega}$$  \hspace{1cm} (6)

where we define two original parameters, $\Omega$ and $\omega$, respectively called inter- and intra-cluster power decay constants.
The parameters $\Omega$ and $\omega$ were extracted from the measured PDPs using a least squares fitting procedure. This parameter extraction procedure is illustrated in Fig. 5. In both exponential ($\Gamma, \gamma$) and power ($\Omega, \omega$) approximations, we computed the standard deviation $\sigma$ of the error in dB between the measured PDP and the best-fit approximation.

When using the proposed approximation regarding the inter-clusters decay, the error standard deviation $\sigma$ decreases from 4.8 dB to 2.9 dB in the LOS case and from 2.4 dB to 1.7 dB in the NLOS case. Regarding the intra-cluster decay, the value of $\sigma$ decreases from 1.9 dB to 1.8 dB in the LOS case and from 1.7 dB to 1.6 dB in the NLOS case. These results validate the proposed model which is closer from the experimental observations. Finally, for the LOS configuration, we observed a significant power attenuation between the main path of each cluster and the following rays, as may be observed on Fig. 5. References [16, 17] also reported this phenomenon.

The mean values of the power decay constants were $\Omega = 4.4$ and $\omega = 11.1$ in the LOS case, and $\Omega = 3.9$ and $\omega = 10.2$ in the NLOS case. In the LOS case, the average attenuation $G$ was observed at 12 dB.

C. Cluster and Rays Arrivals

1) Cluster Arrival Rate

The time of arrival of the $i$th cluster, noted $T_i$, was collected over the whole set of measured PDPs presenting more than one cluster. We then studied the inter-cluster duration $\Delta T = T_{i+1} - T_i$. The average inter-cluster duration was $\Delta T = 27.4$ ns in the LOS case and $\Delta T = 40.1$ ns in the NLOS case, leading to respective cluster arrival rates $\lambda$ of 36.5 MHz and 24.9 MHz. The experimental distributions of $\Delta T$ are well suited to exponential distributions, as illustrated by the percentile-percentile graphs in Fig. 6.

2) Ray Arrival Rate

For the study of the ray arrival rate, a high-resolution algorithm is required to identify the different rays within each cluster. We used the Frequency Domain Maximum Likelihood (FDML) procedure described in [18]. This iterative algorithm optimizes the set of detected rays by minimizing the error between measurement and approximation in the frequency domain. For each measurement location, the FDML algorithm was applied to one of the 90 CIRs. We then studied the distribution of the inter-rays duration $\Delta \tau = \tau_{k+1} - \tau_k$. For the CIRs measured in LOS and NLOS configuration, the average inter-rays duration was respectively evaluated at $\Delta \tau = 0.168$ ns and $\Delta \tau = 0.161$ ns. The corresponding ray arrival rates are $\lambda = 5.95$ GHz and $\lambda = 6.19$ GHz. Again, the experimental distributions of the inter-rays duration were compared to exponential distributions using a percentile-percentile graph, as depicted in Fig. 7. In this case, some differences may be noted between the experimental and theoretical data, but the exponential approximation still provides an acceptable fit to the measurements.

V. SMALL SCALE PARAMETERS

Finally, we studied the small-scale variations of the UWB propagation channel by comparing the 90 CIRs measured locally using a rotating arm. In order to assess the fluctuations of the CIR magnitude, we computed the Nakagami $m$ parameter for each delay of the CIR. An example of computed values for a
A given measurement is depicted in Fig. 8. As we can see, the value of the $m$ parameter was close to 1 for all delays of the PDP, except for the main path. This general observation holds for the majority of the measured PDPs. Consequently, the Rayleigh distribution is well-suited to describe the variations of the CIR amplitude for a local displacement of the antenna, at least within the clusters of dense multipath. This was also observed in [6].

VI. CONCLUSION

In this paper, we described an extensive sounding campaign intended to characterize the indoor UWB channel over the 3.1 GHz - 10.6 GHz frequency band. Over 10,000 CIRs were collected using a frequency domain sounder. As a first step, the path loss parameters $N$, $\sigma_s$ and $PL(d_0)$ were extracted for both LOS and NLOS configurations. We then statistically studied the main wideband radio characteristics, such as the delay spread $\tau_{RMS}$ and the arrival rate for clusters $\Lambda$ and rays $\lambda$. In particular, we proposed a modification to the classical Saleh and Valenzuela approximation for the PDP power decay. Two original parameters, $\Omega$ and $\omega$, were introduced to model the inter- and intra-cluster attenuations as power functions. This approach allows a physical interpretation of our observations while presenting an improved fit to the measured data.

As a main result, this contribution provides a procedure to characterize the UWB propagation channel as well as a complete set of experimentally recorded values for the selected radio parameters. This input will thus serve as a basis for the development of a statistical channel model capable of reproducing the UWB propagation conditions in a realistic way. The practical issues related to the implementation of such a model are addressed in [19]. The presented characterization procedure could finally be applied to other building types, for instance to extend the analysis to the residential environment.

REFERENCES