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Diffuse scattering and physical optics in the propagation of electromagnetic waves applied to mobile communications

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Abstract. In this work, the optical theory of physics helps to understand, analyze, and calculate the received power in a fifth-generation mobile telecommunications receiver. In these communication systems there are statistical models and deterministic physical models. We investigated how diffuse scattering in reflection contributes to specular reflection in received power at a receiver due to materials in the propagating environment in a communication channel using millimeter waves. The dimensions of building construction materials have sizes comparable to wavelength at millimeter wave frequencies. The power transmitted by communication equipment can be reflected in the roughness of these apparently smooth materials or spread out in multiple directions. The results show that the contribution due to diffuse scattering must be considered and that deterministic physical models using optical theory are valid and improve predictive analysis with good fit. With these results, the physical theory allows to make software with high precision and that improves the current applications.

1. Introduction

Nowadays, services on mobile communications are descripted by a popular multimedia demand needing to increase access velocities exponentially. To preceded by four generations of cellular technologies, research effort focuses on possibilities to exploit a feasibility of new frequency bands [1,2]. The next generations have been led for wireless gigabit Allianz (WiGig) who proposed a 60 GHz (57 GHz – 64 GHz) band as next frequency band to communications for wireless personal network (WPAN).

In mobile communication technologies, it is necessary to calculate the geographical locations that the base stations will have to provide coverage to their customers. To implement the mobile operator network, the behavior of the radio channel is estimated using deterministic models of electromagnetic wave propagation or statistical models [2]. The statistical models are based on measurement campaigns under general propagation conditions and do not consider the effects of the channel due to other physical factors, specific to the environment. Deterministic models are described by equations that characterize the behavior of electromagnetic waves in certain environments [3]. The precision of the deterministic model is a function of the characterization of the dispersing elements, the material with which they are built and the effects on electromagnetic waves such as reflection, diffraction, and transmission.

The deterministic methods that use physical optics have had great influence since it considers the dielectric properties of materials. The most precise deterministic technique is that of optical rays' Computational methods have had a great influence on the prediction of wireless channel estimation parameters and the effects of materials, with the optical ray technique being the most accurate [4].

There are two techniques with computational performance and therefore it makes them the most widely used: Ray Tracing (RT) based on the image and ray launch (RL) method using the brute force technique [5]. However, computationally RT is lighter and uses secondary sources that are caused by reflection and diffraction of basic scatters [6]. On the other hand, RL uses a beam shot in all directions. The resolution angle of the initial rays that are launched produce secondary sources by the Huygens-Fresnel principle, increasing the number of rays to analyze given the phenomenon of second-order diffraction and new reflections. One difficulty with these techniques is that they require a great deal of calculations and require a detailed description as well as information from the simulation scenario. Such limiting and restricting conditions tend to affect the accuracy of the results. In addition, there is a bifurcation between required precision and demanded computational resources. The current problem is that there is no computationally efficient deterministic model that allows predicting the diffuse reflection component.

Therefore, this work proposes an implementation of algorithms based on physical optics, phenomena such as reflection and diffraction to model the effects produced by the dielectric characteristics of materials in the propagation of electromagnetic waves, using a spatial geometric representation and a factor roughness. In addition, it incorporates a stochastic treatment to evaluate the diffuse reflection component by roughness. This work proposes a model that describes the main physical parameters of an environment and that is used by the scientific community and that improves the estimates of current generation mobile service operators.

2. Methodology and materials

The main challenge in the millimeter frequency band is to model diffuse scattering, where an incident wave has a specular component and other components due to the roughness of the material, as shown in Figure 1. Determining the diffuse scattering effect of waves electromagnetic does not have a closed form, but there are some methodical proposals to predict it approximately.

To predict the power at the receiver it is required that all the components of the propagated electromagnetic wave be calculated. To determine the precision of the estimate, it is necessary to compare with measurements made at a test site. Next, the methodology for estimating the wave components is described. Subsequently, it is mentioned how a measurement campaign was developed in a specific site. Finally, it is detailed how the comparison is made to estimate the precision of the proposed tool.

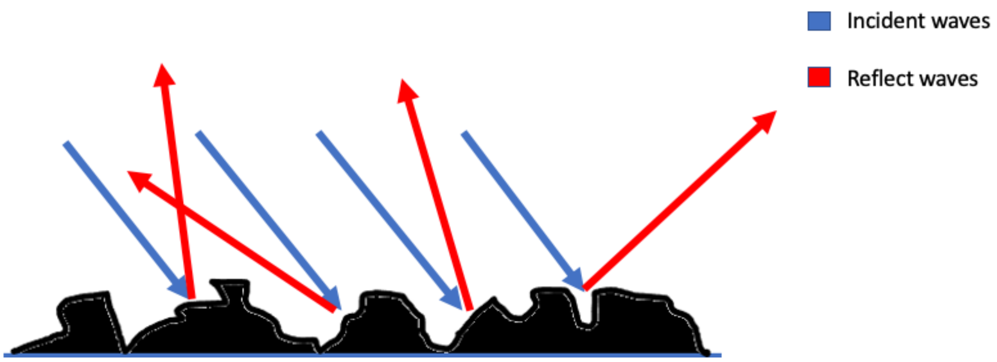

Figure 1. Effect of roughness on incident waves and reflected waves.

2.1. Channel model

The propagation mechanisms using ray tracing allow to study the multiple paths of the wireless channel. some propagation mechanisms such as transmission will not be considered, since interior material thicknesses of a few centimeters have attenuations greater than the power required in reception [6]. Thus, transmission does not contribute to multipath propagation in indoor scenarios and is ignored in this study. The Equation (1) depicts the effects of multipath scattering model for line-of-sight propagation, reflected (specular), diffracted, and diffuse (non-specular) scattered paths is given by [7].

$$E_{rx} = E_{LoS} + E_{Reflec} + E_{Diffrac} + E_{Scatter}. \quad (1)$$

Line of sight propagation (E_{LoS}) described in Equation (2), is the direct path in which the transmitter and receiver do not consider any reflective material to interact. It is also known as free space propagation. In addition, in millimeter waves, propagation is affected by energy propagation, molecular absorptions, and atmospheric attenuations. Thermal noise is neglected. All these factors accumulate in a loss variable (L). Electric filed emitted by a transmitter antenna (T_x) with a gain G_{Tx} is received, affected by a gain G_{Rx} and polarization (E_{Tx}) is given by [8].

$$E_{LoS} = G_{Rx} \cdot G_{Tx} \cdot L \cdot E_{Tx}. \quad (2)$$

In the reflection analyses, a coefficient Γ depends on permittivity, permeability, and conductivity (known as material electrical properties) and the angle of incidence of the reflecting material [9,10]. On the other hand, the polarization of the incident wave is a contribute greatly; for parallel and perpendicular Fresnel reflection coefficients is used an approximation of experimental results. The Rayleigh roughness effect (ζ) [11] is considered and described in Equation (3).

$$\zeta = e^{-\lambda}, \quad (3)$$

where λ is a roughness parameter of a material, showed in Equation (4).

$$\lambda = \frac{8\pi f^2 \sigma^2 \cos(\theta_i)}{c^2}. \quad (4)$$

Affected by the frequency (f) of the incident wave, the standard deviation of the roughness of the material (σ) and the angle of incidence (θ). Also, it is inversely proportional to the square of the speed of light (c). Thus, the Equation (5) represented the contribution of reflection.

$$G_{Rx} \cdot D_{Rx} \times \begin{pmatrix} \zeta \cdot \Gamma_{TE} & \Upsilon_A \\ \Upsilon_B & \zeta \cdot \Gamma_{TM} \end{pmatrix} \times D_{Tx}, \quad (5)$$

where Γ_{TE} and Γ_{TM} are parallel and perpendicular reflection coefficients, γ_A and γ_B are a cross polarization coupling coefficients. D_{Rx} and D_{Tx} represent the geometric depolarization vectors.

Diffraction occurs when a wave hit it an irregular and large dimensions obstacle as compared to the wavelength while is a propagated. The diffracting dispersers in an environment are metallic or wooden edges usually; by diffraction effect, waves transmitted reach the shadow region behind the obstacles. The major analytical diffraction models are the uniform theory of diffraction (UTD) [12] and the knife edge diffraction (KED) [6]. In equation (6) is described the first order diffracted field at the receiving point.

$$E_{Rx} = \phi_D \cdot \phi_A \cdot L \cdot E_{Tx}. \quad (6)$$

When a traveling wave beat a rough surface, the diffuse scattering appears, and its effect spread the wave into a many specular reflections, in many random directions with different energy.

2.2. Indoor scenario

Recent studies have verified the applicability and accuracy of ray tracing (RT) technique in conjunction with uniform theory of diffraction (UTD) [2,8,11-14]. The representation of complex phenomena between the radio wave and the environment is called multipath channel model [15]. The characteristics of the materials present in the scenario play an important role allowing accurate results using RT techniques into the spatial and temporal characterization; by means of RT and multipath channel model is possible to design and theoretically evaluate the wireless communication systems. The test site where the measurement campaign was carried out has dimensions of 6.40 m x 4.44 m x 2.60 m. It features five different types of materials. The windows are glass, the laboratory furniture is wood and metal, and the ceiling is plaster; distribution of the materials that make up the scenario are shown in Figure 2.

2.3. Measurements
The transmitter consists of a virtual uniform 6x6 antenna array (URA) while the receiver is a virtual uniform linear 5X1 antenna array (ULA), located inside of test site as described in Figure 2. A carrier that varies in the millimeter wave range from 57 GHz to 66 GHz with 4096 frequency points. The polarization of the antenna arrays is vertical with a gain that varies between 4 dBi and 5.1 dBi. A Rohde & Schwartz ZVA67 vector network analyzer with a transmission power of -10 dBm was used for the measurement.

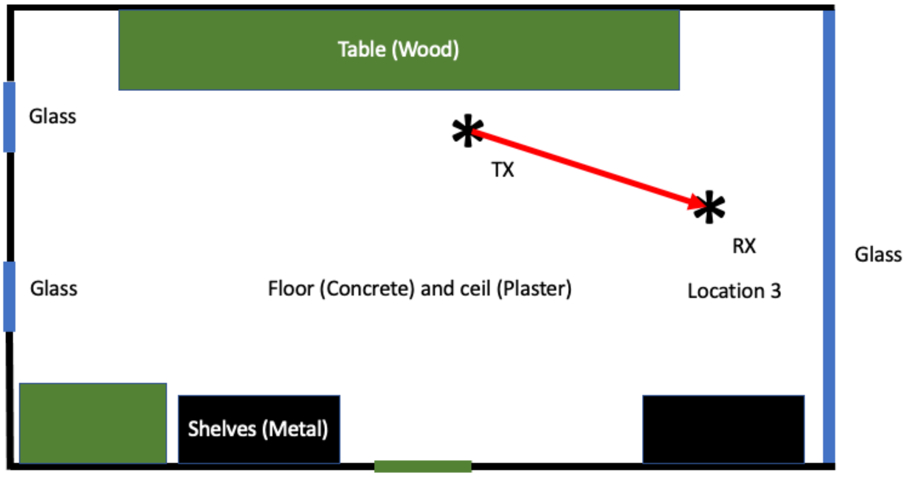

Figure 2. Test site for carrying out the measurement campaign and kind of materials.

2.4. Material parameters
The materials into the scenario must be characterized. For this, values of relative permittivity and conductivity of [5] were used and are shown in Table 1.

Table 1. Values of relative permittivity and conductivity of materials [5].

Material	Relative permittivity	Conductivity
Floor and columns	6.5-0.43i	1.43
Walls and drop-down ceiling	2.81-0.046i	0.15
Furniture	1.54-0.095i	0.32
Glass	6.94-0.176i	0.59
Metal	1	1

2.5. Simulation tools
A RT software was developed in MATLAB. RT algorithm implemented is limited to 5 events, defining an event as a reflection, diffraction or scatter diffuse and a maximum of one diffraction at vertical or horizontal material edges, which is appropriate for indoor environment. In our model, if the ray hit an edge, the rays of the diffraction cone will be computed with a given angle increment.

3. Results and discussion
To verify RT simulation proposed, results of power received are compared in this section with measurements. In this work, the power delay profile (PDP) and root-mean-square (RMS) delay and Path Loss are used as evaluation parameters. However, we choose one location of measurement set and we

summarize results for locations on Table 2. The distance of separation between transmitter and the location 3 is approximately 3 m. In general terms results are quite accurate and very close considering the number of events investigated. In Figure 3 show that there is a very small difference in the measured main tap and the simulated one corresponding to 0.022 ns.

The source of the error may be the accuracy in the positioning of the receiver and transmitter points, which correspond to approximately 6.6 mm. The magnitude of replicas contributions around 16 m makes the difference with measurements. Additionally, Figure 3 shows that the contribution of diffuse scattering (yellow) appears by reflection with materials, located 3.5 and 9 meters from the receiver. Likewise, the contribution of the modeled diffuse dispersion improves the simulation graph (blue) especially in the main tap, helping to determine the real bandwidth of the channel.

Table 2. Summarization of results.

Test	Measured	Simulated	Accuracy
RMS	4.09 ns	4.03 ns	98.5%
Path loss	70.98 dB	70.58 dB	0.37 dB

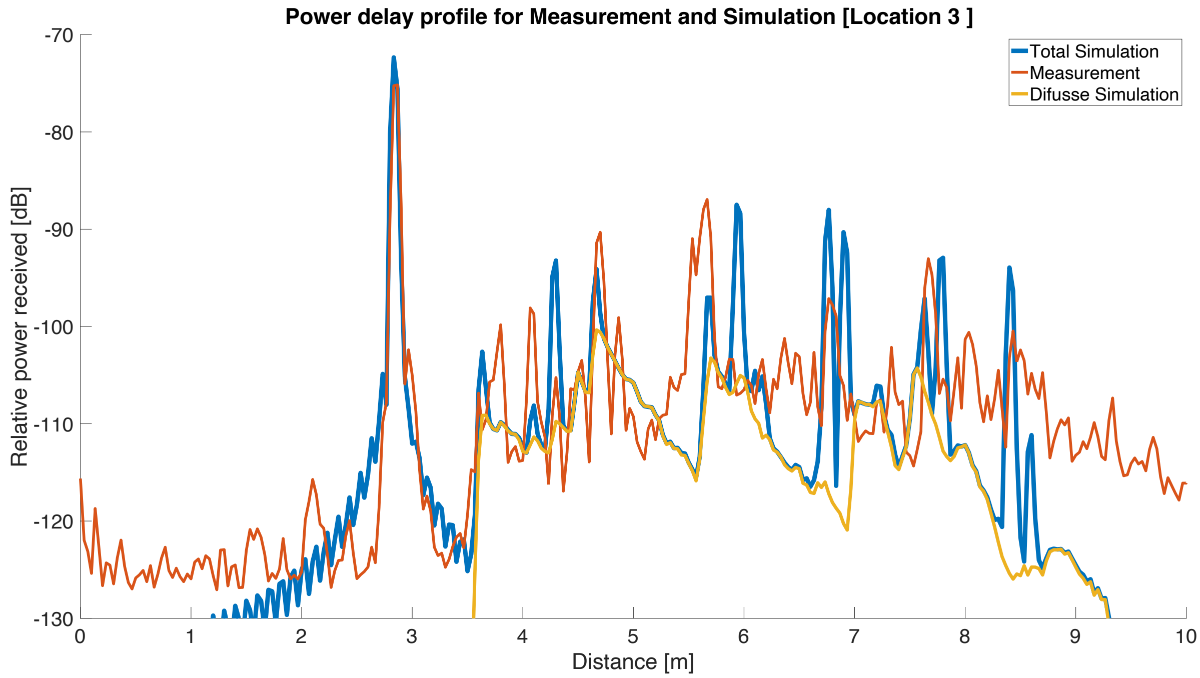

Figure 3. Comparison of PDPs and the contributions of diffuse dispersion.

4. Conclusion

In this work we have shown the results of an application developed in MATLAB that allows simulating a wireless channel using the optical ray launch technique. The precision of the launcher is high, and it has been compared with measurements made on site to prove its efficiency. It is evident that the contributions of the simulated diffuse dispersion improve the results obtained and reveal that there is a significant contribution to the measurements taken.

This kind of applications where the physical models improve and adjust the results of the simulations, it is possible to develop them in all fields of knowledge. Future research work will focus on the following mobile technology. The next mobile generation will try to predict the behavior of electromagnetic waves at Terahertz frequencies, being a challenge from now on.

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