Ray Tracing Interpolation for Continuous Modeling of Double Directional Radio Channel

Radovan Zentner [#1], Ana Katalinić Mucalo [*2]

[#] *University of Zagreb, Faculty of Electrical Engineering and Computing*
Unska 3, Zagreb, Croatia
[1] radovan.zentner@fer.hr

[*] *Croatian Post and Electronic Communications Agency*
Roberta Frangesa Mihanovica 9, Zagreb, Croatia
[2] ana.katalinic@hakom.hr

Abstract—**The paper investigates size of an area where a certain propagation phenomenon is visible in an urban setting, using post-processing of ray tracing (RT) data. The propagation phenomenon is distinctive from its counterparts by unique series of interactions that the radio signal encounters while traveling from transmitter to the receiver. Interactions are uniquely defined by their nature, i.e. diffraction or reflection, and by the object where they occur, i.e. specific building edge, or building side, respectively. The analysis of phenomenon visibility is performed on a set of data along an urban route, obtained from rigorous 3D ray tracing simulations. The rays along the route are divided into "ray entities" (RE), based on the affiliation to unique propagation phenomena. Introduction of REs along the route enables interpolation of the RT results between RT receiver points, thus enabling continuous radio channel model with significantly reduced computational burden. Additionally, based on each RE visibility along the route, the results give an insight into the dynamics of change of propagation modes in a multipath environment. This information provides the conditions under which it is reasonable to decrease the sample rate in ray tracing tools while using interpolation instead.**

Keywords: radio channel modeling, geometry-based stochastic channel models (GBSCM), visibility regions, ray entity, urban model, ray-tracing, interpolation

I. INTRODUCTION

The importance of reference channel models (RCM) as a special niche of radio channel modeling has already been widely established [1]. RCM's purpose is to adequately mimic the radio environment properties in order to serve as a test platform for new modulation and coding techniques, different antenna designs etc. Most of commonly adopted RCMs are stochastic, or more specifically, geometry-based stochastic channel models (GBSCM), meaning that their parameters are generated from some stochastic process [1], [2]. Therefore, these models suffer the risk of unrealistic realizations due to the randomness of the parameterization.

Current GBSCMs are measurement-based . Besides the fact that measurements are time consuming and expensive, additional limitations are caused by antenna properties, phase synchronization, inevitable measurement errors and sometimes random (atypical) events, especially if measurements have not been repeated on the same route or measurement set [3], [4], [5], [6].

Deterministic RCMs are suggested as a possibility in [7], but they are still quite unexplored as a feasible option for RCMs, mainly due to their complexity and system requirements. The feasible alternative for feeding geometry-based deterministic RCM would be a set of ray tracing (RT) simulated environments. Ray tracing allows high-resolution simulations, thus providing a very detailed description of the radio environment and the propagation phenomena. However, RT is a very time-consuming process with extremely high demands for memory capacities, in order to preserve all the data necessary for a very fine spatial resolution. Also, its computational burden grows significantly with number of considered receiver points. In this paper it is investigated how to simplify RT data and enable its interpolation, for decrease of needed computational time and complexity, while preserving the accuracy of the full ray tracing model.

The paper investigates the arrangement of the rays in a multipath environment and in particular virtual sources in case of diffraction propagation. Similar work on spatial dynamics in multipath environment has already been done in [8] and showed that due to the nature of diffraction it is not possible to locate a common stationary virtual source of neighboring rays even when ending very close (below 1 m) to each other and in spite of undergoing identical multipath interactions.

In this paper, appreciating the finding that diffraction causes virtual source of rays to move in correlation to moving of receiver [9], a novel investigation is performed that gives method for detection of visibility area for moving virtual sources. Also the method for obtaining trajectories of virtual sources and their utilization for interpolation of RT results is given. The investigation is limited by taking into account only direct rays, and reflected and diffracted rays up to two interactions per ray. Scattering and over-the-roof diffraction are not considered, although the discussion is easily extensible to them.

The paper is organized as follows. In the next section the notions of propagation phenomenon, ray entity and virtual source will be explained as well as their utilization for interpolation of RT results. In section III ray entity detection will be explained on an example in an urban scenario and the statistics of ray entity lengths will be given. Section IV will discuss trajectories of virtual sources, and their interpolation as a mean for enhancing RT performance and as a practical building block of deterministic RCM. The paper ends with conclusions given in section V.

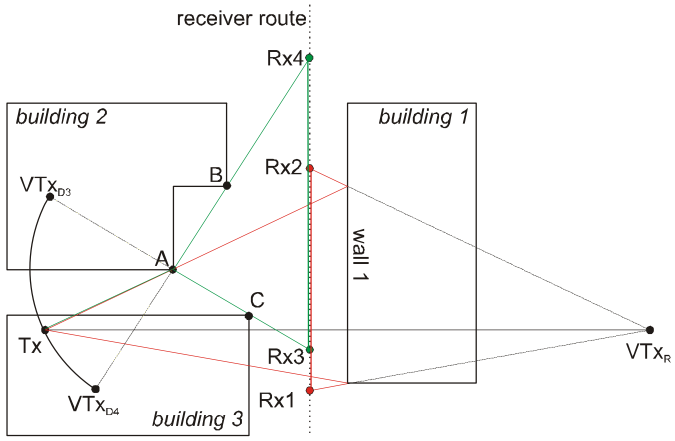


Fig. 1. A simple ground plan illustrating visibility of ray entities and loci of virtual sources

II. Ray Entities and Virtual Sources

Fig. 1 gives a ground plan of a simple setting of one transmitter (Tx), three buildings, and a receiver route where the coverage is of interest. Assuming that the antenna tower at Tx is high enough, rays reflected from wall 1 will, from geometry reasons be present only at the portion of the receiver route, i.e. from Rx1 to Rx2 (red line). The set of rays that thus all undergo same propagation phenomenon, i.e. reflection from wall 1 we shall call **ray entity** (RE). Another property of this RE is that all rays arriving at the receivers come from identical virtual source, VTx_R.

Another ray entity in Fig. 1 is due to single diffraction at the vertical edge A. Due to shadowing beyond edges B and C, this ray entity is present at the receiver route from point Rx3 to Rx4 (green line). Here, in case of diffraction, virtual transmitter is not a single point for the whole entity, but a section of a circle, from VTx_{D3} to VTx_{D4}, and slides circularly as the receiver slides along the route section where entity rays are present.

Generally, when diffraction is involved, the locus of virtual source for the entity is not a point but a section of a circle, at the height of the transmitter and parallel to the ground. This offers an opportunity for interpolation of virtual sources. Thus, rays at the receiver points along the receiver route that were not previously simulated using RT, can be calculated using interpolation of existing RT samples virtually at no computational cost. This understanding can foster also further research into sufficient resolution of RT simulations, where all higher resolutions could be obtained easily by interpolation. Interpolation, linear or other more sophisticated, would include also interpolation of received power. For pure reflections interpolation would not need interpolation of virtual source, since the virtual source is stationary for this kind of propagation.

III. Detection of Ray Entities from RT Results

The analysis is performed on RT simulated radio environments where a mobile unit is slid incrementally along a receiver (Rx) route. All rays obtained from simulations are compared by their interaction points and propagation modes and then grouped into ray entities, consisting of rays which underwent same types of propagation effects, in the same order and on the same objects. Rays within the same RE form an entity visibility region, a section of a receiver route.

An example will be given using a RT simulations [10], [11] on a map of Stockholm (Fig. 1), along a 199 m long route with 1m resolution. The propagation modes simulated were LOS, 1st and 2nd order reflection, 1st and 2nd order diffractions and mixed rays (reflection and diffraction or vice versa).

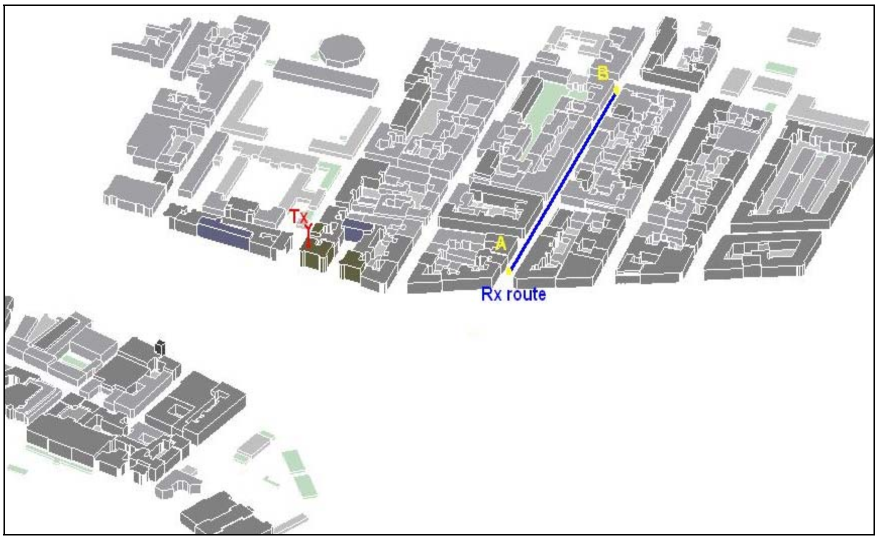
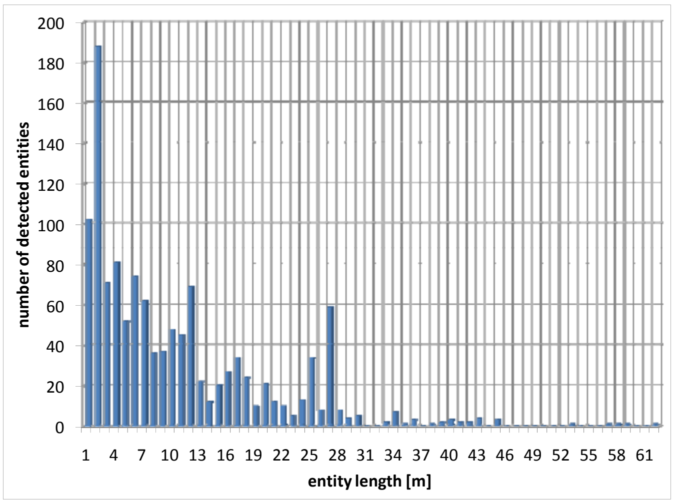


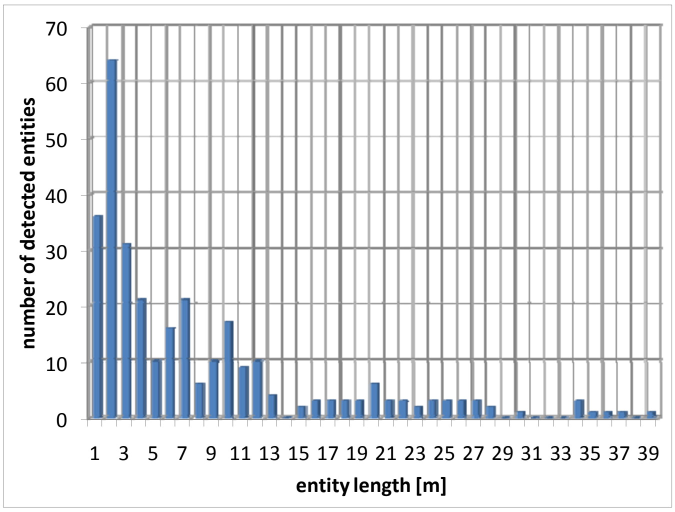
Fig. 2. Simulation scenario: a 199 m long route in a street of Stockholm

There was no line-of-sight (LOS) observed along the route. The number of detected rays was around 15,000 with the number of rays at each RX ranging from around 20 to around 300. The number of considered rays was then reduced to around 2,300, by imposing a power threshold with the number of rays at each RX ranging from 1 to around 30. The power threshold reduced the total power at the RX for negligible 0.03 dB on average and maximal observed reduction at one RX for 0.76 dB. More details on simulation and impact of used power threshold is available in [12].

Fig. 3 shows distribution of entity visibility lengths detected along the Rx route. It is given for a case with no power threshold on rays (Fig. 3. a) and with power threshold (Fig. 3. b).



a)



b)

Fig. 3. Number of detected entities of a specific length along the route. It is given for raw ray data (a) and after applying power threshold (b). There were some entities detected beyond length of 60 m, all way up to 82 m, with negligible representation.

Fig. 3. shows that numerous ray entities of considerable length are detected in considered example scenarios. These results cannot be compared directly

An entity of the longest visibility (82 m) is detected in raw data. It is omitted from Fig. 3 a) for easier display of other data. However, we shall use this entity's properties to illustrate typical relationship between the actual source, interaction points, entity visibility and virtual sources. Fig. 4 gives a ground plan of a scene in Fig. 2, but with a limited number of elements, only those relevant for this entity: location of transmitter (red triangle), actual ray path (red), entity visibility range (green) and locus of virtual sources for the entity.

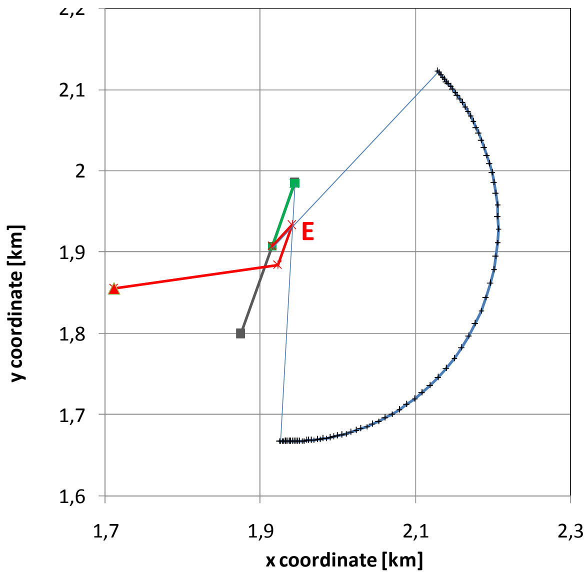


Fig.4. Ground plan of Fig. 1 containing only features relevant for sample entity with visibility of 82 m. Red triangle - Tx; red line - ray path with two interactions; grey line (partially covered with green one) - 199 m long Rx route; green line - "entity visible" section; blue line - locus of virtual Tx along the entity. Note that thin blue lines connect end points of visible section with appropriate virtual Tx. Markers on blue line denote virtual Tx-es for Rx locations sampled at 1m along the Rx route. Note that last interaction point (point E) is constant for the entity only on ground plan, but not in height.

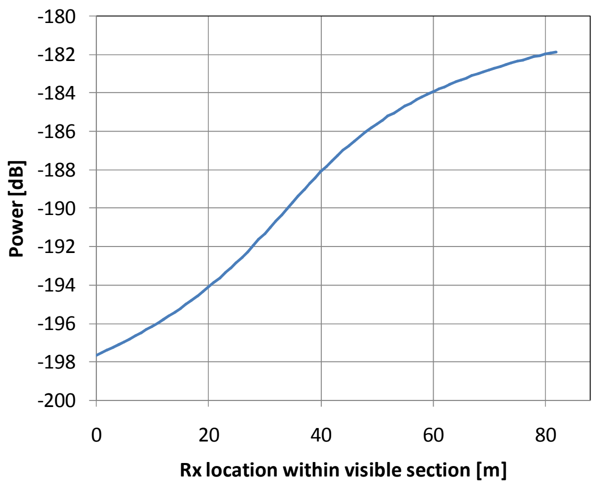


Fig. 5. Power curve along the entity visibility section. Such curves can be easily approximated with polynomials.

Fig. 5 gives the ray power at Rx location along the route section where the entity is visible. These power curves in general are smooth and can be represented with few-element polynomials.

TABLE I
COMPARISON OF NUMBERS OF ENTITIES AND NUMBER OF RAYS, AND CORRESPONDING NUMBER OF VALUES NEEDED TO DESCRIBE THEM

	Number of rays	Number of entities
no power threshold example	12951	1229
power threshold example	2389	305
Values necessary to describe a ray/entity	Ray • Ray length/time delay • elevation angle • azimuth angle • Ray arrival location (integer index) • Ray power	Entity • entity start (integer index) • entity end (integer index) • entity delay offset (i.e. virtual Tx locus radius) • last interaction (edge) x-y coordinates (point E in fig. 5), to ensure calculation of correct virtual Tx on a circle, for each Rx • Entity power Taylor series coefficients (4 values at most)
Values total	For Ray: 4 real + 1 integer	For Entity: 7 real + 2 integer

TABLE II
COMPARISON BETWEEN CLASSICAL RAY-TRACING AND RAY ENTITY BASED INTERPOLATION METHODS

	Simple Ray Tracing	Entity Interpolation RT
Memory usage	Higher (4-5 times)	Lower (4-5 times)
Rx Resolution (number of receivers at a certain area)	Fixed after initial RT run	Unlimited (can be increased arbitrarily after initial RT run)
Computational burden for increased Rx resolution	Increasing significantly	Negligible increase
Versatility for including other effects (over the rooftop diffraction, diffuse scattering)	YES	YES, with simple adaptation for each effect

IV. INTERPOLATION OF RT RESULTS USING RAY ENTITIES

Representation of ray tracing simulations by ray entities can reduce memory usage, and interpolation by virtue of rays sorted in ray entities enables more refined results at small additional computational cost. Reduced memory requirement can be argued by Table I, which gives comparison in two examples of scenario in Fig. 1: with and without power threshold imposed on rays. It shows that storing ray tracing simulation as ray entities would require less than a double memory per entity as per ray. Significant memory reduction is expected since number of entities is significantly smaller then number of rays; in two examples given, the reduction is 7.8-10.5 times. Thus the overall memory usage reduction is about 4-5 times. The table I gives values only for diffraction cases from two reasons. Firstly, because two examples considered, as the most of typical urban environments, were dominated by diffraction (only one pure reflection ray is detected on the route). Secondly, REs based on pure reflections have a stationary virtual Tx, thus making their recording even simpler and less memory consuming. Only a dubious and hard to imagine case of environment dominant by many pure-reflection-kind ray entities of very short duration along the receiver path could see no improvement or even disadvantage in memory usage when using RE approach.

Table II sums up all features of comparison between classical ray-tracing and ray entity based interpolation methods. Although reduced memory usage for a factor of 5 may look as an interesting feature, the major advantage of this approach is the ability to interpolate RT results to arbitrary high resolution. This feature is available after initial RT simulation and RE post-processing is performed, and can be repeated for customized needs of the user. Thus, ray entity introduction enables simulations of radio channel with arbitrarily moving user, with arbitrary modulation and coding scheme, in wide frequency band range and with sufficient spatial resolution. This can be used for deterministic reference channel model of computer efficiency comparable to its stochastic based counterparts, but with much more realistic and standardized performance.

V. CONCLUSION

The paper introduced a novel concept of ray entities as a versatile interpretation and post-processing of ray tracing results in urban, rich multipath environments. It is hypothesized that combining of rays that undergo same propagation phenomenon into one entity can be of some benefit for reduced storage of ray data and may enable interpolation of ray tracing results.

On examples given in the paper is has been shown that memory needed to store ray tracing results was reduced for a factor of around 4 to 5. Further investigation with more case studies is needed for more accurate value of reduced memory requirements, but it is clear that there will always be some reduction except in cases of large number of short entities, which is physically unfeasible except maybe in rare architectural cases. Since two examples in the paper were dominated by diffraction, even more reduction can be expected in reflection rich environments, where ray entity's virtual source is stationary, i.e. simpler to describe.

The existence of ray entities and insight into their nature, such as dynamics of their power, angle of arrival and their visibility area can improve understanding of urban multipath environments and inspire adapting radio system aspects to that understanding. For example, some adaptive beam forming or MIMO system could be designed having in mind facts about continuous change of arriving rays properties, as mobile user is moving along an entity.

Ray entity concept also enables interpolation of ray tracing results obtained for sufficiently closely located set of receivers. It enables, at negligible computational cost, obtaining of ray tracing data of arbitrary high resolution.

Finally, ray entity concept is a step towards feasible deterministic reference channel model, a standardized channel model that would have database of RT-simulated typical environments, recorded in ray entity format. This would enable users, who want to test and compare various wireless system concepts on a real environment, to do so in much more realistic way than it is the case with currently available stochastic-based reference channel models.

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