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Dynamic Ray Tracing: A 3D Formulation

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Abstract—**Ray tracing algorithms can simulate multipath radio propagation in presence of geometric obstacles that can represent buildings, objects or vehicles. When objects or vehicles are moving, which is the case of vehicular environments, it is possible to predict the multipath – and therefore the field - in the near future on the base of the current multipath geometry, assuming constant speeds or accelerations for moving objects, using an analytical extrapolation. A full-3D Dynamic Ray Tracing algorithm is here presented for multiple reflections on moving surfaces.**

Keywords—**Radio Propagation, Ray Tracing, Vehicular Ad Hoc Networks, 5G Mobile Communications.**

I. Introduction

Ray tracing (RT) algorithms have been developed and widely used in the last few decades to simulate multipath radio propagation in urban environments where artificial obstacles, such as buildings and vehicles, can be represented as polyhedrons of a given material [1]. More recently, fast RT algorithms have been proposed for real-time application in dynamic environments, including the estimation of the optimum beam in beam-steering applications for multi-antenna wireless systems [2], or the estimation of the channel state information in vehicular communications [3]. The future frontier in RT modelling is the actual ”ahead of time” prediction (or anticipation) of the multipath, and therefore of the channel characteristics, in dynamic environments. Assuming constant speed or acceleration trends for moving objects, such as vehicles or the radio terminals, analytical extensions can be developed to carry out prediction within a future-time span Δt of the order of seconds on the base of the RT-calculated multipath geometry and electromagnetic field at $t = t_0$. Exploiting such capabilities within wireless systems could be of crucial importance to enhance communication performance and reliability and to foster interesting safety applications in automated and connected driving applications.

Besides fast RT engines, a new “Dynamic Ray Tracing” (DRT) concept is needed to make anticipative channel prediction viable: DRT is a new paradigm where RT is redesigned and extended to compute the speed and acceleration of the rays’ reflection and diffraction points on the objects’ surfaces through analytical formulas on the base of the roto-translation speed and acceleration of the moving objects. At present, research in the field is only at its early stage [4][5]. The great benefits of DRT are that Doppler frequencies as well as field/channel prediction for every time instant $t \in \Delta t$ can be derived with a single RT run through a fast analytical formulation, without resorting to multiple RT runs and therefore with a much lower computation time. The “extrapolation” time interval Δt, that can be called multipath coherence time is the lifetime of the overall multipath structure, i.e. of its major multipath components: when one or more major paths disappear, analytical extrapolation can no longer be applied and a new, full-RT run must be carried out.

In the present work the DRT concept introduced in [5] is extended to a general 3D framework for the case of multiple reflections on flat surfaces, and its algorithm is presented. The algorithm is shown to give the same results as multiple RT runs on successive environment configurations at a small fraction of the computation time.

II. DRT Analytical Algorithm

With respect to the preliminary version presented in [5], the algorithm has been extended to a fully 3D and fully dynamic environment, where any object (e.g. cars and building walls) can have a roto-translational motion. After taking in input geometry and dynamic parameters of each object (position, translation and angular velocities, acceleration) the DRT algorithm performs a RT simulation for the environment at the initial time t_0, and then by applying analytical formulas is able to track the motion of the reflection points, i.e. to compute their position, velocity, and acceleration, at any time instant after t_0 which falls within the multipath lifetime. When Tx/Rx and a reflecting wall move with a certain speed, the corresponding reflection point Q_R “slides” along the wall surface [5]: in general, Q_R velocity is not constant in time, i.e. the reflection point has an accelerated motion. As a starting point, we consider the case where Tx and Rx move with constant speed while the reflecting wall is at rest. Assuming a proper reference system so that the wall lies on the plane y=0, by following geometric optics rules we can derive the position of the reflection point at any time. The x coordinate of Q_R is given by:

$$x_Q = x_{TX} + \frac{y_{TX}(x_{RX} - x_{TX})}{y_{RX} + y_{TX}} \tag{1}$$

The y coordinate of Q_R is equal to 0, due to the choice of the reference system, while z_Q can be obtained again from eq. (1) by replacing all the “x” with “z”. Moreover, by deriving the Q_R coordinates with respect to time, and applying the chain rule, we get the velocity components. For example, the x component of v_Q is:

$$v_{Q_x} = \frac{\partial x_Q}{\partial x_{TX}} = \frac{\partial x_Q}{\partial x_{TX}} v_{TX,x} + \frac{\partial x_Q}{\partial y_{TX}} v_{TX,y} + \frac{\partial x_Q}{\partial x_{RX}} v_{RX,x} + \frac{\partial x_Q}{\partial y_{RX}} v_{RX,x} \tag{2}$$

where the partial derivatives in eq. (2) can be easily computed by deriving (1) w.r.t. x and y. In a similar way, by deriving again the velocity components, we get the acceleration components. In order to apply (1) and (2), the reflecting wall must be in state of quiet, and the reference system must be properly oriented: this can be accomplished by using a local reference system integral with the wall (local frame), with the origin located in the rotation center. Since the local frame is in motion w.r.t. the global reference system, all the velocities and accelerations must be transformed according to the relative motion transformations, to get the "relative" velocities and accelerations w.r.t. the local frame. For example, for the velocity of TX we have:

$$\bar{v}^{I}_{TX} = \bar{v}^{0}_{TX} - \bar{v}_{W} - \bar{\omega} \times \overline{(TX - O)} \qquad (3)$$

where the "0" and "I" to global and relative velocities, respectively, and v_W and ω are the translation and rotation velocities of the wall, respectively. Moreover, as the local frame rotates w.r.t. the global reference system, an "instantaneous" rotation matrix must also be applied to project the point coordinates, and velocity/acceleration components into the local frame. Once the reflection point has been determined, we apply inverse transformations to get back to the global reference system. The procedure explained above can be extended to a multiple-bounce case in a straightforward way, through an iterative procedure, where the real TX is substituted by the image-TX w.r.t. to the first reflecting wall, and then eq.(1)-(3) are applied again.

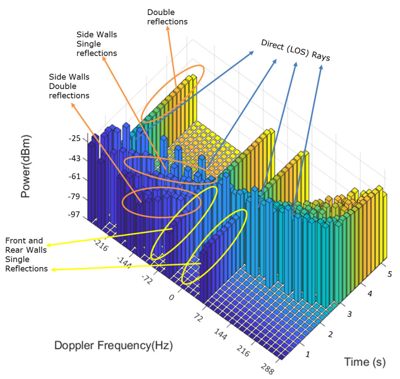

Fig. 1. PDfP evolution in a V2V scenario with a simulation time of 5 seconds (simulation with a maximum 2 reflections).

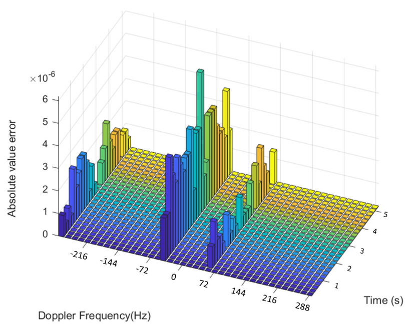

Fig. 2. Absolute value of error between standard multiple-run RT and DRT analytical approach.

III. Results

This section shows the results obtained using the DRT approach in a vehicular environment composed of a street-canyon, a moving parallelepiped made of metal representing a bus, and two moving radio terminals, similar to [5].

TABLE I

RT with snapshots	DRT analytical approach	Speed-up factor
345 seconds	1.75 seconds	197x

All walls have the following standard dielectric parameters: ϵ_r=5, σ=10^2, and Fresnel's reflection coefficients are applied at each reflection. We assume that Tx is moving toward the end of the street at a 50km/h, Rx and the bus are moving in the opposite direction at 36km/h and 30km/h, respectively. Fig. 1 shows the evolution of Power-Doppler frequency profile (PDfP), obtained through DRT with a simulation time of 5 seconds, and discretized with a Doppler frequency step of 14.34 Hz. The main contributions to PDfP (LoS, single and double reflections) are tagged in the plot. The most interesting trend in the contributions can be seen in the direct ray which from a positive Doppler shift becomes negative after Rx passes Tx. The same trend holds for the reflections from the side walls but with lower values and less abrupt transition. We have also compared the DRT analytical approach with the classical approach based on "snapshots", where the RT simulation is repeated at every discrete time instant. In Fig. 2 the absolute value of the error is shown. The error is in general very low: non-zero values are caused by propagation of uncertainties when applying several reference systems transformations, and they are more evident in the cases where there is a strong acceleration of the reflection point, e.g. when the reflecting wall is perpendicular to motion direction of the vehicles. The computation times of both approaches are shown in Table 1. Using DRT, a computation time speed-up factor close to 200 is observed.

IV. Conclusion

In the present work a 3D Dynamic Ray Tracing algorithm for multiple reflections in a moving environment is presented. The algorithm allows to extend ray tracing prediction over a given multipath coherence time using an analytical formulation. This possibility is of great interest for real-time applications in next generation vehicular communication and localization systems. The algorithm is shown to give the same results as multiple RT runs on successive environment configurations with a speed-up of the order of 200x. Further work will have to deal with the extension of the algorithm to diffractions. Moreover, it will have to be applied to a number of use cases and validated vs. measurements.

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