

Advanced Ray-Optical Wave Propagation Modelling for Urban and Indoor Scenarios Including Wideband Properties^{*}

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Abstract. Ray-optical propagation models are often utilized for the prediction of the field strength (and delay spread) in mobile radio networks. However, the practical usage of these deterministic models is limited due to their high computational demands. A new method for the acceleration of ray-optical models is presented in this paper. It is based on a single preprocessing of the database in which the mutual visibility relations between the walls and the edges of the buildings are determined. The propagation model is implemented for urban and indoor scenarios and comparisons with measurements show the gain in computation efficiency as well as in achieved prediction accuracy.

1 INTRODUCTION

The performance of wireless communication systems depends in a fundamental way on the mobile radio channel. As a consequence predicting the propagation characteristics between two antennas still belongs to the most important tasks for the design and installation of cellular mobile communication systems [1].

According to the growing number of subscribers during the last years, the size of cells had to be reduced from radii in the order of tens of kilometres within rural and suburban environments (macro-cells) down to a few hundreds of metres in urban scenarios (micro-cells) and even further down to some 10 m with indoor applications (pico-cells).

With decreasing size of the cells the importance of wave propagation modelling within urban and indoor scenarios increases with regard to the extension of present and the deployment of future systems. Because of the increasing transmission rates propagation models should be able to calculate the field strength coverage as well as the wideband properties for these scenarios. This paper introduces a new approach for modelling wave propagation – leading to predictions of field strength, delay spread and

impulse response -- within these scenarios in an accurate way with minimized computational complexity. Additionally, simulation results gained with the new model are compared to measurements of the different channel parameters.

1.1 THE MOBILE RADIO CHANNEL

The mobile radio channel is characterized by a multipath situation. The signal transmitted by the base station – if only the downlink is considered here as the principle of reciprocity applies – will travel along different paths to the receiving antenna of the mobile station (see Fig. 1).

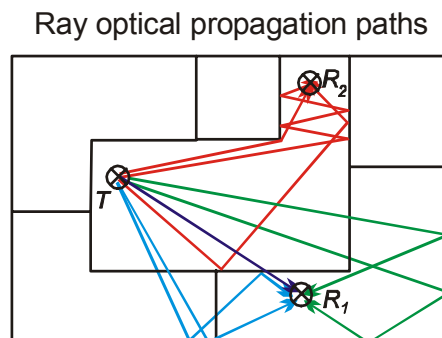


Figure 1: Multipath situation within an indoor scenario.

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In many cases there is no direct line of sight and the only signals reaching the receiver have undergone reflections, scattering and diffractions at a number of different obstacles. Consequently the field strength in a radio cell shows small-scale fading.

While deterministic ray-based propagation models, as described later, are able to compute the small-scale fading, planning tools for the prediction of field strength levels will generally provide only mean or median values as small-scale fading is adequately represented by Rayleigh- or Rice-distributions [2].

1.2 DATA BASES FOR BUILDINGS

The basis for any propagation model is a data base, which describes the propagation environment. Data bases used with radio propagation models contain information on the kind of obstacles between the transmitter (base station) and the receiver (mobile station) and are a compulsory requirement for using the more sophisticated prediction tools.

1.2.1 Urban data bases

While rural propagation models are generally based on terrain and morphological data in pixel format, urban data bases contain information on the location of buildings and are generally vector oriented. In the vector format, the shape of every building is defined by its corners and its height. All buildings are consequently represented by cylinders with a polygonal plan view (see Fig. 2), which leads to a limitation on vertical walls and flat roofs. If the urban area is not flat additionally a terrain data base should be taken into account. According to this information the buildings are shifted in vertical direction.

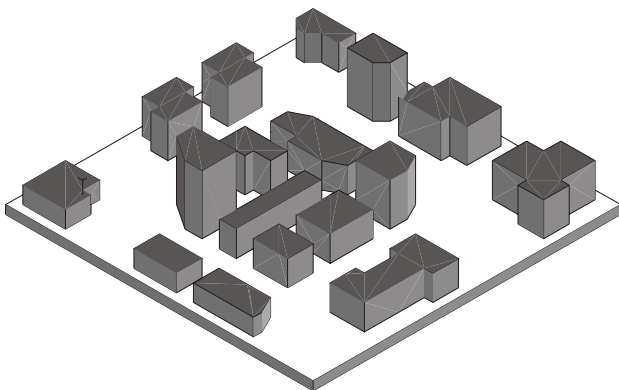


Figure 2: 3D vector data base describing an urban scenario.

1.2.2 Indoor data bases

Indoor data bases are 3D and include all walls, doors, windows and possibly furniture. All elements inside the building are described in terms of plane elements. Every

wall is e.g. represented by a plane and its extent and location is defined by its corners (see Fig. 3). Additionally, for each element individual material properties can be taken into account. With respect to an efficient use it is also possible to import dxf-files, a very common data format in architecture.

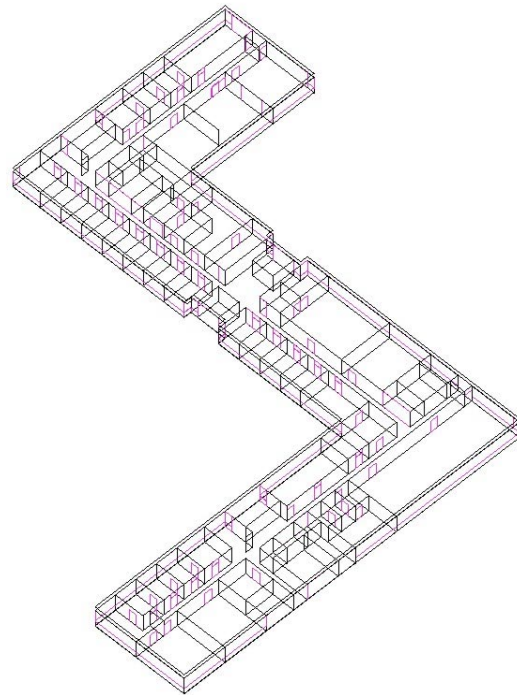


Figure 3: 3D vector data base describing an indoor scenario.

2 WAVE PROPAGATION MODELS

While other wireless communication networks, like e.g. directive radio links, operate under line-of-sight (LOS) conditions and can use a simple free space propagation model, mobile communication, as outlined above, is generally non-line-of-sight (NLOS) and requires more sophisticated approaches.

Most of the widely employed methods for the prediction of field strength in different scenarios are based on empirical equations. Consequently these models offer short computation times but on the other hand less accuracy in comparison to deterministic approaches [3].

2.1 EMPIRICAL MODELS

2.1.1 Urban scenario

An well-known example of an empirical approach which is particularly suited for urban radio cells is the Walfisch-Ikegami or COST-231 model [4]. The basic idea is that in street canyons of densely populated areas the principal wave propagation to the receiving antenna will be due to multiple diffractions over the roof tops of the

buildings between transmitter and receiver. For computation of the diffraction the buildings are replaced by semi-planes. Empirical corrections are used e.g. for different heights of the transmitting antenna with relation to the roof tops. This model considers only the propagation in a vertical plane which contains transmitter and receiver. For the field strength prediction significant parameters have to be extracted from this vertical section (e.g. average building height). Finally equations containing these parameters have to be optimised and fitted to numerous measurements in order to get a prediction model which is applicable in different propagation environments. The advantage of this empirical model is the short computation time. However, the prediction accuracy is limited due to the fact that the assumption of a dominant propagation over the roof tops is only valid if the transmitter is located above the roof tops of the surrounding buildings. In a typical micro-cellular scenario with transmitter heights below roof top level this approach is not suitable, because wave guiding effects in street canyons are dominating which cannot be considered.

2.1.2 Indoor scenario

Concerning the propagation within buildings there are also different empirical models available. The model of Motley-Keenan and the more detailed Multi-Wall-Model [4] 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. Different types of buildings (modern office buildings, libraries, hotels ...) are characterized by different values for the common transmission losses of the 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 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. The equation for the path loss calculation can be calibrated based on measurement results by evaluating a multiple linear regression technique.

It is important to notice that the loss factors do not represent physical wall losses but model coefficients which are optimised by the measured path loss data. Consequently, the loss factors implicitly include the effect of furniture. However, hard partitions like concrete walls are over-emphasized which leads to pessimistic values of predicted field strength behind these elements. Additionally, wave guiding effects and other contributions out of the direct path are not taken into account within this model, thus the accuracy is moderate. Nevertheless, the Multi-Wall-Model has a low dependency on the database accu-

racy and because of the simple approach a very short computation time (in the order of seconds).

2.2 DETERMINISTIC MODELS

Deterministic propagation models are generally based on ray optical techniques. Their common idea is to describe wave propagation by different rays that travel from the transmitting to the receiving antenna and are subject to reflection, scattering and diffraction at walls and edges of buildings, walls, and similar obstacles.

The computations are performed with help of the Uniform Geometrical Theory of Diffraction (UTD). The most time-consuming part of a field-prediction based on this method is finding all the relevant paths from transmitter to receiver.

For this purpose either the ray tracing or the ray launching algorithm is used (as indicated in Fig. 4). 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 angular increment. However, with ray launching several problems occur, such as “ray-multiplication” as a result of diffraction cones and decreasing resolution with growing distance from the transmitter.

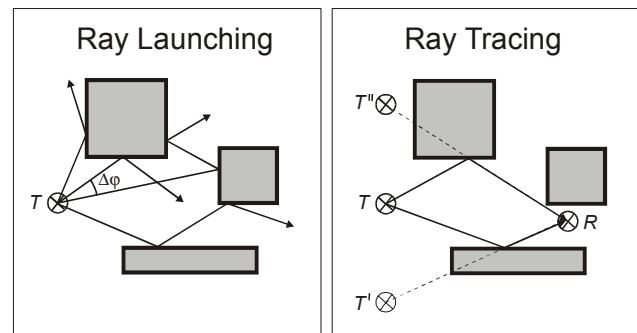


Figure 4: Algorithms for path finding.

While empirical models [4] assume straight propagation from transmitter to receiver, regardless of any obstacles such as buildings or walls, deterministic models consider the physical paths along which the transmitted waves propagate.

As a consequence, deterministic models cope with effects such as wave guiding in street canyons, offer excellent accuracy and are able to provide additional parameters such as small-scale fading or delay spread. Their main disadvantage consists in their sometimes prohibitively large computation time.

2.3 ADVANCED RAY-OPTICAL MODEL BASED ON DATA BASE PREPROCESSING

The main disadvantage of the deterministic prediction models is their excessive computation time (in the order of hours). Different authors presented ideas to accelerate the path finding and some of them lead to considerable acceleration factors [5,6]. However, these approaches consider only the propagation in two dimensions or in two perpendicular planes (horizontal and vertical plane). In contrast to this our approach is rigorously three dimensional.

One of the major applications of propagation models is to evaluate the degree of coverage that can be achieved in a radio cell depending on the position of the base station. As the data base of the considered building remains the same and only the position of the transmitter changes, the overwhelming part of the different rays remains unchanged, only the rays between the transmitting antenna and primary obstacles or receiving points in line-of-sight change [7].

This is the basis for a “Data Base Preprocessing”. In a first step the walls of the building (or other obstacles) are divided into tiles (reflections and penetrations) and the edges (diffractions) into horizontal and vertical segments. Additionally, the prediction grid is subdivided into receiving points.

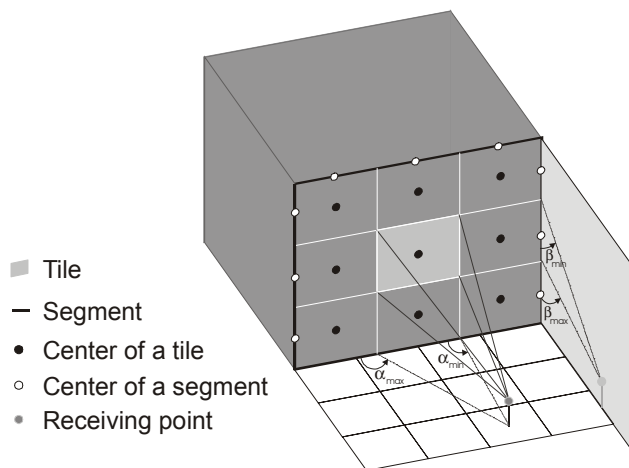


Figure 5: Tiles and segments of a wall.

After this, the visibility conditions between these different elements (possible rays) are determined and stored in a file (as indicated in Fig. 5). The visibility relations between all tiles, segments and receiving points in the database are computed in this preprocessing, because they are independent of the transmitter location. For this purpose all elements are represented by their centres, which leads to the discretization of the problem of path finding (see Fig. 5).

If there is e.g. line of sight between a tile and a receiving point (see Fig. 5), the four connecting straight lines from the receiving point to the corners of the tile are considered. By projecting these four lines into two perpendicular planes, four angles are determined which give an adequate description of the visibility relation. Similar computations for the visibility relations between tiles and tiles, tiles and segments, segments and segments and between segments and receiving points are performed in the following steps and are also stored in a file.

The projection of the connecting straight lines is very important, because by this operation a range of possible penetration/reflection (or diffraction) angles for the illuminated tile (or segment) is defined. Also the angles continue on the neighbouring tile respectively segment, so a very accurate computation of the rays is possible.

The result of this preprocessing can be represented in the shape of a “visibility tree” (see Fig. 6). Each branch of this tree represents a visibility relation between two different elements. For a different transmitter location only the uppermost branches in this tree must be computed again, i.e. determining which elements are in line-of-sight to the transmitter. Consequently all other relations have to be computed only once, which can be done prior to optimising the location of the transmitter.

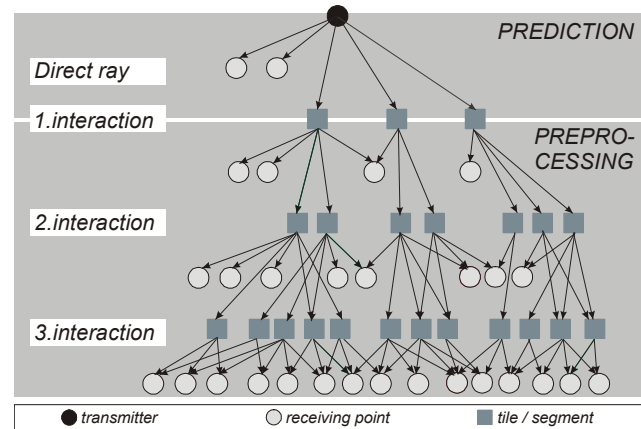


Figure 6: Resulting tree structure of the visibility relations.

With such a tree structure path finding can be done similar to the ray launching algorithm by recursively processing all visible elements and checking if the specific conditions for reflection and diffraction are fulfilled. The ray search is stopped, if a receiving point or a given maximum number of interactions is reached.

This new approach can be utilized in the same way for urban as well as for indoor scenarios. The only difference is that for the propagation modelling within buildings additionally the penetration of tiles is considered. This phenomenon is neglected within urban environments according to the high penetration losses at the outer walls of a building.

3 MEASUREMENTS

For the verification of the model in urban environments different measurements provided by network operators have been taken into account. In order to characterize the mobile radio channel inside buildings and to verify the propagation model several measurement campaigns with different transmitter locations have been carried out at the building presented in Fig. 3.

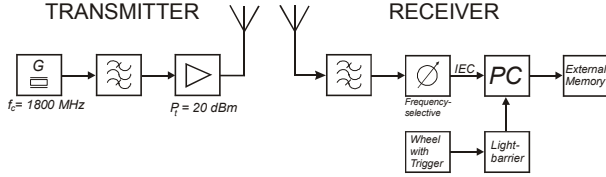


Figure 7: Equipment for CW-measurements.

For the determination of the field strength the simple measurement equipment shown in Fig. 7 has been used. A CW-signal is generated and transmitted with a quarter wavelength monopole. The receiver (containing another $\lambda/4$ -monopole and a spectrum analyser) is mounted on a trolley, which can be moved inside the building. The distance between the measurement points is always 0.8λ . In order to eliminate the fast fading for each measurement point the median value of the field strength is computed with an interval of 15 instantaneous values, corresponding to a distance of 12λ . Fig. 8 shows the median values of the field strength for transmitter Tx 1 with 0.1 W operating at 1800 MHz.



Figure 8: Measured field strength for transmitter Tx 1.

Additionally, a high resolution channel sounder was developed and used for the determination of the channel impulse responses within buildings. A pseudo random binary sequence (PRBS) is generated in the transmitter unit and modulated with a sinusoidal carrier. The principle of the transmitter is shown in Fig. 9. For the measurements presented in this paper a bit rate of 220 MBit/s was cho-

sen, which leads to a resolution of 4.45 ns in the time domain [9].

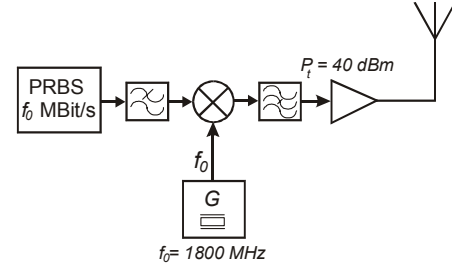


Figure 9: Transmitter of the channel sounder.

The received signal is converted to the base band with a two-step demodulator and split into I and Q parts (see Fig. 10). A sliding correlation technique based on the principle of Cox [10] is used for the determination of the channel impulse response. Further information about the measurement equipment and the performance of the channel sounder is given in [11].

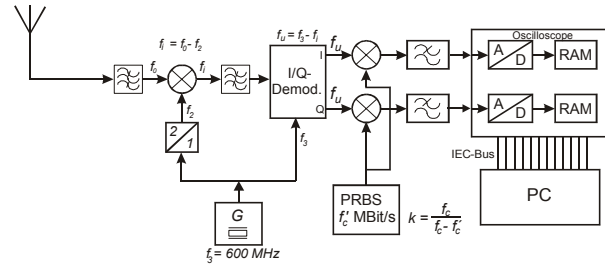


Figure 10: Receiver of the channel sounder.

Figures 11 and 12 show two measured impulse responses for line of sight (LOS) and no line of sight (NLOS). Many thousands of impulse responses were measured with different transmitter and receiver positions in different scenarios.

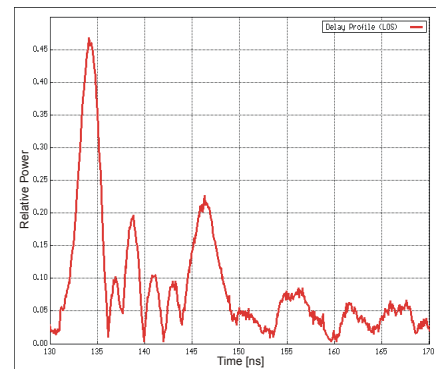


Figure 11: Measured impulse response (LOS).

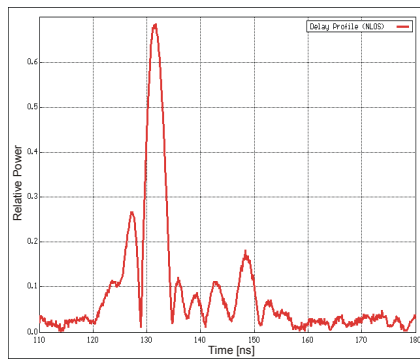


Figure 12: Measured impulse response (NLOS).

The delay spread of each impulse response was computed and Fig. 13 shows the measured delay spread for the indicated transmitter location Tx 2.



Figure 13: Measured Delay Spread for Tx 2.

4 VERIFICATION OF THE NEW MODEL WITH MEASUREMENTS

The performance when utilizing this advanced ray-optical method for the wave propagation modelling within urban and indoor scenarios is shown in the following.

4.1 URBAN SCENARIO

Concerning the wave propagation modelling in urban environments two different scenarios have been investigated. Table 1 indicates the memory requirements and computation times for these two urban scenarios. The given values depend on the size of the database (number of buildings, size of considered area) as well as on the resolution for the discretization of the database. They are gained with a maximum of three interactions (all combinations of reflections and diffractions with max. number of two diffractions), while the resolution of the prediction has been chosen to 10 m.

Table 1: Performance of the advanced ray-optical method within urban environments.

Database	Stuttgart	Munich
No. of buildings	303	2040
Area	5,0 km ²	8,2 km ²
Preprocessing time	19 min	258 min
Preprocessing file	18 MB	75 MB
Prediction time	85 s	237 s

In order to analyse the performance of the advanced ray-optical method measurements in both scenarios have been evaluated. To show the accuracy of the new model within urban environments, the well-known scenario in Munich (Germany) is utilized [4].

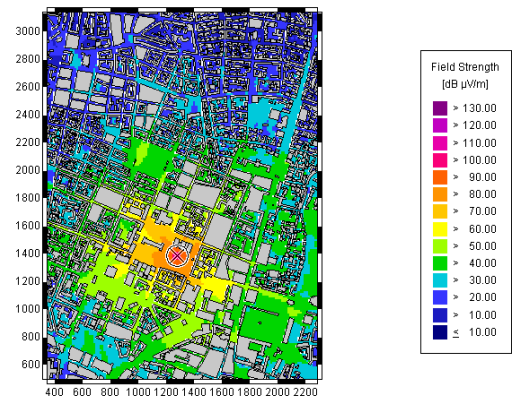


Figure 14: Prediction for the scenario in Munich (frequency 900 MHz).

Fig. 14 presents the prediction for a GSM transmitter (900 MHz) and Fig. 15 shows the difference between the prediction and the measurements for the same scenario. Table 2 presents the statistical values for the comparisons between predictions and measurements for three different routes, which have been provided by [4].

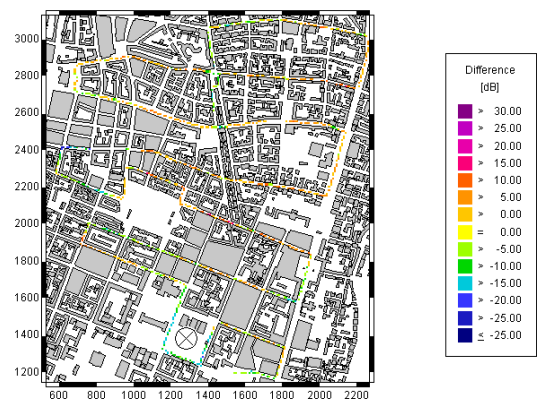


Figure 15: Comparison between prediction and measurements.

Table 2: Accuracy of the advanced ray-optical method for predictions of field strength in an urban scenario.

Scenario Munich	Mean	Std. Deviation
METRO 200	0.6 dB	6.7 dB
METRO 201	-0.2 dB	7.2 dB
METRO 202	-0.8 dB	7.0 dB

4.2 INDOOR SCENARIO

In contrast to the urban model, the indoor model includes also the penetration of walls. But with this exception the same algorithms can be used for urban and indoor modelling.

Measurements of field strength and delay spread with the above introduced equipment have been evaluated in order to verify the accuracy of the new approach for the prediction of the mobile radio channel inside buildings.

The building taken into account for the verification has already been presented in Fig. 3 and is a modern type of office building with floor and ceiling made out of reinforced concrete. The outer walls are made out of plastic and cement asbestos respectively with large windows, while the inner walls are mostly wooden. Only around the elevators also reinforced concrete is used.

Table 3: Preprocessing time, size of the preprocessed file and prediction time for the building shown in figure 2

resolution for the discretization	preprocessing time	size of the preprocessed file	prediction time
1 m	7212 s	51.6 MB	110 s
1.5 m	1835 s	24.9 MB	100 s
2 m	1095 s	12.2 MB	67 s
2.5 m	680 s	7.3 MB	16 s
3 m	457 s	3.2 MB	1 s

Table 3 presents the dependencies of the preprocessing time, size of the preprocessing file and the prediction time for different resolution values used for the discretization of the building database shown in Fig. 3, i.e. extension of the tiles and segments while the resolution of the receiving points remains constant at 1 m. An exponential increase of memory requirement and computation time can be observed when reducing the extension of the tiles and segments.

4.2.1 Field strength

Fig. 16 shows a field strength prediction with the new approach after preprocessing of the building database. This prediction indicates a typical behaviour of a ray optical modelling including wave guiding along the corridor.

The difference between prediction and measurement for transmitter location Tx 2 is presented in Fig. 17.

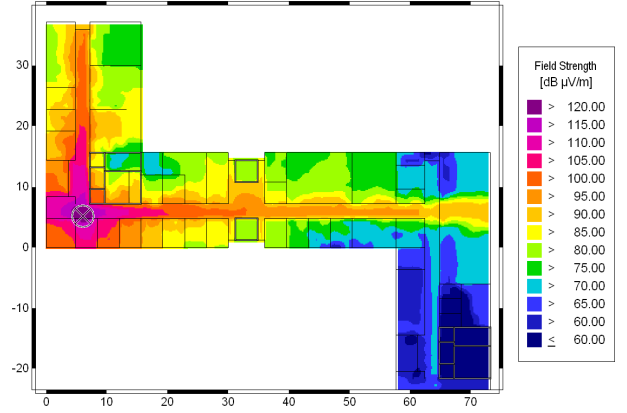


Figure 16: Prediction for the indoor scenario for Tx 1 (frequency 1800 MHz).

In order to minimize the mean error and the standard deviation ray paths with up to five interactions (reflections, diffractions and transmissions) are considered if the transmitter is located in the corridor. For transmitter locations inside rooms seven interactions are necessary. Table 4 shows the statistical values of the comparisons between predictions and measurements for different transmitter locations. While the locations Tx 2 and Tx 3 (located at 51.2, 15.1) are inside a room, Tx 1 and Tx 4 (located at 63.8, 5.8) have been installed in the corridor.

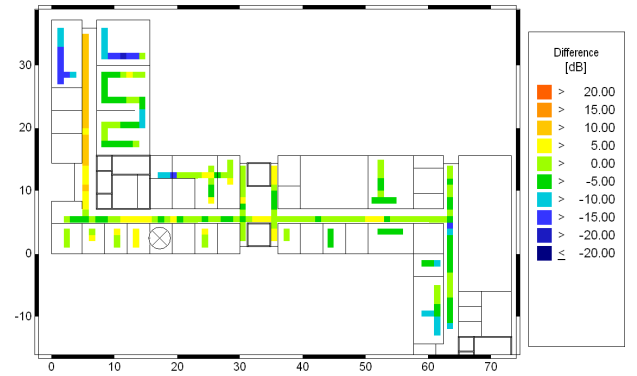


Figure 17: Comparison between prediction and measurements for Tx 2 (frequency 1800 MHz).

While for the predictions taken into account in this paper a resolution of 1.5 m for the discretization of the building database has been selected it is possible to increase this resolution to some extent without losing accuracy. As confirmed by measurements from other buildings, the mean error is generally in the range between 0

and 3 dB, while for the standard deviation values around 5-7 dB are reached.

Table 4: Accuracy of the advanced ray-optical method for predictions of field strength in an indoor scenario.

Scenario: Modern Office	Mean Value	Standard Deviation
Tx 1	0.6 dB	5.2 dB
Tx 2	1.0 dB	5.9 dB
Tx 3	-0.2 dB	6.1 dB
Tx 4	2.8 dB	5.7 dB

4.2.2 Delay Spread

With the new propagation model it is also possible to predict the delay spread. Because of the ray optical approach all waves impinging on the receiver are calculated separately (up to a maximum number of interactions). In comparison to existing ray optical methods more interactions can be considered, which improves the accuracy of the delay spread predictions. With the same settings as for the field strength predictions (i.e. five interactions for transmitters located in corridors and seven interactions for transmitters inside rooms) the statistical values presented in Table 5 have been achieved.

Table 5: Accuracy of the advanced ray-optical method for predictions of delay spread in an indoor scenario.

Scenario: Modern Office	Mean Value	Standard Deviation
Tx 1	1.5 ns	7.5 ns
Tx 2	0.3 ns	8.2 ns
Tx 3	2.0 ns	8.5 ns

5 CONCLUSIONS

In this paper an advanced ray-optical propagation model for the prediction of the mobile radio channel in urban environments as well as inside buildings is presented. The new approach is based on a single preprocessing of the database in which the mutual visibility relations between the walls and the edges of the buildings are determined. For the verification of the model measurements of field strength and delay spread in both urban and indoor scenarios were taken into account. Evaluations of the simulation results show the gain in computation efficiency as well as in achieved prediction accuracy.

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