Deterministic Propagation Models for Radio Transmission into Buildings and Enclosed Spaces

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Abstract—**With the growing interest for broadband mobile services in 3rd generation mobile communication networks, the investigation of radio transmission into vehicles and buildings is getting more important. Models for the propagation into vehicles and buildings enable the calculation of the field strength or received power inside these objects. The inner structure of the vehicles (e.g. metal parts) and buildings (inner walls, furniture) as well as the surroundings (other vehicles, buildings) must be considered, and also different construction materials must be taken into account. A deterministic ray tracing approach has been developed, enabling the computation of the transition from an urban scenario to an indoor scenario and vice versa, thus allowing a very accurate computation of the field strength or received power inside vehicles or buildings. Due to the ray tracing technique, the approach can also be utilized to evaluate wideband properties of the mobile radio channel by computing its impulse response. In order to validate such propagation models, measurements inside and outside a building were made.**

I. Introduction

After the great success of wireless communications used in land mobile radio systems, the wireless communication inside vehicles and buildings becomes more and more important. Possible applications are e.g. in the area of wireless multimedia devices such as video terminals. The demand for the usage of such services in vehicles is expected to grow heavily.

The frequency range that will be available and suitable for wireless communications will be in a range where full wave approaches (e.g. by using the Method of Moments), like widely used in the automotive sector, cannot be used anymore due to their computational effort.

Ray optical propagation models are well known in the domain of indoor radio network planning [1], [2]. These models use 3D vector oriented databases to describe the buildings with their inner structure and different construction materials. An indoor propagation model was adapted, so that it is also applicable for the investigation of wave propagation inside vehicles [3], [4].

In the following section, the approach that allows to compute the transition from an urban scenario into an indoor scenario and vice versa is described.

The usage of MIMO techniques to support high data rate services will increase in the future. The described approach is also well suited for the characterization of MIMO channels, as this requires the computation of the wideband properties.

II. Description of the Approach

As the indoor propagation model allows the vector-oriented definition of an arbitrary number of objects with different materials, a vehicle or building can be modeled accurately (see figure 1). Materials with multiple layers can be considered by computing the individual transmission attenuations.

Ray optical propagation models are often used for the prediction of field strength or received power as well as the impulse response or delay spread in indoor and urban scenarios [1], [2]. Such models are very accurate because they consider waveguiding effects in street canyons (outdoor) or corridors (indoor) and consider diffraction effects at corners.

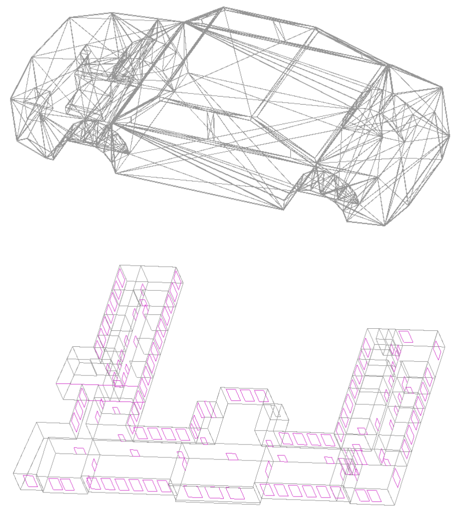

Fig. 1. Vector oriented database of a vehicle and a building

Ray optical models have a large computational demand, because all possible rays must be determined. An approach for the acceleration of such models reduces the computation time nearly to that of empirical models. This approach, which is based on a single preprocessing of the database, is used for both the urban and the indoor model.

All walls of a considered building (or surface elements of the vehicle) are subdivided into tiles and all wedges are subdivided into segments (see figure 2). The visibility relations between all tiles, segments and receiving points in the database are computed in a preprocessing, as they are independent of the transmitter location. All elements are represented by their centers. This approach leads to the discretization of the path finding problem [1].

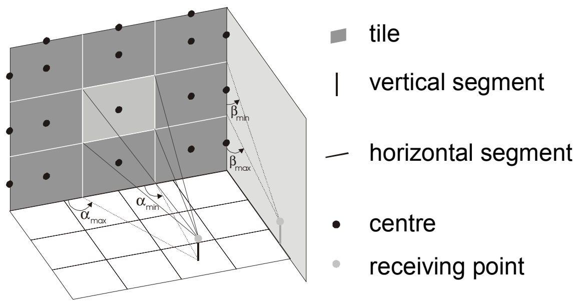

Fig. 2. Tiles and segments of a wall

Figure 3 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 at prediction time 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 scenario.

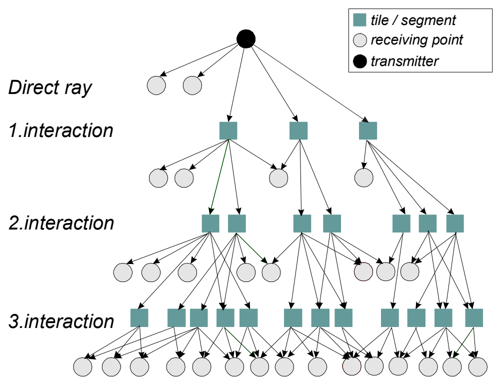

Fig. 3. Tree structure of the visibility relations

With such a tree structure, path finding can be done by recursively processing all visible elements and checking if the specific geometrical 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.

For transmission into an enclosed space this preprocessing can be done for the urban scenario, where it contains the description of the outer walls of all buildings, as well as for the enclosed space, where it contains the outer and inner walls of the object taken into account. The tiles at the walls surrounding the selected building define the interface between the two databases.

An adequate way to handle this interface between the propagation models for both scenarios is to use the angular power delay profile (APDP). The APDP includes the field strength values, the delay time and the angles of incidence of the electromagnetic waves impinging on the outer walls of the vehicle or building. By using this interface a prediction of the impulse response and delay spread of the radio channel is also possible.

The reason for the need for a transition between the two propagation models for urban and indoor scenarios (instead of using one ray tracing model) is explained in the following.

For the indoor or vehicle objects a smaller discretization has to be used than for an urban scenario. If the same discretization was used for the urban and indoor (or vehicle) objects, this would result in a need for memory that could not be handled with standard computers. The urban propagation model can be accelerated further by limiting the objects to horizontal and vertical elements. The indoor propagation model has to account for arbitrarily oriented elements - therefore the orientation has to be described by a normal vector. This emphasizes the need for a transition between the urban and the indoor model.

As border for the interface, a polygonal cylinder with horizontal base around the walls of the indoor database is automatically determined [5] which includes all indoor walls (see figure 4).

The material properties of the cylinder can be defined and are used to determine the reflection and diffraction losses in the urban propagation model. The urban propagation model considers only the walls of the cylinder, while the indoor propagation model considers only the walls (objects) inside the cylinder. The cylinder is transparent for the indoor models (rays are passing the cylinder without any attenuation) and the cylinder is not considered (for reflection or diffraction) during the computation of the indoor prediction.

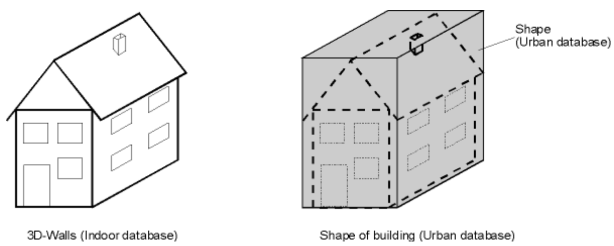

Fig. 4. Vector oriented database of a building

The cylinder itself represents the interface between the urban and the indoor models: All rays reaching the cylinder are passed between the different propagation models (from urban to indoor and vice versa). This can be done multiple times during a propagation run (rays penetrating the building and leaving it again).

Scenarios with vehicles are handled the same way, except that the dimension of the tiles and segments for the vehicle database is chosen differently. Usually, for building databases in indoor scenarios a tile and segment size in the range of 1 to 3 meters is used, whereas in vehicle scenarios values in the range of 0.1 to 0.5 meters are chosen.

III. MEASUREMENTS

In order to validate the approach described above, a measurement campaign using CW signals was performed. In order to especially assess the building penetration effects, a measurement setup was chosen that allows to gain measurements both in the close outer area of the building as well as indoors. One building on the university campus was very well suited for this task because of its surrounding balcony (see figure 5). Details of the measurement setup are available in [6].

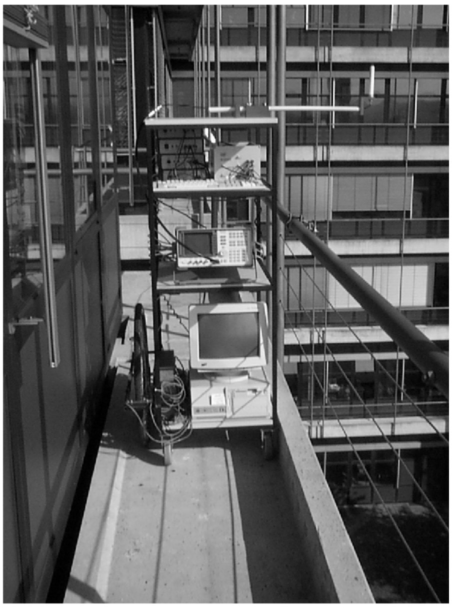

Fig. 5. Measurement setup

The measurements were performed using a spectrum analyzer mounted on a trolley and controlled by a PC. The transmitter was located outside a neighboring building (see section IV). The used frequency was 1500 MHz. Quarter wave monopoles were used for both the transmitter and the receiver.

In order to eliminate the impact of fast fading to the results, the median value of the field strength was computed over a certain interval for each measurement point [7].

IV. RESULTS

A. *Penetration by a Cellular Base Station or a WLAN Access Point into a Building*

The left side of figure 6 shows an example of a university campus where a WLAN access point has been mounted outside a building to cover a part of the campus. The left part of the figure shows the received power as well as the computed rays for one receiver point. The right part shows the computed channel impulse response for that receiver point.

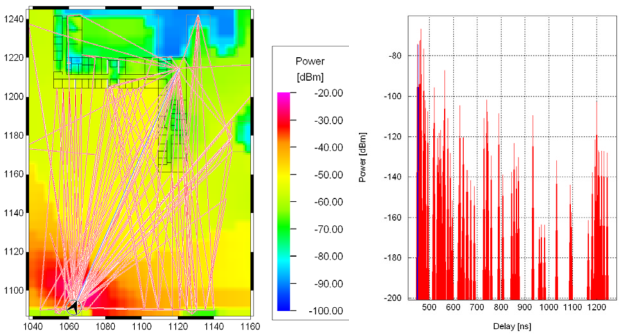

Fig. 6. Received Power and impulse response

B. *Comparison to Measurements*

Figure 7 shows a scenario with two transmitters. The building where the measurements were performed is marked. Both transmitter sites were used separately, the field of both was **not** superposed.

Figure 8 shows the result of the prediction of the field strength of transmitter 1 using the ray tracing model with the transition from the urban to the indoor scenario. In figure 9, the corresponding results of the measurement campaign are shown.

Figure 10 shows the difference of the measurement values subtracted from the prediction values for transmitter 1. A statistical evaluation (also including the results for transmitter 2) is shown in table 1.

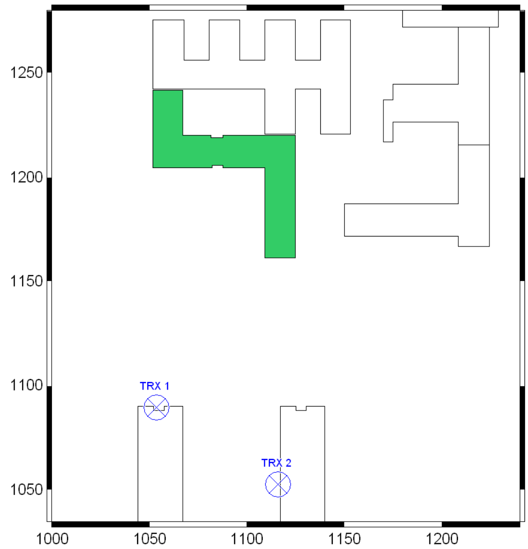

Fig. 7. Scenario with location of the two transmitter sites

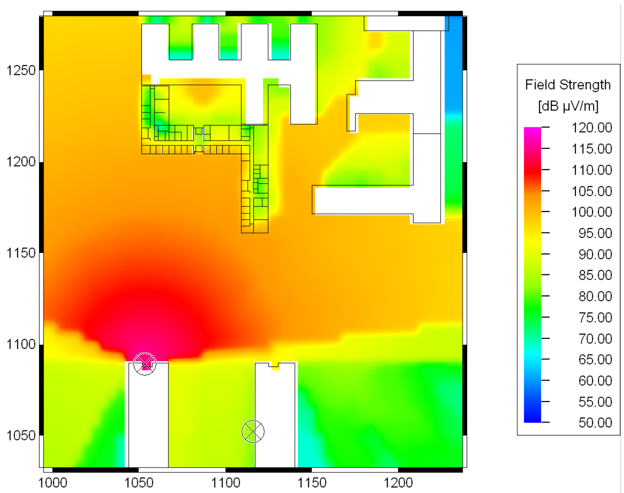

Fig. 8. Prediction results for TRX 1

Transmitter Site	Difference (Predictions – Measurements)	
	Mean Value	***Standard Deviation***
TRX 1	- 0.5 dB	5.6 dB
TRX 2	+ 0.8 dB	6.7 dB

TABLE I. COMPARISON TO MEASUREMENTS

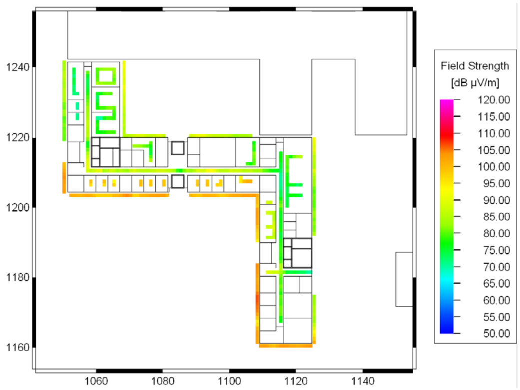

Fig. 9. Measurement results for TRX 1

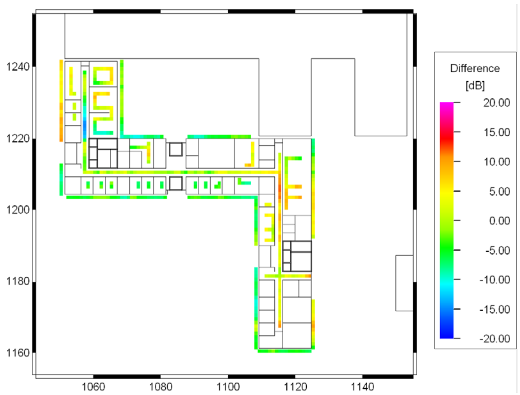

Fig. 10. Difference of Prediction and measurements for TRX 1

C. *Radiation from a Cellular Base Station Located Inside a Building*

The model also allows the computation in scenarios where the transmitter is located inside the vehicle or building (see figure 11).

All rays reaching the cylinder with the indoor model are traced on their way through the urban building database to determine the path loss to all pixels outside the building. Rays leaving the polygonal cylinder are traced back even into the cylinder (penetration of buildings, see above). This allows to consider reflections at neighboring buildings and their influence on the indoor coverage.

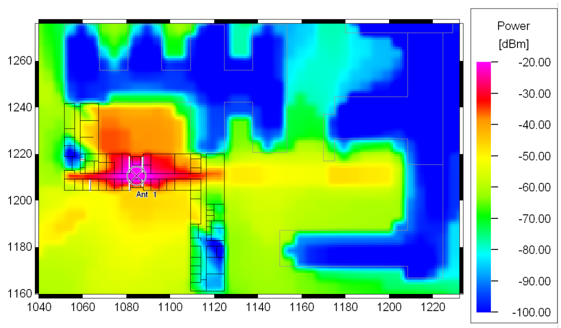

Fig. 11. Transmitter located inside a building and penetration into neighboring buildings

D. *Penetration into a Car*

Figure 12 shows an example in a scenario where a GSM microcell base station is located in an urban environment. The penetration into the car is computed using the new transitional propagation model. The figure shows the received power in the street canyon (upper part of the figure) and inside the car (lower part of the figure).

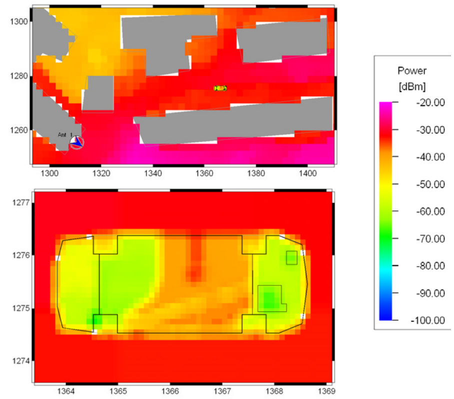

Fig. 12. Penetration into a car by a GSM base station

V. CONCLUSIONS

In this paper a deterministic ray tracing model for the transition between urban scenarios and scenarios in enclosed spaces (like vehicles and buildings) is presented. The model is based on a hybrid, accelerated ray tracing model that was adapted to handle structures with arbitrarily located and rotated objects (as typical for indoor or enclosed spaces) as well as very large areas (urban micro- and macro-cells with cell radii of several kilometers). A transition interface is described that allows the computation of the penetrating rays between the two scenarios.

A measurement campaign confirms that the model delivers very accurate results which was expected due to its physical approach. A new measurement campaign to validate the penetration into vehicles will be set up in the near future.

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