Measurement of Building Penetration Loss and Propagation Models for Radio Transmission into Buildings

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Abstract - **The investigation of radio transmission into buildings is getting more and more important. Models for the propagation into buildings enable the calculation of the indoor field strength coverage based on the given outdoor coverage. In order to develop and to calibrate such propagation models several measurements of the building penetration loss with different transmitter locations were undertaken and evaluated. Additionally, the empirical, semi-empirical and deterministic models we developed are presented in this paper.**

I. Introduction

With the increasing number of subscribers to mobile communication networks and the introduction of new services, e.g. DAB and DVB, there is a growing interest in the question to what extent outside transmitters can provide coverage of indoor scenarios. Generally, electromagnetic waves are attenuated when penetrating into a building. The distribution of the field strength inside the building depends on several parameters, such as frequency, structure of the building, material properties and thickness of the walls. Propagation models enable the calculation of the penetration of radio transmissions into buildings in order to provide results for radio network planning.

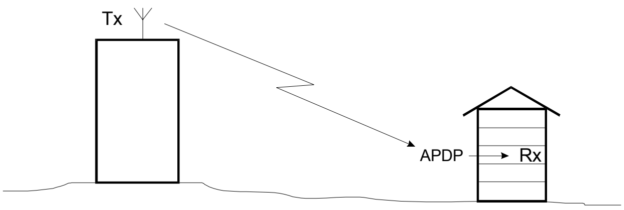

Fig. 1: Propagation problem

An approach to calculating the indoor field distribution is presented in fig. 1. The propagation problem is divided into two steps. In the first step the outdoor coverage of the considered building is computed with empirical or deterministic models [4][5]. In the second propagation models are utilised which enable a prediction of the indoor field strength based on the one determined outdoor.

An adequate interface between the propagation models for outdoor and indoor scenarios is given by the angular power delay profile (APDP), which includes the field strength values, the delay time and the angles of incidence of the electromagnetic waves impinging on the outer walls of the building. By using this interface a prediction of the delay spread is also possible. However, the results presented in this paper are limited to the computation of the electrical field strength.

II. Measurements

In order to develop and to calibrate propagation models which calculate the indoor field strength coverage based on the field strengths at the outer walls of the specific building, measurements of the building penetration loss with different transmitter locations have to be carried out.

Fig. 2: Building of the Institutes of Electrical Engineering at the University of Stuttgart

The building shown in fig. 2 is predestinated for such measurements because of its surrounding balcony. With the equipment shown in fig. 3 (spectrum analyser mounted on a trolley and controlled by a PC) measurements on straight routes in corridors, rooms and on the balcony were performed with equidistant measurement points. Several measurement campaigns with different transmitter locations (see fig. 4 and fig.7) at 230 MHz and 1500 MHz were undertaken.

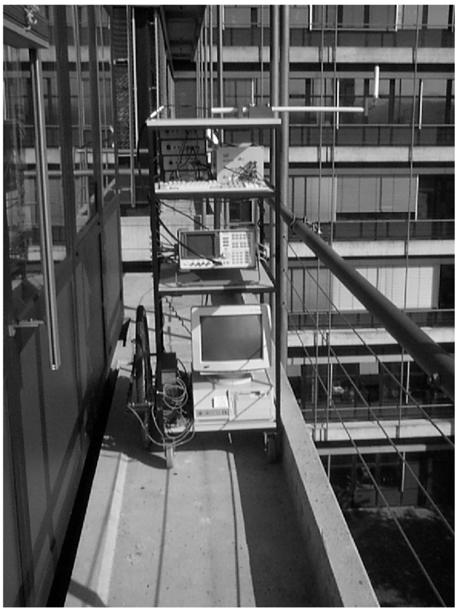

Fig. 3: Measurement situation at the institute

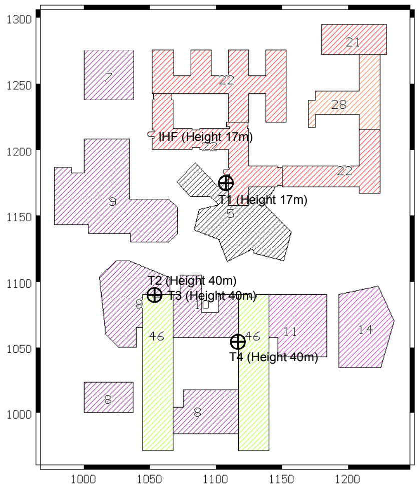

Fig. 4: Buildings (and their heights) of the university campus and different transmitter locations

Additionally, two measurement campaigns in the DAB single frequency networks at 230 MHz and 1500 MHz were carried out with a commercial receiver (see fig. 5, 6 and 8). In this case the measurement bandwidth corresponds to the bandwidth of the DAB-signal (1,5 MHz). Tab. 1 gives an overview of the performed measurements.

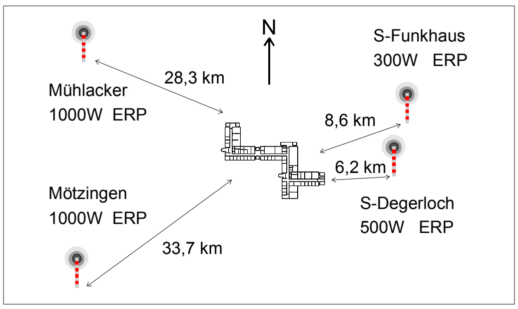

Fig. 5: DAB coverage situation at 230 MHz for the building shown in fig. 2

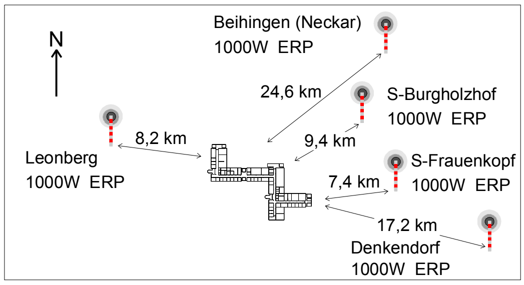

Fig. 6: DAB coverage situation at 1500 MHz for the building shown in fig. 2

Transmitter	see fig.	Frequency/MHZ
T1	4	230
T2	4	230
T3	4	1500
T4	4	1500
DAB I	5	230
DAB II	6	1500

Tab. 1: Performed measurements

Fig. 7: Penetration measurements for transmitter location T3

Fig. 8: Penetration measurements for the DAB single frequency network at 1500 MHz

III. Evaluation of the measurements

An evaluation of the measurements shows that the mobile radio propagation channel in the scenario considered can be characterised statistically by the superposition of two fading processes:

1) *Large scale signal variation* is log-normally distributed with a standard deviation of 7-9 dB in the LOS-case (see fig. 9) and a standard deviation of 4-6 dB in the NLOS-case (see fig. 10).

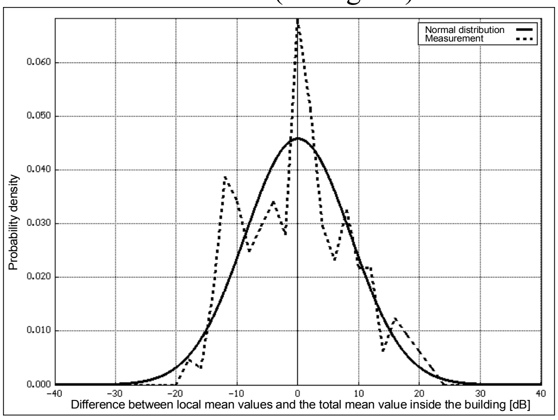

Fig. 9: Probability density function of the difference between the local mean and the total mean of the field strength levels inside the building for the measurements of fig. 7

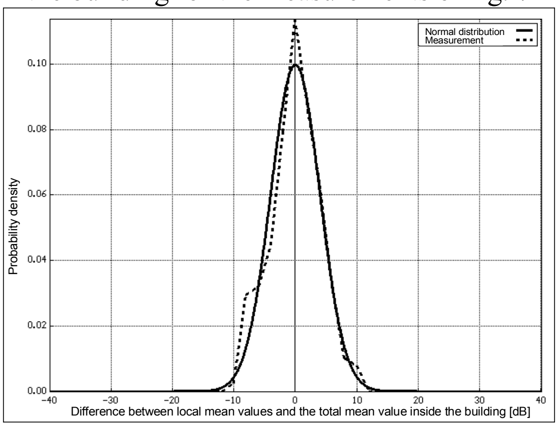

Fig. 10: Probability density function of the difference between the local mean and the total mean of the field strength levels inside the building for the measurements of fig. 8

2) *Small scale signal variation* is Rice distributed with different values of the Rice factor *c* between 0 (see Fig. 11, Rayleigh distribution) and 5 (see fig. 12).

These results agree very well with the statements given in [1], [2] and [3]. The mean building penetration loss from our measurements is in the range of 10 dB (see tab. 2). From table 2 follows that the building penetration loss (BPL) depends only slightly on frequency (building penetration loss increases with increasing frequency).

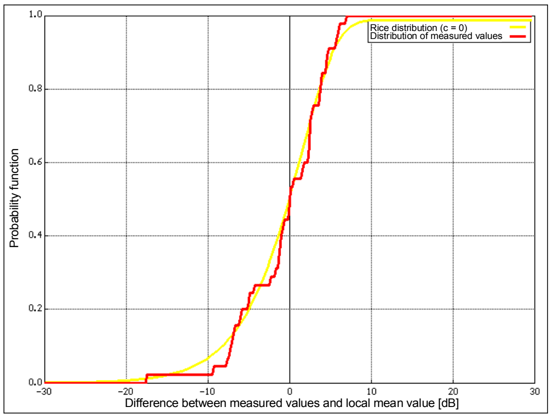

Fig. 11: Probability function of the difference between the measured value and the local mean of the field strength levels for the measurements of fig. 7 (NLOS, Rayleigh distribution)

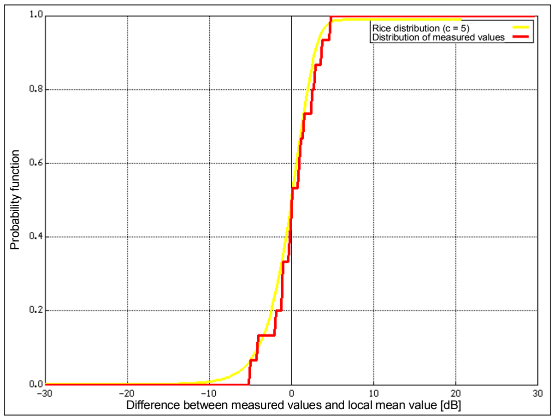

Fig. 12: Probability function of the difference between the measured value and the local mean of the field strength levels for the measurements of fig. 7 (LOS, Rice distribution)

Investigations of the dependency of the received field strength inside the building on the height of the receiving antenna above ground level lead to a height gain in the range of 3 dB per floor i.e. the received field strength level increases with increasing floor number.

Frequency / MHz	BPL-Values $\overline{E}_{outdoor} - \overline{E}_{indoor}$	Std.Dev. $\sigma_{outdoor}$	Std.Dev. σ_{indoor}
230 (T1)	3,4 dB	17,5 dB	13,3 dB
230 (T2)	10,4 dB	8,9 dB	7,6 dB
1500 (T3)	10,9 dB	8,4 dB	7,1 dB
1500 (T4)	9,7 dB	9,6 dB	8,7 dB
230 (DAB)	7,5 dB	4,3 dB	6,0 dB
1500 (DAB)	9,3 dB	2,7 dB	4,0 dB

Tab. 2: Overview of the measurement results

IV. Propagation models

There are different approaches to modelling the building penetration loss. In this paper empirical, semi-empirical and deterministic (ray optical) models are presented [2].

A. Empirical Models

Empirical models consider mainly the distance between transmitter and receiver for the calculation of the field strength. Therefore, empirical models for indoor scenarios assume that the dominant part of the received energy is transmitted along the direct ray. One of the simplest approaches to the calculation of the field strength is given in equation (1):

$$E\left[\frac{dB\mu V}{m}\right] = E_0\left[\frac{dB\mu V}{m}\right] - 10 \cdot n \cdot \lg\frac{d}{m} \quad , \qquad (1)$$

E_0 : field strength level in one meter distance to T_x

d : distance between transmitter and receiver

n : empirical loss exponent (the value of n depends on the propagation environment)

When adapting this indoor procedure to the penetration problem (the computation of the field strength level E_I inside the building) the following assumptions must be taken into account:

- The new reference value is the predicted level at the outer walls $E_{ref,i}$ instead of E_0.
- The dominant direction of propagation of the electromagnetic waves inside the building is perpendicular to the outer walls.
- d_i describes the distance between the outer wall considered and the specific receiving point.
- The predicted field strength level E_I is given by the maximum (because there are several possible contributions to each receiving point):

$$E_I\left[\frac{dB\mu V}{m}\right] = \max_i \left\{ E_{ref,i}\left[\frac{dB\mu V}{m}\right] - 10 \cdot n \cdot \lg\frac{d_i}{m} \right\} \qquad (2)$$

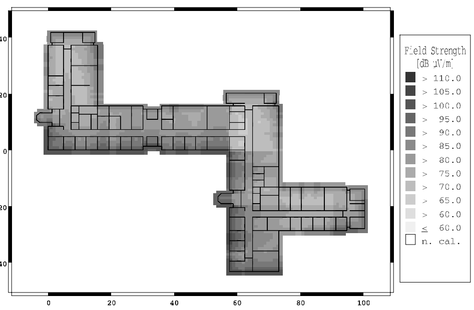

Fig. 13: Prediction with the empirical model for transmitter location T3 (LOS)

As can be seen from table 3, measured values of field strength level and predicted ones are in fair agreement.

Transmitter	T1	T2	T3	T4	DAB 230	DAB 1500
Loss exponent *n*	1,8	1,8	1,8	1,8	1,3	1,3
Mean value [dB]	0,6	-0,1	0,4	-1,1	-1,0	-0,2
Standard deviation [dB]	10,2	4,4	5,7	4,7	5,0	3,7

Tab. 3: Statistical values for the difference between predictions and measurements

B. Semi-empirical models

In contrast to empirical models, semi-empirical models take more parameters of the propagation environment into account for predicting the field strength [1]. Generally only the direct ray between transmitter and receiver is considered but, e.g. number and penetration losses of the penetrated walls are evaluated for the calculation. The values of the different parameters are calibrated by available measurement data. With the higher number of parameters the generalisation capability of the model increases in comparison to empirical models.

After adapting this semi-empirical approach to the given problem by considering the direct rays between all pixels at the outer walls of the building and the specific receiving point inside the building, several parameters have been investigated. Best results in comparison with measurements were achieved by distinguishing between LOS and NLOS and additionally between receiving points next to the outer walls and inside inner rooms of the building.

C. Deterministic models

Ray optical propagation models are often used for the prediction of field strength (and delay spread) with indoor and urban scenarios. They are very accurate because they consider waveguiding effects in street canyons (outdoor) or corridors (indoor) and they include diffraction at corners.

There are two approaches to ray optical modelling: ray tracing and ray launching (see fig. 14). Both have their individual advantages and disadvantages. Ray tracing computes all rays for each receiving point individually and guarantees the consideration of each wall as well as a constant resolution. This individual computation is more time-consuming than the ray launching approach, where the rays are launched from the transmitter with a constant angle increment. However, with ray launching several problems such as “ray-multiplication” as a result of diffraction cones and decreasing resolution with growing distance from the transmitter occur.

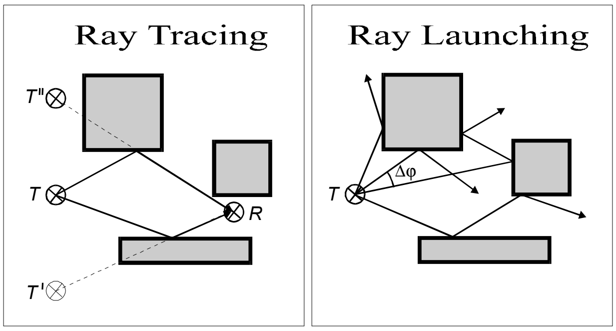

Fig. 14: Deterministic propagation models

Ray optical models are very time consuming, because all possible rays must be determined. A new approach to the acceleration of ray optical models reduces the computation time to that of empirical models. This new method combines the advantages of both ray optical models and neglects their disadvantages [4][5]. It is based on a single preprocessing of the data base. All walls of the buildings are subdivided into tiles and all wedges are subdivided into segments (see fig. 15). The visibility relations between all tiles, segments and receiving points in the data base are computed in the preprocessing, because they are independent of the transmitter location.

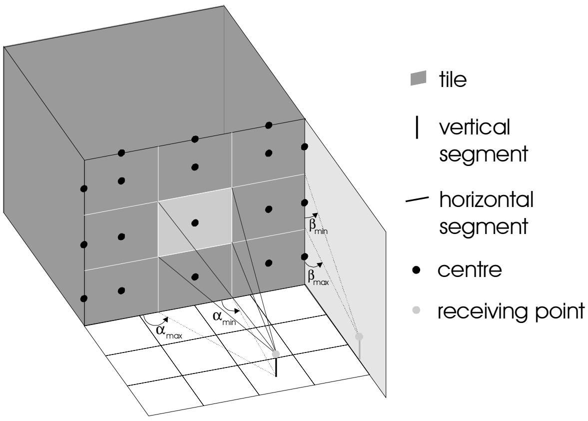

Fig. 15: Tiles and segments of a wall

This preprocessing can be done for the outdoor (contains the description of the outer walls of all buildings) as well as for the indoor data base (contains the outer and inner walls of one building). The tiles at the walls surrounding the selected building define the interface between the data bases. Fig. 16 illustrates the visibility relations computed in the preprocessing in the shape of a "visibility tree". Only the relations in the first layer of the tree must be computed in the prediction which can be done very fast, all other relations are determined in the preprocessing and can be read from a file. The stored visibility relations (except the first layer) can be used for all predictions with the same data base.

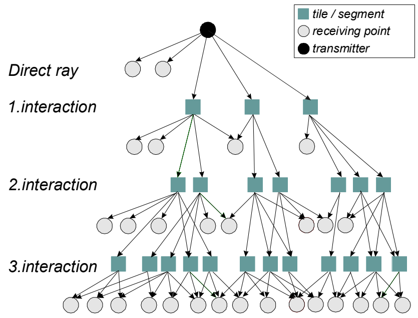

Fig. 16: Tree structure of the visibility relations

All rays and their angles of incidence are stored for each tile of the surrounding walls of the considered building. The following computation of the indoor propagation is made simple by using the information of the incident rays on the surrounding tiles and following these rays on their way through the indoor visibility tree.

V. Conclusions

In this paper a new approach to the calculation of radio transmission into buildings based on the field strength coverage at the outer walls is presented. The propagation models investigated can be distinguished into empirical, semi-empirical and deterministic models. For the development and the calibration of these models several penetration measurements were carried out and results presented. In order to increase the generalisation capability of the models further measurements at different buildings will have to be performed.

VI. Acknowledgement

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VII. References

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