Combination of Geometric and Finite Difference Models for Radio Wave Propagation in Outdoor to Indoor Scenarios

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***Abstract*—In this paper, a new model used to compute the outdoor to indoor signal strength emitted by a base station is presented. This model is based on the combination of 2 existing models: *IRLA* (Intelligent Ray Launching), a 3D geometric-like model especially optimized for outdoor predictions, and *MR-FDPF* (Multi Resolution Frequency Domain ParFlow), a 2D FDTD-like model initially implemented for indoor propagation. The combination of these models implies the conversion of the ray launching signals on the border of the buildings, into virtual source flows that will be used as an input for the indoor model. The performance of the new combined model is evaluated via measurements, and it appears to be an efficient solution for radio network planning, both in term of accuracy and computational cost.**

***Index Terms*—outdoor to indoor, Radio propagation, Channel modeling, Ray-Launching, ParFlow.**

I. Introduction

Indoor networks planning is increasingly important, that is why tools have been developed to help operators to optimize their networks. For example, these tools help to find the best parameters like the positions of the emitters, the optimal radiated power, and the best channels. Moreover, the quality of such tools relies for an important part on the quality of the propagation model. Hence, it is important for operators to optimize both the indoor and the outdoor radio coverage, by using new combined indoor/outdoor propagation models.

Furthermore, attention has been recently given to optimizing the indoor radio coverage by using specific indoor solutions such as Femtocells [1]. Efficient outdoor to indoor propagation tools will be very useful for operators to study the interference in the femtocell due to outdoor macrocells.

A. Related work

In [2], the identification of the outdoor to indoor through walls opening was studied. In [3], it is shown that many factors have an influence on the received power inside a building such as the predicted penetration loss versus frequency for a windowed wall. Moreover, reflections on the outdoor obstacles will have a great influence on the indoor radio coverage, that is why a cluster approach was proposed in [4]. Three-dimensional radio propagation models for outdoor to indoor have been proposed for urban wireless network planning [5] and for Relay Network deployment [6].

B. Contribution

In this TD, the combination of the IRLA model (an outdoor ray launching model) and MR-FDPF (an indoor finite difference model) will be proposed. Since both of these models have been shown to have good performance for specific areas (indoor or outdoor), the new combined model offers an optimal solution for outdoor to indoor network planning.

The TD will be organized as follows: In the next section an overview of the main approaches for deterministic radio propagation will be presented, then in section III the 2 models and their combination will be proposed. In section IV the performance of the new outdoor to indoor model will be presented and finally perspectives and conclusions will be developed in section V.

II. Approaches for deterministic radio propagation

A. Geometric based models

Geometric models or *RO* (Ray Optical) models (see Fig.1.a) use the ray optical laws to compute the rays that are reflected/diffracted in the environment [7], [8]. Geometric based models are implemented in many commercial softwares [9]. Such a model tries to search what are all the possible rays between emitter and receivers. They can been implemented in 3D, however it is important to notice that the complexity of RT can be very high in scenarios where the number of walls is high, thus where numerous reflections occur. The two most common implementations are Ray Tracing and Ray Launching.

Ray Launching emits the rays from the transmitter. Signal strength degenerates as the rays propagate and additional loss is added when rays reflect or diffract from walls.

Ray Tracing traces the rays backwards, i.e it searches all the possible paths arriving at each receiving positions.

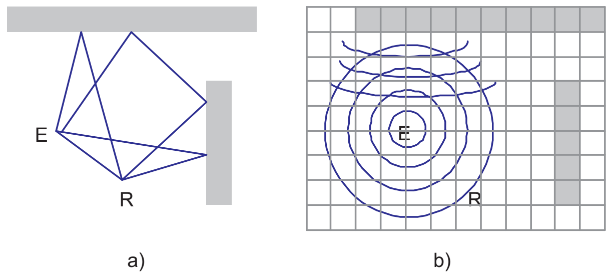

Fig. 1. Geometric (or Ray Optical) based approach based on the computation of the rays (a) vs FDTD based approach based on numerical modeling on a discrete grid (b)

B. Finite difference based models

Finite difference models are based on the resolution of the Maxwell equations on a discrete grid (see Fig.1.b). The most common approach is the well known FDTD (Finite Difference Time Domain) which has been widely applied in the industry for the design of antennas.

Such models have also been used to compute radio coverage, like the approach proposed in [10]. The advantage of such models is that, unlike that for Ray Optical models, all the reflections and diffractions are taken into account. One disadvantage is that the size of the pixels of the spatial grid has to be very small compared to the wavelength of the signal, leading to a high complexity for large scenarios. Hence this kind of model has been generally used in 2D for smaller scenarios like indoors [11], [12].

C. Comparison

Geometric based models and Finite difference models are very different and both of them have advantages and drawbacks. Comparisons between them are given in [13]. In the following, the main criteria are compared:

- Complexity: For FDTD it depends mainly on the size of the scenario, whereas for RO it depends mainly on the number of walls.
- Accuracy: FDTD is in general more accurate because the number of reflections in not limited unlike RO.
- 3D extension: RO is in general less computational demanding than FDTD, that is why a 3D version of the model is easier to implement.

In the litterature, combined models also referred to as hybrid models have been proposed [14], [15], [16], where RO and FDTD models are combined to take advantage of the properties of each model. Thus, in our paper, taking into consideration the properties described in II-C, it appears as a good choice to combine 2 models and choose between them depending on the scenarios:

- *Indoors*: The scenario is not very large, and made of numerous walls that is why the number of reflections is very high. Moreover, in multi floor buildings, the scenario at each floor is quite flat i.e. a 2D approximation of the propagation is not a bad assumption. Hence in this case the 2D FDTD model is a good option.
- *Outdoors*: The environment is large and propagation can not be easily approximated with a 2D model, in particular in scenarios with high buildings and antennas located on the roofs. Furthermore, there is more open space areas and the number of reflections to compute is smaller than indoors. In such scenario 3D RT is preferred.

III. Combination of 2 models

In this section, the geometric like model and the FDTD like model we used are described, and the solution to combine them is detailed.

A. IRLA model

IRLA (Intelligent Ray Launching) is described in [17]. It is a full 3D ray launching especially developped for urban network planning. In this model, the buildings are approximated with a 2.5D database (representing the shape of the buildings and their heights). IRLA is based on a discretization of the environment into cubes, in order to reduce the number of reflections and diffractions to compute. Optimizations to avoid missing rays are also implemented in this model [18].

B. MR-FDPF model

MR-FDPF (Multi-Resolution Frequency Domain ParFlow)[19] is a FDTD-like model based on the ParFlow method. In this approach, the electric and magnetic fields are approximated by a unique numerical vector called flow, thus reducing the complexity. The transposition of the model in the frequency domain [19] allows the problem to be modeled as a linear system, that can be solved with a multi-resolution approach. The 2D implementation of *MR-FDPF* has been shown to be very efficient for indoor radio predictions [20], since the number of reflections and diffractions to compute is not limited.

C. The combined approach

The new model we propose in this TD combines *IRLA* for the outdoor signal prediction with *MR-FDPF* for the indoor part. A great advantage of the models we use is that they are both based on a discrete resolution of the environment for the following reasons:

- *MR-FDPF*, as a FDTD-like model, solves the Maxwell's equations on a 2D grid.
- *IRLA* divides the environment into cubes for complexity reduction.

Hence, the main idea of the combined approach is to find how to link the 2 models, i.e. how to use the *IRLA* 3D outdoor radio coverage as an input for the 2D indoor *MR-FDPF* simulation. The method is illustrated in Fig.2 and can be divied into the following steps:

- Run the *IRLA* prediction (Outdoor ray launching) of the emitter.
- Compute equivalent *MR-FDPF* sources flows on the borders of the building, by summing the rays arriving at each cube on the borders of the indoor floor (see Fig.3).

- Run the indoor *MR-FDPF* using the new equivalent sources as incoming flows of the bottom-up-down approach [19].
- Combine IRLA/MR-FDPF maps to plot both the outdoor and indoor coverages.

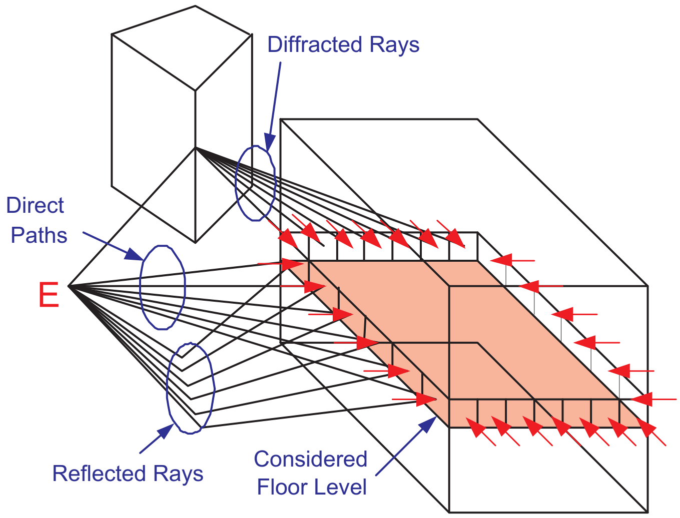

Fig. 2. Schematic representation of the combined approach. First the outdoor part is simulated, then the incoming indoor flows are computed and used for the indoor simulation

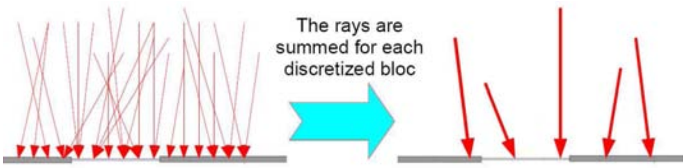

Fig. 3. Computation of the virtual source on the borders of the building.

IV. Results

A. Experiments

The scenario for the evaluation of the model is the *INSA* university campus in Lyon, France (see Fig.5). The 2.5D outdoor database was generated, using Google maps for the shape of the buildings, and a laser meter to measure the height of each building. The indoor database was generated from the architect maps.
The environment was discretized as represented in Fig.4 using a grid cell size of $5cm$.

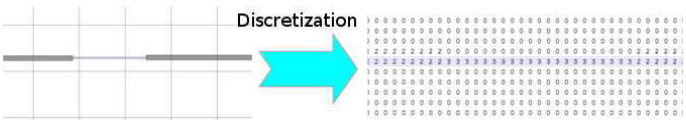

Fig. 4. Computation of the virtual source on the borders of the building.

The directive antenna (E on Fig.5) was placed on a window in one building and was pointing in the direction of the *CITI* building (colored in red on Fig.5), where the indoor measurements have been performed.

Fig. 5. outdoor to indoor scenario. In red: the building where the indoor measurements were performed. E: represents the position of the emitter.

The equipment for the measurements is detailed in table I (emitter) and table II (receiver). A frequency of $3.5GHz$ has been chosen, which is the frequency of *WiMAX* (Worldwide Interoperability for Microwave Access) in Europe.
A total of 104 measurement points were chosen (32 indoors and 72 outdoors). In order to avoid fading effects, for each point the mean value after a 20 seconds time average was recorded.

TABLE I
PARAMETERS FOR THE EMISSION

Emitter	Agilent Digital RF Signal Generator
Output power	0dBm
Frequency	3.5GHz
Antenna model	directive
Antenna height	3 m from street level

TABLE II
PARAMETERS FOR THE RECEPTION

Receiver	N9340A Handheld RF Spectrum Analyzer
Frequency	3.5GHz
Antenna model	Omnidirectional antenna
Antenna height	1.5 m from floor level

B. Performance

After the indoor and outdoor measurements were loaded, a calibration of the tool has been performed. First *IRLA* has been calibrated using a simulated annealing approach. As an illustration, the rays of the outdoor IRLA computation are plotted in figure 6.

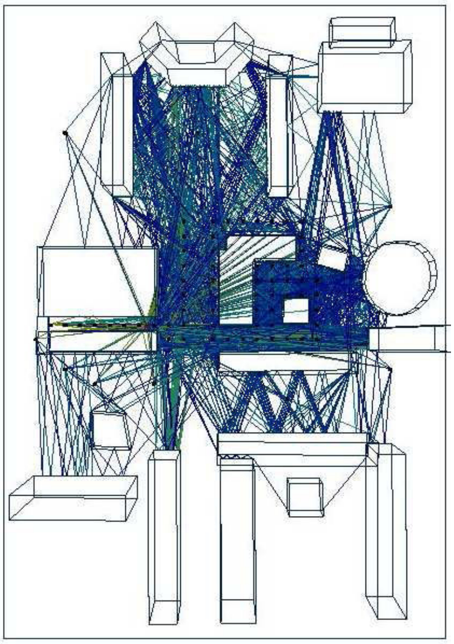

Fig. 6. Outdoor reflections and diffractions rays computed with IRLA model.

Using the rays on the borders of the *CITI* building (colored in red on Fig.5), the incoming virtual sources are computed using the approach presented in section III. Finally the Indoor part of the signal was also calibrated, in particular because the properties of the walls and the windows were not known. For the outdoor simulation, only one material is used representing the buildings.
For the outdoor database, 3 materials were used for the walls: concrete, plaster and glass for the windows.

In figure 7 the simulated signal inside the *CITI* building is plotted. It is verified in this figure that the effect of the windows are very well taken into account.

In order to evaluate the accuracy of the model, the *RMSE* (Root Mean Square Error) is used. It is defined as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=0}^{N-1}(M_i - S_i)^2} \quad (1)$$

Where:

N is the number of comparison points,
M_i is the measured received signal at location i,
S_i is the simulated received signal at location i.

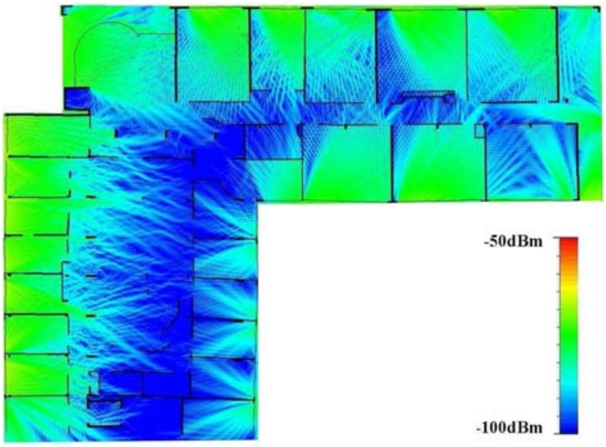

Fig. 7. The final indoor radio coverage. The effects of signal penetration trough windows are easily seen.

The performance of the model have been summarized in table III, where the results concerning respectively the outdoor measurements, the indoor measurements, and all the measurements are given.

TABLE III
PERFORMANCE OF THE MODEL

X	Outdoor points	Indoor points	All the points
Number of points	72	32	104
Pre-processing	0s	41s	41s
Simulation	58s	57s	115s
RMSE	7.9dB	2.4dB	6.2dB

V. Conclusions and Perspectives

The solution provided in this paper has been shown to efficiently compute the outdoor to indoor radio propagation in one building due to the following reasons:

- It combines the advantages of a full 3D geometric model for the outdoor part, and an indoor accurate finite difference model where 2D is sufficient due to the flatness of the floors.
- Only the details of the considered buildings have to be known, whereas the other buildings are only represented by their shape and height.
- It is a deterministic model, i.e. the propagation effects such as the losses through windows are well taken into account, offering a RMSE between simulation and measurements of about 2.4dB indoors for a short simulation time.
- Is can be easily implemented on a standard PC and does not require the use of expensive powerful computers.

Perspectives of this work include:

- The validation of the model in other scenarios and other frequencies. It will be especially interesting to study higher buildings made of many floors, and do more measurements at each floors.

- The extension of this work to the indoor to outdoor case, which is not so obvious and where another solution has to be found to link the MR-FDPF results to the Ray Launching.
- Finally, combined with an indoor to outdoor model, it would be interesting to study the outdoor to indoor to oudoor (for example when a metallic cupboard is located near a window, reflecting most of the signal outside).

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