A Hybrid Ray Launching-Diffusion Equation Approach for Propagation Prediction in Complex Indoor Environments

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***Abstract*—A novel and efficient deterministic approach to model radio wave propagation channels in complex indoor environments improving prediction accuracy is proposed. This technique combines a 3-D Ray Launching algorithm based on Geometrical Optics with a Diffusion Equation method based on the equation of transfer. A comparison between the Geometrical Optics only approach and the new method considering the Diffusion Equation has been presented for studying indoor radio wave propagation. The Geometrical Optics-Diffusion Equation method achieves better agreement with measurements, while resulting in high computational efficiency, with approximately 40% savings in simulation time.**

***Index Terms*—3D-Ray Launching, diffusion, scattering, RF environment modeling, radio channel simulation.**

I. INTRODUCTION

THE significant growth of wireless communications systems over the last years has led to the need of adequate and efficient tools to predict radio wave propagation in different environments. In this context, it is compulsory to reduce time as well resource demands required by radio planning tasks as well as network deployment and optimal base-station location configuration. It is therefore essential to develop an effective propagation model to assist wireless system design and hence, assessment in the coverage/capacity relations of urban macro-cell base stations or indoor high capacity wireless systems [1].

It has been observed that in discrete random media, electromagnetic waves present diffusive behavior, given sufficient multiple scattering takes place [2]. Due to this fact, it is highly advantageous to take into account diffuse scattering when analyzing wireless electromagnetic behavior. In the literature, several methods have implemented this phenomenon in deterministic approaches. Reference [3] presents an implementation of the diffuse scattering within a 3D urban propagation simulation method. A field prediction model which integrates reflection/diffraction with diffuse scattering is shown in [4-5] presenting the impact of diffuse scattering on narrowband and wide-band parameters, revealing the key role of diffuse scattering in urban propagation. Reference [6] presents a novel and efficient hybrid model combining a 2D site-specific model and a statistical model, to characterize the relative mean contribution of diffused scattering.

However, the computational time for the above-mentioned methods can be high depending on the desired accuracy of the results. Reduction of computational complexity and hence overall computation time has been explored following different approaches, such as combination of ray launching with neural networks [7], data storage optimization [8], volumetric space decomposition [9] or diverse tessellation approaches [10], among others.

In this work we present a novel and efficient hybrid Geometrical Optics-Diffusion Equation (GO/DE) approach to analyze radio wave propagation in complex indoor environments. Diffusion process is added to GO to account for material absorption and non-specular scattering by obstacles. The explicit form of the solution to the diffusion equation (DE), based on the equation of transfer, circumvents the much more complicated Hemholtz equation, providing a simple way to predict radio wave propagation when combined with GO methods, improving prediction accuracy. The approach taken here may be contrasted to that in [11] wherein radiosity (reradiation of power through Lambert's cosine law) is applied to determine the diffuse power caused by large roughnesses present on otherwise smooth scattering objects. In both works the goal is to assess diffused power and add to the power determined by the geometric optics field, but the approaches taken are radically different.

II. DIFFUSION EQUATION APPROACH

A. Theory

As previously stated, it has been observed that in discrete random media, electromagnetic waves present diffusive behavior, given sufficient multiple scattering takes place. In the literature, Ishimaru [2] shows that the equation of transfer in the classical transport theory can be simplified to the diffusion equation under the assumption of uniform overall scattering. Xu and Janaswamy [12] study the wave diffusion in 2-D random media and describe under what circumstances a radiowave system starts to behave diffusively, showing that the area density of the embedded obstacles manifests itself to be the most important factor in determining wave diffusion. In 2-D, the obstacle occupational density (p_0) is equal to the ratio of the total area occupied by the obstacles to the total area of the region under consideration, estimated from building floor plans and obstacle sectional areas.

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In transport theory, results are obtained directly with statistically averaged power quantities (specific intensity), and mathematical operations are derived in power instead than in voltage. Hence, the quantity being modeled is the mean incoherent intensity which is the quantity of interest when many obstacles are present. The transmission loss at any point under this model is the result of absorption as well as scattering by the obstacles [12]. The specific intensity in 2-D is a function of three arguments: two spatial coordinates $\rho = (x, y) \equiv (r_a, \varphi)$, r_a being the radial distance and φ being the azimuthal angle, and one angular coordinate ξ denoting the azimuthal direction of the average Poynting vector. After suitable normalization, the specific intensity is expressed as $I(\rho, \xi) = U_d(\rho) + \hat{s} \cdot \vec{F}(\rho)/\pi$, where $\hat{s} = \hat{x}cos\xi + \hat{y}sin\xi$, U_d is the average intensity (units of W/m) and $\vec{F}$ is the flux density vector (units of W/m). The relationship between the specific intensity, the average intensity and the flux vector are

$$U_d(\rho) = \frac{1}{2\pi}\int_0^{2\pi} I(\rho, s)d\xi \tag{1}$$

$$\vec{F}(\rho) = \frac{1}{2\pi}\int_0^{2\pi} \hat{s}I(\rho, s)d\xi \tag{2}$$

In the case of a *z*-directed line source located at the origin and radiating power P_t per unit length, the average intensity satisfies the diffusion equation [13]

$$\nabla^2 U_d - k_d^2 U_d = -\frac{P_t \rho_n \sigma_{tr}}{\pi}\delta(x)\delta(y) \tag{3}$$

in which ∇^2 is the Laplacian operator, $\rho_n(m^{-2}) = p_0/A_0$ is the obstacle number density, A_0 is the average obstacle cross section area, $\delta(.)$ is the Dirac Delta function, $\sigma_{tr}(m)$ is the obstacles transport width, and $k_d = \sqrt{2\sigma_a\sigma_{tr}\rho_n}(m^{-1})$ is the diffusion coefficient, with $\sigma_a(m)$ being the obstacles absorption width. When the size of typical obstacles is very large compared to the wavelength, the approximation $\sigma_a{\sim}\sigma_g$ and $\sigma_{tr}{\sim}\sigma_g$ can be made, where σ_g is the geometric cross section of the obstacles per unit length. The mean excess loss is defined as the ratio of the flux density in the absence of obstacles (i.e., with $k_d = 0$) to that available in the presence of obstacles [13]

$$l_{ex}^T(r_a) = \frac{F_\rho(k_d=0)}{F_\rho(k_d)} \tag{4}$$

where F_ρ is the radial component of the flux density vector and is a measure of the power flow away from the source. The explicit relationship between U_d and $\vec{F}$ can be obtained starting from the equation of transfer. It is given by [12-13]

$$\vec{F} = -\frac{\pi}{\rho_n\sigma_{tr}}\nabla U_d \tag{5}$$

B. *Ray Launching modeling with Diffusion equation*

Following the approach stated above, a new module based on DE has been developed which takes into account absorption and scattering losses due to obstacles. The DE module can be included in the Ray Launching (RL) algorithm with the GO-only-approach. The GO/DE technique ignores edge diffraction; but it is shown in [13] that the effects of edge diffraction can be neglected when the field is averaged with respect to the random locations and orientations of the obstacles within the 3-D scenario, leading to a significant reduction of simulation computational time.

In [12], it has been concluded that the diffusion solutions can be applied to indoor environments if the area density of obstacles exceeds 10%. The area density is defined by the area occupied by obstacles per total area of region of interest.

This is the key factor in order to implement the diffusion equation in the RL algorithm, in the sense that only certain planes of the whole 3D scenario have diffusive behavior. Our approach consists in a decomposition of the whole 3D scenario in terms of horizontal and vertical 2D planes. Then, those 2D planes which behave diffusively (with an area density larger than 10%) are treated with the diffusion equation methodology, considering scattering and absorption losses due to the obstacles, as it is shown in Fig. 2. As stated previously, it is important to emphasize that a grid is defined in the space of the whole 3D scenario.

The vertical and horizontal 2-D planes are separated by the cuboid size, which could be different depending of the layout of the whole scenario. For that purpose of estimating obstacle density it is assumed that transmission and absorption cross sections are approximately equal to the geometric cross section due to the large size of obstacles compared to the wavelength [2]. For each 2-D horizontal and vertical diffusive plane, virtual transmitting locations TX_{Hk} and TX_{Vk}, respectively, have been calculated to apply DE. These virtual transmitters have been calculated considering the spatial sample in those diffusive 2D planes with the minimum distance (obtained through perpendicular projections) to the real transmitter in the 3D scenario. The virtual transmitting locations in the diffusive planes are then considered as the origin from which the radial distances r_a in equation (4) are calculated, leading to a matrix of excess losses due to scattering and absorption in the corresponding planes. The application of DE is valid for LOS as well as NLOS conditions, given the implicit consideration of obstacle interaction The reader is referred to [12] for more details of the approach.

III. SIMULATION EXAMPLES AND VERIFICATION OF THE ALGORITHM

Several simulations of a typical office indoor scenario have been performed, employing the scenario represented in Fig. 1, which shows a 3D office environment with different elements, like tables of different shapes and sizes, chairs, computers and shelves.

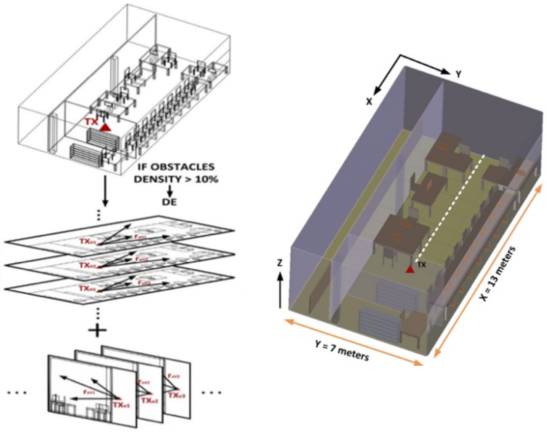


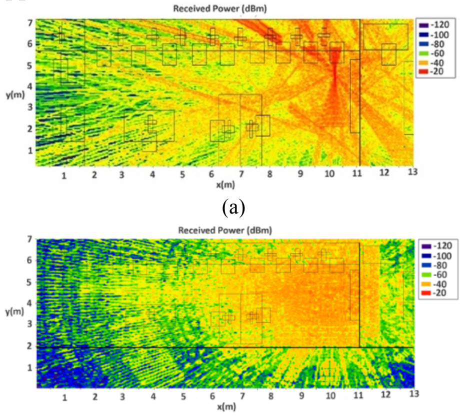
Fig. 1. Principle of the DE approach implemented in the 2-D planes of the whole 3-D scenario and schematic description of the scenario.

The dimensions of the scenario are 13m by 7m by 4.2m. The schematic view depicts all of the elements within the simulation scenario (i.e., furnishings, walls, etc.), which are taken into account in the simulation process. These obstacles have been considered with the GO-only approach in the complete scenario taking into account the permittivity and conductivity of all the materials within the obstacles at 2.4GHz frequency, defined in Table I [14]. The absorption phenomenon by obstacles has been taken into account only with the diffusion equation, and not duplicated with the GO approach. For the diffusive planes, the obstacle density has been considered to apply the diffusion equations in those planes, adding excess losses due to scattering and absorption.

TABLE I. MATERIAL PROPERTIES IN THE RAY LAUNCHING SIMULATION

Parameters	Permittivity (ε_r)	Conductivity (σ) [S/m]	Loss Tangent
Air	1	0	0
Plywood	2.88	0.21	0.026
Brick wall	4.11	0.0364	0.03
Glass	6.06	10^{-12}	0.02
Concrete	5.66	0.142	0.01
Metal	4.5	$4*10^{7}$	
Polycarbonate	3	0.2	0.01

The transmitter has been located at the coordinates (X=9.94m, Y=4.5m, Z=0.60m), depicted with a red triangle in Fig. 1, and simulations have been performed at 2.4GHz frequency. Omnidirectional transceiver antennas with 5dBi gain have been employed. Angular resolution has been set to 1º for both horizontal ($\Delta\Phi$) and vertical planes ($\Delta\theta$). Cuboid size has been set to 5cm^3 and maximum number of reflections to N=7, following previous convergence analysis criteria [15] leading to 84 horizontal XY-planes, 260 vertical YZ-planes and 140 vertical XZ-planes. For this particular environment, the obstacle density which exceeds 10% is present only in the horizontal planes which correspond with the tables and chairs of the scenario. These 2D horizontal planes have been treated with DE approach to obtain accurate results for those planes.



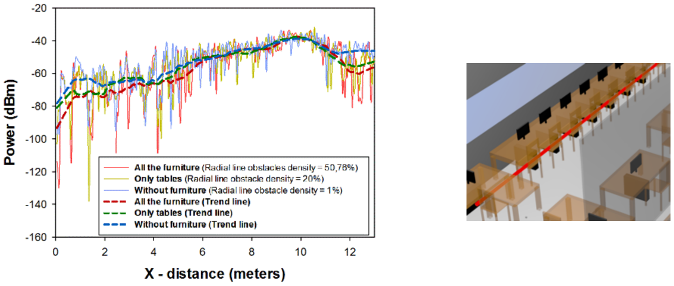
(a)

(b)

Fig. 2. Bi-dimensional plane of received power (dBm) for 0.8m height considering all the furniture in the scenario (a) 2D RL simulation results (b) 3D RL simulation results.

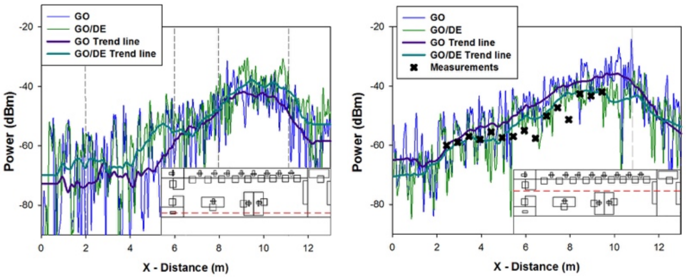
Firstly, the impact of furniture within the scenario has been assessed. Fig. 2 shows the XY-plane of received power for a height of 0.8m. The area density of obstacles in the presented plane is 14.34%. A comparison between 2D and 3D RL simulation has been done. Fig. 2 shows the XY-plane of received power for a height of 0.8m, for 2D and 3D case, respectively. Table II shows that the mean error in the 2D simulation results increases 95% with respect the 3D simulation accuracy. However, the simulation computational time also increases significantly in the 3D simulation.

Fig. 3a shows the radial of received power for three different cases of considered obstacles, for Y=5.75 meters along the X-axis. It can be seen in the trend lines that the predicted power is rightly lower when all the furniture is taken into account. Fig. 3b represents in a 3D perspective the radial line which is depicted in Fig. 3a. It is shown that the proposed method is also adequate for Non-Line-of-Sight condition.



(a) (b)

Fig. 3. (a) Comparison between radials of received power with all the furniture in the room, with only tables and without furniture. (b) View of the radial line in the 3D scenario which is represented in Fig. 3a.



(a) (b)

Fig. 4. Comparison between radials of received power (dBm) for the GO only approach and the GO/DE approach with its trend lines. (a) Y=2.5m, X-axis. (b) Y=4.5m, X-axis. Measurements for 2.4GHz frequency have been also included for comparison.

In order to assess the influence of scattering in this typical complex indoor environment, different simulations have been done considering the scattering behavior with the diffusion equation modeling. A comparison between the GO-only approach and the inclusion of DE has been done. Fig. 4 shows the comparison of the received power for the different techniques with its trend lines along the X-axis for Y=4.5m and Y=2.5m. It can be seen that, for Y=2.5m, the inclusion of DE in the GO-only approach predicts greater values of received power along most of the radial. This is because the scattering phenomenon, which is always present in practical situations, can contribute to excess gains. But it is also observed that scattering also introduces lower values of received power in some zones of the radial line (from 6 to 8 meters) and in the case of Y=4.5m. The vertical dash lines in the pictures represent the different positions of the obstacles.

IV. MEASUREMENT RESULTS AND DISCUSSION

Validation of the proposed simulation method is achieved by performing measurements within the simulated scenario. Measurements have been performed at the frequency of operation of 2.4GHz, with the aid of a transmit antenna, located at the position denoted by a red triangle in Fig. 1, corresponding to coordinates (X=9.94m, Y=4.5m, Z=0.60m). The transmitter employed is an Agilent N1996A, whereas the receiver is a portable Agilent N9912 Field Fox spectrum analyzer, with 100MHz bandwidth, both connected to Antenanova Picea 2.4GHz Swivel Antennas. Measurements were obtained along the radial white dash line depicted in Fig. 1 at a height of 0.8m, with a spacing of 0.5m between them.

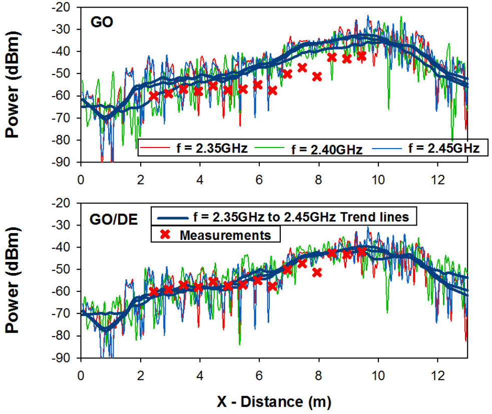


Fig. 5. Comparison simulation versus measurements.

Fig. 5 shows the comparison between simulation and measurement results. Measurement time duration of each point was set to 60 seconds, providing the maximum received power level obtained within the given measurement time span in the measurement bandwidth. Estimation of received power levels provided by simulation results compared with measurements have been obtained for the same spatial locations within the defined 3D cuboid mesh of the simulation scenario. It can be seen that results obtained by the proposed hybrid method provides a closer fit to the measured power trend curve, generally decaying with increasing transmitter-receiver distance.

TABLE II

MEAN ERROR AND STANDARD DEVIATION FOR THE DIFFERENT APPROACHES

	3D RL		2D RL
	GO	**GO/DE**	**GO**
Mean error (dB)	3.011	0.691	14.63
Std. Deviation (dB)	2.305	0.489	4.385
Computational Time (s)	129000	130194	2492

Table II shows the mean error, standard deviation and computational time of the different approaches. The mean error and standard deviation have been calculated comparing measurement results with instantaneous fading power associated with the same spatial cuboid on the 3D scenario for the different approaches. For comparison, full blown ray launching approach that includes diffraction takes 217204 seconds to achieve the same kind of mean and standard deviation of error. It is observed that with the GO/DE approach, which presents a trade-off between computational complexity and final accuracy, a considerable improvement in the accuracy of the results can be achieved compared to GO technique, with a negligible increase of the computation time. The computational time is of the order of minutes or hours depending on the implementation and CPU speed.

V. CONCLUSION

In this paper, a novel and efficient approach for coverage prediction in complex indoor environments is presented. This technique combines 3-D Ray Launching with a Diffusion Equation, the latter of which is based on power transport theory. The GO/DE technique presents only a small increase in the CPU time compared to GO-only, while significantly improving the accuracy of the latter.

The quantity that one deals with in the diffusion equation approach is the average intensity. The flux density vector is proportional to the spatial gradient of the average intensity and can be calculated from the average intensity. Other quantities such as angular spread that depend on the angular distribution of averaged power at the receiver can also be obtained from the DE approach. This will be pursued in the future.

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