Ray tracing based model using point scatterers for time-Varying radio channels

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Abstract—The work presented in this paper aims to continue the progress obtained in the development of a ray tracing based simulation platform for realistic doubly selective radio channels. This framework is the integration of various propagation models present in literature, with a novel method to characterise the obstacles present in the radio path, relying only in point scatterers with specific characteristics, which allows the characterisation of a wide variety of obstacles. Such simulator will allow the extraction of various parameters of the channel under simulation, such as, the received signal complex envelope, Doppler spectrum and power delay profile (PDP). This paper also presents an assessment of this simulation platform against measurements performed in a controlled environment inside an anechoic chamber.

Keywords—Ray tracing; Doubly selective channels; Directional propagation models, Point scatterers.

I. INTRODUCTION

Realistic radio channel models are critical for the success of emergent radio systems feasibility studies. Both time and frequency selectivity of the radio channels are important subjects when predicting the signal in a radio channel. Furthermore, propagation phenomena such as diffraction, reflection, (diffuse) scattering, etc., must also be conveniently understood in order to obtain a relatively good precision while extracting the output parameters of the channel under simulation, such as received complex envelope, Doppler spread and channel impulse response or power delay profile (PDP).

There are several methods to predict which can be found in literature, [1 to 4], to predict propagation phenomena through channels with various kinds of obstacles. These methods can be divided into statistical, empirical and theoretical models. However, these models are usually applied to a specific obstacle, phenomena or case study, e.g. theoretical models are usually applied to edge diffraction.

In order to simulate the propagation phenomena in radio channels with a variety of obstacle kinds, so that multidimensional (time and space) channel parameters can be extracted, such as the received signal complex envelope, channel impulse response and Doppler spectrum in dynamic channels, it was proposed in [5] a ray tracing based simulation platform that predicts the propagation phenomena inherent to each obstacle, and subsequently, combines all the individual interactions between them.

The framework presented in this paper, is a novel method to characterising the obstacles present in the radio path, utilising groups of point scatterers with specific characteristics, namely specific re-radiation patterns.

II. FRAMEWORK OVERVIEW

A. Ray tracing algorithm

As presented in [5], in this simulation platform all the geometric obstacles present in the simulation channel are modelled using groups of point scatterers. These points are characterised by a particular re-radiation function (depending on the obstacle), which affects the relation between the powers levels of the incident and scattered rays. Subsequently, to gather all the interactions between the obstacles, a ray tracing algorithm is used.

The adopted ray tracing algorithm is based on two iterations. In the first iteration, the algorithm calculates both the direct ray, and the rays travelling from the transmitter to the received antenna, through all the point scatterers defined in the geometry.

However, and for the purpose of taking into account propagation phenomena such as double diffraction or interactions between 2 (or more) different obstacles, a 2nd iteration was introduced. This iteration considers the point scatterers illuminated by the rays generated from the 1st iteration as new transmitters. To this extent the rays from the 1st scatterer to all other point scatterers are defined in the simulation geometry and are reflected (or diffracted) to the receiver. Therefore, in a simulation with this algorithm, the number of multipath components defined is given by (1).

\[ N_{\text{multipath components}} = N_{\text{scatters}}^2 + 1 \]  \( \text{(1)} \)

B. Propagation models for geometric obstacles

The proposed ray tracing simulation platform was essentially developed with the intent of performing simulations in doubly-selective channels, allowing the calculation of channel parameters such as the signal complex envelope, the Doppler spectrum and channel impulse response. Several realistic simulation scenarios include some obstacles in order to provide the desired multipath richness.

Point scatterers were successfully used in [5] to study propagation effects due to multipath. Such scatterers were considered as ideal source points located in the simulation
space and were used as a reference for the calculation of the channel impulse response and Doppler spectrum. To this extent, the point scatterer approach was adopted in the development of the proposed simulation platform and are assumed to be perfect reflectors.

Buildings are usually present in the radio path of mobile communications channel and to this extent, the study of propagation phenomena around such obstacles is very important. However, when compared to the point scatterers approach, modelling the propagation phenomena due to the presence of buildings becomes more complex, since it deals mainly with diffraction and reflection phenomena.

Several studies concerning such phenomena are present in literature, namely GTD/UTD based models, as presented in [6]. However, for the purpose of the ray tracing algorithm described in subsection 2.1, an adaptation was necessary for these formulations in order to model the propagation of each ray individually.

Therefore, when a building is inserted in the simulation space, the ray tracing algorithm defines a set of point scatterers around the building, which are modelled with diffraction and reflection models, as according to Fig. 1.

![Diffraction scatterer Reflection scatterer](Image)

**Fig. 1 – Building modelling using point scatterers.**

The reflection scatterers are assigned to the faces of the buildings and their effect in incident rays evaluated through a GTD/UTD reflection model [6]. The reflection model formulation derived from [6] is presented in equation (2), where \( \rho' \) and \( \rho \) are the distance travelled by the incident and reflected rays, respectively, \( \theta_i \) and \( \theta_s \) stand for the angles between the surface’s normal and the incident and reflected rays and \( k \) is the wave number.

\[
E_r = E_t \left( \frac{\rho'}{\rho(\rho + \rho')} \left[ e^{-j \frac{2 \pi}{\lambda} \rho} \cos(\theta_i) - e^{-j \frac{2 \pi}{\lambda} \rho} \cos(\theta_s) \right] \cos(\theta_i) + \frac{1}{\sin\theta_i} \cos(\theta_s) \right)
\] (2)

Reflection scatterers still have one particularity which is, if during the simulation of the ray tracing algorithm, it defines the reflection scatterer at the centre of the building face, it could occur a situation like the one depicted in Fig. 2, where the power of the reflected wave is minimised due to the angle difference between \( \theta_i \) and \( \theta_s \).

![Wrong reflection situation / Corrected reflection situation](Image)

**Fig. 2 – Wrong reflection situation / Corrected reflection situation.**

If such situation occurs during simulation, the ray tracing algorithm will search, in the building face, for the optimal reflection point and the scatterer will be moved accordingly, as shown in Fig. 2.

As far as diffraction scatterers are concerned, these are assigned to all building edges except the ground based edges. Diffraction, analogously to reflection, is modelled using a formulation adapted from [6] for corner diffraction. This GTD/UTD diffraction model relies on Eq. 3, where \( \rho' \) and \( \rho \) are the distance travelled by the incident and reflected rays, respectively, \( \theta \) is the incidence angle and \( \phi \) is the angle of diffraction.

\[
E_d = E_r \frac{\rho'}{\sqrt{\rho(\rho + \rho')}} \left[ e^{-j \frac{2 \pi}{\lambda} \rho} - e^{-j \frac{2 \pi}{\lambda} \rho'} \right] \left( \frac{1}{\sin(\theta - \phi)} - \frac{1}{\sin(\phi - \theta)} \right)
\] (3)

Despite the diffraction and reflection phenomena are predicted in simulations with buildings, at this point in time the developed simulation platform still has a limitation concerning the propagation phenomena caused by buildings. Although this is in development, the transmission of the radio signal that may occur through building walls is not implemented yet, therefore, the rays that eventually cross the building are simply discarded.

C. Simulation results

The value of the mobile station received signal complex envelope, is calculated by adding all the multipath components arriving at the mobile. This is done at each step of movement of the mobile and/or point scatterers, through equation 4, where \( N_{\text{paths}} \) is the number of multipath components arriving at the receiver, \( d_i \) is the distance travelled by the \( i \)th component and \( a_i \) represents the attenuation caused by the channel to that particular component.

\[
\text{Signal}_{\text{complex, env}} = \sum_{i=1}^{N_{\text{paths}}} \frac{e^{-j2\pi di \lambda}}{4\pi d_i^2} \times \frac{1}{a_i}
\] (4)

Furthermore, when simulations considering both transmitter and received antenna radiation patterns are required, the received components must be convolved with the antenna radiation patterns, considering the antenna orientation angles and the angle of arrival and/or departure of each multipath component.

It is also important to highlight that these calculations do not take into account intersymbolic interference due to the step by step nature of the simulator which considers a stationary channel.

After the calculation of the received signal complex envelope, the proposed ray tracing platform will enable the estimation of the Doppler spectrum caused by the dynamics of the simulation channel, using a method presented in [7]. Such method applies the Fourier transform to the signal complex envelope, as shown in (5).

\[
\text{Doppler}_{\text{spectrum}} = \frac{1}{n} \sum_{i=1}^{n-1} \text{Signal}(j) \times e^{-j \left(\frac{1}{n} \pi \right) jk}
\] (5)

To estimate the channel PDP, the proposed algorithm evaluates the delay of each multipath component, which is approximately the travelled distance \( d_i \) multiplied by the speed of light \( c \), and creates an ideal channel impulse response.
Subsequently, the platform will create a variable width triangular pulse, depending on the sequence length and chip rate of the desired channel sounder. Finally the PDP of the channel is obtained by convolving both ideal channel impulse response and the generated triangular pulse, simulating the correlation peaks obtained by a real channel sounder [8].

III. ASSESSMENT OF THE SIMULATION PLATFORM

A preliminary assessment of this simulation platform, namely the assessment of Doppler spectrum calculation, channel PDP analysis and building diffraction is presented in [5]. This preliminary assessment was based in comparisons between results extracted from the developed framework and other theoretical models present in literature. However, to really assess this framework, it is required to analyse its performance against results obtained from several realistic measurement campaigns. In next subsections an assessment is performed relying on the 18.8GHz measurement system, for Doppler spectrum, building diffraction and PDP. For that purpose, it was used a wideband channel sounder based on the STDCC technique, which was presented in [8]. This method allows the characterisation of highly dynamic channels, and it can provide both amplitude and Doppler spectrum measurements.

A. Doppler spectrum

In order to assess the results calculated with the developed simulation platform while predicting Doppler spectrum, we used a robot to add motion to the measurement geometry. Therefore, the robot was programmed to move in a straight line with a constant velocity, transporting the receiver antenna. The remaining of the measurement geometry might be seen in Fig. 3, where initially both receiver and transmitter antennas are spaced out 1m, and the robot was moved away the transmitter, at a constant velocity of about 505mm/s. Due to the flexibility of the developed simulation platform in defining simulation geometries, the geometry adopted to perform this simulation closely mimics the measurement geometry.

![Fig. 3 – Measurement and simulation geometry for Doppler spectrum assessment.](Image)

Through equation 6, the corresponding Doppler frequency deviation when the receiver box is travelling away from the transmitter box can be estimated. This yields to -31.48Hz, with the negative sign representing an increasing distance. This negative sign is a result of \( \cos \Theta \), which stands for the angle between the vector that unites the receiver and the transmitter, and the velocity vector of the receiver.

\[
\text{Doppler}_{\text{freq}} = \frac{\text{velocity}}{4} \cos \Theta
\]  

(6)

Both measurement and simulations results for the Doppler spectrum can be seen in Fig. 4, where one can observe a relatively good agreement between the data at -37.47Hz.

B. Building diffraction

With the purpose of assessing the building corner diffraction calculations with actual measurement results, two concrete slabs weighing 120kg each (1m by 1m by 5cm) were used. Slabs were positioned inside the anechoic chamber mimicking a building corner, as depicted in Fig. 5 (b). The transmitter was placed at 2m from the building corner with an incidence angle of 45°, and the receiver was moved by means of the robot from a NLOS to a LOS position, as depicted in Fig. 5 (a).

![Fig. 5 – Corner diffraction assessment geometry.](Image)

It is important to emphasise that for this simulation, despite all propagation phenomena inherent to building diffraction and reflection, the antennas radiation pattern of both transmitter and receiver were also taken in consideration. In Fig. 6, both measured and simulated building corner diffraction can be observed. In the LOS region both measured and predicted results present a relatively good agreement. However in the NLOS zone, the simulation platform appears to underestimate the received signal. Although this underestimation may occur due to errors in diffraction calculations, it is believed that this issue is simply due to the fact that we do not take into account the transmission component, and the walls that we used for measurements are relatively thin consequently allowing a significant signal transmission.

![Fig. 6 – Corner diffraction results.](Image)
Finally, and to assess the presented simulation platform while extracting the PDP of the channel under simulation, three metallic cylinders were placed in the anechoic chamber to cause multipath components due to reflection of the transmitted signal. These cylinders were located with different distances between them, as depicted in Fig. 7 (a), where one also may observe that both transmitter and receiver antennas were close to each other, mimicking a monostatic system. The measurement geometry inside the anechoic chamber is also presented in Fig. 7 (b).

As metallic cylinders were not characterised with the presented method, metallic cylinders were represented by ideal point scatterers. Therefore, with this measurement setup only the excess delay of the multipath components can be assessed discarding their relative amplitudes. In this particular assessment, the direct component was also discarded, and normalised the excess delay of the first multipath component which is caused by the reflection on first cylinder. Therefore, two more components are expected, caused by the second and third cylinders, arriving with the excess delay of 4ns and 16ns, respectively.

Figure 8 shows both measured and predicted PDP of the corresponding channel. One may observe that in the simulation results, disregarding the fact that the amplitude of multipath components is not meaningful, the time of arrival of the three main components appears to be coherent with the measurements. However, as can be analysed in Fig. 8, other measured multipath components can be distinguished from the same image at around 6ns and 10ns. Both multipath components are due to double reflections between the first cylinder and the RF cases containing the transmitter and receiver equipments, which are not considered by the developed simulation platform.

A ray tracing simulation platform for doubly selective channels, which can provide the calculation of various parameters from the simulation channel is presented. The results from the framework include the received signal complex envelope, Doppler spectrum and the PDP from a simulated channel.

The characterization of the obstacles present in the simulated radio path is based on a point scatterer method which allows the ability of introducing a great variety of obstacles. To this extent a simple previous characterisation of these obstacles is needed. However, this pre-calculation can be performed separately from the simulation platform.

Finally the predicted results of the developed simulation platform such as, Doppler spectrum, building corner diffraction and channel power delay profile, presented a relatively good agreement when compared against measurements performed in a realistic controlled environment.

Further work will address transmission component therefore modelling propagation through buildings. The extension of the obstacle characterisation method, based on point scatterers, in order to model several other obstacles, such as trees, cars, etc., will also be foreseen. Finally, the presented simulation platform may be used to perform simulations in complex realistic scenarios so that appropriate channel matrices, both in time and space can be obtained for subsequent development of robust channel coding techniques.

V. 6 REFERENCES