A Simple Approach to a Statistical Path Loss Model for Indoor Communications

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Abstract
Path-loss in indoor environments is investigated at 1.8 GHz, using a power-law model where the exponent of the distance is the descriptive random variable. The model is extremely simple and easily applicable in practice by working engineers who need only make a few measurements to get a knowledge of path loss sufficient for many applications. The model fits well experimental data in various environments under different propagation conditions, including cross polarization, and the observed behavior of the exponent suggests the possibility of using only one distribution function to statistically characterize path loss.

1. Introduction
A complete channel description requires a good knowledge not only of path loss, but also of delay spread, angle of arrival distribution, etc. However, in many engineering applications where the main objective is to define the required transmitted power, necessary to cover a specific service area for a given signal to noise ratio of the received signal, a simple statistical path loss model is a useful tool which allows to estimate the fade margins with which a system must operate in a particular indoor environment. The model investigated is statistical and does not require a detailed knowledge of environment topography. However, its application requires of measurements in order to get the statistical parameters, i.e., mean and standard deviation, to be used in a particular propagation environment. The descriptive parameter in this path loss model is the exponent of the distance; i.e. the received power can be expressed as:

\[ P_r = \frac{P_{rad}}{d^n} \left( \frac{\lambda}{4\pi} \right)^2 \]  

(1)

where \( P_{rad} \) is the radiated power, \( d \) the distance in meters between transmitting and receiving antennas, and \( \lambda \) the wavelength. \( n \) is the exponent of the distance and is assumed a random variable in this model. In small or local areas a few wavelengths in radius, \( n \) varies randomly, its mean and standard deviation being larger at distances up to about 20\( \lambda \) from the transmitting antenna. At larger distances, the local means tend to be nearly constant in a given environment under the same propagation conditions. This characteristic in the behavior of \( n \) was observed for various propagation conditions in different buildings: line-of-sight (LOS), shadowing (NLOS) and total obstruction between the transmitting and receiving antennas by walls and floors (OBS), and suggests that, in the range of distances encountered in indoor communications, only one type of statistics can be used to describe path loss.

2. Theory
In (1) the received power, \( P_r \), can be assumed random and expressed as:

\[ \langle P_r \rangle = P_{fs} \langle \alpha_p \rangle \]  

(2)

Where \( P_{fs} \) is the free space value of the received power and \( \langle \alpha_p \rangle \) is an attenuation (or gain) factor, dependent on propagation mechanisms which, in general, are not possible to quantify individually, and include directive gains of antennas, reflection, diffraction, etc. The bracket notation is used to stress the random nature of the variable. From (1) it can be seen that:
\[ \langle \alpha_r \rangle = \frac{1}{d^{\alpha_{0.2}}} \]  

(3)

is the excess attenuation referred to free space conditions. Using dB form, the path loss can now be written as:

\[ L_{\text{dB}} = 10 \langle n \rangle \log(d) + K \]  

(4)

where \( K \) is the free space attenuation at 1 m. The value of \( n \) can be obtained directly as:

\[ \langle n \rangle = \frac{P_{\text{rad}} - \langle P_r \rangle - K}{10 \log(d)} \]  

(5)

where, in actual conditions, \( P_{\text{rad}} \) is known and the samples of the received power, \( \langle P_r \rangle \) are obtained through measurements in the particular environment. The model given by equation (4) is formally equal to other models previously reported in the literature [1]-[3], the main difference is that here, the exponent of distance is treated as a random variable and no further variables are introduced, nor assumptions made about its statistical behavior.

3. Experimental procedure

Various experiments were made in different buildings of the University of Cantabria, Spain. One of them, of simple geometry with open areas and straight aisles. The other, of complex geometry, with narrow aisles occasionally curved, and with numerous obstructions by walls, columns and furniture. Measurement environments were chosen for well differentiated propagation conditions: line-of-sight (LOS), non line of sight (NLOS), mainly shadowing, and total obstruction between transmitter and receiver (OBS). Additionally the effect of depolarization was also measured. All experiments were made with a 10 dBm unmodulated carrier at 1.8 GHz using an RF signal generator as transmitter and a spectrum analyzer as receiver at distances ranging between 1 and 32 m. Transmitting and receiving antennas were \( \lambda/4 \) vertical monopoles at 2 m and 1.5 m height respectively. A \( \lambda/2 \) rotatable dipole was also used for reception, thus the copolar and crosspolar powers of the received signal could be easily measured at the same sampling points. The measurement procedure was mainly manual, and devised in order to make it easily applicable in practice, bearing in mind that it is essential that signal measurements should be made in a manner that permits the basic parameters to be extracted with an appropriate level of accuracy [4]. Thus, the sampling interval, i.e. the distance between individual samples, distance between local areas, and minimum number of samples per local area, must be properly defined. An empirical approach was followed with this purpose. Local areas were defined as squares of maximum area of 1 m², with a minimum separation between them of 20λ. and several sets of measurements were taken over the same local areas, with sampling intervals of 1, 2.5 and 5 cm. Differences in the mean received power were within \( \pm 1.5 \text{ dB} \) for 1 and 2.5 cm intervals, and in the order of \( \pm 5 \text{ dB} \) for 2.5 and 5 cm intervals. A maximum sampling interval of 2.5 cm was considered adequate for practical purposes.

In order to establish the minimum number of samples required per local area, a similar approach was followed. Various sets of measurements were made over the same local areas in LOS and NLOS conditions, taking first 500 samples, then 100 and finally several sets of 50 samples. In all cases, the errors in the mean values of the exponent were less than 5%, and of 7.5% in the standard deviations. As a consequence, a minimum value of 50 samples per local area was considered sufficient. Such figure is in good agreement with the criteria suggested by other authors [5], [6], and with those drawn theoretically [7]. The distance between samples, as well as the number of samples per local area, results in a very simple measurement procedure to be used by practicing engineers who need to make only a few measurements in order to extract the basic parameters to get good idea of path loss behavior, and who do not need to have a deeper knowledge of channel dynamics. Such knowledge is sufficient in many practical applications where the main
objective is to dimension the power of a communications system and provides reliable information about the fading margins required in a practical design.

LOS measurements were performed in corridors and open areas, at distances between 1 and 32 m. NLOS, between perpendicular corridors, corridors into open areas and open areas partially obstructed by clutter at distances up to 25 m and, finally OBS measurements were made with the transmitter inside a closed room and the receiver in separated rooms and corridors at distances up to 18 m from the obstructing wall. Measurements with transmitter and receiver in different floors were also performed. In all cases, transmission was vertically polarized, and the transmitter kept fixed for each set of measurements while moving the receiver. Finally, polarization measurements were made taking, at each measurement point, two samples of the received power, one with the receiving antenna vertical and then, rotating it to an horizontal position. Measurements were made in 73 local areas in the various environments and for the propagation conditions already mentioned.

4. Statistics of the exponent
The statistical behavior of either received power, envelope amplitude, or path loss can always be described by unimodal and asymmetrical probability density functions (pdf), and it is assumed that the statistics of the exponent of distance should behave in the same way. However, since the relationship between $n$ and the power is not linear, the function that best describes $n$ will not, necessarily be the same as that of the power, and it cannot be assumed a priori that $n$ will follow distributions such as Rayleigh, Rice or log-normal. Fitting of $n$ to these functions was investigated with acceptable results, however, large deviations were observed in a significant number of cases, particularly at the tails. Such deviations would lead to very pessimistic predictions of fade margins, unless some corrections are introduced. Several empirical corrections were attempted to obtain better fittings to actual data, however, no general rule was found for a correction that worked in all cases. Therefore, fitting to other distributions was investigated, in particular gamma [8], Weibull [9] and Nakagami [10], with remarkably better results. In most cases, differences in fitting to these functions were only marginal, with the gamma distribution producing smaller errors and higher correlation coefficients between the theoretical function and the distribution of the samples. It must be said that the particular distribution functions used to fit the experimental data were used only as mathematical tools capable of describing the exponent behavior, and no attempt was made to establish a relationship between their parameters and the physical process. Fitting of data to probability density functions used the mean and standard deviation of the samples as input variables; the resulting cumulative distributions (cdf) being easily obtained from them. Goodness of fit was measured in terms of the rms error in pdf’s between the theoretical function and experimental data, cdf’s, and correlation coefficients in each case. Fitting errors with gamma distribution were in the order of 0.025 to 0.1 for pdf’s, and between 0.01 and 0.068 for cdf’s, whereas correlation coefficients were between 0.75 and 0.99 for pdf’s and between 0.975 and 0.9995 for cdf’s. Similar figures were observed with Weibull and Nakagami distributions.

In all cases investigated, two distinct regions of exponent behavior can be identified. At distances up to about 20 $\lambda$ from the transmitter in LOS and OBS conditions, and from the scattering edge in NLOS, means and standard deviations are higher and decay, approximately, in exponential form to nearly constant values, with small fluctuations, at distances greater than, approximately, 20 $\lambda$. Typical values for LOS conditions in corridors are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>In the near region ($d &lt; 20 \lambda$), values of $n$ as high as 8.4 and as low as 0.2 were observed in local areas at 2 m distance, with standard deviations about three times as large as those observed in the distant region ($d &gt; 20 \lambda$), where maximum and minimum values of $n$ were 4.1 and 1.2 respectively. The terms near region and distant region used before are arbitrary, and not necessarily related with the concepts of near (induction) field and far (Fraunhofer) field and must not be confused with them. No attempt is made here to relate the observed multipath effects with such concepts. It can be said that the measurements made at distances</td>
</tr>
</tbody>
</table>
smaller than 20%. From the transmitting antenna do not reflect actual propagation conditions in large area, and from a practical point of view, if values of the exponent in this region are considered, a pessimistic coverage prediction will result. However, attention must be paid to NLOS (shadowing) cases where, in the vicinity of diffracting corners, the received power follows a similar behavior than that in the neighborhood of the transmitting antenna. In practical situations these conditions must be properly evaluated for particular cases. In Table II, the statistical parameters of the exponent are presented for the various experimental cases. Such values correspond to samples in the distant region defined before.

Table 2

Mean values of the exponent are in reasonable agreement with those reported by others [11], [12]. Standard deviations are environment-sensible, being higher where the amount of furniture, columns and objects is larger. This effect has direct consequences on the fade margin as can be seen in figure 1, where the gamma cumulative distribution for two LOS cases in corridors in different buildings is shown. The mean values of the exponent are almost equal (1.96 and 1.97), however the standard deviation is larger in building 1. From the figure it seems clear that the second building offers better LOS propagation conditions. For the cases shown in figure 1, 99% of values of the exponent will be below 3.75 for building 1, and below 2.6 for building 2 and, for a distance of, say, 100 m, the excess path loss with respect to free space conditions will be 22.8 dB for the first building and 7.8 dB for the second. The differences in the expected path losses in worst conditions (99% of values of the exponent in this example), are due only to the different standard deviations, since mean values are approximately equal.

Figure 1

Similar plots can be produced for other environments and propagation conditions. As mentioned before, the gamma distribution function fits very well in general, to experimental data, and equation (4) can be easily used to describe the statistical behavior. Since the mean value of the exponent is assumed constant in the range of distances of interest, there is no need to specifically describe the large area behavior with this model. Furthermore, all sets of samples under the same propagation conditions in a given environment can be grouped in a larger set whose parameters adequately describe the path loss behavior. A remark must be made for the case of total obstruction (OBS) between antennas: a total obstacle introduces a fixed attenuation which, in general, is not known and causes that the exponent after the obstacle be distance-dependent. Such dependence has not been found significant in the range of distances of the experiments, except at short distances from the obstacle. However, in this situation, the following expression can be used for the exponent:

\[ n(d) = n_o + \frac{L_{OBS}}{10 \log(d)} \]  \hspace{1cm} (6)

where \( n(d) \) is the mean value of the exponent after the obstacle, \( n_o \) is its value in the region before the obstacle, \( L_{OBS} \) is the mean of the attenuation introduced by the obstacle, and \( d \) is the distance from the obstacle to the measurement point. \( L_{OBS} \) can be easily obtained with the above expression, through measurements in the regions before and after the obstacle.

Polarization effects [13]. In the indoor propagation environment, electromagnetic waves suffer depolarization as a consequence of multiple scattering. The amount of depolarization was measured, as described in Section 3, in most of the experiments performed in building 2, and the statistical behavior of the exponent for copolar and crosspolar components analyzed. The results are resumed in Table 3 in terms of the exponent values, as well as path loss difference between copolar and crosspolar components.

Table 3
Values in Table 3 suggest that the amount of depolarization depends strongly on clutter in the environment, being greater when LOS and OBS conditions prevail. Crosspolar components can also be characterized with the gamma distribution function, and it is interesting to notice that, in the experiments performed, observed standard deviations are very similar for copolar and crosspolar components. In the worst conditions observed, the received crosspolar component was higher than the copolar in about 35% of the samples, which strongly suggests the convenience of polarization diversity in such in such circumstances.

6. Conclusions
A very simple model in which the exponent of distance is considered a random variable has been investigated to statistically characterize path loss at 1.8 GHz in indoor environments. Such model can be used by working engineers who, through a few measurements, can obtain the basic information needed to estimate the power budget of communications systems in a particular environment, and who do not require a deeper knowledge of channel dynamics. The exponent can be described with a gamma distribution function through which, the necessary information about fading can be extracted. Since the behavior of the exponent is fairly constant in large areas, only one distribution function is necessary to characterize it. Polarization effects were also measured and strong depolarization was observed in cases of shadowing (NLOS), and total obstruction in the signal path, suggesting the convenience of polarization diversity in such cases.

References
8. CCIR Report 1007-1.
Table 1. Typical values of the exponent ($n$) and its standard deviation ($\sigma_n$) for LOS conditions in corridors.

<table>
<thead>
<tr>
<th>distance</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>16</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>2.49</td>
<td>2.21</td>
<td>1.94</td>
<td>1.96</td>
<td>2.05</td>
</tr>
<tr>
<td>$\sigma_n$</td>
<td>1.26</td>
<td>0.81</td>
<td>0.47</td>
<td>0.46</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Table 2. Statistical parameters of the exponent in various environments.

<table>
<thead>
<tr>
<th>Case</th>
<th>Building 1</th>
<th>Building 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n_{\text{mean}}$</td>
<td>$\sigma_n$</td>
</tr>
<tr>
<td>LOS Corridors</td>
<td>1.96</td>
<td>0.453</td>
</tr>
<tr>
<td>Open areas</td>
<td>2.05</td>
<td>0.535</td>
</tr>
<tr>
<td>NLOS Corridors</td>
<td>3.1</td>
<td>0.347</td>
</tr>
<tr>
<td>Corridors into open area</td>
<td>2.6</td>
<td>0.235</td>
</tr>
<tr>
<td>Open area with partitions</td>
<td>3.79</td>
<td>0.45</td>
</tr>
<tr>
<td>OBS One wall</td>
<td>2.54</td>
<td>0.53</td>
</tr>
<tr>
<td>Three walls</td>
<td>4.35</td>
<td>0.28</td>
</tr>
<tr>
<td>Five walls + stairs</td>
<td>4.93</td>
<td>0.54</td>
</tr>
<tr>
<td>Adjacent floors</td>
<td>4.28</td>
<td>0.286</td>
</tr>
</tbody>
</table>

Table 3. Statistical parameters of exponent and path loss difference for copolar and crosspolar components.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Polarization T-R</th>
<th>$n_{\text{mean}}$</th>
<th>$\sigma_n$</th>
<th>$I_{\text{av}}$ (dB)</th>
<th>$\sigma_L$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS - Open areas and aisles. Small clutter.</td>
<td>V-V</td>
<td>2.07</td>
<td>0.53</td>
<td>15.6</td>
<td>7.0</td>
</tr>
<tr>
<td>NLOS - Open areas. Heavy clutter and metallic objects</td>
<td>V-V</td>
<td>3.8</td>
<td>0.24</td>
<td>8.05</td>
<td>4.25</td>
</tr>
<tr>
<td>NLOS - Aisles and open areas. Mild obstructions</td>
<td>V-V</td>
<td>2.6</td>
<td>0.45</td>
<td>6.6</td>
<td>6.3</td>
</tr>
<tr>
<td>OBS - Thick brick walls</td>
<td>V-V</td>
<td>4.55</td>
<td>0.53</td>
<td>6.6</td>
<td>6.0</td>
</tr>
<tr>
<td>OBS - Concrete walls and areas with heavy clutter</td>
<td>V-V</td>
<td>4.93</td>
<td>0.26</td>
<td>1.44</td>
<td>3.7</td>
</tr>
</tbody>
</table>
Figure 1. Gamma cumulative distributions for LOS conditions in corridors in two different buildings.