A Multi-Wall-and-Floor Model for Indoor Radio Propagation

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Abstract

A requirement for the performance evaluation of wireless systems by means of simulations is the knowledge of the path loss between transmitters and receivers. In this paper a new indoor path loss model for large-scale attenuation is proposed. The Multi-Wall-and-Floor (MWF) model considers the nonlinear relationship between the cumulative penetration loss and the number of penetrated floors and walls. The model has been derived from ray tracing simulations in different scenarios and respective parameters are provided for 5.2 GHz. For validation purposes measurements and extensive comparisons with results found in literature have been performed.

Because of the simple structure of the MWF model it is an interesting alternative to ray tracing for system simulations in indoor environments.

1. Introduction

The indoor radio channel has been subject of extensive investigations and much effort has been spent to develop appropriate models [1, 2, 3]. With the rapid deployment of wireless multimedia systems and new technologies for digital signal processing in combination with intelligent antennas, current research focus on directional wideband channel models. These models are important for the design and performance evaluation of advanced receiver structures but they are very complex and many times they do not provide information on the path loss that is a prerequisite for system simulations. For the latter application many measurements have been performed [7-16] and appropriate path loss models have been derived [1, 17-22]. Still, for the performance evaluation of *Wireless Local Area Networks* (WLAN) like IEEE 802.11a or the European HIPERLAN type 2, appropriate models for the indoor radio channel at 5 GHz are very rare.

Next to the power decay index[1] the penetration losses owing to walls and floors between the transmitter and receiver have a significant impact on the overall loss. Especially, for interference calculations the penetration loss plays an important role and has a considerable impact on estimating the overall system capacity.

In this paper, a path loss model that takes into account multiple penetrated walls and floors is presented and described in Section 2. This *Multi-Wall-and-Floor* (MWF) model has been derived from ray tracing simulations. The used ray tracing method is based on an enhanced ray-launching approach that is briefly described in Section 3. In Section 4 the resulting parameters for 5.2 GHz are presented. For validation purposes radio channel measurements in the frequency and time-domain have been performed. Furthermore, results from literature are quoted and are compared with the simulation results.

2. The MFW Model

First path loss models for the large-scale attenuation for the indoor radio channel are based on simple models, e.g. where the path loss exponent accounts for all propagation phenomenon. One example is the one-slope model [20] where the free space loss term is modified.

$$L_{one-slope} = L_0 + 10\ n \log(d)$$

L_0 denotes the path loss in a distance of one meter, d is the distance between transmitter and receiver and n is the slope factor (power decay index), which becomes 2 for free space propagation. Models that try to account the increasing path loss owing to penetration of walls/floors and/or obstacles vary the power decay index with the distance (see [1]).

A more sophisticated model has been developed by Motley and Keenan [21]. This model takes into account all penetrated walls and floors by individual penetration

[1] The power decay index is also referred as "distance power gradient" [3] or "slope factor" [20].

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losses depending on their thickness and material. Walls or floors of the same category (thickness and material) contribute a constant loss no matter whether other walls or floors have been penetrated before.

Recent measurements and ray tracing simulations indicate a nonlinear dependence of the overall penetration loss and the number of penetrated floors of the same category. In the multi-floor model proposed in [20] an empirical exponent has been introduced that contains the number of penetrated floors. Similar to the attenuation owing to traversed floors it has been found that the attenuation caused by the first traversed wall is greater than the incremental attenuation caused by each additional wall [10].

So far, no model exists that comprises both effects of multiple penetrated walls and floors. Furthermore, the derivation of the empirical exponent for the penetrated floors as described in [20] requires the validation by means of other models or measurements for new scenarios and material characteristics at different frequencies.

The MWF model proposed in this paper takes into account the decreasing penetration loss of walls and floors of the same category as the number of traversed walls/floors increase. The walls and floors that have to be considered are determined by the *Obstructed Line-Of-Sight* (OLOS) path.

$$L_{MWF} = L_0 + 10\ n \log(d) + \sum_{i=1}^{I}\sum_{k=1}^{K_{wi}} L_{wik} + \sum_{j=1}^{J}\sum_{k=1}^{K_{fj}} L_{fjk}$$

where

L_0 = path loss at a distance of 1 m

n = power decay index

d = distance between transmitter and receiver

L_{wik} = attenuation due to wall type i and k-th traversed wall

L_{fjk} = attenuation due to floor type j and k-th traversed floor

I = number of wall types

J = number of floor types

K_{wi} = number of traversed walls of category i

K_{fj} = number of traversed floors of category j.

The parameters of the model have been derived by means of ray tracing simulations and can be extracted from results found in literature. In the following sections the ray tracing technique and various model parameters are presented.

3. Ray Tracing

Ray tracing methods are based on *Geometrical Optics* (GO). Rays are followed until they hit an object, where a reflected/transmitted ray is initiated in the next reflection/transmission depth [23, 24]. The direction of the new ray is determined by Snellius' law. Losses due to reflections and transmissions take into account the thickness of the hit walls/floors and the material characteristics at the respective frequency. Furthermore, diffracted rays can be considered by means of the *Uniform Theory of Diffraction* (UTD). In the target frequency range of 5 GHz diffracted rays are neglected since they only have a minor contribution.

Ray tracing can be distinguished in ray launching and ray imaging techniques. Applying the imaging method where new image sources are constructed of all existing (image) sources in the current reflection/transmission depth for all planes, each ray (path) from the transmitter to the receiver is exactly determined.

Alternatively, a computational efficient solution, especially for a high number of reflections and transmissions, is provided by the launching method. Rays are homogeneously emitted from a unit sphere centered on the transmitter location and all regions are covered uniformly by rays. Rays that intersect an imaginary detection area (reception sphere) around the receiver after a number of reflections, transmissions, and diffractions will account to the received signal.

Increasing the number of rays reduces the probability for a detection error, but as long as the detection area is a sphere, rays will miss the receiver owing to detection gaps (sphere is too small) or a ray hits the area that normally will not reach the antenna (sphere is too large), resulting in an inflated count of received power.

In a new twofold detection algorithm, it is first checked whether a circular detection area around the emitted ray hits the receiver, which increases with traveling distance and therefore defines a cone [23]. In case of success, in the second step the triangular detection area is used to check whether a ray hits the receiver. Triangular detection areas result from subdividing the sides of an icosahedron.

Owing to the twofold recursion, the quick and computational optimal circular detection area is used to select a small subset of potential rays that hit the receiver. The circular detection areas are dimensioned to preclude detection gaps. In the second step, double counts are eliminated due to the triangular detection area that is covered by the circular detection area.

To avoid systematic errors owing to ray launching in combination with circular detection areas, the new two-fold detection routine has been used to gain the MWF model parameters that are presented in the next section.

4. Scenarios and Model Parameters

For evaluation of the parameters of the MWF model ray tracing simulations with two different tools have been performed and for validation purposes reference measurements have been done in typical scenarios. Furthermore, values found in literature that are fitted to the parameters of the proposed model are presented.

4.1 Parameters derived by means of ray tracing

Measurements and ray tracing simulations have been performed for different rooms with up to 2 penetrated walls and floors. The ray tracing tool has been developed at the chair of Communication Networks (ComNets) at the RWTH Aachen and comprises the advanced twofold detection routine as described in the previous section.

The ray tracing simulations in an office building have been validated by means of measurements with a frequency-swept analyzer. The simulations in rooms of a university have been compared with measurements done with the vector channel sounder RUSK ATM in the time domain [27]. Measured and simulated values are in good agreement.

Different rooms with various sizes have been investigated. Up to 1000 values with a separation of more than one half wavelength to avoid correlation have been considered in each room. For rooms in an office with $O_1 = 13$ sqm, $O_2 = 29$ sqm, and $O_3 = 94$ sqm power decay indices between $n = 1.96$ and $n = 2.03$ have been observed. It is found that there is a correlation between the attenuation and the room size. The power decay index increases as the room becomes larger.

Dependent on the material each traversed wall contributes an additional propagation loss. Table 1 holds complex permittivities for some common building materials.

Table 1: Complex permittivities

Material	ε_r	ε_r tang δ
Concrete	6.95	0.74
Brick	4.44	0.004
Stone	2.12	0.48
Wood	4.44	0.004
Glas	6.3	0.06

For the penetration of one concrete wall ($k = 1$) and a second concrete wall ($k = 2$) each with thickness 20 cm and the permittivities found in Table 1, a loss of 29 dB and 24 dB is encountered, respectively [25]. The results for the attenuation of walls of 10 cm and 20 cm thickness in the OLOS conditions are summarized in Table 2.

Table 2: Penetration loss values for MWF model

Wall material	Thickness	$k = 1$	$k = 2$
Concrete	10 cm	$L_{w11} = 16$ dB	$L_{w12} = 14$ dB
Concrete	20 cm	$L_{w21} = 29$ dB	$L_{w22} = 24$ dB

Comparison with the simulated values indicate a standard deviation of approximately 5-6 dB for small and medium sized rooms and approximately 8-9 dB for large rooms.

More ray tracing simulations have been performed within different rooms in an university building. It is an regular scenario with one corridor and rooms on one floor. Interior walls, which are made of concrete, are assumed to be 24 cm thick. Next to different complex permittivities for glass ($\varepsilon_r = 6.3$; ε_r tang $\delta = 0.06$) and wood ($\varepsilon_r = 1.85$; ε_r tang $\delta = 0.235$) the parameter for concrete has been changed according to Table 3. The material parameter M_1 considers dry concrete, whereas the material characteristic M_2 accounts for porous concrete.

Table 3: Complex permittivities for concrete

Material	ε_r	ε_r tang δ
Concrete M_1 (dry concrete)	5.1	0.23
Concrete M_2 (porous concrete)	2.2	0.14

The resulting penetration losses for the different material characteristics M_1 and M_2 are summarized in Table 4.

Table 4: Penetration loss values for different material characteristics

Material	$k = 1$	$k = 2$
M_1	$L_{w21} = 35$ dB	$L_{w22} = 29$ dB
M_2	$L_{w31} = 34$ dB	$L_{w32} = 26$ dB

The loss exponent is found to be $n = 1.998$. For the attenuation of the first wall with thickness 24 cm a value of 35 dB has been found. The second wall accounts for an additional loss of 29 dB.

4.2 Parameters derived from literature

Further values for the penetration loss, which are comparable to the results in Table 2 and Table 4, can be found in [26]. The values are based on the summary report on Building Shielding Loss at 5 GHz which was presented by the Radio Technology and Compatibility Group of the UK Radiocommunications Agency.

The penetration losses for different material types and measurements at 5.8 GHz are summarized in Table 5. The results have been derived from measurements for perpendicular polarization.

Table 5: Wall penetration loss values for MWF model for 5.8 GHz [26]

Wall material	Thickness	$k = 1$
Plywood	0.4 cm	$L_{w11} = 0.9$ dB
Gypsum wall – plastered gypsum wall with 1 mm max. thickness of plaster	13.5 cm	$L_{w21} = 3.0$ dB
Rough chipboard	1.5 cm	$L_{w31} = 1.0$ dB
Glass plate		$L_{w41} = 2.5$ dB
Double-glazed window – with a 12 mm air layer	2.0 cm	$L_{w51} = 12$ dB
Concrete block wall – reinforced concrete block	30.2 cm	$L_{w61} = 10$ dB

For building facades with 50 % window area and 50 % wall material an average penetration loss through the exterior wall of 5 dB can be expected for single-glazed windows and 10 dB for double-glazed windows. Comparable results have been found in [13].

In the following Table 6 values for measurements at 5 GHz are summarized [26].

Table 6: Wall and floor penetration loss values for MWF model for 5 GHz and $n = 2$ [26]

Wall material	$k = 1$	$k = 2$
Breeze block – furniture included desks, wooden and metal bookshelves and metal filing cabinets	$L_{w11} = 7.1$ dB	$L_{w12} = 5.4$ dB
Floor material	$k = 1$	$k = 2$
Office building - no further details	$L_{f11} = 19$ dB	

A power decay index $n = 2$ is assumed. Again, the second wall accounts for less penetration loss than the first wall.

To consider the excess loss as function of the number of sections traversed the following non-linear model is suggested in [10].

$$L_{ex} = L_s n_s^{\left[\frac{n_s+5}{n_s+3} - b\right]}$$

The number of traversed walls in the direct path is denoted by n_S. The factor b is an empirical factor and is estimated to $b = 0.5$. The average loss per wall L_S is found to be 6.9 dB. With this equation the penetration losses for the first and second wall become $L_{w11} = 6.9$ dB and $L_{w12} = 6.0$ dB, respectively. With a higher penetration loss for the first wall of $L_{w21} = 29$ dB the loss for the second wall becomes $L_{w22} = 25$ dB and is in good agreement with the results found by means of ray tracing, cfg. Table 2.

5. Conclusions

In this paper a novel path loss model called *Multi-Wall-and-Floor* (MWF) model has been described. It considers the non-linear cumulative penetration loss of penetrated walls and floors. Several values for the penetration loss for one and two traversed walls are presented. The proposed model is appropriate for realistic system simulations since it is easy to use and accounts for the discontinuities at the traversed walls or floors, which is relevant for interference calculations. Because of the simple application of the model to complex scenarios, which only needs the number of walls and floors traversed by the obstructed line of sight, it is appropriate for fast system simulations.

The results motivate to develop a further model that takes into account the inter-action of penetrated walls and floors. It is expected that the penetration loss of a wall decrease as the number of floors increase, which have been penetrated beforehand, and vice versa. In this model the indices of the number of penetrated walls and floors will not be independent anymore.

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