Modeling and Simulation of Radio Signals Attenuation Using Informed Virtual Geographic Environments (IVGE)

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***Abstract*—A radio communication system is a complex dynamic phenomenon where transmitter and receiver antennas are constantly constrained by the physical environment in which they are deployed. In the real world, radio transmissions are subject to propagation effects which deeply affect the received signals because of geographic and environmental characteristics (foliage and vegetation, buildings, mountains and hills, etc.). Multi-Agent Geo-Simulation aims to simulate such phenomena involving a large number of autonomous situated actors (implemented as software agents) evolving and interacting within a representation of the physical environment. Using a geo-computation approach, we propose to use an Informed Virtual Geographic Environment (IVGE) along with MAGS paradigm. In addition, we propose a multi-agent prototype to analyze the attenuation effect due to the radio signal's traversal between antennas (simulated as software agents) through terrain shape, vegetation area, and buildings using a 3D line-of-sight computation technique.**

Keywords-Line of Sight*; *Excess attenuation*; *Vegetation and Foliage*; *Radio Propagation*; *Informed Virtual Geographic Environments

I. INTRODUCTION

Rapid advances in wireless communications have made mobile data applications a high-growth area of development. So far, most applications only focus on geographic data collection and access using geographic information systems. However, many emergency management applications need such geographic data in order to ensure that field workers and command center operators collaborate under acceptable operating conditions. Under emergency conditions, emergency systems need to quickly establish an *ad hoc*, ground-level network of radio stations mounted on temporary command centers, vehicles, or temporary masts, interacting with moving field operators using mobile devices.

Radio Frequency (RF) communication does have some limitations that must be considered. The maximum line-of-sight range between two shoulder-height devices is limited to $12km$ considering the curvature of the earth but not considering refraction of radio waves. The actual range may be considerably less depending on transmission power and receiver sensitivity, and the radio signal can be attenuated or degraded due to obstruction resulting from its interactions with features on its transmission path. In an urban environment, possible obstructions include buildings, trees, and bridges (Figure 1). The difficulty of evaluating an ad hoc radio network with hundreds of nodes and various levels of mobility operating in a complex geographic environment (i.e., rugged terrain, dense foliage, buildings, etc.) motivated us to use our IVGE model to analyze communication attenuation. In order to analyze the communication attenuation in real geographic environments, we propose to use the Multi-Agent Geo-Simulation (MAGS) approach involving an enriched description of the geographic environment representation to precisely compute the radio transmission's attenuation. The radio transmission is computed using the line of sight between two points located in the IVGE.

During the last decade, the Multi-Agent Geo-Simulation (MAGS) approach has attracted a growing interest from researchers and practitioners to simulate phenomena in a variety of domains including traffic simulation, crowd simulation, urban dynamics, and changes of land use and cover, to name a few [1]. Such approaches are used to study phenomena (i.e., car traffic, mobile robots, mobile networks, crowd behaviours, etc.) involving a large number of simulated actors (implemented as software agents) of various kinds evolving in, and interacting with, an explicit description of the geographic environment called Virtual Geographic Environment (VGE). Nevertheless, simulating such autonomous situated agents remains a particularly difficult issue, because it involves several different research domains: geographic environment modeling, spatial cognition and reasoning, situation-based behaviours, etc. When examining situated agents in a VGE, whether for gaming or simulations purposes, one of the first questions that must be answered is how to represent the world in which agents navigate. Since a geographic environment may be complex and large-scale, the creation of a VGE is difficult and needs large quantities of geometrical data describing the environment characteristics (terrain elevation, location of objects and agents, etc.) as well as semantic information that qualifies space (building, road, park, etc.). Current approaches usually consider the environment as a monolithic structure,

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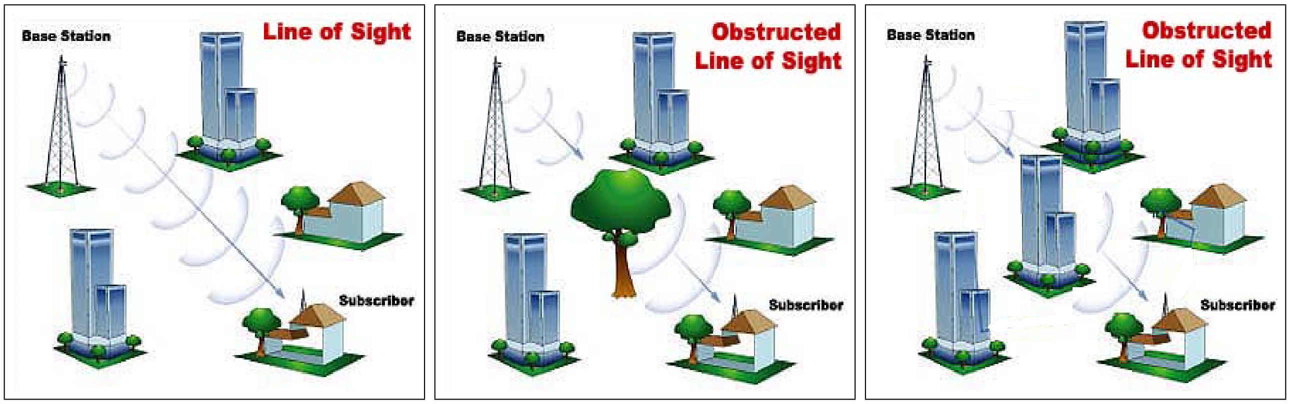

(a) (b) (c)

Figure 1: Radio signal propagation: (a) an obstruction-free propagation; (b) propagation obstructed by vegetation and foliage; and (c) propagation obstructed by buildings.

which considerably limits the way that large-scale, real world geographic environments and agent's spatial reasoning capabilities are handled.

In this project, our goal is to analyze the radio communication attenuation in complex, dynamic and large-scale geographic environments. In order to achieve such a goal, a geographic environment model should precisely represent geographic features. It should also integrate several semantic notions characterizing these geographic features. Since we deal with large-scale geographic environments, it would be appreciable to have a VGE organized efficiently in order to reduce the spatial computation algorithms such as line-of-sight algorithms. There is also a need for autonomous situated agents representing antennas, either transmitters or receivers which are able to communicate using radio signal propagation in presence of both *static* and *dynamic* obstacles located in the VGE. Static obstacles correspond to areas that affect radio signal propagation such as walls, fences, trees, rivers, etc. Static obstacles also include obstructions resulting from terrain elevation (mountains, hills, etc.). Dynamic obstacles correspond to moving or stationary antennas which may interfere with the radio communication system.

In this paper, we propose a novel approach to model and simulate radio communication networks using multi-agent systems evolving in and interacting with a virtual geographic environments. The rest of the paper is organized as follows: in Section II, we provide a brief overview on related work in the field of environment representation and analysis of radio communications. Section III presents our methodology for the creation of informed virtual geographic environments. Section IV highlights the unique properties of our IVGE model which easily and efficiently enable spatial reasoning algorithms and geometrical computations such as line-of-sight computation. Section V details the radio communication analysis tool. Finally, Section VI concludes and presents our perspectives.

II. Related Works

In this section we provide a brief overview of prior works related to *environment representation*, and *analysis of radio communications* in virtual environments.

A. Environment Representation

Virtual environments and spatial representations have been used in several application domains. For example, Thalmann *et al.* proposed a virtual scene for virtual humans representing a part of a city for graphic animation purposes [2]. Donikian *et al.* proposed a modelling system which is able to produce a multi-level data-base of virtual urban environments devoted to driving simulations [3]. More recently, Shao *et al.* proposed a virtual environment representing the New York City's Pennsylvania Train Station populated by autonomous virtual pedestrians in order to simulate the movement of people [4]. However, since the focus of these approaches is computer animation and virtual reality, the virtual environment usually plays the role of a simple background scene in which agents mainly deal with geometric characteristics. Indeed, the description of the virtual environment is often limited to the geometric level, though it should also contain topological and semantic information for other types of applications. Therefore, most interactions between agents and the environment are usually simple, only permitting to plan a path in a 2D or 3D world with respect to free space and obstacle regions.

B. Analysis of Radio Communications

Jiancheng *et al.* proposed a prediction of mobile radio propagation by regression analysis of signal measurements, investigated path loss characteristics of mobile radio signals in urban and rural areas [5]. The results were used to evaluate the accuracy of Okumura-Hata and Lee prediction models [6]. In his perspectives on the effects of harmattan on radio frequency waves, Dajab computed harmattan dust particle densities in air and observed that attenuation due to dust particles increases as harmattan intensity increases [6]. Eyo *et al.* researched into microwave signal attenuation in harmattan weather along Calabar-Akampkpa terrestrial line of sight microwave link [7]. Using measured results in conjunction with some meteorological data they were able to deduce the mean signal level, fog attenuation, fade depth and fade margin of the link.

Most works achieved towards on radio propagation modeling and simulation do not consider the geographic environments in which the communication system is located (See Figure 2 for an illustration of a typical radio communication system). Signal specialists currently have limited capabilities for predicting radio performance in complex geographic environments that may involve jammers and may have combinations of open terrain and obstructed locations [8]. Foliated areas, buildings, or terrain may cause obstructions to the radio line-of-sight path [9]. Therefore, there is a need for a communication analysis tool that helps fill this void [10]. We propose to use geo-computation techniques in order to build a tool for the analysis of radio communications attenuation involving a geometrically-accurate and semantically-informed virtual geographic environment model. This tool is an easy to use, stand-alone, GUI-based application that runs on a PC and provides a rich set of functionalities to aid the user to compute the total path loss of a given operational scenario that is directly coupled to an operational area using reliable GIS data.

This tool enables the user to plan radio deployments and determine link connectivity using actual radio parameters, taking into account the presence of obstacles, while accounting for the excess attenuation due to terrain, foliage (vegetation), and building obstructions. To compute the total path loss, our tool uses the following parameters: height of transmitter antenna (meters), height of receive antenna (meters), transmitter antenna position (x, y, z), receiver antenna position (x, y, z), and frequency of operation (GHz).

III. Computation of IVGE Data

In this section, we present our automated approach to compute the IVGE data directly from vector GIS data. This approach is based on four stages which are detailed in this section (Figure 3): *input data selection*, *spatial decomposition*, *maps unification*, and finally the generation of the *informed topologic graph*.

GIS Input Data Selection: The first step of our approach consists of selecting the different vector data sets

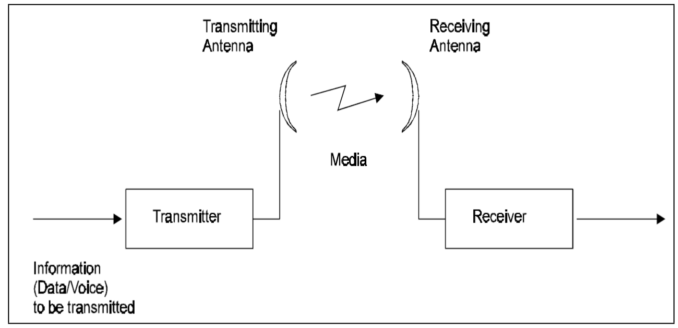

Figure 2: Typical Radio Communication System

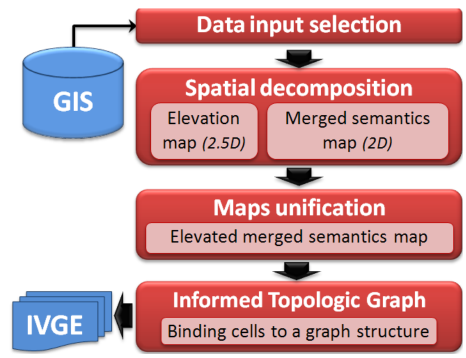

Figure 3: The four stages to obtain an IVGE from GIS data. All the stages are automatic but the first.

which are used to build the IVGE. The only restriction concerning these data sets is that they must respect the same scale. The input data can be organized into two categories. First, *elevation layers* contain geographical marks indicating absolute terrain elevations. As we consider $2.5D$ IVGE, a given coordinate cannot have two different elevations, making it impossible to represent tunnels for example. Multiple elevation layers can be specified, and if this limitation is respected, the model can merge them automatically. Second, *semantic layers* are used to qualify various types of data in space. Each layer indicates the physical or virtual limits of a given set of features with identical semantics in the geographic environment, such as roads or buildings. The limits can overlap between two layers, and our model is able to merge the information.

Spatial Decomposition: The second step consists of obtaining an exact spatial decomposition of the input data into cells. This process is entirely automatic using Delaunay triangulation, and can be divided into two parts in relation to the previous phase. First, an elevation map is computed, corresponding to the triangulation of the elevation layers. All the elevation points of the layers are injected into a 2D triangulation, the elevation being considered as an attribute of each node. This process produces an environment subdivision composed of connected triangles. Such a subdivision provides information about coplanar areas: the

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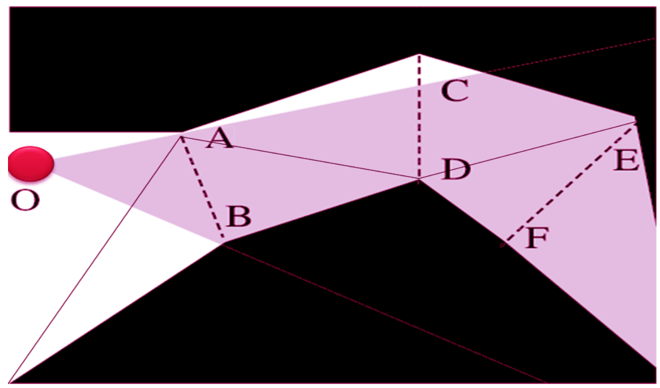
elevation of any point inside a triangle can be deduced by using the elevation of the three original data points to form a plane. Second, a merged semantics map is computed, corresponding to a constrained triangulation of the semantic layers. Indeed, each segment of a semantic layer is injected as a constraint which keeps track of the original semantic data by using an additional attribute for each semantic layer. The obtained map is then a constrained triangulation merging all input semantics. Each constraint represents as many semantics as the number of input layers containing it.

Merging Elevation and Semantics Layers: The third step to obtain our IVGE consists of unifying the two maps previously obtained. This phase can be depicted as mapping the $2D$ merged semantic map onto the $2.5D$ elevation map in order to obtain the final $2.5D$ elevated merged semantics map. First, preprocessing is carried out on the merged semantics map in order to preserve the elevation precision inside the unified map. Indeed, all the points of the elevation map are injected into the merged semantics triangulation, creating new triangles. This first process can be dropped if the elevation precision is not important. Then, a second process elevates the merged semantics map. The elevation of each merged semantics point P is computed by retrieving the corresponding triangle T inside the elevation map, i.e., the triangle whose $2D$ projection contains the coordinates of P. Once T is obtained, the elevation is simply computed by projecting P on the plane defined by T using the Z axis. When P is outside the convex hull of the elevation map then no triangle can be found and the elevation cannot be directly deduced. In this case, we use the average height of the points of the convex hull which are visible from P.

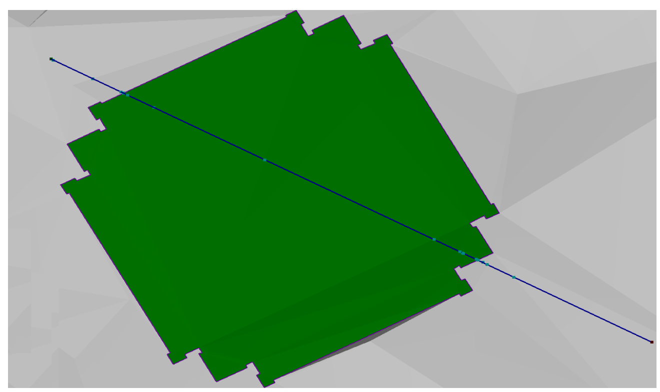
Informed Topologic Graph: The resulting unified map now contains all the semantic information of the input layers, along with the elevation information. This map can be used as an *Informed Topologic Graph* (ITG), where each node corresponds to the map's triangles, and each arc corresponds to the adjacency relations between these triangles. Then, common graph algorithms can be applied to this topological graph, and graph traversal algorithms in particular. One of these algorithms retrieves the node, and therefore the triangle, corresponding to given $2D$ coordinates. Once this node is obtained, it is possible to extract the data corresponding to the position, such as the elevation from the $2.5D$ triangle, and the semantics from its additional attributes. Several other algorithms can be applied, such as path planning or graph abstraction, but they are out of the scope of this paper and will not be detailed here.

IV. Properties of Informed VGE

The subdivision of space into convex cells allows us to preserve the original geometric definition of the geographic environment, unlike the grid-based representations that discretise the environment. Furthermore, the proposed data reorganization produces triangles that feature good properties: convexity which facilitates the geometric calculations; support of heterogeneous geometric constraints (points, segments, polygons); Since each constraint is linked to its nearest neighbor, it is easy to compute the widths of the bottlenecks in the virtual geographic environments. The width computation corresponds to the minimum of borders' width that are not qualified as obstacle (Figure 4(a)).



(a)



(b)

Figure 4: (a) Computation of the widths of the bottlenecks; (b) Computation of the ray tracing.

The subdivision of space into convex cells also allows us to extract an informed topologic graph of the environment featuring relatively few nodes compared to grid-type representations. Additionally, the triangulation is not dependent on a fixed spatial scale for the environment, but only on its complexity (number of constrained segments). It should also be emphasized that curved geometries will produce a lot of triangles since they are represented by a large number of constrained segments. However, since the produced triangulation is represented as a graph, it is possible to abstract it in order to reduce the number of elements. All these properties are of interest to address the issue of line-of-sight computation.

A. Line of Sight's Computation

The spatial subdivision provides a structure of convex cells which facilitates and accelerates the calculation of ray tracing in three dimensions. We define the radius α using the following information: the position of the origin p; the direction vector $\vec{d}$; and the maximum distance considered. Let $Get_{free}(Cell)$ and $Get_{constrained}(Cell)$ be two functions returning respectively the list of free (S_{free}) and constrained (S_{const}) borders bounding the convex cell $Cell$. Let $N(Cell, b)$ be a function returning the normal vector to the border b which belongs to the cell $Cell$ and directed towards the inside of the cell. Finally, let us note $\wp(\beta)$ the $2X2$ rotation matrix of $\vec{d}$. The test checking if there is an intersection between the ray and the border b, which links the vertices I and J, is performed using the following expression:

$$(\alpha \leq 0) \wedge (\beta \times \gamma) \leq 0 \tag{1}$$

The parameters α, β, and γ, in equation 1, are computed as detailed in equations 2, 3 and 4.

$$\alpha = \vec{d} \cdot N(Cell, b) \tag{2}$$

$$\beta = (\frac{I+J}{2} - p) \tag{3}$$

$$\gamma = \wp(\frac{\pi}{2} \cdot (I-p)) \times ((\frac{I+J}{2} - p) \times (\frac{\pi}{2} \cdot (J-p))) \tag{4}$$

The line of sight computation algorithm proceeds as follows:

- ***Step 1***: the cell $Cell$ containing the source of the line of sight vector $\overrightarrow{LoS}$ is determined.
- ***Step 2***: an intersection test is performed between $\overrightarrow{LoS}$ and each border b of $Cell$.
- ***Step 3***: compute $S_{free}(Cell)$ using $Get_{free}(Cell)$ and $S_{const}(Cell)$ using $Get_{constrained}(Cell)$.
- ***Step 4***: if no intersection is found with borders from $S_{free}(Cell)$, then $\overrightarrow{LoS}$ must intersect with a border from $S_{const}(Cell)$.
- ***Step 5***: the border b is pushed back to the list of borders crossed by $\overrightarrow{LoS}$.
- ***Step 6***: the cell $Cell$ is pushed back to the list of cells crossed by $\overrightarrow{LoS}$.
- ***Step 7***: the cell sharing the border b which intersects with $\overrightarrow{LoS}$ becomes the current cell. Proceed to Step 2.

The line of sight algorithm, due to its low computational cost, can be extensively used in MAGS involving a large number of agents evolving in a complex IVGE.

V. Analysis of Radio Communication

Planning communications links requires the ability to assess the performance of each link in the presence of a number of degrading factors. In addition to the normal free space signal attenuation loss, other losses reduce the signal level. These additional losses can be caused by obstructions such as buildings and vegetation (foliage). Analyzing obstruction losses can be difficult because of the geometric, topologic, and semantic characteristics of the geographic environment and the need for path loss models.

We use a ray-tracing approach which determines the path that a radio signal takes to arrive at the receiver's position from a given transmitter within our 3D IVGE. The ray-tracer implemented in the tool uses optimized algorithms for detecting direct (i.e., line of sight) paths (Figure 4(b)). An analytic ray-tracing technique [11] is used rather than the approximate technique, for example, as used in [12]. For the analytical approach, the transmitter and receiver are each modelled as infinitesimally small points such that paths are computed precisely and cannot be duplicated or missed as sometimes could happen in the approximate approach. Obviously, the analytical technique is more precise and reliable. Our approach computes the total source-to-destination path length and then determines whether the vector defined by the source and destination points (locations in the IVGE) passes through an obstruction area. Doing so, it is able to compute the total path loss between transmitter and receiver antennas. One of three cases may occur: 1) *Obstruction-Free Path*: Vector does not penetrate any obstruction; 2) *Obstruction Block Penetration*: Vector penetrates one or more foliage obstruction blocks and/or one or more building obstruction blocks; and 3) *Ground Penetration*: Vector penetrates the ground (earth) once or several times.

The computations performed by our tool, to quantify the path attenuation for each of the three cases defined above, are based on the following well-established mathematical models described in [13].

Plane-Earth Attenuation Model: Let L_p be the path attenuation using the plane-Earth model (dB):

$$L_p = 40Log(D) - 20Log(H_t) - 20Log(H_r) \tag{5}$$

where D is the total source-to-destination path length (meters), and H_t and H_r are the heights of the transmitter and receiver antennae above ground level, respectively (meters).

Free-Space Attenuation Model: Let L_{fs} be the path attenuation using the Free-Space model (dB):

$$L_{fs} = 32.45 + 20Log(D) + 20Log(f) \tag{6}$$

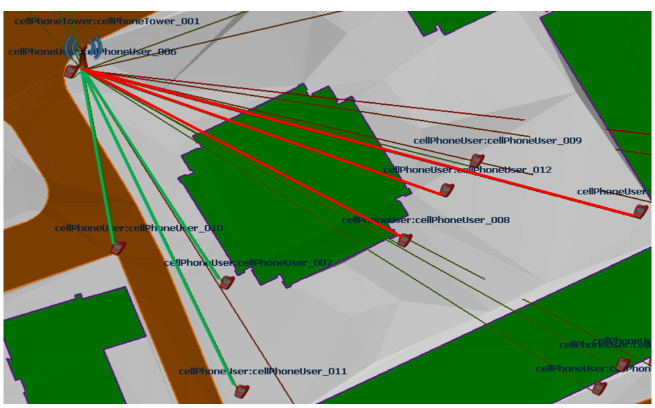
where D is the total source-to-destination path length (meters) and f is the RF frequency (GHz).

Obstruction Block Penetration Model: Let L_B be the path attenuation term due to propagation through a building obstruction block (dB) [14]:

$$L_B = K_1(0.6)^f + K_2 D_B \qquad (7)$$

where f is the RF frequency (GHz), K_1 is a constant used to map the first expression above to building penetration data reported in [13]. $K_1 = 35$; K_2 is a constant to account for the attenuation (per meter) of the signal within the building. $K_2 = 1$ (dB/m); and D_B is the distance that the signal propagates through the building (meters). The first term in Equation 7 accounts for the penetration into and out of the building by the signal and was derived from data reported in [13] using a regression analysis technique. The second term in the equation above accounts for the attenuation through the building and is based on data reported by Willassen in [15].

(a)



(b)

Figure 5: Simulation of radio communications' attenuation; yellow lines correspond to obstacle-free line-of-sight radio signal propagation; red lines correspond to obstructed line-of-sight; (1) represents the transmitter antenna implemented using the agent paradigm; (2) an example of a plane-earth obstruction; (3) an example of a block-penetration obstruction.

Foliage obstruction Attenuation Model: If the penetration is through a foliage obstruction block, the tool computes an excess path attenuation term called L_f using the Wiessberger model [16] as follows:

$$L_f = 1.33 f^{0.284}.D_f^{0.588}, 14 < D_f \qquad (8)$$
$$L_f = 0.45 f^{0.284}.D_f^{1.0}, \quad 0 \le D_f \le 14m \qquad (9)$$

where D_f is the distance that the signal propagates through the foliage obstruction (meters) and f is the RF frequency (GHz). The term "excess attenuation" refers to the additional attenuation above the basic transmission loss, for a given path length, in the absence of foliage. Our analysis approach applies equations 5 to 9 to calculate the basic transmission loss for the link. Thus, the total path attenuation for the obstruction penetration case called L_{total} is calculated as follows:

$$L_{total} = max(L_p, L_{fs})_{Deff} + sum(L_f) + sum(L_B) \qquad (10)$$

where $max(L_p, Lfs)_{Deff}$ means that this term is calculated at $Deff$; $Deff$ is the effective path length over which the *Plane-Earth* and *Free-Space* path attenuation model is applied and is equal to the total path length minus the sum of the building obstruction block path length segments or sum(DB); $sum(L_f)$ is the sum of the excess attenuation terms in dB due to signal propagation through the foliage obstruction block(s) (dB); and $sum(L_B)$ is the sum of the path attenuation terms due to propagation through the building obstruction block(s) (dB).

Figure 5 illustrates the agent-based simulation tool that we developed in order to implement our approach to analyze the radio signal attenuation in informed virtual geographic environments. This figure presents a snapshot of the simulation at time t_0 with an agent representing a transmitter antenna and several agents representing receiver antennae. Red lines in Figure 5(a) highlight the strength of the radio signal attenuation with comparison to an arbitrary user-defined threshold Δ: (red) for severe signal attenuation, (green) for acceptable signal attenuation. Moreover, Figure 6 shows how to collect the list of cells crossed by the radio signal propagation path.

VI. Discussion and Conclusion

Using reliable GIS data along with the line of sight algorithm (ray tracing feature) provided by our IVGE allows the system to compute the exact locations of intersections occurring between the radio signal propagation path and the terrain shape (Figure 5). Our IVGE also allows us to collect the list of cells crossed by the radio signal propagation path and to determine which analytic model to apply in order to precisely compute the path loss.

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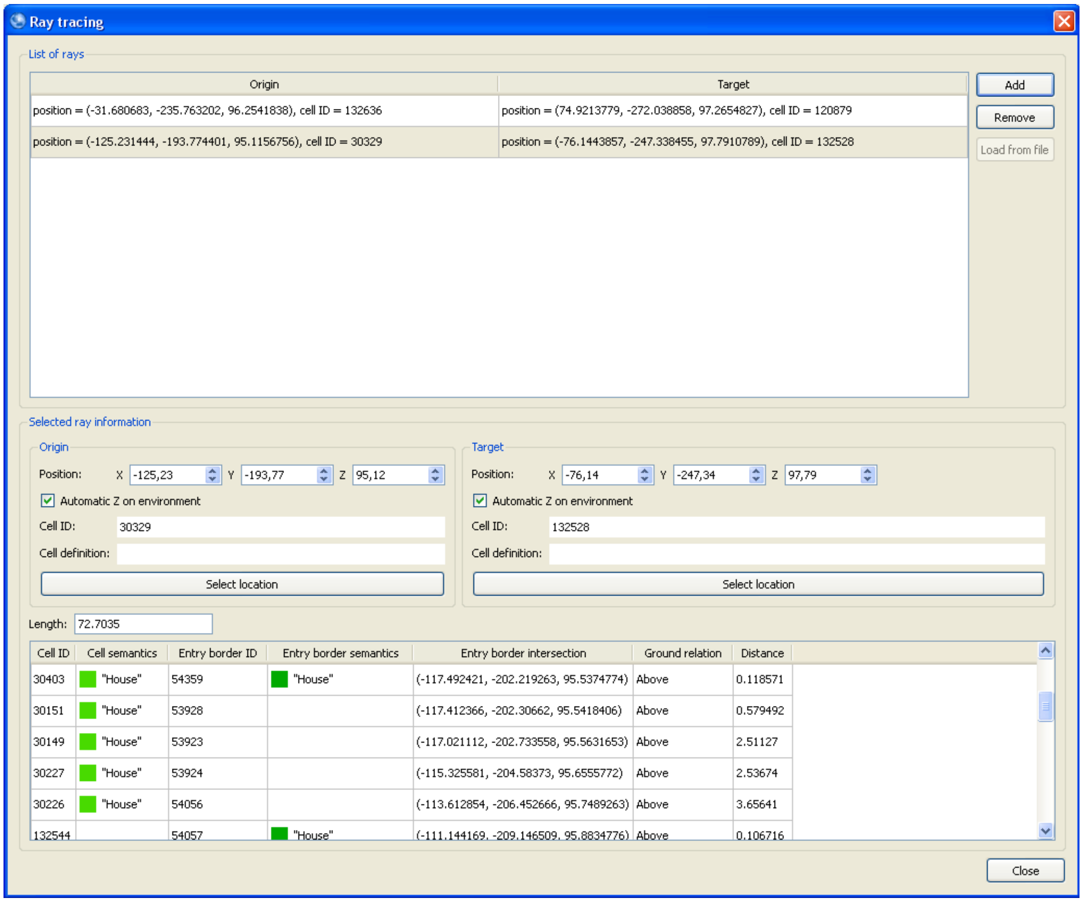

Figure 6: The graphic user-interface for the computation of the radio signal line-of-sight; Cells and borders.

We have shown a tool that leverages the enriched description of the IVGE and computes the radio signal attenuation due to buildings, foliage and field obstructions. However, other phenomena can also degrade the radio signal transmission. Examples of such phenomena include transmitter power, receiver sensitivity, and radio signal's absorption, reflection, and scattering from interaction with features on or near its transmission path. The proposed tool should be easily extended to take into account absorption, reflection and scattering phenomena when computing the radio signal attenuation.

In the future, we propose to extend our tool in order to integrate an advanced ray-tracing process [17] which combines both the geometric optics and Keller's [18] geometric theory of diffraction (GTD). Moreover, we propose to include the uniform theory of diffraction (UTD) [19] extension to GTD which removes the inaccuracies close to the incident and reflection boundaries.

To conclude, our geometrically-precise and semantically-enhanced IVGE enables us to provide wireless network planners with a tool for the analysis of the communications' attenuation. In contrast with mathematical models which only approximate the radio signal attenuation based on a coarse-grained qualification of the geographic environment: *urban*, *suburban* and *rural*, we compute more precisely the radio signal propagation path and qualify obstructions in order to apply the appropriate analytical model.

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