FP7-PEOPLE-2008-IAPP : Indoor radio network PLANning and optimization

Contractual date of delivery to EC: before month 30
Actual date of delivery to EC: 26/06/2012
Lead beneficiary: INSA Lyon
Nature: Restricted
Version: 1.0
Project Name: Indoor radio network PLANning and optimisation
Acronym: iPLAN
Start date of project: 01/06/2009 **Duration:** 48 Months
Project no.: 230745

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1. Summary

In the context of Femtocell deployment, the important issue of interaction between outdoor macrocells and indoor femtocells needs to propose some efficient tools to simulate the behavior of radio waves at the interface between those to kind of environments: large scale outdoor and smaller scale indoor.

In this report, we propose a new hybrid modeling method for indoor-to-outdoor or outdoor-to-indoor radio coverage prediction. The proposed method is a combination of a ray-optical channel modeling approach and the frequency domain ParFlow method. While the former is widely used for modeling outdoor propagation environments, the latter is computationally efficient and accurate for modeling indoor environments.

The proposed hybrid method is evaluated by comparing the simulation results to the real-world measurements.

2. Description of the work

1. Introduction

The ubiquitous deployment of various wireless communication networks, particularly in urban areas, requires careful planning of new wireless networks, as well as optimization of the existing ones. Successful accomplishment of these tasks calls for efficient radio network design tools.

Unavoidably, any debate about merits and demerits peculiar to a concrete tool, or more precisely, to an underlying electromagnetic wave propagation modeling approach, leads to a discussion about the trade-off between the computational load and the achievable accuracy of the prediction. To a large extend, the compromise between efficiency and accuracy depends on the modeled propagation environment.

It has been demonstrated that the multi-resolution frequency domain ParFlow (MR-FDPF) method [20] is an efficient and accurate radio network design tool for indoor and indoor-like environments. Yet the computational load associated with this method quickly becomes excessively large due to the size increase of the propagation environment as, for example, in outdoor wave propagation scenarios. On the other hand, the well-known ray-optical approaches [10] are widely used for modeling the outdoor as well as indoor environments. Even so, using the ray-optical methods for accurate prediction of the electrical field strength inside a building might not be as computationally efficient as employing the MR-FDPF method. Moreover, MR-FDPF method is usually more accurate since it does not restrict the number of reflections to be computed as it is the case in ray-optical approaches.

For scenarios where both the indoor and outdoor wave propagations have to be considered, a combination of the MR-FDPF and the ray-optical methods promises advantages in providing accurate prediction results without sacrificing the computational efficiency. Indeed, performing the simulation of the whole indoor-to-outdoor scenario based on MR-FDPF only would require too much memory.
The combination of the ray-optical and the MR-FDPF methods for predicting the electrical field strength in outdoor-to-indoor wave propagation scenarios has been first explored in [8]. Afterwards, we proposed a new method for combining the ray-optical and the MR-FDPF approaches in order to accurately and efficiently predict the field strength in indoor-to-outdoor wave propagation scenarios.

The rest of the report is organized as follows. In Section 2 we present the advantages and drawbacks of different deterministic approaches for radio coverage prediction. Then in Section 3 we propose the combination of ray-tracing and MR-FDPF for outdoor and indoor co-simulation, with the associated implementation for outdoor-to-indoor scenario. Measurements setup is described in Section 4 and the results detailed in Section 5. Finally the reverse problem of indoor-to-outdoor simulation is studied in Section 6, with both principle and evaluation.

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:

- Ray Optical (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.
- Finite Difference (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, 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:

- 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.

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 Intelligent Ray Launching (IRLA) [13] has been proposed in which the following optimizations are used:

- 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].
- 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].

- 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 report.

2.2 Finite difference based models

The most common approach is the well-known Finite Difference Time Domain (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 Multi Resolution Frequency Domain ParFlow (MRFDPF) based on a transposition of the ParFlow equations in the frequency domain has been proposed [20], in which the following optimizations have been proposed:

- A multi-resolution 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].
- 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].
- An improvement of the model in order to perform Orthogonal Frequency Division

Multiplexing (OFDM) simulations which is out of scope of this report [22].

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

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 be summarized as follows depending on 3 criteria:

- 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.
- Accuracy: FD is in general more accurate because the number of reflections/diffractions is not limited unlike RO.
- 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 for outdoor-to-indoor

3.1 Concept

Taking into consideration the properties described in 2.3, it appears as an optimal choice to select the most appropriate approach depending in the location, i.e.:

- 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 multi-floored buildings, the scenario at each floor is quite flat i.e. 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.

- Outdoors: The environment is not flat and cannot be easily approximated with a 2Dmodel, 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 indoors. Finally the size of the scenario is too large to be computed with a 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 indoor, 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.

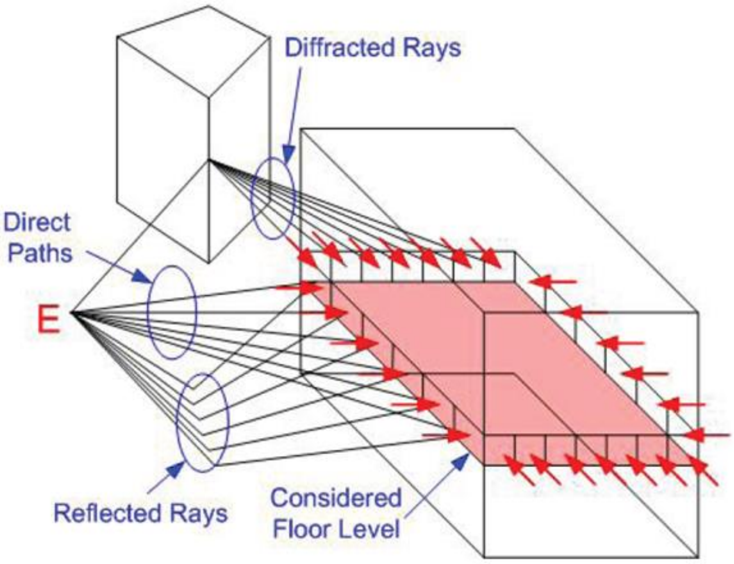

Figure 1: Schematic representation of the combined approach. First the outdoor part is simulated, then the incoming indoor flows are computed and used for the indoor simulation.

3.2 Implementation

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

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 5cm is chosen, i.e. 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, i.e. $V = \sum_{i=0}^{N-1} v_i$. 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 5cm 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 order 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]. 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:

- Calibration of IRLA is based on Simulated Annealing [27].
- 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 in the later scenario there are 3 kinds of walls with 2 coefficients for each of them) 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, i.e. 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, furniture) are not simulated, reaching the absolute global minimum is not of practical use.

The function to minimize during the calibration is the Root Mean Square Error (RMSE) defined as:

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

Where:

N is the number of comparison points,

Mi is the measured received signal at location i,

Si 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 phenomena such as moving vehicles and fast fading.

4. Scenario and Measurements for outdoor-to-indoor

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

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 combined models require to work at two scales i.e. an outdoor scale where a database of the buildings without their content is used, and an indoor scale where the details of the building to simulate are taken into consideration.

Hence two databases of the scenario were generated:

- 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 3Ddatabase but a 2.5D database, in a .dat format similar to the one used by commercial RO software. A unique material coefficient was used for all the buildings.

- 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 3 different materials for the obstacles: concrete for the main walls, plaster for the internal walls and glass for the windows.

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

	Experiment 1	Experiment 2
Frequency	3.5GHz	2.4GHz
Position on map	E1	E2
Emitting antenna	ETS-Lindgren Horn antenna Model 3115	Stella Doradus Parabolic antenna Model 24 SD21

Table 1: Measurement campaign

The directive antennas, simulating sector of external macrocells, located at approximately 3m height, were pointing on CITI building in the directions represented in Fig.2 (represented by arrows).

The equipment for the measurements is based on an Agilent generator ESG4438C and an N9340A Handheld RF Spectrum Analyzer. A total of 104 measurement points were chosen (32 indoors and 72 outdoors). At the receiver's side, omnidirectional 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 8dB, 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 Fig.4.b for the location of these points).

5. Results

As an illustration, the rays and the coverage map computed with IRLA and corresponding to experiment 1 are plotted in Fig.3. The simulated signal inside the CITI building based on the new combined model is plotted in Fig.4 (Experiment1) and Fig.5 (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.

In order to evaluate the accuracy of the model more in details, the RMSE values are plotted in Tab.2, depending on if MR-FDPF is calibrated, and depending on the number of points used for the calibration.

X	Experiment 1	Experiment 2
No calibration	2.80dB	2.28dB
Calibration (4 points)	2.61dB	1.77dB
Calibration (all points)	2.39dB	1.17dB

Table 2: Performance of the model: accuracy

It is verified that, even without calibration (default material values for the indoor walls) the model performs well (less than 3dB RMSE 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 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 2dB 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 2dB), since the accuracy of the measurement equipment (even after the small scale fading is removed) may have larger variations.

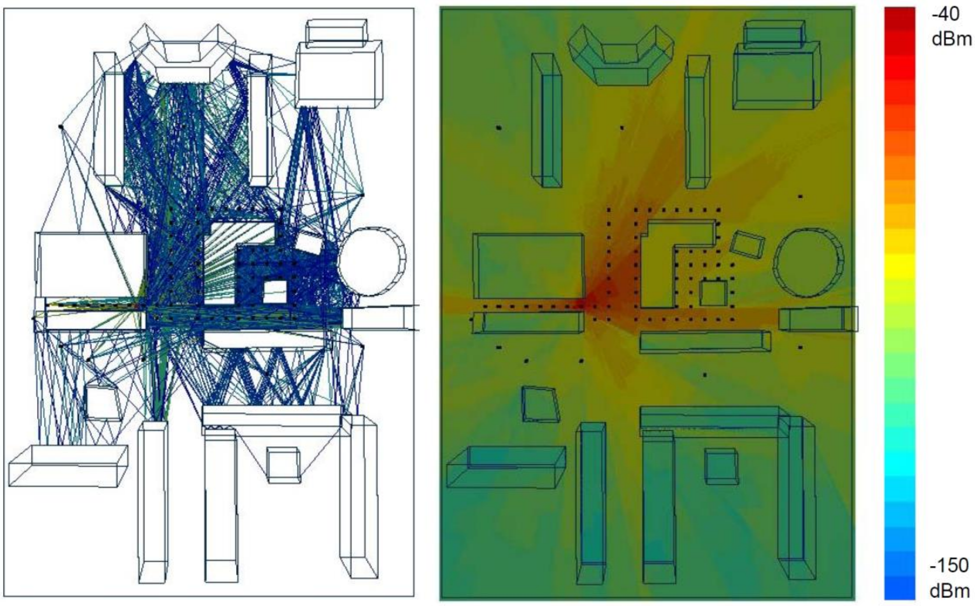

Figure 3: IRLA simulation (Experiment 1), left: outdoor rays, right: outdoor coverage map

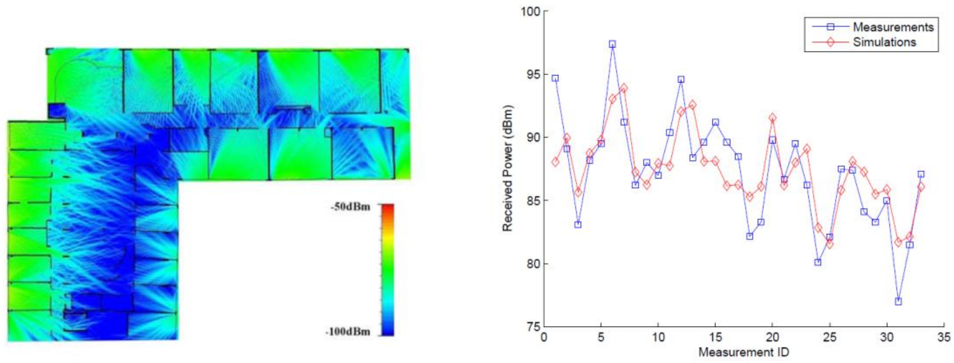

Figure 4: Outdoor to Indoor simulation results (Experiment 1)

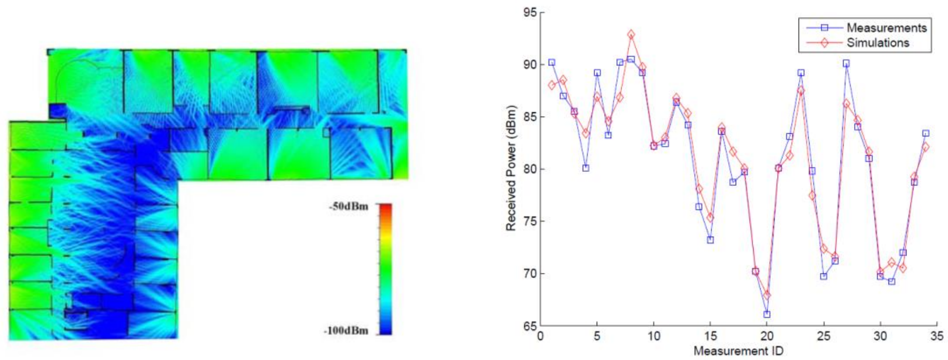

Figure 5: Outdoor to Indoor simulation results (Experiment 2)

The time durations of the simulations are given inTab.3 and it is shown that the total simulation time (once the MRFDPF preprocessing has been already done) for one outdoor to indoor prediction is less than 2 minutes on a standard computer. 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.

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

Table 3: Performance of the model: simulation times (on PC, 2.4GHz, 2Gb RAM).

5.1 Advantages of the model

It is important to notice that, without combining MRFDPF 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(log2(N).N2), 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 log2(560/100).(560/100)2 = 78 times slower, i.e. it would take approximately 2.5 hours instead of less than 2minutes (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 simulatedin3D.Consequently, the new model proposed in this study is advantageous both in term of speed and accuracy.

6. Indoor to outdoor hybridization

As it has been mentioned above, the MR-FDPF method cannot be directly interfaced with the ray-optical methods, even for the reverse problem of indoor-to-outdoor propagation.

6.1 Principle of MR-FDPF to IRLA link

In this section, we propose a method that allows combining the the MR-FDPF method and the ray-optical methods in attempt to efficiently model indoor-to-outdoor propagation environments.

At every point characterized by the radius-vector r, the complex scalar electrical field strength *E*(r, *f*) predicted by the MR-FDPF method at the frequency f ∈ B, where B denotes the signal bandwidth, satisfies the wave equation [20].

Thus, it is eligible to approximate the field strength by a finite sum of plane waves arriving at the point from different directions, i.e.,

$$E(\mathbf{r}, f) = \sum_{n=1}^{N} g_n e^{-j2\pi f \tau_n} e^{-j\langle \mathbf{k}_n, \mathbf{r} \rangle} + w(\mathbf{r}, f) \qquad (2)$$

where each of the N plane waves is characterized by the complex-value amplitude g_n, propagation delay τ_n, and the wave vector k_n pointing in the direction of the wave propagation.

The operator ⟨. ⟩ denotes the scalar product of two vectors.

The term *w*(r, *f*) in (2) (the approximation error) corresponds to the diffuse wave component (see, e.g., [20]).

In spite of the deterministic nature of the MR-FDPF method, we assume that the field strength *E*(r, *f*) (2) predicted by the MR-FDPF method is a single available realization of the corresponding stochastic process. To some degree, this assumption can be justified by observing that multiple uncertainties are inherent in modeling of any complex propagation scenario.

For example, adjustments (corrections) made to the model geographical database, would result in a new realization of the predicted field strength *E*(r, *f*).

We also presume that the term *w*(r, *f*) is a realization of the random zero-mean Gaussian process uncorrelated with respect to the frequency and the spatial position.

$$\{g_n, \tau_n, \mathbf{k}_n\}_{n=1}^{N}$$

The task is to estimate the parameters from the values of the electrical field strength predicted by the MR-FDPF method at the point r and its vicinity.

For this purpose, we employ the space-alternating generalized expectation-maximization algorithm (SAGE) [9], [10].

Note that under the assumptions made above, the estimates $\{\hat{g}_n, \hat{\tau}_n, \hat{\mathbf{k}}_n\}_{n=1}^{N}$ asymptotically approach the maximum likelihood (ML) estimates.

As the parameter $\{\hat{g}_n, \hat{\tau}_n, \hat{\mathbf{k}}_n\}_{n=1}^{N}$ estimates are determined for all points along the border of the propagation environment covered by MR-FDPF method, the rays can be launched in the directions defined by the wave vectors $\widehat{k_n}$ pointing outside of the indoor area. A further propagation of the rays is controlled by the ray-optical method, where the rays are propagated in the outdoor environment, thus allowing to compute the received signal in the whole scenario. In the next section a measurement campaign is performed in order to evaluate the performance of this approach.

6.2 Performance evaluation

The propagation scenario considered in this section is the same as previously: INSA university campus in Lyon, France, already shown in Fig. 1.

The size of the environment is 800 by 560 m. Marked in red in Fig. 1 is the CITI building. The CITI building dimensions are approximately 110 by 100 m.

The electrical field strength $E(\mathrm{r}, f)$ inside the CITI building and its immediate surroundings has been computed with a spatial resolution of 5 cm in the frequency band B = 60 MHz.

The power of the electrical field obtained by the MR-FDPF method at the central frequency f = 3,5 GHz is shown in Fig. 6.

The electrical field at every 40 cm (8 times 5 cm) interval located at 2 m outside the walls around the CITI building is modeled by the sum (2) of N = 20 plane waves propagating from the inside of the CITI building. Note that the choice of the number N of the plane waves in (2) is mainly dictated by the trade-off between the prediction accuracy and the computational load associated with estimating the parameters

of the plane waves. The useful parameters for each of the intervals are estimated by using the SAGE algorithm. The estimated amplitudes and the propagation directions in the horizontal plane defined by the estimated wave vectors are then supplied to the intelligent ray launching algorithm (IRLA) [12].

The rays constructed based on the estimated parameters for the considered propagation scenario are visualized in Fig. 7. The coverage map computed with the IRLA for the outdoor environment is depicted in Fig. 8.

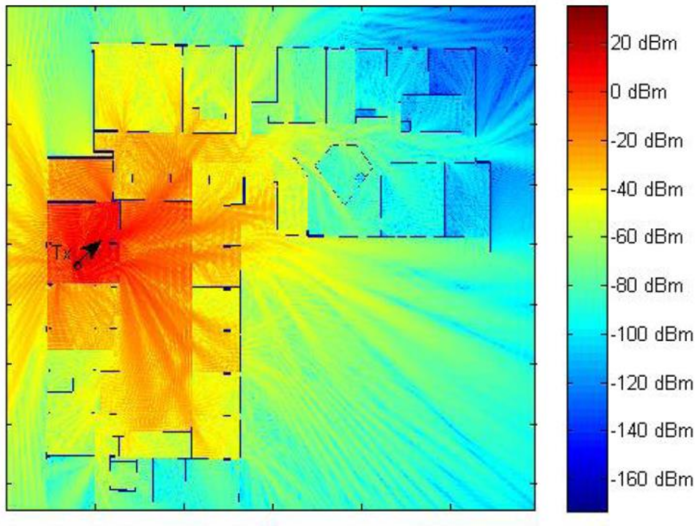

Figure 6: The predicted indoor radio coverage

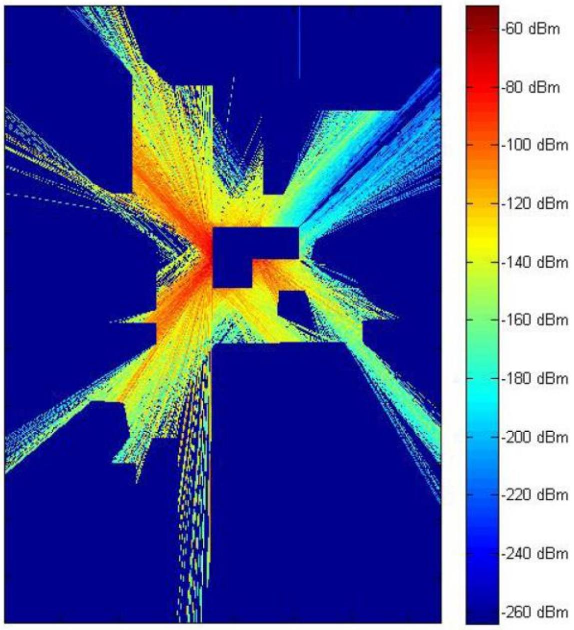

Figure 7: Rays constructed based on the indoor radio coverage prediction.

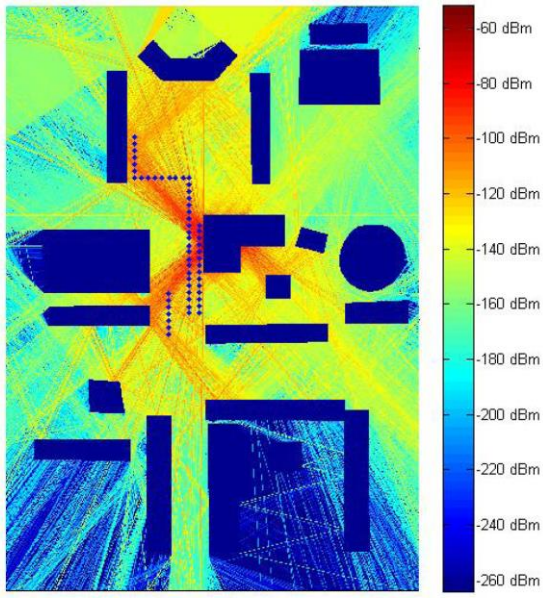

Figure 8: The predicted outdoor radio coverage.

In order to evaluate the performance of the new combined model a measurement campaign has been carried out. A transmitter equipped with a directive antenna has been deployed inside the CITI building. The transmitting antenna has been located approximately 10 m above the ground. The position of the transmitter (Tx) and the orientation of transmitting antenna's diagram are depicted in Fig. 6. Radio measurements have been performed at the locations marked with the dots in Fig.8. The omnidirectional antenna has been used at the receiver. The height of the receiving antenna is approximately 1.5 m. To reduce the effect of uncertainties inherent in the modeling and measurement processes, the calibration of the IRLA has been conducted. It is to be noticed that, due to restricted details in the outdoor buildings database, all the buildings have been modeled using the same unique material.

Hence, during the calibration process, the path loss coefficients for reflection and diffraction for both LOS and NLOS cases have been optimized. The approach is based on a hill climbing algorithm whose cost function to minimize is the root mean square error (RMSE) between the measurements and the simulations. In order to avoid the algorithm stopping in a local minimum, a random change of parameters is regularly performed.

In Fig. 9 the comparison between the measurements and simulation results (after calibration) is plotted. A relatively large discrepancy between the simulation results and the measurements observed in Fig. 9 can partly be explained by the fact that the transmitting and the receiving antennas have been positioned at different heights. The question of antenna height compensation for the indoor-to-outdoor model will be considered in the following works.

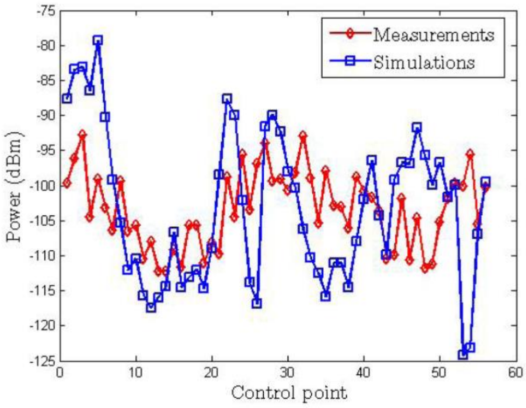

Figure 9: Comparison between measurements and simulation results.

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3. Perspectives

This deliverable summarizes the development of a link between two different radio propagation tools: IRLA and MR-FDPF. This work permits to evaluate very complex scenarios such as I2O and O2I propagation, enabling the evaluation of radio link quality for heterogeneous networks combining macrocells and femtocells.

4. Publications and software results

Journal papers

[1] G. de la Roche, P. Flipo, Z. Lai, G. Villemaud, J. Zhang and J-M. Gorce, Implementation and Validation of a New Combined Model for Outdoor to Indoor Radio Coverage Predictions. EURASIP Journal on Wireless Communications and Networking, vol. 2010, Article ID 215352, 9 pages, 2010.

Conferences with proceedings

[2] G. De La Roche, P. Flipo, Z. Lai, G. Villemaud, J. Zhang and J-M. Gorce. Combination of Geometric and Finite Difference Models for Radio Wave Propagation in Outdoor to Indoor Scenarios. In EuCAP 2010, Barcelona, Spain, April 2010.

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