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Wave Propagation Characterization in Complex Urban Areas using *EM*Terrano

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I. Introduction

The prediction of radio wave propagation in highly scattering environments, such as urban areas, has received significant attention in recent years. The ability to accurately predict coverage and it's associated statistics, in an urban microcell would be an invaluable asset to the telecommunications engineer in site planning and the strategic placement of transmitter and repeater locations. While measurements can provide useful information to the site planner, they are expensive, time consuming, and effected by measurement system variations at the time the measurements were taken. Also it would be quite impossible to gather a general database, which can account for all variations in the physical environment.

In order to provide more general and useful information to the systems engineer, the trend in recent years has been toward the development of physics-based propagation models [1]–[3]. These models represent various features in the physical environment, tend to be more accurate than heuristic or simplified analytic models, and when integrated, provide for a more complete and accurate simulation of the propagation environment. These models are site-specific, and the intent is to allow for the simulation of any environment for which the physical scenario is know (such as through the use of geophysical data from satellite databases). Their limitation is in the accuracy of the canonical model applied for a specific physical feature, and this is an ongoing area of research, the development, improvement, and integration of these models into a complete propagation simulation.

Recently, the trend in physics-based propagation prediction for urban areas has been toward the so called quasi-3D methods, such as the vertical plane launch method (VPL) [4], [5]. Their application is based on the premise that full 3-D ray-tracing (rays shot over a full spherical area, 4π steradians) in a highly scattering environment is essentially intractable and the time taken to run such a simulation, taking into account every relative scattering and diffraction mechanism, is prohibitive. Based on this premise, methods such as VPL, confine the ray coverage area to the 2-D, horizontal plane, and extend the rays to the 3-D plane, by calculating the difference between transmitter and receiver height, essentially it corrects the phase and amplitude from the 2-D, to the 3-D path length. Ground reflection is accounted for by applying image theory. These methods however, apply only 2-D reflection and diffraction coefficients, and because of this, significant error in the received ray strength can be accumulated at each point of interaction between the individual rays and object faces and corners. It is expected that this error will be especially significant for situations in which the transmitter and receiver are at a substantial height difference. In addition, for indoor scenarios, a full 3D ray tracer is essential to account for both floor and ceilings.

Because of these limitations in the quasi-3D methods, an investigation has begun into methods for improving the timing efficiency of full 3D ray tracing, so as to make it of practical use for the simulation of highly scattering environments, such as urban areas. With this in mind, a full 3D ray tracing algorithm [6] has been incorporated into the propagation simulation tool *EM*Terrano, developed at EMAG Technologies, Ann Arbor, Michigan. By the application of ”intelligent ray tracing,” preliminary results are shown in this paper, which testify as to the practicality of using a full 3D ray tracing engine in a propagation simulation tool such as *EM*Terrano.

II. Intelligent 3D Ray Tracing

The basis for intelligent 3D ray tracing in *EM*Terrano is to apply a simple, common sense approach to ray tracing in three dimensions. The following basic assumptions are made:

1) The ray generated from each source point (source, reflection, diffraction) will not interact with any object behind, or to the sides of it.
2) When checking for ray interaction with a given receiver, the same assumption can be made.
3) The sole criteria for when to discard a particular ray is it's power amplitude, based on receiver sensitivity, not the number of reflections or diffractions that it has gone through, as these are not necessarily representative of a ray's power.

Figure 1*a* illustrates the concept described in item 1) above. Basically the user defines an angular search area, in steradians, for each ray generated by the transmitter, reflected by a building (or the ground), or diffracted by a corner. For each one of these ray sources, only objects in the angular area defined are checked for interception by the given ray. Application of this algorithm can result in significant savings in time, proportional to the reduction in the angular search area for each ray, without any significant degradation in accuracy. Applying the same concept to test for rays captured by a receiver, a further 30% reduction in simulation run time is observed. While further investigation must be performed, it is believed that item 3) above will result in additional improvements in computer run times, especially in more densely populated scattering environments. Many ray tracers base the decision on when to disregard a ray, at least in part, on the number of reflections or diffractions that a ray undergoes. In a highly scattering environment, this number must be set fairly high, as it is more likely that the dominate ray path will be one with significant reflections. This is inefficient however, as many rays, whose power levels have dropped below the receiver sensitivity, will continue to be traced. Basing the criteria for disregarding a ray solely on it's power level (usually set to the expected receiver sensitivity), will result in maximum efficiency in the ray tracing algorithm, both in terms of accuracy and simulation run time.

III. Accuracy of Quasi-3D Ray Tracing

As mentioned previously, quasi-3D ray methods usually apply 2D reflection and diffraction coefficients, that is, it is assumed that the ray is always incident in a plane perpendicular to the vertical in the propagation scenario. Depending on the actual incident angle of the 3D ray with the building or object structure, significant error in the reflection or diffraction coefficients can be introduced. This error increases as the actual incident angle of the ray moves away from the 2D plane, and at or near Brewster's angle (parallel polarization only), where no reflected field is present, can become even more acute. The effects of this error are cumulative, increased at each interaction point for a given ray. To illustrate this point Figures 1*b* and *c* show the percent error (in dB) in the magnitudes of the 2D Fresnel reflection coefficients applied in the quasi-3D methods, when compared to the magnitudes of the actual 3D reflection coefficients, as a function of the 3D incident angles θ_{3D} and ϕ_{3D}. Figure 1*b* shows the percent error for perpendicular polarization and Figure 1*c* for parallel polarization, where the percent error E, is defined as, $E = (|\Gamma_{3D}| - |\Gamma_{2D}|)/|\Gamma_{3D}|$, and the angle used in the calculation of the approximate 2D reflection coefficients, θ_{2D}, is determined from the 3D angles by, $\theta_{2D} = \arctan(|k_x|/\cos\theta_{3D}/k_0)$, where k_0 is the free space propagation constant, and $|k_x|$ is the magnitude of the x component of k_0, given by, $|k_x| = |k_0 \sin\theta_{3D} \cos\phi_{3D}|$. Figure 1*d* shows the geometry of the problem.

IV. Results

In this section some example results will be shown from the 3D ray tracer, and compared with those generated from a VPL engine, also available in *EM*Terrano. The 3D engine includes all ground reflections (the ground is included simply as another obstacle with which the ray can intersect), while the VPL, which uses the method of images for ground reflection (this VPL assumes the same path length for direct and reflected field amplitudes), only includes the ground reflection between the transmitter and first obstacle, and between the last obstacle and the receiver. Also note that building penetration, available in the 3D engine, is turned off, for a reasonable comparison between the two methods. Receiver sensitivity was set for the 3D method at -90 dBm, relative to the transmitted signal power of 1 W (120 dB range of path loss), while in the VPL simulation the number of reflections is limited to 10. Figure 2*a* shows a rendition of downtown Ann Arbor, Michigan, which will be used as the example scenario. It consists of 84 buildings of various heights (note that while the VPL engine accounts for over rooftop diffraction, the 3D ray tracer currently does not). A vertical transmitter, operating at 1 GHz, is located at Point A in the figure (Tx), and placed at 12 m height. To determine coverage in the scenario, a grid of 5700 vertically polarized receivers is placed throughout the scene, at 2 m height. The permittivity of both the ground and all buildings are assumed to be $\epsilon_r = 6.0$, and the conductivity of both is $\sigma = 0.005\ S/m$.

Figure 2*b* shows the path loss (in dB), for the scenario, simulated using the VPL engine, while Figure 2*c* shows results from the full 3D ray tracer. The differences in the two sets of results is best observed in Figure 2*d*, which shows the absolute difference between the two methods. While the positive difference in levels can to some extent be attributed to the inclusion of rooftop diffraction in the VPL calculations (the difference, ΔPath Loss in the figure, is defined as the path loss levels of the VPL minus the path loss levels of the 3D engine), the large negative values in Figure 2*d* can be attributed to the inclusion of full 3D effects in the 3D ray tracer. For example, note the darker areas in the building shadows at width (vertical axis in the figure) equaling 0 to 50 m, and at length (horizontal axis in the figures) equaling 0 to 50 m, 150 to 200 m and approximately 225 to 325 m, which shows a difference of up to at least -20 dB. As an example of the efficiency of the intelligent ray tracing method described previously, a timing comparison is given in Table I. The table shows runtimes for the 3D engine, with building penetration both on and off, and for the VPL with and without rooftop diffraction. Simulations were done on a PC, with a 1.7 GHz processor, and with 500 MB of RAM. The angular search area set for the 3D engine simulations was $\pi/2$ steradians. Considering that the VPL is in fact searching 2π steradians (remember in the quasi-3D methods, rays are launched $360°$ in the horizontal plane only), the ratio of the search area for the VPL method to that of the 3D engine is 4, therefore a speed-up in the runtime for the 3D method, over that of the VPL of approximately 4 would be expected, but as noted in the table, the speed-up is in fact greater than 4. The difference may be attributed to other factors, for example the efficiency of the implemented algorithms in both engines.

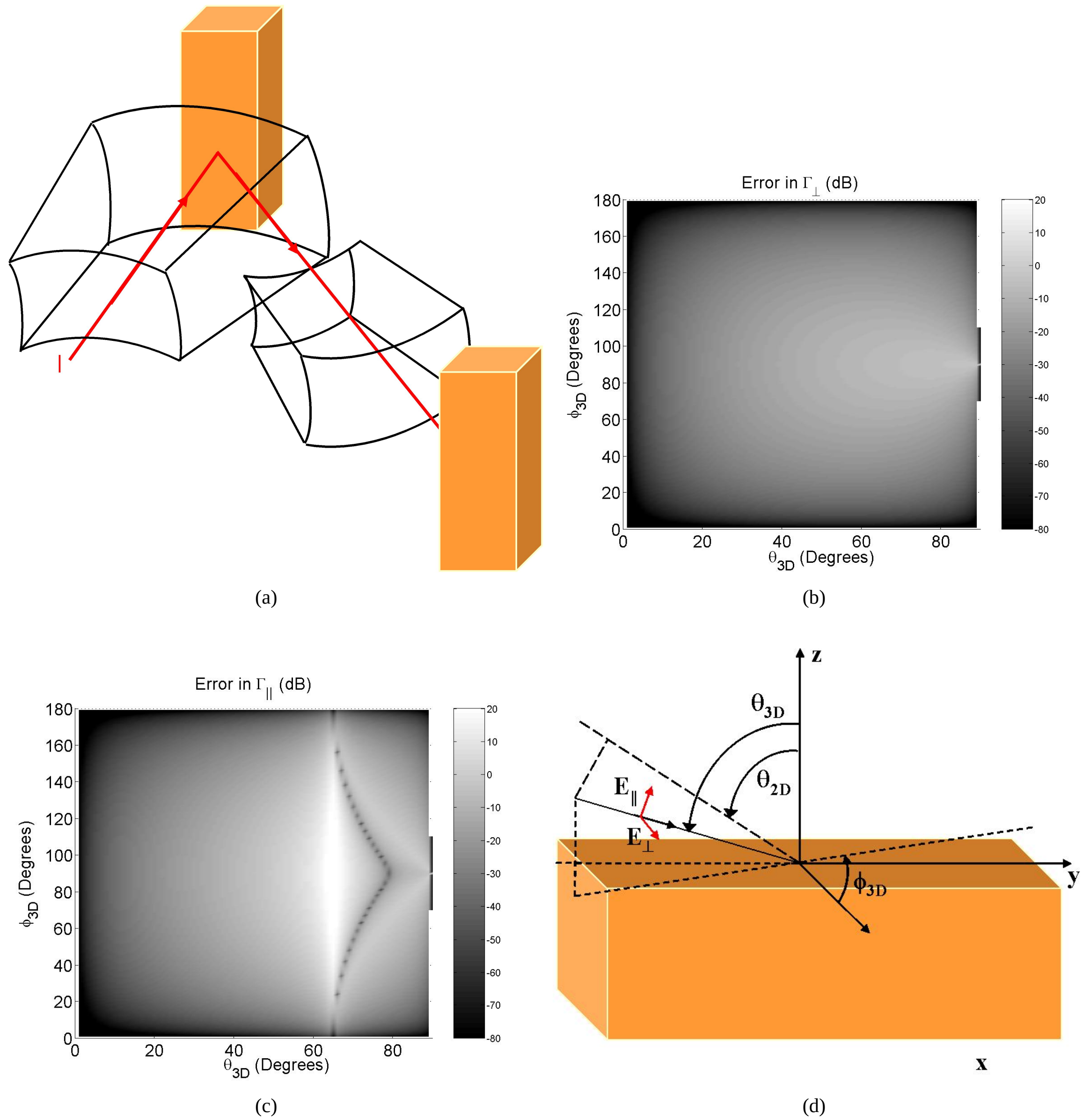

Fig. 1. Intelligent ray tracing (a) , Error in Fresnel Reflection Coefficients for 2D approximation, (b) Perpendicular Polarization, (c) Parallel Polarization, (d) problem geometry.

V. Conclusion

In this paper an intelligent, full 3D ray tracing method was presented and simulation results from it compared to those generated by a quasi-3D engine, using the VPL method. By limiting the angular search area for each generated ray, significant speed-up was achieved. Applying the technique for detecting a ray captured by the receiver, resulted in an additional speed-up of 30%, thus showing the practicality of applying 3D ray tracing to scenarios where the accuracy of 2D and quasi-3D methods are suspect. While additional studies need to be performed, to determine in a more complete manner the situations where 3D ray tracing is necessary for reasonable accuracy, preliminary results, for downtown Ann Arbor, Michigan, show differences between the full 3D approach, and the VPL method that could be attributed to the application of more accurate reflection and diffraction coefficients at each point of a ray interaction with a structure.

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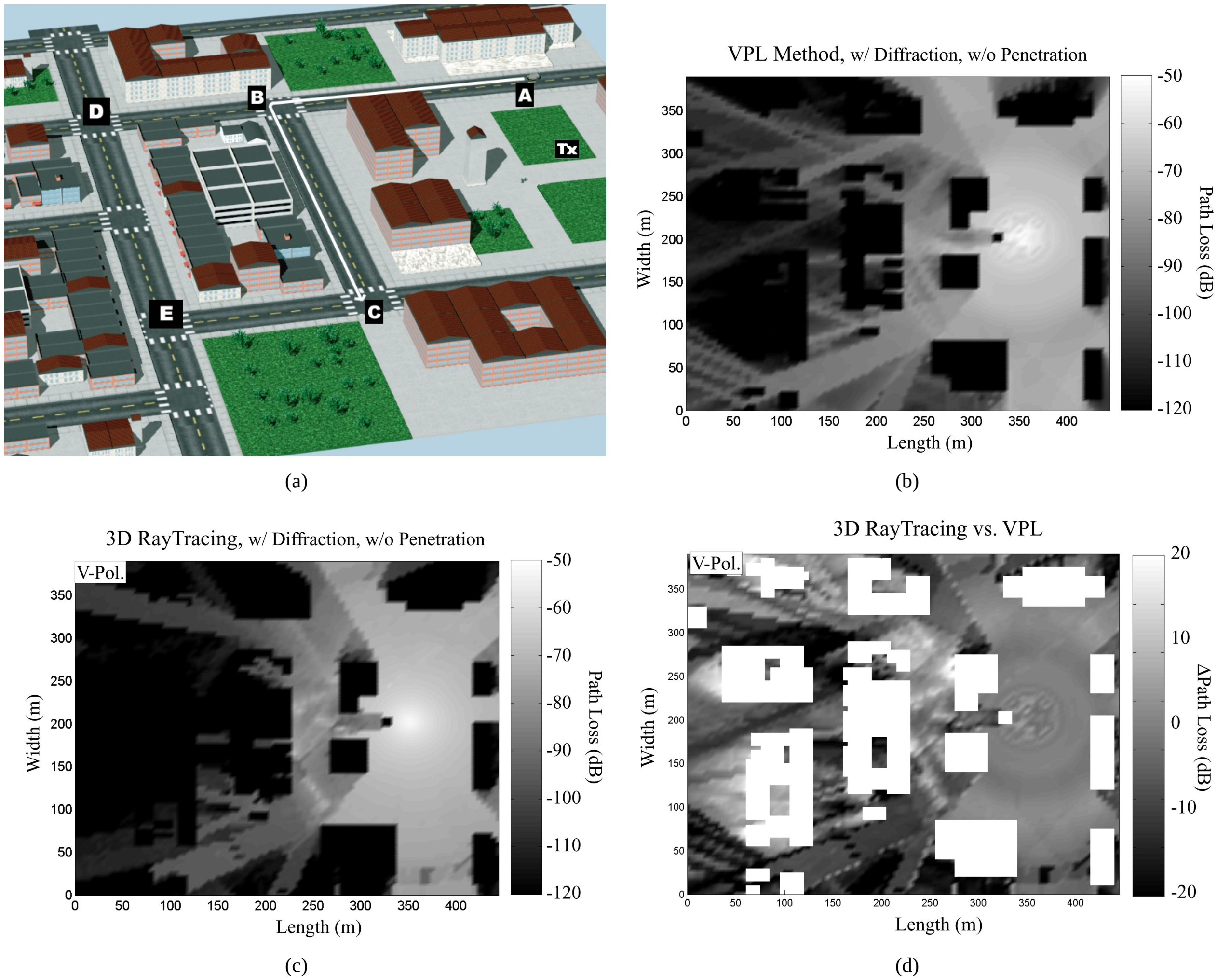

Fig. 2. Comparison of the quasi-3D VPL method with full 3D ray tracing for downtown Ann Arbor, Michigan. (a) Rendition of Ann Arbor, Michigan, (b) VPL results, (c) 3D results, (d) VPL path loss minus 3D path loss.

TABLE I

DOWNTOWN ANN ARBOR, MICHIGAN: RUN TIME COMPARISON FOR VPL, AND 3D. SCENARIO CONTAINS 84 BUILDINGS AND 5700 RECEIVERS.

Method	Rooftop Diffraction	Reflection	Diffraction	Transmission	Run time (min.)
3D	no	yes	yes	no	21
3D	no	yes	yes	yes	27
VPL**	no	yes	yes	no	110
VPL	yes	yes	yes	no	120

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