A New Deterministic Hybrid Model for Indoor-to-Outdoor Radio Coverage Prediction

Dmitry Umansky*†, Guillaume de la Roche‡, Zhihua Lai§, Guillaume Villemaud*†, Jean-Marie Gorce*†, Jie Zhang‡§
*CITI, INSA-LYON, F-69621, Villeurbanne, France
†INRIA, Université de Lyon, F-69621, Villeurbanne, France
‡CWiND, University of Bedfordshire, Park Square Campus, Luton, LU1 3JU, UK
§Ranplan Wireless Network Design Ltd, 1 Kensworth Gate, Luton LU6 3KS, UK

***Abstract*—In this article, we propose a new hybrid modeling method for indoor-to-outdoor 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.**

I. 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 [1] 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 [2], [3] 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 (see also discussion in [4]). 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. It is to be noticed that a 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 already explored in [5]. In this article, we propose 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. Several works related to this subject can be found in [6] and the references therein.

The rest of the paper is organized as follows. In Section II, we briefly introduce the principal problem associated with combining the ray-optical and the MR-FDPF approaches. The method that allows combining the two modeling approaches is described in Section III. The results of the performance evaluation of the proposed hybrid modeling method are presented in Section IV. The concluding remarks are given in Section V.

II. Problem Formulation

Before going into the details related to the development of the hybrid model, we briefly describe the different paradigms, which the MR-FDPF and the ray-optical modeling approaches are based on.

In the ray-optical modeling method, the electrical field strength at each point is calculated as a sum of the rays passing through the point. Each ray obeys the laws of geometrical optics. The reflections and diffractions of transmitted signals on the obstacles are computed by tracing all the possible rays between transmitters and receivers.

In contrast, the MR-FDPF method is based on the cellular automata formalism [7]. The electrical field strength is obtained by summing the fictitious flows traveling along a regular grid of transmitting lines and experiencing scattering at the nodes of the grid.

It follows that additional post-processing is required in order to transform the prediction results provided by the MR-FDPF method into a set of appropriate parameters of the rays to be used in the ray-optical methods. This will be described in the next section.

III. Combination of Models

As it has been mentioned above, the MR-FDPF method cannot be directly interfaced with the ray-optical methods.

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 $\mathbf{r}$, the complex scalar electrical field strength $E(\mathbf{r}, f)$ predicted by the MR-FDPF method at the frequency $f \in B$, where B denotes the signal bandwidth, satisfies the wave equation [7]. 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.,

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

where each of the N plane waves is characterized by the complex-value amplitude g_n, propagation delay τ_n, and the wave vector $\mathbf{k}_n$ pointing in the direction of the wave propagation. The operator $\langle \cdot \rangle$ denotes the scalar product of two vectors. The term $w(\mathbf{r}, f)$ in (1) (the approximation error) corresponds to the diffuse wave component (see, e.g., [8]).

In spite of the deterministic nature of the MR-FDPF method, we assume that the field strength $E(\mathbf{r}, f)$ (1) 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 $E(\mathbf{r}, f)$.

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

The task is to estimate the parameters $\{g_n, \tau_n, \mathbf{k}_n\}_{n=1}^{N}$ from the values of the electrical field strength predicted by the MR-FDPF method at the point $\mathbf{r}$ 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 estimates $\{\hat{g}_n, \hat{\tau}_n, \hat{\mathbf{k}}_n\}_{n=1}^{N}$ 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 $\hat{\mathbf{k}}_n$ 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.

IV. Performance Evaluation

The propagation scenario considered in this section is the INSA university campus in Lyon, France, shown in Fig. 1. The size of the environment is 800×560 m. Marked in red in Fig. 1 is the CITI building. The CITI building dimensions are approximately 110×100 m.

Fig. 1. The INSA university campus in Lyon, France.

The electrical field strength $E(\mathbf{r}, f)$ inside the CITI building and its immediate surroundings has been computed with a spatial resolution of 5 cm[1] 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. 2.

The electrical field at every 40 cm (8×5 cm) interval located at $2 - 3$ m outside the walls around the CITI building is modeled by the sum (1) 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 (1) 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 parameters $\{g_n, \tau_n, \mathbf{k}_n\}_{n=1}^{20}$ for each of the intervals are estimated by using the SAGE algorithm (see Section III). The estimated amplitudes $\{\hat{g}_n\}$ and the propagation directions in the horizontal plane defined by the estimated wave vectors $\{\hat{\mathbf{k}}_n\}$ 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. 3.

[1]The MR-FDPF method is restricted to modeling two-dimensional (2D) propagation environments (see, e.g., [5], [11]).

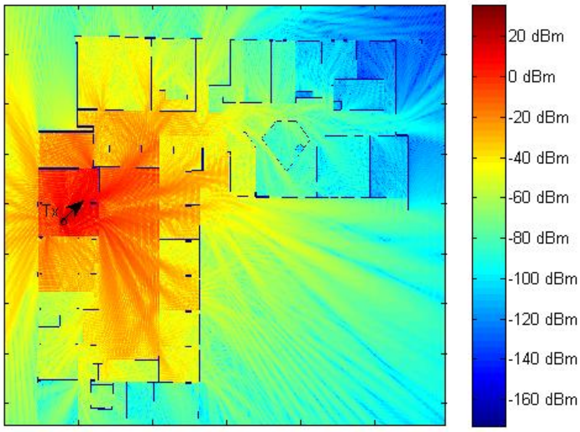

Fig. 2. The predicted indoor radio coverage.

The coverage map computed with the IRLA for the outdoor environment is depicted in Fig. 4.

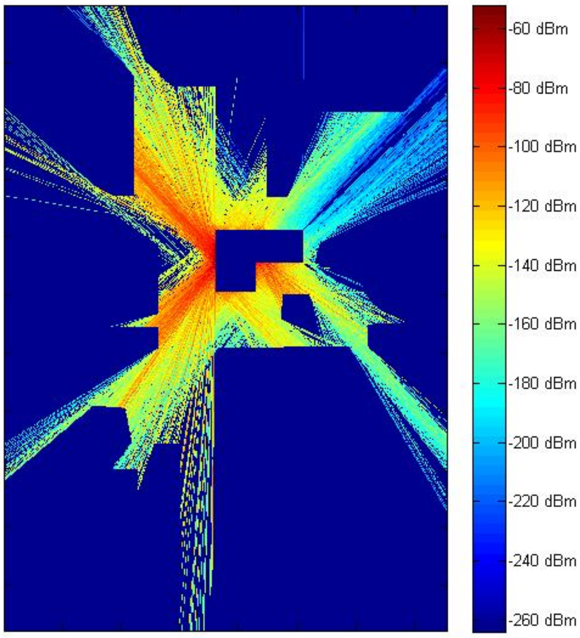

Fig. 3. Rays constructed based on the indoor radio coverage prediction.

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. 2. Radio measurements

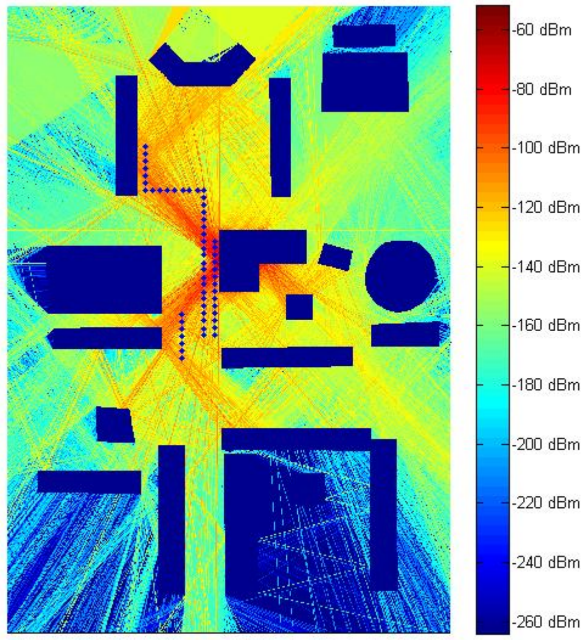

Fig. 4. The predicted outdoor radio coverage.

have been performed at the locations marked with the dots in Fig. 4. 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 5 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 5 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 publications.

V. Conclusions

A new hybrid model for indoor-to-outdoor radio coverage prediction is proposed. An initial feasibility study of the

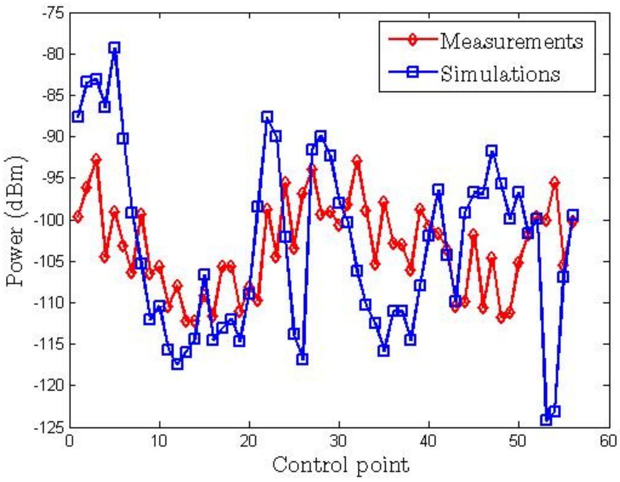

Fig. 5. Comparison between measurements and simulation results.

proposed hybrid model has been presented in this paper. The results show that this deterministic model, which combines the advantages of the MR-FDPF and the ray optical approach, has a potential in providing accurate predictions. Future work will be dedicated to an efficient implementation of the proposed modeling approach. Our intention is also to evaluate this hybrid model in other propagation scenarios.

ACKNOWLEDGMENT

This project is funded by the FP7 IPLAN Project.

REFERENCES

[1] J.-M. Gorce, K. Jaffres-Runser, and G. de la Roche, "Deterministic approach for fast simulations of indoor radio wave propagation," vol. 55, no. 3, pp. 938–948, 2007.

[2] R. Hoppe, P. Wertz, F. M. Landstorfer, and G. Wölfle, "Advanced ray-optical wave propagation modelling for urban and indoor scenarious including wideband properties," *Europian Transactions on Telecommunications*, vol. 14, pp. 61–69, 2003.

[3] A. F. Molisch, *Wireless Communications*. Chichester: Wiley-IEEE Press, 2005.

[4] J.-M. Gorce, K. Jaffrès Runser, and G. De La Roche, "The Adaptive Multi-Resolution Frequency-Domain ParFlow (MR-FDPF) Method for Indoor Radio Wave Propagation Simulation. Part I : Theory and Algorithms," INRIA, Tech. Rep. RR-5740, 11 2005. [Online]. Available: http://hal.inria.fr/inria-00070278/PDF/RR-5740.pdf

[5] 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*, 2010.

[6] Z. Zhang, R. K. Sorensen, Z. Yun, M. F. Iskander, and J. F. Harvey, "A ray-tracing approach for indoor/outdoor propagation through window structures," vol. 50, no. 5, pp. 742–748, 2002.

[7] B. Chopard and P. O. Luthi, "Lattice boltzmann computations and applications to physics," *Theor. Comput. Sci.*, vol. 217, no. 1, pp. 115–130, 1999.

[8] G. D. Durgin, *Space–Time Wireless Channels*. NJ: Prentice Hall, 2003.

[9] J. A. Fessler and A. O. Hero, "Space–alternating generalized expectation–maximization algorithm," vol. 42, no. 10, pp. 2664–2677, Oct. 1994.

[10] B. H. Fleury, P. Jourdan, and A. Stucki, "High-resolution channel parameter estimation for MIMO applications using the SAGE algorithm," in *2002 Int. Zurich Seminar on Broadband Communications*, Zurich, Switzerland, Feb. 2002, pp. 30–1–30–9.

[11] G. de la Roche, K. Jaffres-Runser, and J.-M. Gorce, "On predicting in-building wifi coverage with a fast discrete approach," *International Journal of Mobile Network Design and Innovation*, vol. 2, pp. 3–12, 2007.

[12] Z. Lai, N. Bessis, G. de laRoche, H. Song, J. Zhang, and G. Clapworthy, "An intelligent ray launching for urban prediction," in *Proc. 3rd European Conf. Antennas and Propagation EuCAP 2009*, 2009, pp. 2867–2871.