Dominant Path Prediction Model for Urban Scenarios

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***Abstract*—Currently, for the planning of wireless cellular networks in urban scenarios either empirical (direct ray or over rooftop ray) or ray-optical (ray tracing) propagation models are used. In this paper both approaches are compared to one another and to measurements in different urban city centers. Additionally a new concept - which is called Dominant Path Model (DPM) - is presented in this paper. This new concept does not focus only on the direct ray (like empirical models) and it does not consider hundreds of rays for a single pixel (like ray tracing), but it focuses on the dominant path(s) between transmitter and receiver. The parameters of these dominant paths are determined and used for the prediction of the path loss between transmitter and receiver. Thus the computational effort is far below ray tracing and in the range of empirical models. But the accuracy of the new model in very complex environments (with high shadowing of the direct ray) is even higher than the accuracy of ray tracing models (because of their limitations in the number of interactions). This very high accuracy is shown with the comparison to measurements in several international cities.**

Keywords—wave propagation, urban, ray tracing, dominant paths, measurements

I. INTRODUCTION

The planning of wireless communication networks in urban scenarios is based on accurate propagation models for the prediction of the path loss between fixed base station antennas and mobile terminals. Many different approaches have been investigated during the last years to obtain accurate and fast propagation models. Today either statistical/empirical models or ray-optical models are used [4]. For the ray-optical models significant accelerations based on a single preprocessing of the building data are available and lead to computation times in the range of empirical models [1].

Today vector databases of cities or buildings are available and can be used without any restrictions. These databases provide a high accuracy – but small errors in the material definitions or in the coordinates of single corners lead to significant errors if ray-optical propagation models are used. So there is a demand for models which are fast and do consider multiple interactions (e.g. diffractions) – but which do not rely on each detail of the vector database. In this paper such an approach is presented and compared to empirical and ray-optical propagation models as well as to measurements.

II. DOMINANT PATH MODEL

A. Current status

The left picture in fig. 1 shows the problem of empirical propagation models. They are based on the direct ray between transmitter and receiver [4]. In urban scenarios this ray passes over the rooftops and is not always dominant as it is highly attenuated. Focusing a model on this path must lead to errors in scenarios where over-rooftop propagation is contributing only a very small part to the total received signal power.

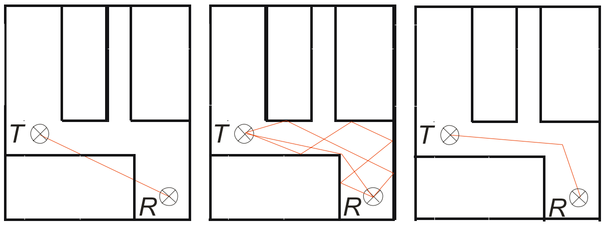

Figure 1. Empirical models use only the direct path (left), Ray Tracing computes many paths (center) and the Dominant Path Model determines only the most relevant (right)

In the center part of fig. 1 the principle of ray-optical propagation models is shown. Up to hundreds of rays are computed for each receiver [2]. The contributions of all rays are superposed to obtain the received power. In most cases only 2 or 3 rays are contributing more than 95% of the energy, i.e. by focusing on these dominant rays the accuracy (of the logarithmically superposed contributions) would be sufficient.

A second disadvantage of ray-optical models is their high dependency on small inaccuracies in the databases. As angular criteria are evaluated during the ray-optical prediction, the orientation of walls is extremely important. Unfortunately databases with this very high accuracy are not available for most applications.

In addition to the two disadvantages mentioned above, another problem of ray-optical models arises: Either the computation time is very long or, if a preprocessing is done, the computation time for the preprocessing is high [1]. During the preprocessing the database is divided into tiles and segments and the visibility between these tiles and segments is determined. As databases consist of a large number of tiles and segments, this process can take a considerable amount of time – from some hours up to several days for very large scenarios.

B. Requirements for a new model

After analyzing the status of the models currently available, the requirements for a new model can be defined:

- Model should not depend on each micro-detail in the vector database.
- Focusing on the dominant paths and not computing hundreds of paths with small contributions (see fig. 1).
- Simple calibration possible with reference data (e.g. measurements).
- The computation time required for the preprocessing of the database has to be short.

With these requirements the Dominant Path Model (DPM) was defined [6]. The Dominant Path Model deals with urban and indoor scenarios, as well as with rural areas. In this paper the focus is on urban scenarios – so the model is called **U**rban **D**ominant **P**ath Model (UDP).

C. The algorithm of the Dominant Path Model

A detailed description of the algorithm can be found in [5] and [9]. The prediction of the path loss at a receiver location can be subdivided into the following two steps.

Step 1: Determination of the dominant paths

In the first step, the dominant paths are determined. Fig. 2 shows a scenario where the transmitter *T* is located in a street. The information about the arrangement of the buildings is used to determine the types of corners.

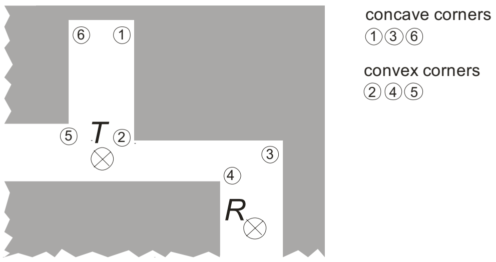

Figure 2. Scenario with buildings (gray), transmitter (T), receiver (R) and different types of corners

The dominant path from *T* to *R* must lead via convex corners to the receiver. For the determination of the path, a tree with all convex corners is computed. All corners visible from the examined corner are new branches in the tree. As shown in fig. 3, the corner-tree starts with the corners visible from the transmitter *T*. The receiver *R* is also included in the tree. Each time the receiver is found in the tree, the corners along the path can be determined by following the branches back to the transmitter *T*.

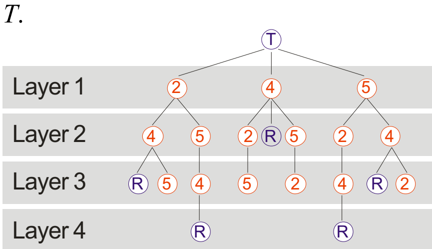

Figure 3. Tree structure of the scenario from fig. 2

Fig. 3 shows that more than one path between transmitter *T* and receiver *R* exists. After computation of the tree, the algorithm has to decide which path is the best one. This is done by comparing the path losses of the different paths to each other, see step 2.

Step 2: Prediction of the path loss along a path

The prediction of the path loss along a propagation path is used to decide which path is the best one. This is done with the following equation:

$$L = 20 \cdot \log\left(\frac{4\pi}{\lambda / m}\right) + 20 \cdot p \cdot \log\left(d / m\right) + \sum_{i=0}^{n} \alpha(\varphi, i) - \frac{1}{c}\sum_{k=0}^{c} w_k$$

L is the path loss in dB of a path with a length of *d*. λ is the wavelength. The factor *p* depends on the visibility state between the current pixel and the transmitter. Adapting *p* to the current situation (LOS and NLOS areas) with different path loss exponents can be considered as well as individual breakpoints for these two states. In fig. 4 (left) different visibility areas are displayed.

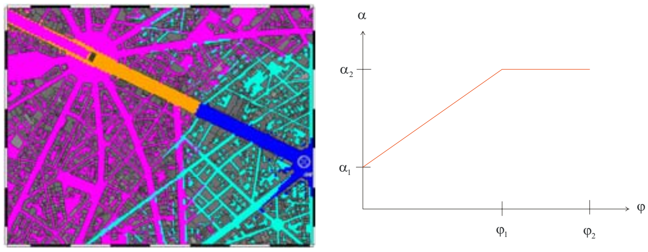

Figure 4. *Left:* Urban scenario with different visibility areas: ***LOS***, *NLOS*, ***LOS after the breakpoint*** and ***NLOS after the breakpoint***. *Right*: Function $\alpha(\varphi,\iota)$ which delivers the interaction loss

$\alpha(\varphi,\iota)$ is a function (see fig.4, right) which determines the loss in dB due to an interaction, i.e. changing the direction of propagation. The angle between the former direction and the new direction of propagation is φ_i. The loss increases linearly with the angle, starting with an offset α_1. The linearity ends at angle φ_1 and the loss will be constant at α_2 for the remaining angles larger than φ_1. *i* is the number of the interaction, i. e. *i=2* means the second interaction on this propagation path. For example $\alpha(\varphi,1) > \alpha(\varphi,2) > \ldots > \alpha(\varphi,n)$ would emphasize the first interactions compared to the latter. And this is reasonable because the more interactions the less planar the wave will be (more diffuse waves allow multiple options for interactions and the total loss is not that high). The algorithm can distinguish between horizontal and vertical interactions by weighting them differently.

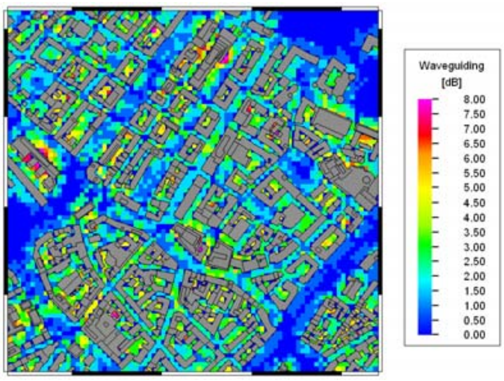

Figure 5. Gain due to waveguiding in an urban scenario

The parameter w_k is called waveguiding factor. It is explained in detail in [6]. The reflection loss of the walls along the path as well as their distance to the path influence the value. The smaller the reflection loss and the closer the wall to the path, the higher the waveguiding factor. The gain by waveguiding is determined for each pixel before the prediction starts. During the prediction this gain is accumulated along the propagation path. Fig. 5 shows an example for the gain due to waveguiding in the streets of a typical urban scenario.

The model could be improved with more details to increase the accuracy. But this would slow down computation speed and if an automatic calibration (e.g. linear regression) of the parameters (p, $\alpha(\varphi,\iota)$, w_k) is requested, the dependency should not be too complex – otherwise the automatic calibration will not work successfully.

Moreover, it is possible to determine more than only one propagation path. If the parameters in the equation above are weighted in different ways for each run with the prediction model, then each result consists of individual dominant paths.

As already stated in section I, the building databases available today have a limited accuracy. For wave propagation modeling in urban scenarios, the databases usually have limited

3 D information, i.e. for each building a polygonal cylinder and the uniform height of the cylinder are defined (see fig. 6). Therefore, the shape of the roof can not be considered in the modeling approach, which can have an impact especially if over-rooftop propagation is dominant.

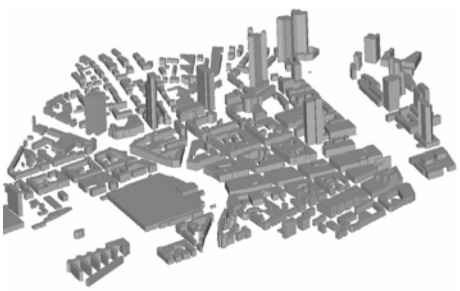

Figure 6. 3D building database of a part of downtown Frankfurt

This may be the case in scenarios with antenna locations above the mean building height. In this case the Urban Dominant Path Model offers advantages as it is less sensitive to the inaccuracies that are caused by the simplification of the diffractions at the roofs.

Especially in scenarios where the transmitter is located below the mean building height, waveguiding effects are more dominant for the propagation. This is impressively demonstrated in fig 7. For a transmitter (omni antenna, transmit power 10 W, frequency 947 MHz) located below rooftop level (antenna height 15 m, mean rooftop level 38 m), the results of the vertical plane based COST 231 Walfisch-Ikegami model (COST), a 3D Ray Tracing Model (here: IRT [7]) and the Urban Dominant Path Model (UPD) model are shown. The COST 231 model is too pessimistic in most parts of the scenario as there is a building obstructing the direct ray near the transmitter. The dominant effects of the diffractions at this building as well as the reflections are responsible for the waveguiding effects in streets– which are not considered.

These effects are very well considered by the IRT model, however far away from the transmitter, especially in the north-western part of the prediction area, the results are too pessimistic as the number of interactions (max. 6 in this prediction) limits the accuracy of the model, as obviously the rays that were found are not the ones which carry the main part of the energy. The Urban Dominant Path Model result does not show these disadvantages. The whole scenario shows comprehensive results.

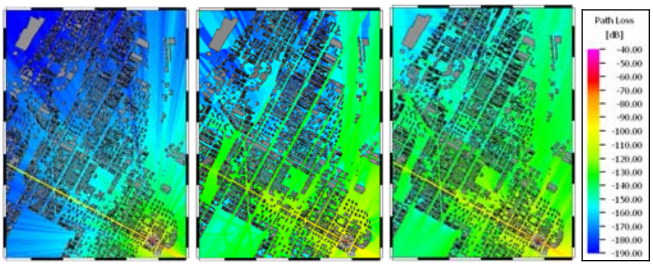

Figure 7. Prediction of path loss (COST 231 W.-I., IRT and UDP) with a transmitter below rooftop level

In general, the topography of urban scenarios must also be taken into account, as it influences the visibility between interaction points examined during the computation.

Fig. 8 shows a prediction of a part of a city with a hilly topography in the downtown area. UDP was used for the prediction. The area in the upper right part shows lower received power values due to the shadowing effect of the topography. If the topography would not be considered a too optimistic prediction in this area would occur.

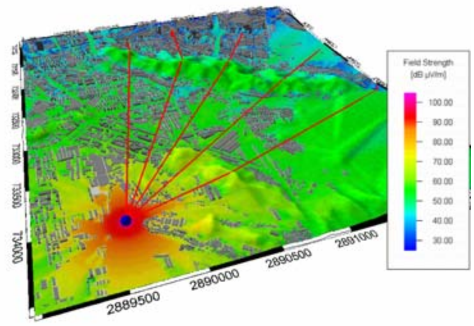

Figure 8. Prediction of field strength in a city with hills – five dominant propagation paths are marked (omni antenna, 10 W, 947 MHz)

Both the IRT Ray Tracing Model and the Urban Dominant Path Model allow the consideration of the topography while the Walfisch Ikegami model is not able to consider topography.

III. Sample Predictions

To demonstrate the performance of UDP and to show that it can handle extremely large scenarios, several computations were accomplished. As only a very simple and fast preprocessing is required for UDP, the treatment of large scenarios is easily possible. The only limiting factor is the RAM of the computation system. If not enough RAM (< 512 MB) is available, the operating system has to swap out memory to the hard disc which slows down the computation speed.

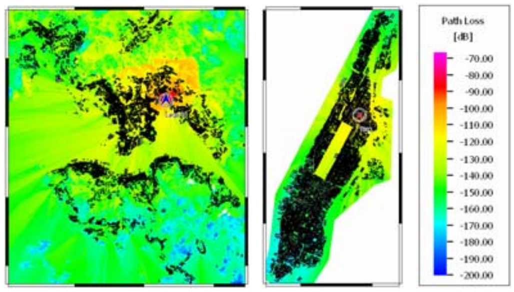

Figure 9. Predictions of path loss in Hongkong (334 km², left) and Manhattan (80 km², right) computed with UDP (f=948 MHz, omni antenna)

TABLE I. Statistical data of computations

Scenario	Area	Buildings	Pixels	Comp. Time
Alexandria (Egypt)	66 km²	21,834	660,000	35 min
Manhattan (USA)	80 km²	15,759	800,000	40 min
Shenzhen (China)	143 km²	33,326	1,400,000	1 hour
Hongkong (China)	334 km²	22,036	1,484,000	1 hour, 15 min

The computations were accomplished on an ordinary PC with an AMD™ Athlon™ 2800+ CPU and 1 GB of RAM. The results are shown in fig. 9 and listed in table I.

A comparison with Ray Tracing for these scenarios is not possible, because – as mentioned above – Ray Tracing needs a preprocessing of urban databases [1]. Preprocessing of such extremely large databases is currently not possible, because of the hardware limitations of the PC. Thus UDP is the only highly accurate model for such large areas [3].

IV. Benchmarks

A. COST 231 Benchmark in Munich

Several urban microcell prediction models have been developed and reviewed in COST 231 [4]. To verify and compare these models in a semi-blind test, vector-building data of downtown Munich (Germany) and three different measurement routes have been supplied by the German GSM network operator Mannesmann Mobilfunk GmbH [4].

Figure 10. Downtown Munich scenario (3D View)

Table II shows some details of the scenario, fig 10 shows a 3D view of the scenario. In fig. 11 (left) the prediction result with UDP is given. Fig. 11 (right) shows the difference between prediction and measurement route 0.

TABLE II. Scenario description for downtown Munich

Scenario	*Area*	1.9 x 2.8 km = 5.4 km^2
	Number of buildings	2032
	Resolution of prediction	10 m
Transmitter	*Frequency*	947 MHz
	Antenna type	omni

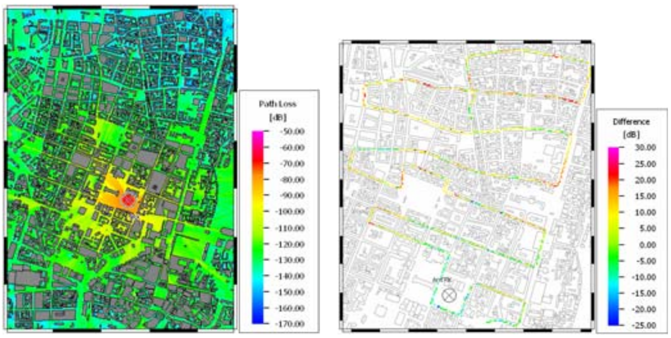

Figure 11. *Left:* Prediction of path loss with UDP
Right: Difference to measurement route 0

TABLE III. Evaluation of the UDP prediction

Route	**Urban Dominant Path**			
	Computation Time (AMD™ Athlon™ 2800+))		**Difference** (Predictions – Measurements)	
	Preprocess.	***Prediction***	***Mean value***	***Std. Dev.***
0	some seconds	36 s	5.04 dB	7.16 dB
1			3.75 dB	6.41 dB
2			2.77 dB	7.99 dB

In [4] several prediction models (pure empirical as well as ray-optical) were compared to the 3 measurement routes. Their standard deviations (between prediction and measurements) were between 6.9 dB and 16.1 dB. Table III shows the results of UDP. The high accuracy of UDP must be seen together with the very short computation time (see also table III) which cannot be achieved with ray-optical prediction models.

B. Benchmark in Helsinki

A measurement campaign with two transmitter locations (one of them in the 2 GHz band) was made in Helsinki [7] (transmitters close to or on top of buildings). Table IV shows some information about the scenario and the transmitters.

TABLE IV. Scenario description for Helsinki

Scenario	*Area*	1.9 x 1.7 km = 3.3 km^2
	Number of buildings	1651
	Resolution of prediction	5 m
Transmitters	*Frequency*	TRX 2: 0.9 GHz TRX 3: 2.1 GHz
	Antenna type	TRX 2: omni TRX 3: sector

The prediction of the path loss with UDP for TRX 3 and the probability density function for the difference between prediction and measurements for this site are shown in fig. 12.

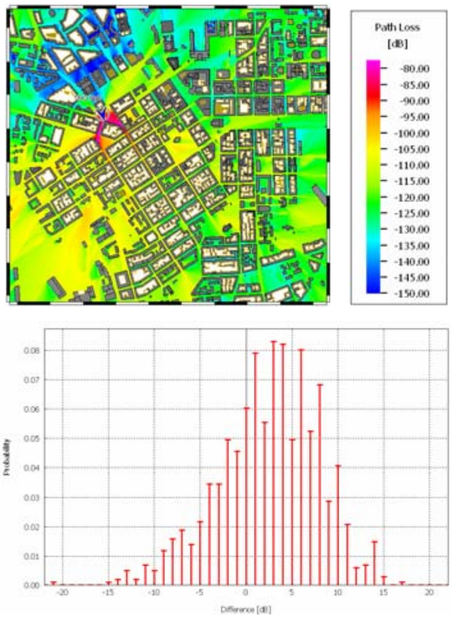

Figure 12. Prediction of path loss with UDP for TRX 3.
Probability density function for difference (TRX3)

The statistical evaluation for the predictions with Ray Tracing (3D IRT) [7] and UDP are shown in table V. The comparison of the computation times can be found in table VI. The accuracy of UDP exceeds the accuracy of Ray Tracing in this scenario.

TABLE V. Comparison to measurements

Site	**Difference (Predictions – Measurements)**			
	3D Ray Tracing (3D IRT)		**Urban Dominant Path**	
	Mean value	***Std. Dev.***	***Mean value***	***Std. Dev.***
2	-3.36 dB	7.09 dB	0.38 dB	5.86 dB
3	-3.60 dB	7.81 dB	2.49 dB	5.51 dB

TABLE VI. Comparison of computation times

Site	**Computation times** (PC with AMD™ Athlon™ 2800+ CPU and 1 GB RAM)			
	Intelligent Ray Tracing		**Urban Dominant Path**	
	Preprocess.	*Prediction*	*Preprocess.*	*Prediction*
2	3 hours, 17 min	20 s	some seconds	64 s
3		18 s		62 s

C. *Benchmark in Hong Kong*

Two routes measured in Hong Kong were also used for the evaluation of the UDP model. As shown in fig. 13 the terrain is very hilly in the prediction area. In table VII some information about this scenario is summarized.

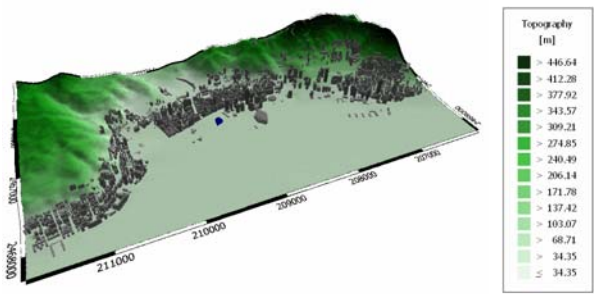

Figure 13. Database of Hong Kong (incl. topography)

TABLE VII. SCENARIO DESCRIPTION FOR HONG KONG

Scenario	*Area*	2.4 x 5.9 km = 14.3 km²
	Number of buildings	3306
	Resolution	10 m
Transmitters	*Frequency*	948 MHz
	Transmit power and antenna types	TRX1: 28.5 dBm, sector TRX2: 24.9 dBm, sector

Fig. 14 shows a prediction with UDP and the corresponding difference between prediction and measurement.

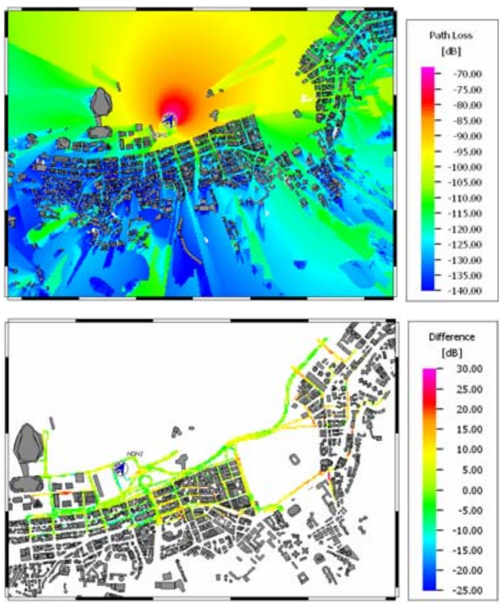

Figure 14. Prediction of path loss with UDP
Difference betwwen prediction and measurement

The statistical evaluation for the prediction models 3D IRT and UDP are shown in table VIII. Again, UDP exceeds the accuracy of ray tracing and is significantly faster (see table IX).

TABLE VIII. COMPARISON TO MEASUREMENTS

Site	**Difference (Predictions – Measurements)**			
	Intelligent Ray Tracing		**Urban Dominant Path**	
	Mean value	***Std. Dev.***	***Mean value***	***Std. Dev.***
1	9.21 dB	6.52 dB	3.14 dB	6.20 dB
2	6.85 dB	7.99 dB	0.03 dB	7.78 dB

TABLE IX. COMPARISON OF COMPUTATION TIMES

Site	**Computation times** (PC with AMD™ Athlon™ 2800+ CPU and 1 GB RAM)			
	Intelligent Ray Tracing		**Urban Dominant Path**	
	Preprocess.	*Prediction*	*Preprocess.*	*Prediction*
1	24 hours, 34 min	127 s	some seconds	20 s
2		80 s		39 s

D. *Further Comparisons*

Further measurement campaigns were carried out in several other cities (in Europe, North America and Asia). The 3D Ray Tracing (IRT) [7] and the Urban Dominant Path Model (UDP) were compared to those measurements. The results (published in [8]) are similar to the ones presented here.

V. CONCLUSIONS

A new approach for propagation modeling in urban scenarios based on 3D vector building databases incl. topography is presented in this paper. The approach is based on the fact that not all rays between transmitter and receiver contribute a similar part of the energy. Some paths are dominant and by determining only these dominant paths, the computation time is reduced without influencing the accuracy.

The new UDP Model is compared to measurements in different urban scenarios. In comparison to results obtained with 3D ray tracing models it is shown that the new propagation model exceeds the accuracy of ray tracing. The computation times are very short (similar to empirical models).

No complex preprocessing of the building data is required. Thus the new model is suitable for extremely large scenarios, where predictions with ray tracing models are still not possible.

As the new model computes multiple dominant ray paths, also wideband properties of the channels (channel impulse response, delay spread) could be computed with statistical channel models. This will be the object of further studies.

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