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Research Article

Implementation and Validation of a New Combined Model for Outdoor to Indoor Radio Coverage Predictions

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A new model used to compute the outdoor to indoor signal strength emitted from an outdoor base station is presented. This model is based on the combination of 2 existing models: *IRLA* (Intelligent Ray Launching), a 3D Ray Optical model especially optimized for outdoor predictions, and *MR-FDPF* (Multiresolution Frequency Domain ParFlow), a 2D Finite Difference model initially implemented for indoor propagation. The combination of these models implies the conversion of the ray launching paths on the border of the buildings, into virtual source flows that will be used as input for the indoor model. The performance of the new combined model is evaluated via measurements at 2 frequencies (WiMAX and WiFi). This solution appears to be efficient for radio network planning, in term of both accuracy and computational cost.

1. Introduction

Indoor networks planning is increasingly important; that is why tools have been developed to help operators to optimize their networks. For example, such tools are necessary 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.

1.1. Context. Recently, attention has been given to optimizing the indoor radio coverage by using specific indoor solutions such as Femtocells [1]. Such femtocells are deployed directly inside buildings, thus efficiently enhancing both the indoor radio capacity and coverage. However it is also important to notice that femtocell users, since the femtocells share the same spectrum than the other outdoor cells, can be highly interfered by the outdoor cells [2]. Hence accurate outdoor to indoor propagation tools, that are able to compute the in-building signal due to outdoor cells, are currently highly demanded by mobile operators. The aim of this paper is to propose a new combined propagation model, which could be a good approah for this purpose.

1.2. Related Work. Some works related to outdoor to indoor radio prorogation were proposed in the past in another context than femtocells. However, in most of these approaches it was not requested to have such a detailed knowledge of the indoor signal, whereas, in our case, very detailed coverage maps are necessary in order to study for example performance of femtocells in different typical scenarios. In [3], the identification of the outdoor to indoor signal through walls opening was studied. Then in [4] 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 also have a great influence on the indoor radio coverage; that is why a cluster approach was proposed in [5]. Finally, three-dimensional radio propagation models for outdoor to indoor have been proposed for urban wireless network planning [6] and for Relay Network deployment [7].

1.3. Contribution. In [8], we recently proposed a combination of two propagation models for outdoor to indoor radio propagation predictions, as well as an initial evaluation giving promising results. This paper, in addition to the preliminary results presented in [8], has two major contributions:

(i) the details about the implementation of the combined model are given;

(ii) the validation of the model with two measurement campaigns is presented.

The paper will be organized as follows: in Section 2 an overview of the main approaches for deterministic radio propagation will be presented, then in Section 3 the combination of two carefully chosen models will be proposed. In Section 4, the 2 measurement campaigns will be described, followed by an evaluation of the performance of the model in Section 5. Finally, perspectives and conclusions will be developed in Section 6.

2. Approaches for Deterministic Radio Propagation

As explained in the introduction, the context of the present work is to compute environment-specific radio coverage maps that take as accurately as possible into account the geometries of the environment. Approaches for deterministic simulation of radio waves can be divided into two main families, depending on the theoretical laws on which they are based on.

(i) RO models use Descartes laws, where the reflections and diffractions of the signal on the obstacles are computed by tracing all the possible paths between the emitters and the receivers.

(ii) FD models use partial differential equations in order to numerically solve the Maxwell's equations on a discrete grid.

In the following, properties related to these two families of models will be investigated.

2.1. Ray-Optical-Based Models. RO models, has been widely used for predicting radio propagation [9, 10]. At each receiving point, the signal level is computed as the sum of all the rays (due to transmissions, reflections, and diffractions) passing through this point. RO models are nowadays a common approach for deterministic radio coverage simulation, hence they have been implemented in commercial software such as [11, 12]. The two most common implementations are Ray Tracing and Ray Launching where:

(i) 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;

(ii) ray Tracing traces the rays backwards, that is, it searches all the possible paths arriving at each receiving positions.

It is important to notice that the complexity of such models can be very high in scenarios where the number of walls is high, thus where numerous reflections/diffractions occur. This is especially the case in 3D environments. That is why most of the recent research has been focused on the reduction of the complexity of RO models. Recently, a Ray Launching model called IRLA [13] has been proposed in which the following optimizations are used:

(i) a cube approach where the initial environment is divided into cubes. In this approach the rays between faces of cubes are computed, thus avoiding to compute all the rays between all the points inside the cubes [13];

(ii) an optimized approach for reducing the angular dispersion which is often a concern in Ray Launching when the distance from the emitter becomes large, since the number of rays to be launched has to be limited [14];

(iii) a parallel implementation where the computation of the rays is distributed among processes thus reducing a lot the simulation time [15].

IRLA is one component of the combined approach proposed in this paper.

2.2. Finite-Difference-Based Models. The most common approach is the well known FDTD proposed in [16] which numerically solves Maxwell's equations and thus provides a high accuracy. However, a 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. That is why, due to its high memory requirements, such FD models used to be applied only to antenna design or electronic circuits. Nevertheless, since computers become more and more powerful, researchers have started to use such models for radio coverage predictions as well, and more especially for indoor areas [17, 18]. Moreover, and in order to reduce the complexity, another FD model called ParFlow has been proposed [19]. In this approach, restricted to 2D, the magnetic fields are approximated with a unique scalar field thus reducing the number of variables (there is only one field to take into consideration instead of E and H fields). Recently, a similar approach called MR-FDPF based on a transposition of the ParFlow equations in the frequency domain has been proposed [20], in which the following optimizations have been proposed:

(i) a multiresolution approach, in which most of the complexity of the resolution of the equations is gathered into a unique preprocessing. Therefore the time duration for simulating each source becomes very fast compared to usual FD models in the time domain [20];

(ii) an calibration of the parameters of the model in order to make it suitable for indoor simulation even if the model is restricted to 2D [21];

(iii) an improvement of the model in order to perform OFDM simulations which is out of scope of this paper [22].

MR-FDPF model is the second component of the combined approach of this paper.

2.3. Comparison. RO models and FD models are very different and both of them have advantages and drawbacks. Comparisons between them have been developed in [23] the main properties can been summarized as follows depending on 3 criteria:

(i) complexity: For FD models, it depends mainly on the size of the scenario, whereas for RO models it depends mainly on the number of walls;

(ii) accuracy: FD is in general more accurate because the number of reflections/diffractions is not limited unlike RO;

(iii) 3D extension: RO is in general less computational demanding than FD; that is why 3D RO models are commonly implemented in 3D whereas FD models are usually in 2D in order to simulate large enough scenarios.

3. Combination of 2 Models

3.1. Concept. Taking into consideration the properties described in Section 2.3, it appears as an optimal choice to select the most appropriate approach depending on the location, that is:

(i) *indoors*: the scenario is not very large, and made of numerous walls; that is why the number of reflections/diffractions is very high. Moreover, in case of multifloored buildings, the scenario at each floor is quite flat, that is, a 2D approximation of the propagation is a suitable assumption. Hence in this case a 2D FD model such as MR-FDPF appears to be the most favorable;

(ii) *outdoors*: the environment is not flat and cannot be easily approximated with a 2D model, in particular in scenarios with high buildings where antennas can be located on the roofs. Furthermore, there is more open space areas and the number of reflections to compute is smaller than that indoors. Finally the size of the scenario is too large to be computed with FD model. That is why in this case a 3D RO model such as IRLA is preferred.

Hence the new model for outdoor to indoor predictions proposed in this paper combines IRLA (for the outdoor propagation part) with MR-FDPF (for the in-building propagation). It is to be noticed that, in the literature, other combined RO/FD models such as [24–26] have been proposed. However these models were restricted to indoors, and a FD model was used only for the parts of the scenario requiring more details. Thus, at the knowledge of the authors, no combined RO/FD approach for outdoor to indoor has been already proposed.

3.2. Implementation. The method is illustrated in Figure 1 and can be divided into the following steps:

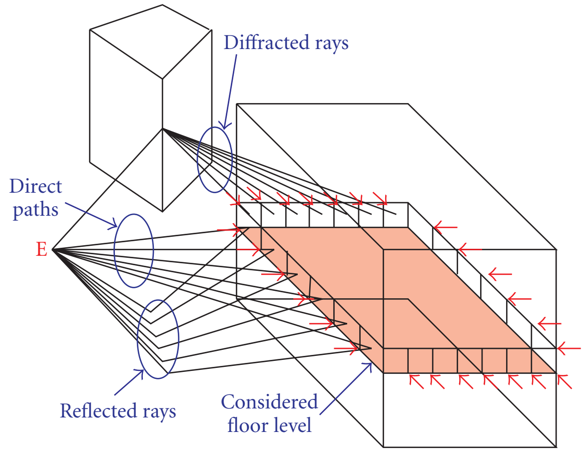


FIGURE 1: Schematic representation of the combined approach. First the outdoor part is simulated, then the incoming indoor flows are computed and used for the indoor simulation.

3.2.1. Outdoor IRLA Prediction. The outdoor *IRLA* prediction is performed. 3D rays are launched in all the directions and recursively reflected and diffracted on the obstacles. The tool is based on a maximum number of 15 reflections and 15 diffractions, which provides high accuracy. Since IRLA has a cube approach, a resolution of 5 cm is chosen, that is, the received signal power is computed every 5 centimeters. The 3D antenna pattern is generated from horizontal and vertical 2D antenna pattern obtained from the data sheets [15].

3.2.2. MR-FDPF Equivalent Sources Computations. In each cube located on the borders of the building (at the height corresponding to the floor), the amplitudes and directions of all the N rays reaching the cube are stored. Each arriving ray is represented by a vector v_i and the equivalent ParFlow source (flows are represented by complex numbers [20].) can be computed from the vector V corresponding to all the rays, that is, $V = \sum_{i=0}^{N-1} v_i$. In this case, the amplitude of the equivalent source corresponds to the amplitude of V and the phase of the equivalent source corresponds to the direction of V.

3.2.3. Indoor MR-FDPF Prediction. The indoor radio coverage is computed in 2D (a 5 cm resolution 2D cut of the scenario at the height of the floor is taken) using the MR-FDPF model and using the previously calculated equivalent sources. It is to be noticed that, due to the properties of MR-FDPF model, the complexity of simulating many sources (i.e., all the borders of the building) is in the same oder than for one source only.

3.3. Calibration. In the case when the parameters corresponding to the materials are not perfectly well known it may be useful to calibrate the model. This is the common approach used by all propagation tools and most of commercial network planning software such as [11, 12]. Moreover, based on the fact that MR-FDPF is restricted to

$2D$, it is important to compensate for this approximation by properly adapting the parameters of the model based on measurements as explained in [21]. In this paper, it was show that, by modifying the attenuation of air, it was possible to fit a $3D$ free-space model with a $2D$ modeling.

Since the number of materials could be high it is not possible to test all the possible values in a short time. That is why meta heuristic methods have been implemented.

(i) Calibration of IRLA is based on Simulated Annealing [27].

(ii) Calibration of MR-FDPF is calibrated using the Direct Search algorithm [28].

The choice of a search method is due to the fact that IRLA has few parameters to optimize (since the buildings are represented by a single material) which can be solved in a short time using Simulated Annealing. On the contrary MR-FDPF models all the materials of the different walls (for example, as we be detailed later, there are 8 parameters to calibrate in this scenario, which cannot be optimized in a short time using Simulated Annealing. Therefore Direct Search is chosen providing a less accurate result but in a shorter time. Let us remind that the model we propose in this paper is aimed at wireless network planners, that is, the calibration of the materials has to be performed in a short time, and since all the elements of the scenario (such as passing users, furnitures) are not simulated, reaching the absolute global minimum is not of practical use.

The function to minimize during the calibration is the RMSE defined as:

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

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

Typically, calibration of IRLA takes few seconds (since all the rays as stored in the memory it is not required to run numerous simulations), whereas MR-FDPF is calibrated in few minutes because multiple independent predictions have to be run. Based on our experience, calibration is important mostly outdoors where database information of the environment is limited, and due to more frequent unpredictable phenomenas such as moving vehicles and fast fading.

4. Scenario and Measurements

The scenario for the evaluation of the model is the *INSA* university campus in Lyon, France (see Figure 2). The size of the scenario is 800×560 meters. The size of *CITI* building (surrounded in red in Figure 2), where the indoor radio coverage is simulated, is approximately 110×100 meters. Its height is 11 meters.

The combined models requires to work at two scales, that is, an outdoor scale where a database of the buildings without their content is used, and an indoor scale where the details of

Figure 2: Outdoor to indoor scenario. In red: the building where the indoor measurements were performed. E1 and E2 represent the position of each emitter and the black arrows show the directions where the directive antennas were pointing.

the building to simulate are taken into consideration. Hence two databases of the scenario were generated:

(i) The outdoor database, required by IRLA, was created using *google* maps for extracting the shapes of the buildings, and a laser meter to measure the height of each building. Hence it is not a real full 3D database but a 2.5D database, in a *.dat* format similar to the one used by commercial RO software. After calibration based on the approach detailed in Section 3.3, it was verified that it was suitable to use the same unique material for all the buildings. Hence there was three parameters to calibrate for the ray launching, corresponding to the losses for transmission, reflection and diffraction.

(ii) The indoor database containing all the walls of the floors used by MR-FDPF was generated from the *.dxf* format architect files. A 2D cut of the floor in the horizontal plane was used. The environment was modeled using one material corresponding to *air* plus 3 other materials for the obstacles: *concrete* for the main walls, *plaster* for the internal walls and *glass* for the windows. In MR-FDPF there are two parameters to define a material, that is, the refraction index n and the electrical permittivity on which the attenuation coefficient α relies. That is why in this case there was 8 parameters in total to calibrate.

To validate the model, two measurement campaigns at different frequencies and emitters' locations were performed in the same scenario, as detailed in Table 1. The two frequencies chosen for the validation (i.e., 3.5 GHz and 2.4 GHz) correspond respectively to the frequencies of Worldwide Interoperability for MicrowaveAccess (WiMAX) andWireless Fidelity (WiFi) in Europe.

(a) ETS-Lindgren Antenna (b) Stella Doradus Antenna

Figure 3: Directive antennas used at the emitter.

Table 1: Measurement campaigns.

	Experiment 1	Experiment 2
Frequency	3.5 GHz	2.4 GHz
Emitted power	0 dBm	0 dBm
Position on map	E1	E2
Emitting antenna	ETS-Lindgren Horn antenna Model 3115	Stella Doradus Parabolic antenna Model 24 SD21
Gain	10 dBi	20.5 dBi
HPBW	38°(V), 45°(H)	15°(V), 15°(H)
Polarization	Vertical	Vertical

Table 2: Measurement equipment.

Emitter	Agilent Digital RF Signal Generator
Receiver	N9340A Handheld RF Spectrum Analyzer

The directive antennas (see Figure 3), located at approximately 3 m hight, were pointing on *CITI* building in the directions represented in Figure 2 (represented by arrows).

The equipment for the measurements is detailed in Table 2. A total of 104 measurement points were chosen (32 indoors and 72 outdoors). At the receiver's side, omni-directionnal antennas were used. Moreover, in order to avoid fading effects, these antennas were slightly moved and the mean value after continuous 20 second measurements was recorded.

Before running the MR-FDPF simulations, IRLA has been calibrated for both measurement campaigns, providing a RMSE of 8 dB, which is acceptable considering the arguments given in Section 3.3 and also the fact that the points where distributed in the scenarios and some of them far from the building of interest (see Figure 4(b) for the location of these points).

Table 3: Accuracy of the model: RMSE/ME in dB.

X	Experiment 1	Experiment 2
No calibration	2.80/0.301	2.28/ − 0.53
Calibration (4 points)	2.61/ − 0.22	1.77/ − 0.32
Calibration (all points)	2.39/0.09	1.17/0.21

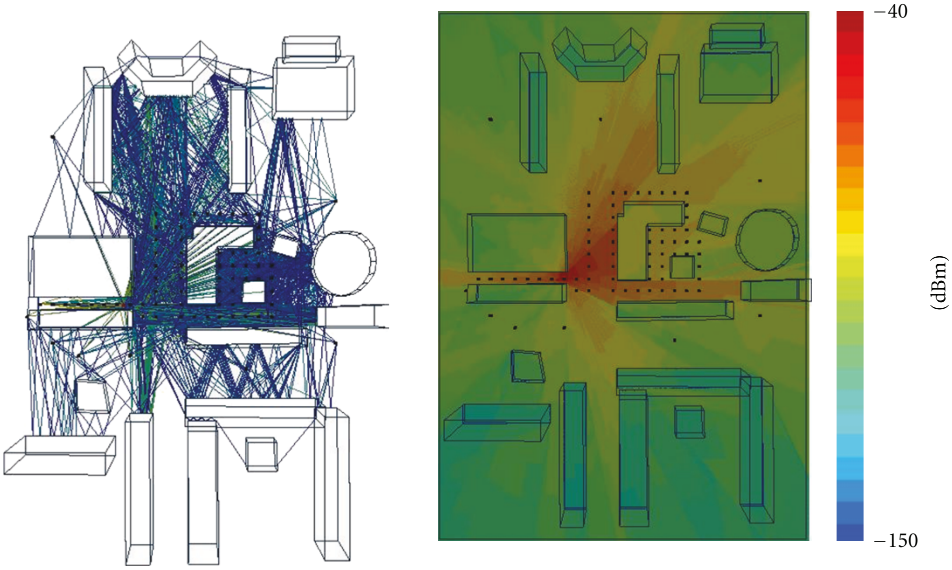
5. Results

As an illustration, the rays and the coverage map computed with IRLA and corresponding to experiment 1 are plotted in Figure 4.

The simulated signal inside the *CITI* building based on the new combined model is plotted in Figure 5 (Experiment 1) and Figure 6 (Experiment 2), as well as the comparison between simulation and measurements for the received signals (before calibration of MR-FDPF). It is seen on these figures that the effects of the windows are well taken into account, and that the measurements and simulation are well in accordance. Moreover, and especially in Experiment 1 (due to the height of the buildings) the reflections of the signal on neighboring buildings coming through the windows is visible.

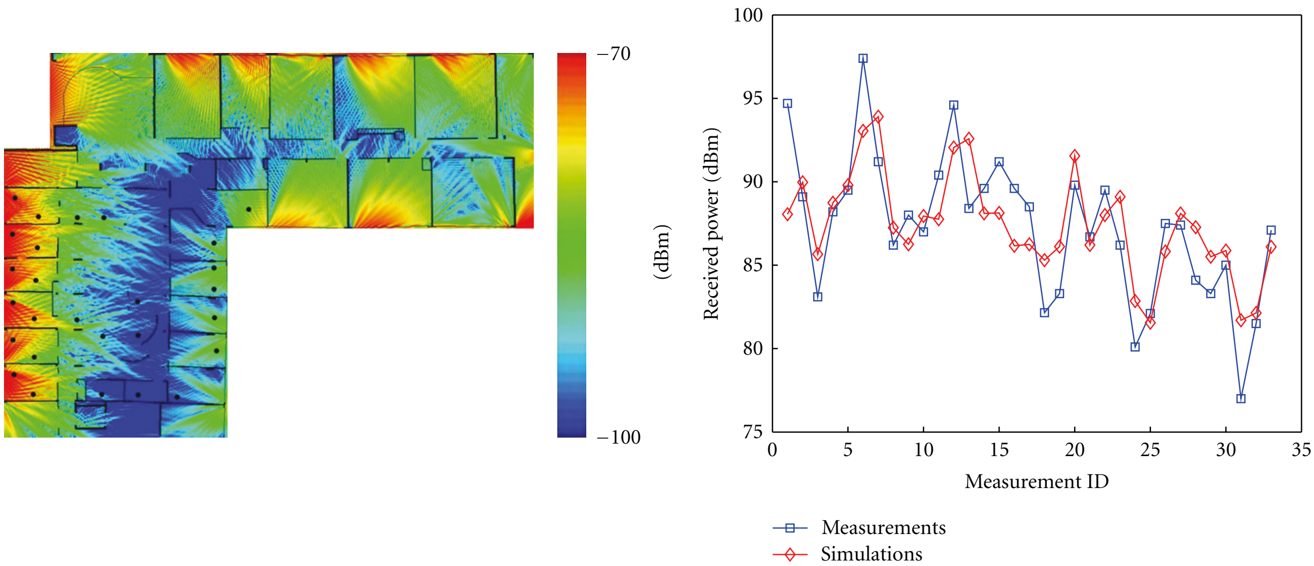
In order to evaluate the accuracy of the model more in details, the RMSE values as well as the ME are plotted in Table 3, depending on if MR-FDPF is calibrated, and depending on the number of points used for the calibration.

It is verified that, even without calibration (default material values for the indoor walls) the model performs well (less than 3 dB RMSE and less than 1 dB ME, which corresponds to the accuracy that MR-FDPF reaches for indoor simulations only [21]). Moreover, and as expected, calibrating the model using few points (4) improves the accuracy. As an illustration of what is the best possible accuracy the model could reach, the RMSE after calibrating using all the points is also given. However and as said bellow, the aim of such model is to be used by radio engineers in



(a) Outdoor Rays (b) Outdoor coverage map

Figure 4: IRLA simulation (Experiment 1).

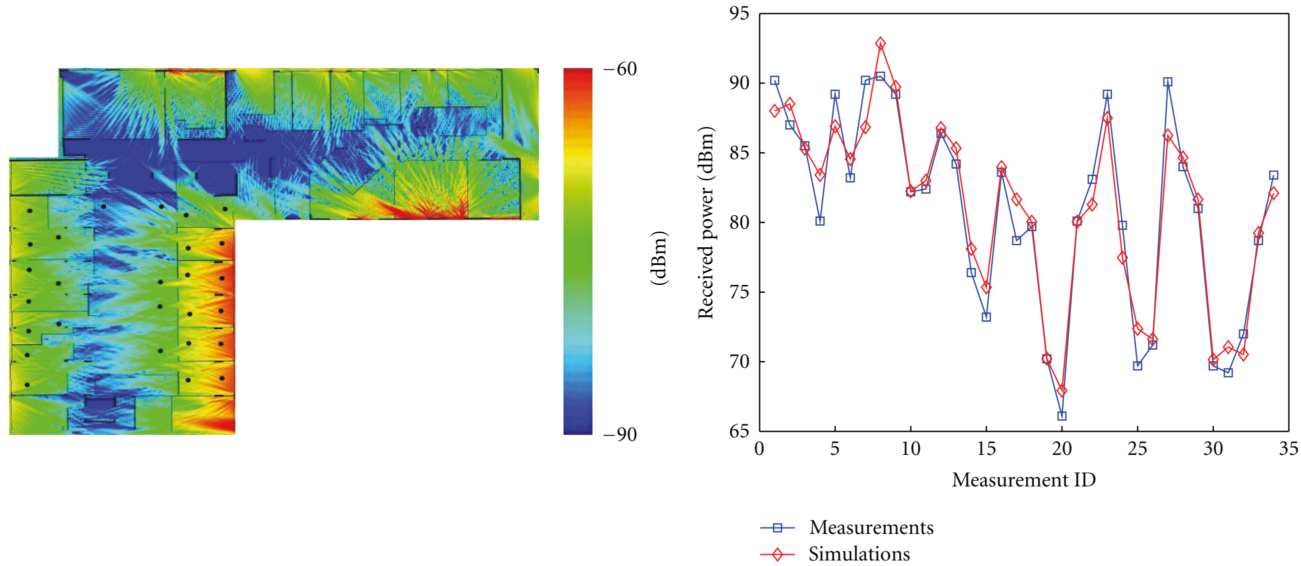


(a) Radio coverage map (b) Comparison between measurements and simulation

Figure 5: Outdoor to Indoor simulation results (Experiment 1).

order to save time due to radio measurement campaigns that is why such calibration using all the points has no practical meaning. Nevertheless it is proven in this experiment that only few measurement points suffice to improve the model and reach a high accuracy (Less than 2 dB in the case of WiFi). Finally, let us just notice that in practice it makes no sense to reach lower values of accuracy (typically less than 2 dB), since the accuracy of the measurement equipment (even after the small scale fading is removed) may have larger variations.

The time durations of the simulations are given in Table 4 and it is shown that the total simulation time (once the MR-FDPF preprocessing has been already done) for one outdoor to indoor prediction is less than two minutes on a standard computer. The time durations we give are for the full radio coverage, that is, for all points of the scenarios. Let us remind here that the preprocessing of MR-FDPF does not need to be run if the walls are not modified, since the ParFlow scattering matrices does not depend on the location of the sources.



(a) Radio coverage map

(b) Comparison between measurements and simulation

Figure 6: Outdoor to Indoor simulation results (Experiment 2).

Table 4: Performance of the model: simulation times (on PC, 2.4 GHz, 2 GbRAM).

X	IRLA	MR-FDPF	Total
Preprocessing	0 s	41 s	41 s
Simulation	58 s	57 s	115 s

5.1. Advantages of the Model. It is important to notice that, without combining MR-FDPF with IRLA, it would not have been possible to compute the whole scenario with MR-FDPF only, due to high memory requirements during the preprocessing step. However, by supposing that this amount of memory is large enough, it is then possible to interpolate the simulation time duration it would take for simulating the whole scenario with MR-FDPF. Indeed, and as detailed in [20], the complexity of the propagation phase of MR-FDPF varies in $O(\log_2(N) \cdot N^2)$, where N is the smallest dimension of the scenario in pixels. Thus a simulation of the full environment (560 meter large) at the same resolution would be $\log_2(560/100) \cdot (560/100)^2 = 78$ times slower, that is, it would take approximately 2.5 hours instead of less than 2 minutes (115s) with the proposed combined model. Furthermore, such simulation would only simulate a 2D cut, where the height of the outdoor emitters would not be properly taken into account, hence it would provide a low accuracy, compared to the approach we use where the outdoor signal effects are simulated in 3D. Consequently, the new model proposed in this paper is advantageous both in term of speed and accuracy.

6. 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:

(i) it combines the advantages of a full 3D geometric model for the outdoor part, and an indoor accurate FD model where 2D is sufficient due to the flatness of the floors;

(ii) only the details of the considered buildings have to be known, whereas the other buildings are only represented by their shape and height;

(iii) it is a deterministic model, that is, the propagation effects such as the losses through windows are well taken into account, offering a RMSE between simulation and measurements of less than 3 dB indoors for a simulation time of less than 2 minutes;

(iv) is can be easily implemented on a standard PC and does not require the use of expensive powerful computers;

(v) the combined approach gives the opportunity to use the MR-FDPF for large scenarios, which would have not been possible based on MR-FDPF only.

This model, due to is performance will thus be used in a network planning tool in particular to study the interference produced by outdoor cells on indoor femtocells. However it is to be noticed that this paper only provides information about the expected mean power, which cannot be sufficient to completely characterize a complex radio link for modern systems. Hence our future work include the two following tasks:

(i) MR-FDPF provides us with an accurately discretized map of the power, thus enabling to evaluate the spatial behavior of the channel, which was presented in [29] for indoor scenarios. However this needs to be validated with measurements for outdoor to indoor scenarios;

(ii) ongoing work [22] gives us the possibility to perform wideband simulations, leading to more information such as Power Delay Profiles, delay spread, Doppler spread. Thus new measurements have to be performed in order to verify if such features are also true in outdoor to indoor scenarios using the combined model.

Acronyms

FDTD: Finite Difference Time Domain,
FD: Finite Difference,
IRLA: Intelligent Ray Launching,
ME: Mean Error,
MR-FDPF: Multi Resolution Frequency Domain ParFlow,
OFDM: Orthogonal Frequency Division Multiplexing,
RMSE: Root Mean Square Error,
RO: Ray Optical,
WiFi: Wireless Fidelity,
WiMAX: Worldwide Interoperability for MicrowaveAccess.

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