Ray tracing: techniques, applications and prospect

Ray tracing: techniques, applications and prospect

Vittorio Degli Esposti

Department of Electrical, Electronic, and Information Engineering "Guglielmo Marconi" (DEI)

University of Bologna, Italy

Email: v.degliesposti@unibo.it

Abstract – **Ray tracing models have been used since the beginning of the nineties for both field prediction and channel simulation in mobile radio systems. Since then, ray tracing has undergone tremendous progress in terms of algorithm efficiency and application capabilities. Some of the most recent frontiers in RT progress are described in this paper. The development of fast algorithms and their real-time use inside smart wireless systems to improve performance will probably revolutionize the panorama of deterministic propagation modelling in the future.**

Keywords — **Radio Propagation, mm-wave Propagation, Vehicular Propagation, Ray Tracing, Ray Launching**

I. INTRODUCTION

Ray Tracing (RT) models, based on the ray-optics approximation of the propagating field, were initially applied to optical problems and then to radio propagation prediction in urban environment starting from the early nineties [1][2]. With the advent of multiple-input multiple-output (MIMO) and of mm-wave wireless systems RT models have become increasingly popular, also because of their intrinsic capability to simulate multipath propagation and space-time channel dispersion characteristics, which are crucial for MIMO systems design [2].

RT algorithms can be divided into two main groups: i) image-RT where rays propagating between the transmitting point (Tx) and the receiving point (Rx) are found using the image-method and ii) Ray Launching (RL) (also called Shooting and Bouncing Ray, SBR) where rays – or better, ray tubes - are launched and ideally propagated from the Tx with a given angular separation, regardless of the position of the Rx [3]. Although a limited angular resolution is implicit in RL, the algorithm is more efficient than RT for prediction over large areas or volumes containing many Rx points.

The trend toward the use of higher frequencies in the mm-wave and THz ranges, more suitable for the ray-optics approximation and with smaller propagation ranges, has favored once again the use of deterministic RT models for both system design and channel simulation purposes [4].

At the same time, a great deal of work has been carried out to overcome RT limitations: faster algorithms have been developed and diffuse scattering has been introduced to model surface roughness or the presence of electrically small objects and irregularities within RT algorithms [5].

In the present paper, some of the most recent techniques to improve RT performance and capabilities and are briefly described. An interesting application prospect is then presented in section III.

II. NOVEL RT TECHNIQUES

Ray tracing, with all its variants, has undergone tremendous progress in the last three decades and has been proven increasingly useful for both field prediction and channel simulation. A number of techniques have been proposed to improve computational efficiency and extend capabilities. Two of these, that are relatively new and promising, are described with some detail in this section.

A. DED Ray Launching

Ray Launching (RL), also called SBR is known to be more efficient than image-RT for field prediction over vast areas. However, standard RL is also inefficient because many of the rays launched get lost sooner or later in space instead of hitting an object and generating other rays that can give a contribution to the field in the desired Rx area. The basic ideas behind Discrete, Environment-Driven RL (DED-RL) are the following [3]:

i) discretization of the object's surfaces into pixels (or tiles) beforehand and pre-determination of *visibility* between couples of pixels for a given environment database, saving this information into a file associated to the database (the *visibility matrix*)

ii) launching rays from the current virtual source (pixel) only toward visible pixels, instead of toward all directions with a fixed angular grid, thus reducing the number of operations to a minimum and automatically adapting RL angular resolution to the environment's characteristics

iii) parallelization of both visibility preprocessing and ray launching at each iteration – which require a huge number of similar, independent operations – on parallel hardware architectures such as Graphics Processing Units (GPU)

Techniques i)-iii) combined together allow to achieve a dramatic computation speed-up factor of several orders of magnitudes for RF coverage prediction over an urban area, with respect to a traditional image-RT algorithm, virtually without accuracy loss [3]. The speed-up factor is shown to increase exponentially with the number of prediction pixels (receiving points) and linearly with the number of considered bounces, i.e. reflections, diffractions and scattering interactions, as shown in [3], Fig. 11.

B. Dynamic Ray Tracing

The baseline assumption of Dynamic Ray Tracing (DRT) is that the multipath characteristics in a time-variant

environment, where both the radio terminals and the scattering objects can move, don't change significantly within a given *multipath coherence time* T_c: this means that no major path should either appear or disappear within T_c. Under this assumption, a single RT run can be carried out for the initial environment state at t_0 to determine the multipath layout, then the multipath evolution for every instant $t \in [t_0, t_{0+}T_c]$ can be computed using an analytical formulation. Such a formulation expresses speed and acceleration of the rays' interaction points on the objects' surfaces on the base of the roto-translation speed and acceleration of the moving objects and of the radio link ends [6][7]. An example for a single reflection on a roto-translating surface with moving radio terminals is shown in Fig 1: note that the velocity of the Tx image, $\overline{v}_{TX'}$, is not specular to $\overline{v}_{TX}$ due to the reflecting surface motion.

Computation time can be orders of magnitude lower than running RT over and over for each time-instant within T_c. The estimation of T_c in realistic use cases is still an open problem [6]. DRT is particularly attractive for real-time applications in dynamic scenarios, where it allows "anticipative" prediction of the channel, which is a very attractive feature for vehicular applications, as highlighted in the next section.
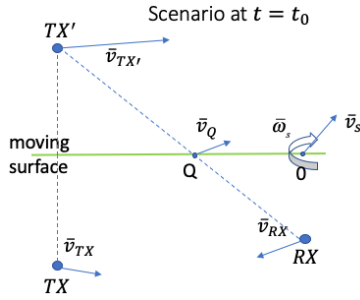

Fig. 1. – DRT single reflection scenario (only velocities are shown): TX' is the image of TX and Q the reflection point.

III. FUTURE APPLICATIONS

Real-time RT application *within* the system to estimate the radio channel's characteristics, is particularly promising: if the instantaneous environment configuration is available through digital maps and localization, real-time RT can use it to generate useful multi-dimensional channel estimates without using antenna arrays and complex estimation techniques. Real-time use of RT has been mainly proposed to assist initial beam acquisition in beamforming schemes [8] or to realize cooperative localization applications [9].

Even more promising is the use of DRT to predict "ahead-of-time" (or anticipate) of the channel in highly dynamic or vehicular applications [6] and realize the so-called *predictive radio awareness* [10]. Exploiting such capabilities could be of paramount importance to guarantee reliable connectivity in critical application such as automated and connected driving and to foster interesting vehicular safety applications to detect dangerous situations in advance on the base of radio environment prediction.

The availability of reliable DRT models would be of great help to realize multipath-exploiting localization techniques that are crucial for vehicular applications [9]. On the other hand, accurate localization of both radio terminals and moving objects within the current scenario is necessary for DRT prediction. Therefore, the two goals might be achieved in synergy to realize an *environment-aware system* and enhance both connectivity and safety, See scheme in Fig. 2.
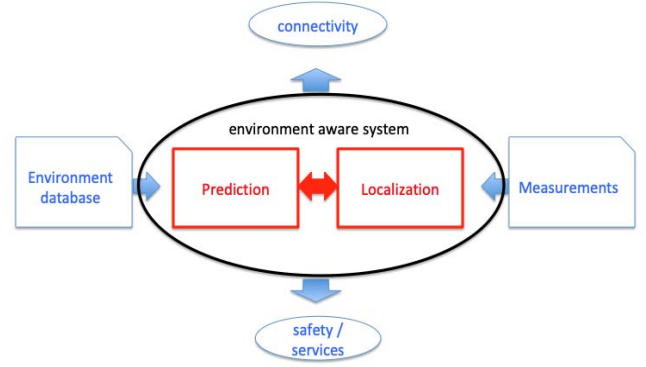

Fig. 2. –Scheme of an environment-aware system including both channel prediction and localization

REFERENCES

[1] S.Y. Seidel and T.S. Rappaport, "A ray tracing technique to predict path loss and delay spread inside buildings," IEEE Global Telecommunication Conference, Vol. 2, pp. 649-653, Orlando, FL, USA, 1992.

[2] Z. Yun and M. F. Iskander, "Ray Tracing for Radio Propagation Modeling: Principles and Applications," in IEEE Access, vol. 3, pp. 1089-1100, 2015.

[3] J. S. Lu, E. M. Vitucci, V. Degli-Esposti, F. Fuschini, M. Barbiroli, J. Blaha, H. L. Bertoni, "A Discrete Environment-Driven GPU-Based Ray Launching Algorithm," IEEE Transactions on Antennas and Propagation, Vol. 67 No. 02, pp. 1558-2221, February 2019.

[4] S. Priebe, M. Kannicht, M. Jacob, and T. Kürner, "Ultra broadband indoor channel measurements and calibrated ray tracing propagation modeling at THz frequencies," Journal of Communications and Networks, vol. 15, no. 6, pp. 547–558, Dec. 2013.

[5] F. Fuschini, E. M. Vitucci, M. Barbiroli, G. Falciasecca, V. Degli-Esposti, "Ray tracing propagation modeling for future small-cell and indoor applications: a review of current techniques," Radio Science, Volume 50, Issue 6, Pages: 469–485, June 2015.

[6] D. Bilibashi, E. M. Vitucci, V. Degli-Esposti, "Dynamic Ray Tracing: Introduction and Concept," 14th European Conference on Antennas and Propagation (EuCAP 2020), Copenhagen, Denmark, 15-20 March, 2020.

[7] D. Bilibashi, E. M. Vitucci, V. Degli-Esposti, "Dynamic Ray Tracing: a 3D formulation," 2020 International Symposium on Antennas and Propagation (ISAP), Kyoto, Japan, to be published, 2021.

[8] F. Fuschini, M. Zoli, E.M. Vitucci, M. Barbiroli and V. Degli-Esposti, "A Study on Mm-wave Multi-User Directional Beamforming Based on Measurements and Ray Tracing Simulations," IEEE Transactions on Antennas and Propagation, Vol 67, No. 4, pp 2633-2644, April 2019.

[9] N. de Sousa, M.; S. Thomä, R. Enhancement of Localization Systems in NLOS Urban Scenario with Multipath Ray Tracing Fingerprints and Machine Learning. Sensors 2018, 18, 4073.

[10] R. Alieiev, T. Hehn, A. Kwoczek and T. Kürner, "Predictive Communication and its Application to Vehicular Environments: Doppler-Shift Compensation," IEEE Transactions on Vehicular Technology, vol. 67, no. 8, pp. 7380-7393, Aug. 2018