A High-Speed 2.5D Ray-Tracing Propagation Model for Microcellular Systems, Application: Smart Cities

Taha ALWAJEEH[1], Pierre COMBEAU[1], Rodolphe VAUZELLE[1], Ahcene BOUNCEUR[2]
[1] XLIM Laboratory, UMR CNRS 7252, University of Poitiers, Poitiers, France, pierre.combeau@univ-poitiers.fr
[2] Lab-STICC, UMR CNRS 6285, University of Western Brittany, Brest, France, Ahcene.Bounceur@univ-brest.fr

***Abstract*— This paper introduces a new high-speed 2.5D deterministic radio propagation model. This model is suitable for outdoor urban configurations where transmitter and receiver nodes are below the rooftop level of the surrounding buildings. This model can provide narrow-band and wide-band predictions. In this paper we combine three acceleration strategies in order to achieve a high-speed site-specific urban microcellular model. The first strategy is an efficient implementation of a ray-tracing model based on the visibility tree technique. The second strategy is to consider only a limited portion of the propagation environment that has a significant contribution on the received signal estimation. The third strategy is based on a pre-calculation of the exact 2D visibility trees, in order to be used to reconstruct very quickly all the possible paths between a transmitter and a receiver. Simulation results for the implemented ray-tracing model with the first acceleration technique are presented and compared with measurements. Then, the other acceleration techniques were combined to further reduce the overall execution time to the minimum extent with a small impact on the accuracy.**

***Index Terms*—microcells, radio propagation models, smart cities, deterministic models, ray-tracing, visibilty tree, wireless sensor networks (WSN), WSN simulators, pre-calculation.**

I. INTRODUCTION

Smart city applications continue to evolve; there are a wide variety of applications such as environmental measurements, security applications, intelligent transportation, smart parking, smart water networks, etc. In the future, the number of sensing devices will definitely grow. The technology which supports inexpensive interconnection of sensing devices to internet is wireless sensor networks WSNs [1]. A WSN consists of a number of autonomous spatially distributed nodes that are connected via wireless links to perform their assigned tasks. In order to design and deploy a WSN in the most efficient manner, propagation models along with the related protocols and algorithms are required to be integrated in the simulation tools. One of the challenges in this field is the accuracy and rapidity of the radio propagation models. Since the site measurements are costly, propagation models have been developed as accurate and low cost alternative [2]. The purpose of the propagation modeling is to obtain a good estimation of the field strength when some parameters are known, such as the frequency, antenna heights, the propagation environment, and so on [3]. In our context, due to the specific nature of the urban environments of the smart cities, we need site-specific or geometry-based propagation models such as ray-tracing (RT) models. This leads us to exclude the empirical/statistical models in this context, despite the fact that they are extremely fast and can be easily implemented. RT models are accurate but they need a huge amount of data related to the geometry of the propagation environment so they require high computational time for finding the rays' trajectory. Let us formulate the problem in another way: we are searching for a propagation model that could be as accurate as the deterministic models and as fast as the empirical/statistical models. This ideal model does not exist and for this reason we have to propose a trade-off between the accuracy and the execution time.

To further clarify the objective of this paper, we present briefly the context in which this paper was written. The work presented here is part of a project which aims to develop a 3D Virtual Platform for Wireless Sensor Network Simulation [4]. Our role in this project focuses on the radio channel modeling. The required models that will be integrated into this platform must meet these requirements:

- Accurate propagation models that consider the geometry of the propagation environment
- Ability to support up to thousands of nodes.
- Ability to support mobile nodes.
- Within a reasonable computational time

The following sections propose deterministic channel modeling with a small loss of precision but with a considerable gain in time. The rest of this paper is organized as follows: section II presents our ray-tracing model based on the visibility tree technique. Section III evaluates the impact of using limited propagation scene on both accuracy and execution time, and then it suggests the optimum number of interactions. Section IV illustrates the concept of tree pre-calculation and presents some results for a WSN application.

II. RAY-TRACING BASED ON VISIBILITY TREE

A. Ray-Tracing

Deterministic modeling in urban environments has been widely addressed in particular ray-based models. Ray-based models such as ray-tracing use ray-optical approximation, which is based on Geometrical-Optics [5] and on the Uniform Theory of Diffraction [6]. Ray-based models describe the propagating field as a set of rays undergoing multiple reflections and diffractions from the obstacles in the propagation environment. Although ray-tracing models have shown to be accurate, they have a major disadvantage of being computationally expensive due to the use of the source image technique to find the intersection points of rays with the scene obstacles. They also need a detailed description of the environment [7]. This is one of the reasons why we have to use another technique for our application. The prime candidate for this purpose is the visibility tree technique.

B. Horizontal Visibility Tree

In microcellular configurations, the antennas are lower than the average height of the surrounding buildings. Hence, almost all the significant rays are found in the horizontal plane (except for the ground reflected ray) while the vertical plane contains less significant diffracted rays (diffracted over the roof-tops of the buildings). For this reason, some authors propose 2D and 2.5D (quasi 3D) ray-tracing approaches for microcells such as those in [8-11]. This can justify our choice of using a horizontal plane for the proposed model.

The principle of the visibility tree is quite easy, but its implementation in an efficient way demands specific techniques that will not be explained in this paper. Rather, we present the general procedure. Still, if you are interested in more details, refer to [12-14]. The visibility technique is an algorithm that starts from a 2D layout of the propagation environment and from a root node (Tx) to construct a layered structure which is the visibility tree. The visibility tree consists of nodes and branches. The root node corresponds to the transmitter, the first level of the tree represents the visible zones, and next level consists of new zones that have undergone a reflection or diffraction and so on.

The first step of our algorithm is to simplify the propagation scene into a horizontal 2D scene. Fig. 1 shows (neglect the colored zones for the moment) a 2D top-view of a simple environment with five buildings (the white blocks), a transmitter (Tx), and a receiver (Rx).

Let us consider one reflection and one diffraction:

- From the transmitter (Tx), the algorithm determines a set of geometric zones that are visible from this point (the nine visible blue zones V.1 –V.9 in Fig. 1).
- For each visible zone, if it encounters a wall/diffracting edge in the scene, the algorithm generates the corresponding reflected/diffracted zones (the red/pink zones in Fig. 1). For simplicity, Fig. 1 shows the diffracted zones for only one edge P.
- Then, the algorithm attaches the generated zones to their parents and it repeats the same procedure until it reaches the maximum number of interactions.

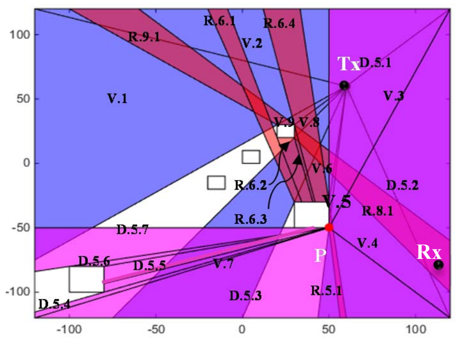

Fig. 1. Visible, reflected, and diffracted zones

Fig. 2 shows the visibility tree that corresponds to the example of Fig. 1.

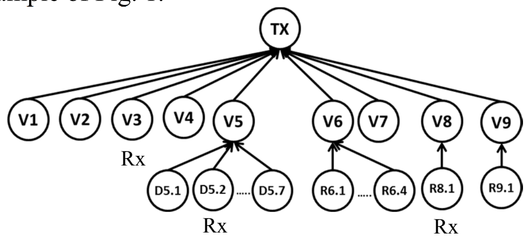

Fig. 2. SimpleVisiblity Tree.

Let us consider the receiver (Rx) as shown in Fig. 1 and Fig. 2. Rx is found in these zones: V3, R.8.1, and D.5.2 of the tree, so we can easily identify three rays (direct, reflected, and diffracted rays). These rays can be quickly constructed in 2D by the source image technique, because we know the order, the type of the interactions, and the objects that caused these interactions.

C. Transformation into a 2.5D Model

Now, we still need to transform the found rays into 3D rays. Using Fermat's principle of least time, we can adjust the rays' trajectory on the z-axis only because the rays already have the right coordinates in the x-y plane. To achieve this, a simple algorithm was implemented to satisfy Fermat's principle by considering the exact antenna heights, and then by using formulas of the right triangle, we can adjust the intermediate points. Equation (1) and Fig. 3 illustrate this procedure for the reflection point P. The same procedure applies for multiple reflections and diffractions.

$$Z_p = d_1 \times ((H_r - H_t) / (d_1 + d_2)) + H_t \qquad (1)$$

This model was enhanced by introducing the ground reflected ray because it has a great impact especially in near ground scenarios [15]. Despite the fact that this model finds the rays in 3D, it cannot be considered as a full 3D model because it does not include the diffracted rays over the rooftops (horizontal edges), so it is called a 2.5D model.

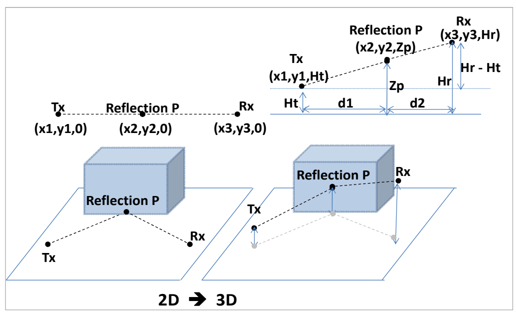

Fig. 3. 2D to 3D transformation

D. Model Validation and Time Gain

Fig 4 shows the (étoile) neighborhood in Paris for which we have field measurements conducted by France Telecom R&D. This is a typical urban scenario with quite high buildings. The transmitter is located at a height of 21 m with a transmit power of 45 dBm using a vertical dipole antenna.

The measurements were conducted at 932 MHz through a route of 5 km (corresponding to 1651 equidistant receivers).

For the simulation, the propagation scene was modeled with 10330 faces and 15504 edges. Antenna heights and theoretical radiation pattern for a dipole have also been taken into consideration. Simulation results were conducted for four reflections and one diffraction (because it was found that for this configuration the simulation converges at 4R1D).

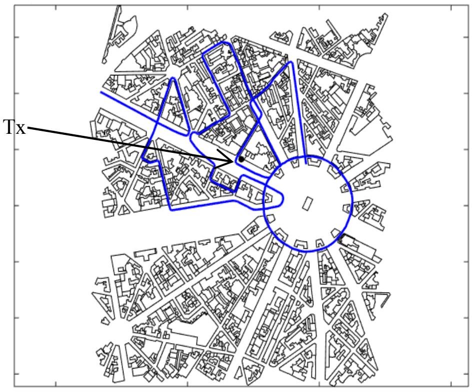

Fig. 4. The (étoile) neigborhood with the measurement route, Tx position

Fig. 5 shows the simulation results for the proposed 2.5D model (the blue curve) in comparison with the field measurements (the red curve). We can observe a good agreement between the simulation and the measurements. The mean absolute error is about 7.5 dB, the mean error is about - 0.15 dB and the standard deviation is about 9.4 dB (pink parts in Fig. 5 were not considered). The error can be justified by many facts: the propagation environment does not include all the details of the scene. The buildings were modeled as typical concrete blocks (relative permittivity ε_r = 9, conductivity σ = 0.01 S/m) and the ground was modeled as a perfectly flat concrete surface. Furthermore, vehicular traffic and vegetation were not considered. Another source of error is that the diffracted rays from rooftops were neglected. Despite the fact that the model can compute all paths' characteristics (delay, complex magnitude, angles, etc.), we could not compare the wide band parameters because the measurements were limited to path loss.

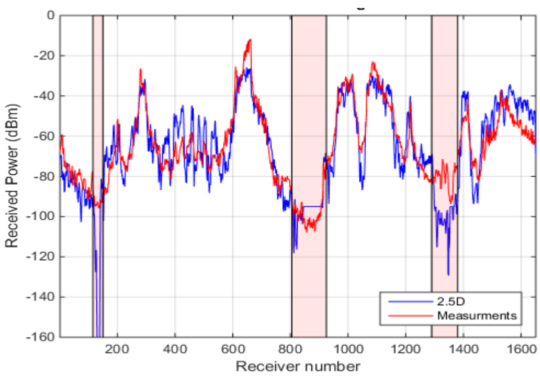

Fig. 5. Measerment vs Simulation.

Table I shows a very considerable gain in the execution time for the 2.5D model compared to a full 3D ray-tracing model. Moreover, the execution time is almost independent of the number of receivers. Hence, for the same transmitter, we can use the same visibility tree for all the receivers, whereas a 3D ray-tracing model needs to perform a new simulation for every single receiver. The term incalculable in the table indicates that it would take weeks or even months.

TABLE I. GAIN IN TIME

Number of Interactions	*2.5D RT 1651 receivers*	*3D RT per link*	*3D RT 1651 receivers*
1R1D	~ 1.2 s	~ 1 m 44 s	~ 17h 25m
2R1D	~ 6.2 s	~ 2d 3h 56m	incalculable
3R1D	~ 19.8 s	incalculable	incalculable
4R1D	~ 52 s	incalculable	incalculable

III. LIMITED PROPAGATION SCENE

A. *Optimum Range*

Deterministic models tend to be computationally more expensive as the propagation scene becomes more complex. In microcellular configurations, only the surrounding buildings have a considerable impact on the signal estimation. In our context, the nominal transmit power for the famous family of WSN that uses the IEEE 802.15.4 physical layer - 2003 is 1 mW (0 dBm) [16], giving a radio range of at most a few hundred meters. This leads us to exploit these facts by considering only a portion of the propagation environment that affects the simulation results.

The concept is as follows: starting from the transmitter and for a given radius, we will consider all the geometry that is found completely or partially within this radius and neglect what exists outside this range. By using this concept, the visibility tree will be calculated for a smaller window and consequently the rays will be found within this window, which will reduce the execution time. The question that arises now is: what is the optimum range that we should consider so that there is a negligible impact on the accuracy?

This question was answered thoroughly using several test scenarios (as those shown in Fig.7). We used a grid of receivers to get more reliable and accurate results. For the sake of brevity, we will present only the results of one scenario of Fig.6, where the transmitter is placed in an intersection. The grid of receivers (the blue points) is distributed in a uniform manner at a distance between 80 – 100 m (where the error values are higher than the near receivers due to the limitation of the scene). Then we will vary the size of the portion of the propagation scene (the circles around the transmitter of 100 m, 150 m, 200 m, 250 m, 300 m, and the whole propagation environment). This model will be used as a self-reference for evaluating the impact of the limited scene.

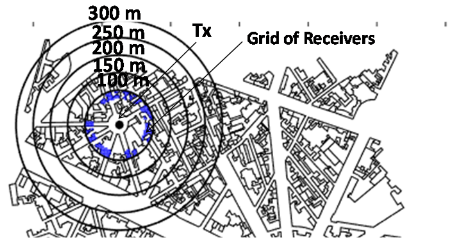

Fig. 6. Test Senarion : Impact of the limited propagation scene.

Table II shows the impact of considering a portion of the propagation scene (as shown in Fig. 6) on the accuracy by evaluating the mean error with respect to the estimations in which the whole scene was used. Moreover, similar results were found for the other scenarios as those in Fig. 7. In general, all the interactions followed the same trend, the smaller the portion, the higher the error, the faster the execution time. Furthermore, the introduced errors are negligible starting from 150 m (≤ 0.1 dB). Let us take as an example 4R1D; instead of conducting a simulation that takes 22 s with the whole scene, we can conduct a simulation that considers only 150 m and we get almost the same results in about 6 s with a negligible mean error of 0.1 dB. Through this study, we came to the conclusion that the optimum portion to consider could vary and depends on the Tx-Rx distance and on the propagation environment.

TABLE II. IMPACT OF THE LIMITED SCENE ON THE ACCURACY

Parameters / *Range*		*100 m*	*150 m*	*200 m*	*250 m*	*300 m*	*Whole scene*
1R1D	Error [dB]	0.18	0.091	0.016	0.009	0.008	--
	Time [s]	0.43	0.61	0.73	0.96	1.1	1.2
2R1D	Error [dB]	0.24	0.094	0.018	0.009	0.007	--
	Time [s]	1.2	1.7	2.0	2.6	2.9	3.5
3R1D	Error [dB]	0.26	0.11	0.04	0.01	0.008	--
	Time [s]	1.8	4.4	4.9	6.3	7.3	10.2
4R1D	Error [dB]	0.34	0.10	0.05	0.012	0.011	--
	Time [s]	3.8	6.5	7.2	9.8	12.6	21.8

B. *Optimum Number of Interactions*

After having determined the optimum range, the next question that arises is: what is the optimum number of interactions that we should consider?

We are searching for a trade-off that minimizes the error, minimizes the execution time, and maximizes the coverage percentage. For this reason, this trade-off was proposed using several test scenarios that summarize the main urban cases as shown in Fig. 7. In order to get more reliable results, we evaluated the error and the execution time using a large number of receivers (uniformly distributed in a grid as shown in Fig. 7). The test scenarios are as follows:

- An open place, 1082 receivers (LOS:1067, NLOS:15)
- A wide street, 537 receivers (LOS: 300, NLOS: 237)
- A narrow street, 347 receivers (LOS:97, NLOS:250)
- An intersection, 613 receivers (LOS:352,NLOS:261)

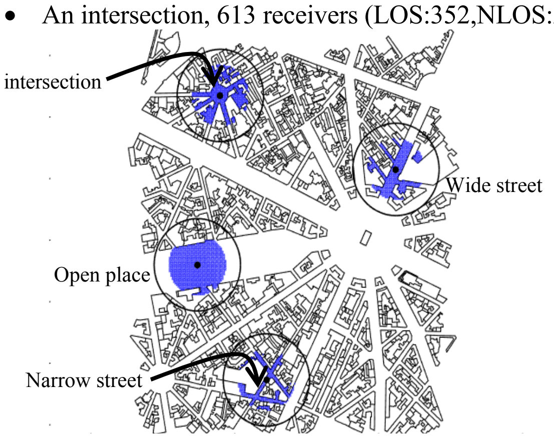

Fig. 7. Test Scenarios

From the above study we found that, in open scenarios, a ray that has undergone some reflections and diffractions has no significant contribution to the channel estimation. On the other hand, narrow streets are rich in multipaths so, even if a ray has undergone some reflections and diffractions, it can contribute significantly to the estimation.

We also came to the conclusion that, there is no magic number of interactions that is ideal for all scenarios. However, 4R1D could be an acceptable answer to the mentioned question. For this reason, we would rather give indicative guidelines as shown in Fig. 8, and then according to the application (in terms of accuracy restrictions and time tolerance) you can choose the most convenient one. Fig. 8 summarizes the results of the conducted study to evaluate the margin of error (with respect to the number of interactions for which the estimation converges) and the execution time (for a calculation window of 150 m for this and next section).

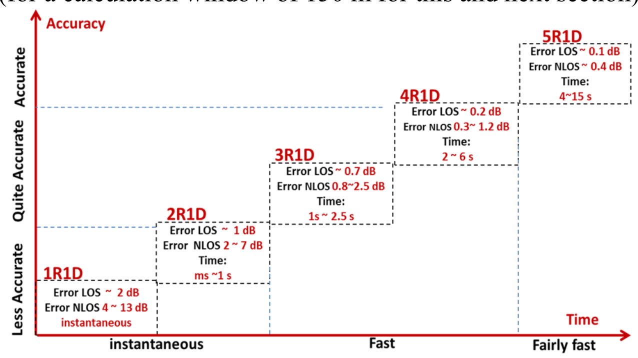

Fig. 8. Guide for the optimum number of interactions

The error was evaluated with respect to the number of interactions for which the simulations converge. Another important point is that we evaluated the error in LOS and NLOS because if we took the average for both cases, it would hide the higher values of error in NLOS.

IV. PRE-CALCULATION

At this stage, we have a 2.5D ray-tracing model based on the visibility tree technique. The calculation of a visibility tree can be conducted for a small portion of the propagation environment with a negligible loss of precision and with a considerable gain in time. Up to now, the execution time for quite accurate simulation is in the order of a few seconds (150 m, 4R1D, even for a few thousands of receivers). Nevertheless, smart cities may contain mobile nodes; hence our model should support these nodes, i.e. we still need to further reduce the execution time. For this reason we are proposing the pre-calculation concept. The idea here is to save the visibility trees in the most compact form possible (to reduce the writing time, reading time, treating time, and the storage size on the hard disk). To achieve this goal, we did not save the whole structure of the tree, but rather we saved only the required information to reconstruct the paths, and neglect all the information used to construct the tree itself.

Table III shows the execution time that is required to search for the pre-calculated tree, read it, reconstruct the rays from the tree, and to calculate the field strength. As the simulations were conducted for a large number of receivers, the times in Table III were calculated per link (averaged over all the receivers). Table III shows that, the final proposed model can perform very high-speed simulations even for quite a large number of interactions.

TABLE III. EXCUTION TIME AND SIZE FOR PRE-CALCULATED VISIBILTY TREES

Number of Interactions	*Time Per Link*	*Size Per Tree*
1R1D	< 1 ms	50 KB ~ 250 KB
2R1D	~ 2 ms	100 KB ~ 1 MB
3R1D	~ 6 ms	200 KB ~ 2.8 MB
4R1D	~ 10 ms	500 KB ~ 5 MB

Ideally visibility trees should be pre-calculated for every potential position of the transmitter in order to avoid any loss in precision, which is not possible. Instead, we propose discretizing the space with a small spatial step and pre-calculate the trees for this fictive grid. But that means that, for a given transmitter we will use the nearest visibility tree if the exact one was not found. Hence, the final question is: what is the optimum step size to be used to pre-calculate the trees so that the error is negligible or even acceptable?

In [17], the minimum separation between two adjacent receivers is 0.8λ so that they are uncorrelated samples. As the radio propagation channel is reciprocal, this value could be used for this purpose. However, this value corresponds to 10 cm (at f = 2.4 GHz), which is an extremely small value for a city-scale discretization. For this reason, we are going to use larger steps and estimate the error empirically.

Table IV evaluates the error due to the use of the nearest tree instead of the exact one. 150 transmitters were distributed through a route of 500 m, each transmitter will pick the nearest pre-calculated tree to reconstruct the paths. The mean error was estimated over a grid of receivers (about 150 receivers) around each transmitter. Table IV shows that the error becomes smaller for fine discretization (more space on the hard disk). However, optimum grid size is determined in terms of the required accuracy of the application.

TABLE IV. STEP SIZE VS MEAN ERROR

Test Parameter	*Step Size*	*Mean Error*
4R1D	10 m	4.4 dB
	5 m	3.2 dB
	2 m	1 .6 dB
	1 m	0.78 dB

IV. CONCLUSION

In this paper, we have presented a fast deterministic 2.5D ray-tracing model for microcellular configurations. The simulation results for this model were compared and with measurements that were conducted in an urban scenario. The simulation results corresponded closely to the measurements. The first phase of the model was accomplished by implementing a ray-tracing model based on the visibility technique. With the first phase, we can perform accurate deterministic simulations in the order of tens of seconds (for 4R1D). The second phase was implemented by limiting the propagation scene to the right portion. With the second phase, we could perform accurate deterministic simulations in the order of a few seconds (for 150 m, 4R1D) with a negligible impact on the accuracy. The third phase of the model was proposed by pre-calculating the visibility trees; we can obtain estimations in the order of a few milliseconds per link (for 150 m). However, a fine discretization is required to ensure that the error is small. Finally, this model satisfies the requirements of WSN simulators, it considers the propagation scene, supports a large number of nodes, supports the mobile nodes, and within a reasonable time.

ACKNOWLEDGMENT

Our thanks to the French National Research Agency "ANR" that supports the research project "PERSEPTEUR".

REFERENCES

[1] A. Hrovat and T. Javornik "Analysis of radio propagation models for smart city applications" International journal of communication, Issue 4, vol 7, 2013.

[2] T.K. Sarkar, Zhong Ji, K. Kim ; A. Medouri, and M. Salazar-Palma "A survey of various propagation models for mobile communication," IEEE Ant. and Prop. Mag., Volume: 45, Issue: 3, pp. 51 – 82, 2003.

[3] Z. Yun and M. Iskander "Ray tracing for radio propagation modeling: principles and applications," IEEE, vol. 3, pp. 1089-1100, 2015.

[4] www.agence-nationale-recherche.fr/?Project=ANR-14-CE24-0017

[5] Balanis, C. A., Advanced Engineering Electromagnetics, John Wiley and Sons, 1989.

[6] Kouyoumjian, R. G. and P. H. Pathak, "A uniform geometrical theory of diffraction for an edge in a perfectly conducting surface,". IEEE, vol. 62, No. 11, pp. 1448–1461, 1974.

[7] E. M. Vitucci et al. "Ray tracing RF field Prediction: an unforgiving validation", International J. of antennas and propagation, vol 2015.

[8] Y.-S. Feng, L.-X. Guo, P. Wang, and Z.-Y. Liu, "Efficient ray-tracing model for propagation prediction for microcellular wireless communication systems," IEEE ISAPE, pp. 432-435, 2012.

[9] K. Rizk, J.-F. Wagen, and F. Gardiol, "Two-dimensional ray-tracing modeling for propagation prediction in microcellular environments," IEEE Trans. Veh Tech, vol 46, 1997.

[10] G.E. Athanasiadou, A.R. Nix, and J.P. McGeehan, "A ray tracing algorithm for microcellular and indoor propagation modeling," IEEE, Antennas and Prop International Conf, 1995.

[11] Z. Ji, B.-H. Li, H.-X Wang, H.-Y. Chen, and T. Sarkar, "Efficient ray-tracing methods for propagation prediction for indoor wireless communications," IEEE trans. Ant. Prop., vol 46, pp 907-919, 1998.

[12] P. Combeau, L. Aveneau, R. Vauzelle, and Y. Pousset, "Efficient 2-D ray-tracing method for narrow and wideband channel characterisation in microcellular configurations," IEEE Proc on Microwave Antennas and Propagation, vol 153, pp. 502-509, 2006.

[13] L. Aveneau, P. Combeau, R. Vauzelle, M. Meriaux, "Efficient computation of radio coverage zone using a spatial partitionment approach," IEEE Veh. Tech. Conf, vol 1, pp 65-68, 2003.

[14] T. Alwajeeh, P. Combeau, R. Vauzelle, A. Bounceur, " Efficient method for associating radio propagation models with spatial partitioning for smart city applications," ICC2016, International Conf on Internet of things and Cloud Computing, Cambridge ,2016

[15] T. Stoyanova, F. Kerasiotis, A. Prayati, and G. Papadopoulos, "A practical RF propagation model for wireless network sensors," Sensor Tech. and App. Conf., Athens, pp. 194-199, 2009.

[16] Institute of Electrical and Electronics Engineers IEEE. Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks, 2003.

[17] W. C. Y. Lee " Estimate of local average power of a mobile radio signal", IEEE Trans. on Veh. Tech., vol. VT-34, pp. 22–27, 1985.