Characterization of large-scale fading for the 2.4 GHz channel in obstacle-dense indoor propagation topologies

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***Abstract*—Wireless channel characterization is of critical importance in providing reliable tools for link budget prediction and estimation of wireless propagation, particularly in the case of an obstacle-dense environment. Based on measurements performed in a series of indoor propagation topologies, a novel empirical method for the calculation of shadow depth has been implemented and evaluated. This work presents further investigation into the log-normal nature of large-scale fading, by examining the variations of the measured values of local-mean received power throughout these topologies. The impact of these variations on the estimation of Outage Probability is shown, and the realistic deviations from the theoretical log-normal scenario are discussed. Furthermore, a shadow-based approach for the calculation of the attenuation over distance is presented and evaluated compared to the Devasirvatham model. It should be noted that whereas our work focuses on the 2.4 GHz channel, this methodology can be applied to any frequency of interest. Results confirm the importance of this novel methodology concerning wireless channel characterization for obstacle-dense indoor propagation topologies.**

Keywords-Indoor propagation; Path Loss; Wireless Channel Characterization; Large-scale fading; Log-normal shadowing; Attenuation over distance

I. INTRODUCTION

Wireless channel characterization is of critical importance so that engineers and researchers alike will be able to provide reliable predictions for wireless transmission of information over a complex, real-life propagation environment with reflection, scattering and diffraction phenomena [1]. Free Space propagation loss as well as losses caused by obstacles and other materials of varying size and proportions can cause severe attenuation of the propagated signal [2]-[3]. In order to estimate the average received power at a given distance from a transmitter, various (logarithmic) path loss models have been developed [4]-[6].

Attenuation in an indoor propagation environment is even more complex in terms of mathematical formulation, due to the increased number of obstacles of various type and dimensions, causing severe shadowing and scattering (depending on the obstacle size). In addition, the mechanisms of reflection and diffraction are even more influential on the signal propagation. According to ITU specifications [7], indoor propagation topologies are generally grouped in three major categories: the office topologies, the home (residential) topologies and the public commercial topologies.

The indoor propagation channel has been investigated in recent published works [8]-[13] where multipath propagation and its impact on wireless channel characterization have been brought into study. A series of published works [14]-[17] took the initiative to investigate large-scale (shadow) fading from the standpoint of wireless channel characterization based on intrinsic topology characteristics, namely, taking into consideration attenuation losses from obstacles, walls and floors, for the 2.4 GHz channel. Thus, a measurement-based validation of indoor path loss models was conducted, including more recent, site-specific path loss models [18]-[19]. Measurements were performed late in the evening so as to minimize the effect of body shadowing [20].

In this work, the large-scale variations of the received signal strength on wireless channel characterization for obstacle-dense indoor propagation topologies are furthermore investigated. More specifically, Section II discusses the fundamental concepts of large-scale fading (shadow fading) in relation to the log-normal model. In Section III, the log-normal nature of the fluctuations of the local mean values of the received power is confirmed via comparison of the empirical Cumulative Distribution Function (CDF) to the Gaussian CDF of the logarithmic values (dBm), and the statistical properties of the received signal power are presented. Section IV presents a fast-track calculation of attenuation over distance based on knowledge of obstacle-bound shadow depth. Finally, Section V summarizes our findings and concludes this work.

II. LARGE-SCALE FADING

The large-scale variations of the average received signal over a given propagation environment, namely the local mean values of the received power, have been known to follow the log-normal distribution [1]-[5], the Probability Density Function (PDF) of which is given by [21]:

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\bar{x})^2}{2\sigma^2}} \quad (1)$$

Where x is the received power (logarithmic value) in each measurement location (local mean strength), $\overline{x}$ is the average received power (logarithmic value) for all measurement locations (mean value of the received power overall the topology in question), and σ is the standard deviation of the shadowing losses (in dB).

The mean value and the standard deviation of the variation of the local mean values of the received signal strength can be calculated experimentally measured samples as given by [1]:

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (2)$$

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2 \qquad (3)$$

In order to provide unbiased results, a significantly large number of samples are required [1].

The large-scale variations of the received power have been attributed to losses by obstacles of proportions significantly larger than the signal wavelength, which remain constant over a time scale of seconds or minutes (large-scale fading). The shadowing deviation, or shadow depth, expresses the excess path loss, defined by Jakes as "the difference (in decibels) between the computed value of the received signal strength in free space and the actual measured value of the local mean received signal" [21]. However, as argued in [22], a common misconception is to estimate the shadow depth as the residue from distance-dependent free space propagation (the slope-factor path loss validation). Thus, the shadow losses caused by obstacles and other materials are not regarded as an independent attenuation factor.

A novel empirical method for the calculation of the shadow depth as a consequence of obstacle-caused attenuation has been developed and evaluated in terms of mean error (%) reliability in [15]-[17]. The mathematical expression of this method, which assumes that the shadow depth can be calculated directly from obstacles within the topology regardless of free space propagation, is provided by:

$$\sigma_{sh}(dB) = \frac{\sum_{i=1}^{I}\sum_{k=1}^{K_{wi}} L_{wik} + \sum_{j=1}^{J}\sum_{k=1}^{K_{fj}} L_{fjk}}{z} \qquad (4)$$

Where:

I, J is the number of types of walls and floors

L_{wik} is the attenuation due to kth traversed wall type i

L_{fjk} is the attenuation due to kth traversed floor type j

K_{wi} is the number of walls type i

K_{fj} is the number of floors type j

The parameter z stands for the percentage of coverage probability. Assuming a coverage probability of 95%, z equals 1.645.

This method does not require extensive RF measurements. It only requires knowledge of the penetration losses that can be easily derived by limited measurements around the obstacles, and it can be applied to any frequency of interest. This methodology confirms that shadow fading is independent of free space propagation losses.

III. Statistical Properties of Received Power

The reliable prediction of path loss and subsequent average power reception is very important in order to calculate accurately the probability that the average received signal strength will drop beneath a specific threshold, i.e. the Outage Probability [1]. The Outage Probability is given by the Cumulative Distribution Function (CDF) of the fading distribution that describes the received signal [4].

Based on the measured values of the signal power, an empirical CDF was plotted for each case study. Table I features the values of the statistical parameters of the signal power for each propagation topology. It is obvious that the lowest mean value is observed in the multi-floor scenario of the office topology, where a difference of two floors between transmitter and receiver is achieved.

The largest signal variation, however, is observed in the case of the library topology, with values ranging from -81 dBm (reaching the respective minimum value of the multi-floor office scheme) to -37 dBm, and a standard deviation of 11.76 dB. It is also interesting to note that the smallest value of standard deviation (smallest fluctuation of the signal power around its – logarithmic - mean value) is observed in the case of the multi-floor office scheme, which constitutes a "worst-case" scenario in terms of signal attenuation (complexity of propagation, interfering floors and walls, lowest mean value). We conclude, therefore, that the standard deviation as a statistical metric of signal fluctuations is not directly linked to severity of obstacle obstruction and respective losses.

Fig. 1-3 depict the empirical CDF of the measured values of the signal power (red line with marker) compared to the Gaussian CDF based on the area-mean value (in dBm) and the standard deviation (in dB) provided by Table I for each propagation scenario. The purpose of this comparison is to validate whether the actual measurements of the received power (local mean values) comply with the log-normal distribution, which in this case is depicted by the Gaussian distribution of the logarithmic values of signal power (dBm), derived from the area-mean values of Table I.

TABLE I. Statistical Parameters of Received Power

Statistical Parameters	Office (same floor)	Office (multi-floor)	Library (same floor)
Min (dBm)	-75	-81	-81
Max (dBm)	-40	-58	-37
Mean (dBm)	-57.09	-73	-59.22
Median (dBm)	-55	-76	-58
standard deviation (dB)	10.95	7.4	11.76

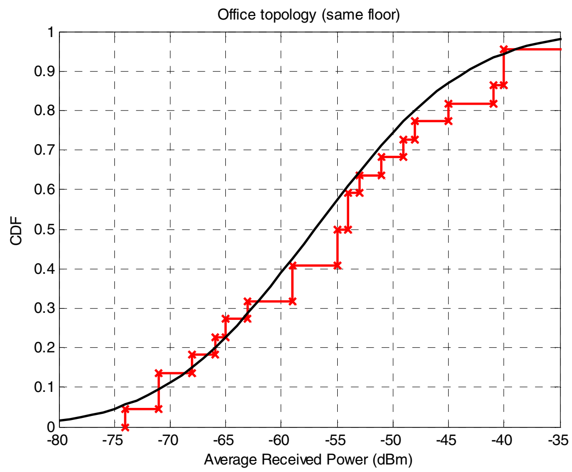

Figure 1. Gaussian CDF vs. Empirical CDF (Office same floor)

The purpose of the comparative depiction of the empirical CDF versus the Gaussian CDF is to depict graphically the ability of the log-normal scenario (Gaussian distribution of the logarithmic values) to estimate the Outage Probability in similar fashion as the CDF from the empirical data. Interestingly enough, the Gaussian CDF fits the data more accurately in the case of the library topology, where the largest "spread" of signal power around its mean value is observed (standard deviation from Table I). The less accurate fit is obviously in the case of the multi-floor office scheme (where the smallest value of standard deviation is observed).

The standard deviation derived out of the measured values does not express the shadow depth but rather the higher or lesser spread of local mean values of received power around the area-mean value. It is therefore erroneous to apply this value of standard deviation as a metric of shadow depth (losses caused by obstacles, walls and floors). In such a case, on the basis of Eq. 4, the largest value of the standard deviation would be in the case of the multi-floor office propagation, where the highest attenuation losses due to interfering floors and walls are observed.

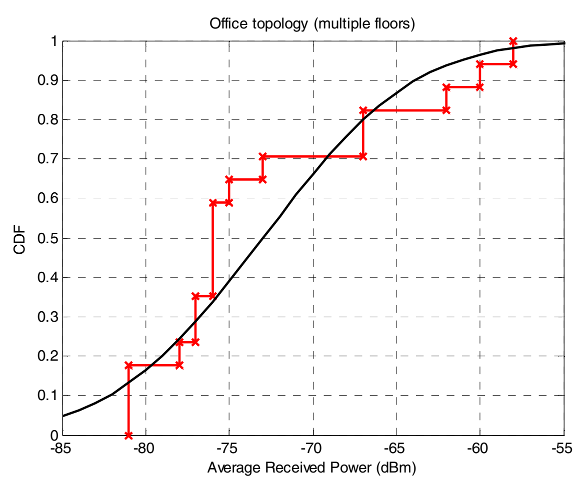

Figure 2. Gaussian CDF vs. Empirical CDF (Office multiple floor)

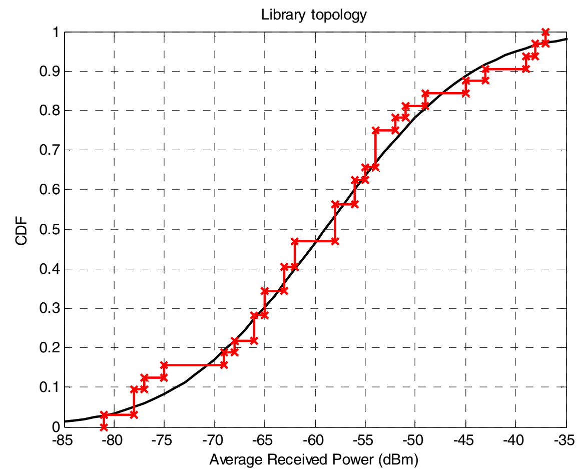

Figure 3. Gaussian CDF vs. Empirical CDF (Library)

IV. ATTENUATION OVER DISTANCE

Attenuation over distance (dB/m) is a key parameter in wireless communications, especially in indoor modeling, as it is a metric of excess path loss. Attenuation over distance can be calculated via the Linear Attenuation Model (LAM), also known as the Devasirvatham model [5]:

$$P_L(dB) = P_{L0}(dB) + 10n\log_{10}(d) + ad \quad (5)$$

Where $P_L(dB)$ stands for the average path loss (dB), $P_{L0}(dB)$ stands for the frequency-dependent reference path loss (path loss at 1m distance from the transmitter), n is the path loss exponent that expresses the rate of attenuation losses, a the attenuation over distance (dB/m), and d the transmitter-receiver distance (T-R separation), in meters.

When average received power values are experimentally measured (in dBm) over selected locations of a given propagation topology, and the total EIRP is known (in dBm), then attenuation over distance is calculated (in dB/m) by the following formula:

$$a = \frac{EIRP(dBm) - P_r(dBm) - 10n\log_{10} d - 40dB}{d} \quad (6)$$

Where 40 dB stands for the reference path loss (path loss at 1m distance from the transmitter) for the 2.4 GHz frequency.

In [23], this methodology was applied for the computation of attenuation over distance on the basis of the Devasirvatham model for all the indoor propagation topologies at hand. Three methods were proposed, depending on the value of the path loss exponent n (fixed, variable, universal), and curve fitting for the values of attenuation over distance was performed.

In addition, various measurements have been conducted in indoor propagation environments, providing empirical values for the attenuation over distance, mostly for the 900 and 1800 MHz bands [24].

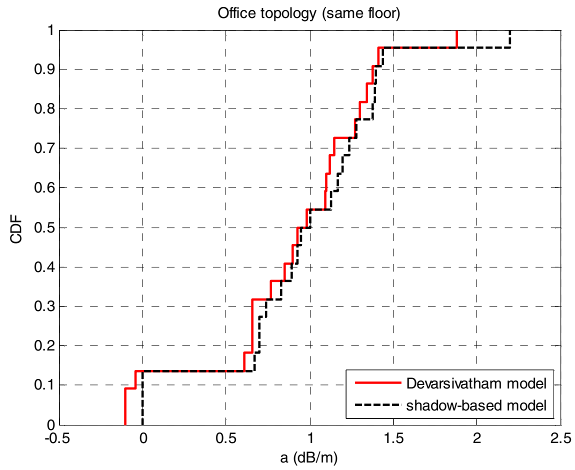

Figure 4. Devarsivatham model CDF vs. shadow-based model CDF (Office topology – same floor)

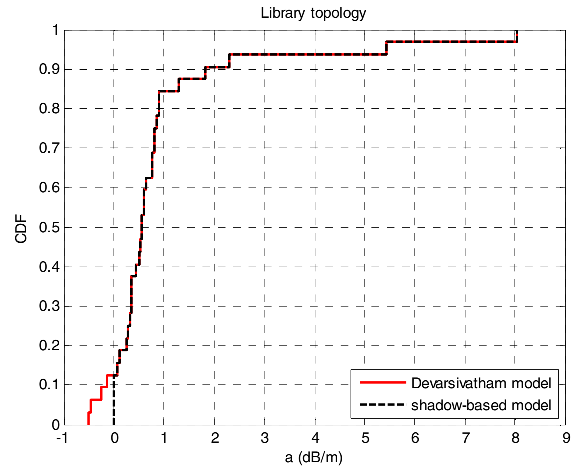

Figure 6. Devarsivatham model CDF vs. shadow-based model CDF (Library topology)

Computation of attenuation over distance (in dB/m) on the basis of the Devasirvatham model (Linear attenuation model) requires a pool of measured values of received signal power, as an input data to Eq.6. In order to be able to provide estimation of excess path loss in terms of attenuation over distance (in dB/m) without extensive RF measurements, a fast-track method is needed.

The calculation of the shadow depth throughout the obstacle-dense topology on the basis of Eq.4, as already mentioned, does not require but a limited number of measurements around the obstacles of significant proportions compared to the signal wavelength. Assuming knowledge of the shadow depth values on the basis of this method, an alternative, obstacle-bound method for the calculation of attenuation over distance is derived:

$$a = \frac{z}{d}\sigma(dB) \tag{7}$$

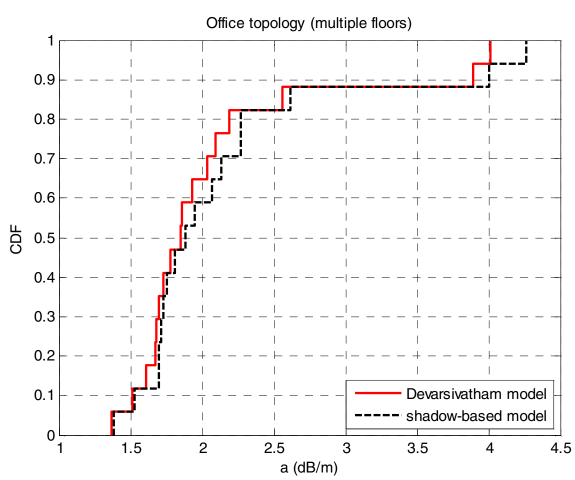

Figure 5. Devarsivatham model CDF vs. shadow-based model CDF (Office topology – multiple floors)

Figures 4-6 depict the comparison of the results from the computation of attenuation over distance on the basis of the Devasirvatham model (Eq.6), to the values derived from the shadow-based model (Eq.7). The calculation of the shadow depth is achieved by taking into consideration the obstacle losses which have been provided from extensive measurement throughout the topologies [15]-[17].

From the comparative CDF plots it is obvious that the shadow-based model follows closely the values of attenuation over distance provided from the measured received signal power (Devasirvatham model, n=1.8 path loss exponent assumption). A notable difference lies in the lower range of a (dB/m) values for the office same floor scheme and the library (same floor) scheme, where the attenuation over distance on the basis of the measured local mean values of signal power assumes negative values, while shadow based model provides an attenuation over distance of zero. These cases correspond to Line-of-Sight (LOS) measurement locations, where attenuation over distance, calculated from the measured values of received signal power, assumes negative values, albeit with a small absolute value (an overall minimum of -0.50 dB/m is observed in the case of the library topology). For these respective measurement locations, the shadow depth is set to zero (in dB) therefore Eq.7 will produce a zero value for the attenuation over distance.

TABLE II. MEAN ERROR (%) OF SHADOW-BASED MODEL COMPARED TO DEVARSIVATHAM MODEL

Propagation Topologies	Mean Error (%)
Office - same floor	18.63%
Office - same floor (LOS locations omitted)	5.78%
Office - multiple floor	3.43%
Library	14.71%
Library (LOS locations omitted)	2.53%

Table II presents the mean error (%) of the shadow-based model in relation to the measurement-based calculated values of attenuation over distance derived from the Devasirvatham model with n=1.8. The multiple floor scenario of the office topology provides a highly accurate approximation in the estimation of a (dB/m), with a mean error of 3.43%. The same floor scheme of the office topology and the library topology provide less accurate estimations, with a mean error of 18.63% and 14.71% respectively. This increased error is due to the aforementioned deviation due to the LOS topologies where shadow depth is assumed to be zero (in dB). Should the LOS topologies be omitted from our calculations for these two case studies, then the mean error is remarkably reduced: the office same floor topology with LOS-omitted measurement locations presents a mean error of 5.78%, whereas the library topology with the LOS-omitted measurement locations presents a mean error of 2.53%.

V. Conclusions

In this work, the impact of large-scale variations of the received signal strength on wireless channel characterization was investigated for obstacle-dense indoor propagation topologies. The log-normal nature of the fluctuations of the local mean values around the area-mean value was confirmed via CDF graphs for all said topologies, derived out of the pool of measured values of local mean power.

The fundamental limitation of the conventional Log-normal scenario was examined, where the shadowing deviation is merely a statistical metric in relation to the area-mean value and does not express the shadow depth, and requires a large pool of samples for unbiased results. On the basis of solving these problems, the advantages of a novel obstacle-based methodology were emphasized.

Furthermore, this method was employed in order to evaluate an alternative, fast-track calculation of attenuation over distance. The mean error of these estimations can be reduced if the LOS locations are omitted or if a similar fast-track method for the calculation of attenuation over distance can be employed for LOS-based topologies.

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