Performance, Accuracy and Generalization Capability of Indoor Propagation Models in Different Types of Buildings

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Abstract — **In the last years different prediction models for indoor environments were developed for the frequency range between 500 MHz and 5 GHz. Each of these models has its own advantages and disadvantages.**

In this paper four of the most popular models are compared to one another and to measurements in different buildings. The comparison is limited to the prediction of the received power because two models are only able to predict the power. Two models are also able to predict the delay spread and one model is additionally able to predict the standard deviation of the instantaneous field strength (fast fading) related to the median field strength. For this last model a comparison of the results for the delay spread and the fast fading is also presented in this paper.

Three different buildings were used for the comparison of the models. A new office building with concrete walls at the University of Stuttgart (Germany), an old office building with brick walls in Vienna (Austria) and the villa of Marconi, which is a very old building (brick and wood) in Bologna (Italy).

I. Introduction

Different approaches to the prediction of the indoor wave propagation were developed in the last years. Because of the established wireless systems the models are calibrated for the frequency range between 500 MHz and 5 GHz. Within this frequency range there are different applications and services which require efficient planning tools.

First there are mobile telephone network operators who are interested in indoor coverage for their mobile radio networks. They want to know, where they have to place their repeaters or basestations to guarantee a sufficient coverage inside buildings.

The second group of interested people are working in the field of local indoor networks like WLAN (HIPERLAN) or other computer networks. They need a very efficient planning tool to determine the positions for their basestations (and repeaters).

In the recent years some telephone companies have also started their investigations in indoor propagation, because they want to reach their customers not with expensive wires but with wireless technology (WLL – Wireless Local Loop).

So the very high demand for indoor network planning tools is obvious and many companies have developed their own propagation and prediction tools.

The indoor propagation tools can be subdivided into the following four groups:

- Statistical models
  These models need no information about the walls in the buildings. Only a description of the type of the building is necessary (Office, hotel, hospital, old building,...) [1], [13].

- Empirical direct-path models
  They are based on the direct path between transmitter and receiver, no further rays are considered [1], [2].

- Empirical multi-path models
  This new approach is based on the multipath propagation between transmitter and receiver. Different types of paths are computed and their parameters are used for the prediction [3], [8].

- Ray optical models
  The UHF frequency range can be described with quasi-optical propagation models considering reflections at walls and diffractions at corners (wedges). Different approaches are established like ray tracing and ray launching [4], [5], [6].

Each group contains different implementations of the basic idea, but all models belonging to the same group lead to nearly similar results and have the same advantages (and disadvantages).

This paper will focus on the comparison of the different models and not on the description of the models, because the models for themselves are presented in many publications by different authors - but a comparison of the different models requires the implementation of all models in the same software package [7]. And this will lead to interesting results concerning the accuracy of the models, especially if they are calibrated in one building and used in another building (generalization capability).

At least one representative of each group is presented in this paper to explain the limitations of the models.

The data bases containing the information about the walls of new buildings are available in CAD-files (DXF data files) and the maps of old buildings are scanned and converted into DXF data with different CAD converting tools (available for architects) [7].

II. Propagation models

A. Statistical Propagation Models (SPM)

The most famous implementation of a statistical model is the *modified free space model* [1]. The field strength E_e for a base station with transmitted power P_T and transmitter gain G_T is:

$$E_e^2 = \frac{P_T\, G_T\, Z_{F0}\, c_0^2}{(4\,\pi\, f)^2\, d^n} \tag{1}$$

In most cases the path loss L_F is used for the characterization of the channel. Using the received power P_R in equation (2) leads to equation (4) for the path loss L_F:

$$P_R = \frac{P_T\, G_T\, c_0^2}{(4\,\pi\, f)^2\, d^n} \tag{2}$$

$$L_F = 10 \log P_T - 10 \log P_R \tag{3}$$

$$= 10 \log \frac{(4\,\pi\, f)^2\, d^n}{c_0^2\, G_S} \tag{4}$$

Instead of the exact position and the material of the walls a more general approach is implemented where a high penetration loss of all walls leads to an increasing exponent n. So different types of buildings are characterized by different values for the parameter n [1].

This model was implemented in a software package [7] and it is very fast, because only the distance between transmitter and receiver must be determined, all other parameters are constant for the whole building.

B. Empirical Direct-Path Models (EDP)

The model of *Motley-Keenan* [2] and the more detailed *Multi-Wall-Model* [1] determine all walls intersecting the direct ray between transmitter and receiver.

The model of *Motley-Keenan* uses the same transmission loss for each wall and only the number of walls influences the total transmission loss of the path [2]. Different types of buildings (office buildings, new or old buildings, libraries, hotels, ...) are characterized with different values for the common transmission losses of walls. If the materials of the walls are available, the median loss of the walls inside the building can be computed.

The *Multi-Wall-Model* uses an individual transmission loss L_{W_i} for each wall and therefore the materials of the walls and not only the number of the walls are considered for the computation of the total transmission loss L_{Wall} [1]. If m walls are passed by the direct path, the transmission loss is computed with:

$$L_{\mathit{Wall}} = \sum_{i=1}^{m} L_{W_i} \tag{5}$$

With $n = 2$ in equation (4) the total path loss of the Multi-Wall-Model is determined with:

$$L_{MW} = L_F + L_{\mathit{Wand}} \tag{6}$$

C. Empirical Multipath Models (EMP)

The multipath propagation is very important in indoor environments and a prediction model should consider multipath parameters to achieve accurate results. Therefore the new *Dominant Path Model (DPM)* was developed [8]. It computes the dominant paths between the transmitter and the receiver [3], considering the actual multipaths and reducing the computation time nearly to the computation time of the EDP models.

After the determination of the rooms (only a vector-oriented description of the walls of the buildings is necessary in the data base), the neighboring rooms for each room are computed and the neighboring relations between the rooms are stored in the data base, because they are independent of the transmitter location and can be used for all predictions.

Based on the neighboring relations of the rooms, a tree for the room structure of the building is computed, representing the layout and arrangement of the rooms [3]. The paths from the transmitter to the receiver and the rooms passed by these paths are determined in the room-tree and are therefore not related to specific walls. Further information about the tree of the rooms and the determination of the paths is available in [3] and [8].

Different algorithms for the computation of the field strength were developed. The two most important models are neural networks [3] and empirical regression [8].

A very accurate prediction of the delay spread and the fast fading is also possible with the dominant paths [9].

This model has a very small dependency on the accuracy of the data base, because the exact locations of the walls are not considered and only the information about the room and the neighboring rooms influences the determination of the paths.

D. Ray-Optical Models (RO)

Ray-optical models are the most common approach to the computation of the field strength inside buildings [4], [5]. They compute all relevant rays between the transmitter and the receiver, which leads to long computation times. Different approaches to the acceleration of these models were presented reducing the computation times to acceptable values [5].

Two different algorithms are established: *Ray tracing* and *ray launching* [4], [6]. The number of considered interactions (reflections, diffractions, transmissions) depends on the computation power of the computer. Most models are limited to max. 6 interactions (all combinations of reflections and diffractions with max. two diffractions).

The field strength along a single ray is computed with the with the GTD/UTD for the diffraction [10] and with the Fresnel equations for the reflection/transmission [11]. Empirical equations, calibrated with measurements are also available.

Besides the prediction of the field strength, a prediction of the delay spread is also possible with these models.

One of the main disadvantages of the ray-optical models is their dependency on the accuracy of the data base [5], [6]. If the material of a wall is not accurately defined [11] or if the location of a wall differs from the actual location, the prediction leads to different and wrong results [12].

III. Measurements

For the validation of a prediction model, many measurements in different types of buildings are necessary. Modern office buildings are important as well as old buildings with furniture.

Measurement campaigns in different types of buildings were used for the validation of the accuracy and for the determination of the generalization capability of the models. The power measurements were performed with a standard measurement equipment as described in [9]. For the determination of the impulse responses and for the measurement of the delay spread a wideband PRBS channel sounder was developed [9].

A. Measurements in a new office building

A very new office building at the University of Stuttgart [8], built in the last years mainly with concrete and glass was used as a first test scenario. Especially the concrete walls lead to a very good waveguiding effect if the transmitter and the receiver are located on the same floor. 15 different transmitter locations with a total number of 8000 measurement points were determined for the validation of the propagation tools.

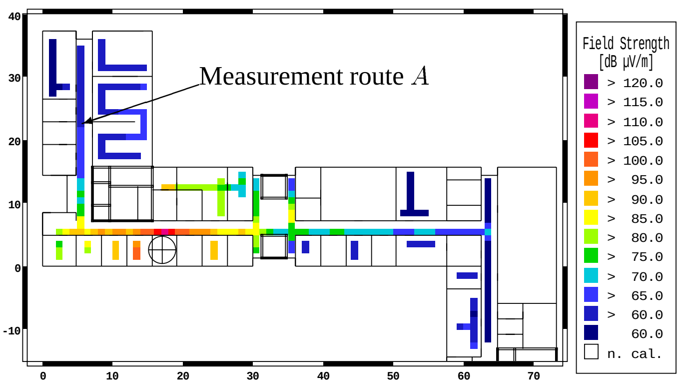

Fig. 1: Measurements in a new office building at the University of Stuttgart with $f = 1800$ MHz (TR power $P = 30$ dBm).

B. Measurements in an old office building

The University of Vienna performed measurements in an old office building, built at the beginning of the 20th century [3]. The materials of the walls are mainly brick and wood.

Five different transmitter locations in two different floors and many thousands of measurement points are available in this building [13] and were used for the evaluation of the models.

C. Measurements in an old building

The villa of G. Marconi, one of the first and most important researchers in the field of propagation and wireless communication, represents the group of very old buildings and the group of non-office-buildings with a different layout and arrangement of the rooms [5], [6] (see figure 2). The furniture of the building is very important for the wave propagation and should therefore be included in the data base of the building [6]. Most walls are built with brick and wood.

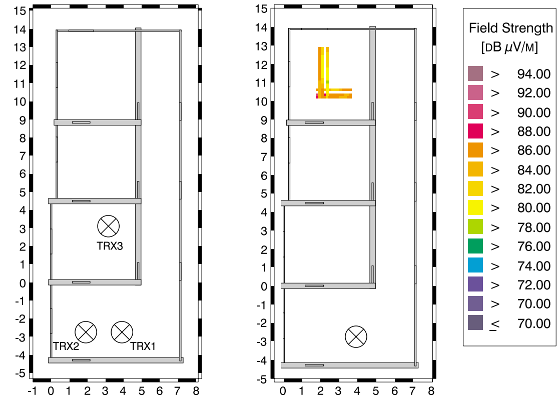

Fig. 2: Transmitter locations (left) and measurements for location TRX1 (right) in the villa of Marconi ($f = 900$ MHz, $P = 1$W).

IV. Comparison between measurement and prediction

A. New office buildings

Figure 1 shows the measurement route A inside the new office building in Stuttgart. The predictions of the four models are compared to the measurements in figure 3. It is obvious that the dominant path and the ray-optical approach lead to the most accurate results and that the statistical and direct-path-model predict errors with more than 10 dB.

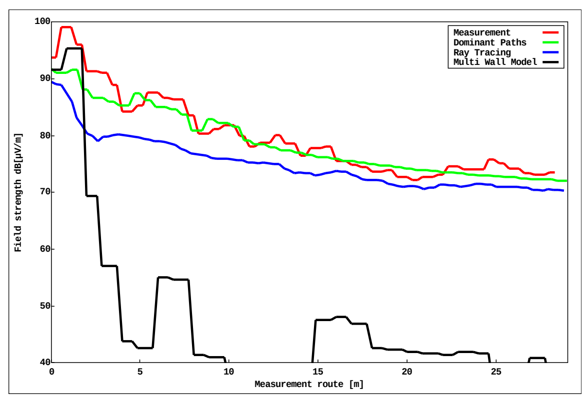

Fig. 3: Prediction with different models for the measurement route A of figure 1

Table I shows the mean errors and standard deviations for the different models and the three test scenarios. Scenario 1 is described in figure 1, scenario 2 in [3] and scenario 3 in [8].

B. Old office buildings

The figures given in [3] show a good agreement between measurement and prediction in the old office building in Vienna (Austria). A comparison between the prediction models for the scenario in Vienna is given in table II and it must be mentioned that the models were not calibrated in Vienna and that the material parameters of the walls were estimated (important for the generalization capability).

		Scenario 1	Scenario 2	Scenario 3
Multi Wall	Mean err.	12.4 dB	5.1 dB	16.3 dB
	Std.-dev.	16.8 dB	11.5 dB	20.5 dB
Dom. Path	Mean err.	0.6 dB	1.2 dB	2.5 dB
	Std.-dev.	4.6 dB	3.7 dB	3.8 dB
Ray Trace	Mean err.	0.1 dB	-2.4 dB	2.0 dB
	Std.-dev.	6.5 dB	7.3 dB	11.9 dB
Reference		Fig. 1	[3], Fig. 15	[8], Fig. 10

TABLE I: Mean error and standard-deviation for different test scenarios in the new office building in Stuttgart

Multi Wall	Mean err.	15.3 dB
	Std.-dev.	12.5 dB
Dom. Path	Mean err.	6.0 dB
	Std.-dev.	8.1 dB

TABLE II: Mean error and standard-deviation for the scenario in Vienna

C. Old buildings with furniture

The difference between the predictions for the villa of Marconi in Bologna is shown in figure 4. The values of the Dominant Path model are higher than the Multi-Wall-Model because of the waveguiding along the corridor and the coupling into the rooms. The differences to the measurements are given in table III and they confirm the results of the former scenarios. The ray tracing results were already published in [5] and [6].

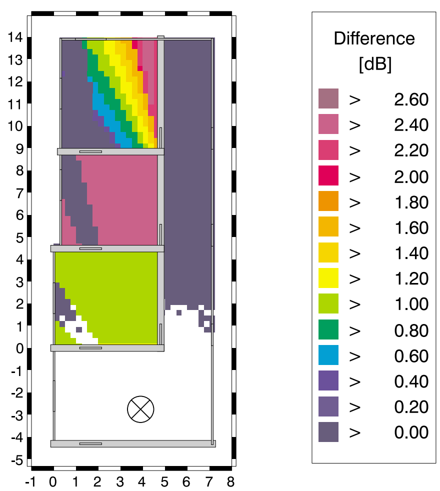

Fig. 4: Difference between the prediction with the Dominant Path Model and the Multi-Wall-Model for the scenario in Bologna

D. Conclusion for the power predictions

The empirical direct-path models and the statistical models have very strong limitations in their generalization capability. If they are calibrated with measurements of one building, the results in different types of buildings are not very accurate.

		TRX 1	TRX 2	TRX 3
Multi Wall	Mean err.	1.1 dB	-4.3 dB	-1.0 dB
	Std.-dev.	2.4 dB	5.0 dB	4.9 dB
Dom. Path	Mean err.	0.3 dB	-4.1 dB	-1.0 dB
	Std.-dev.	2.3 dB	5.0 dB	4.5 dB
Ray Trace	Mean err.	2.2 dB		-8.0 dB
	Std.-dev.	3.7 dB		4.5 dB

TABLE III: Mean error and standard-deviation for different transmitter locations in the villa of Marconi in Bologna

The dominant path model and the ray-optical models are very accurate in all types of buildings. Only the number of interactions limits the accuracy of the ray-optical models, if the prediction points are far away from the transmitter. The limited accuracy of the data base leads to errors in the ray-optical models while the dominant path model is very tolerant concerning small errors in the data base.

V. Prediction of delay spread and fast fading

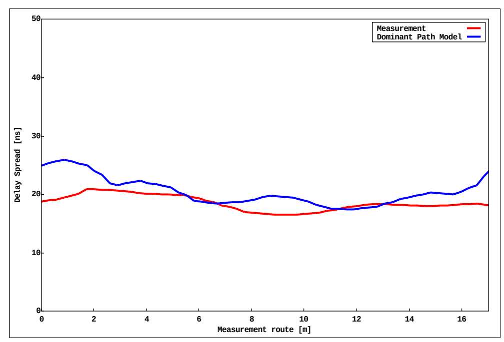

Fig. 5: Prediction and measurement of the delay spread for the measurement route A presented in figure 1

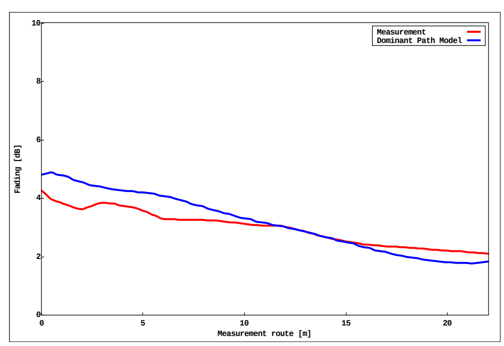

Fig. 6: Prediction and measurement of the fast fading for the measurement route A presented in figure 1

Figures 5 and 6 present the prediction of the delay spread and the standard deviation of the instantaneous field strength related to the median field strength (fast fading). A very good accuracy is achieved with the dominant path model and it is ideally suited for the prediction of these two important parameters. Further information concerning the prediction of delay spread and fast fading with the Dominant Path model is given in [9].

VI. Sensitivity of the models

The sensitivity of the models was analyzed by changing the material parameters of the walls [6]. In contrast to the the statistical and the direct-path models, which compute nearly the same results, because they don't use the specific information about the material, the dominant paths and the ray-optical model are influenced by the material properties.

While the influence of the material or the location of the walls on the accuracy of the prediction is very small for the dominant paths, the ray-optical models compute really different results [6] and are therefore very sensitive to changes in the data base. A description of the data base for ray-optical models should even include the furniture of the building [5], which is not possible in many buildings.

Therefore ray-optical models should only be used if the data base of the building is very accurate and detailed. In all other cases the dominant path model should be preferred.

VII. Conclusions

Four different types of propagation models for indoor scenarios were presented in this paper and compared to one another [7]. Very simple statistical and direct-path models and more complicated dominant path (multipath) and ray-optical models.

The ray-optical and the Dominant Path model achieved the highest generalization capability and the best accuracy of all models (compared to measurements), but the ray-optical models suffer from their high dependency on the accuracy of the data base and are therefore only suited for the prediction, if an exact and detailed data base is available. If only a very simple description of the building is available, the dominant path model leads to the best results.

Even an accurate prediction of the delay spread and the fast fading is possible with the Dominant Path approach.

All models were implemented in a free software package [7] and so the results can be compared easily to other tools and models.

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