A Practical Radiosity Method for Predicting Transmission Loss in Urban Environments

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The ability to predict transmission loss or field strength distribution is crucial for determining coverage in planning personal communication systems. This paper presents a practical method to accurately predict entire average transmission loss distribution in complicated urban environments. The method uses a 3D propagation model based on radiosity and a simplified city information database including surfaces of roads and building groups. Narrowband validation measurements with line-of-sight (LOS) and non-line-of-sight (NLOS) cases at 1800 MHz give excellent agreement in urban environments.

Keywords and phrases: propagation model, power coverage, prediction tool, transmission loss, urban environment, radiosity.

1. INTRODUCTION

The increasing demand for commercial personal communication services (PCS) system and the consequent reduction of cell size has led to the need for efficient prediction tools and coverage predictions, especially in complicated urban microcellular environments, where conventional empirical models fail. These models do not take into account the physics of the problem and, in spite of their low computation time, they have a restricted area of application. The need for more accurate models has stimulated the development of theoretical methods, considering the structure of real buildings and the influence of rough surfaces.

Except for the empirical models for field strength prediction in urban environments, another main approach is the deterministic model. In previous published papers for this purpose, the latter indicated the ray-tracing or ray-launching methods that have been usually employed to calculate transmission loss of radio propagation approximately. Ray-tracing methods, taking account of possible reflection and diffraction on roads and building surfaces, can easily determine all important propagation paths from each receiver position to the transmitter. However, computational effort increases with the number of receiving stations, so that predicting field strength in an entire region is usually too time-consuming. Appropriate preprocessing is a way to reduce computation time significantly. On the other hand, since rays are emitted in discrete angular steps, areas far away from the transmitter are less frequently visited than the areas of the same size in the vicinity of the transmitting station. Moreover, diffraction sources might be ignored. Both effects produce misleading prediction.

In recent years, several ray-optical wave propagation models for different environments have been proposed. Not yet satisfactorily handled are heavy urban scenarios. For a practical tool of coverage prediction purposes, we must produce an appropriate model or method that can accurately and quickly simulates field strength distribution in complicated urban environments, and that is also of easy software implement.

Radiant flux transfer methods, known to the computer graphics community as "radiosity," have been used successfully to lighting simulation and rendering for architectural lighting applications [1, 2]. In past few years, radiosity has also been brought into the research region of propagation modeling and rough-surface scattering in mobile scenarios [3, 4]. Some experimental discussions about simple mobile scenarios show that radiosity approach is more efficient than ray-tracing method in computation of transmission loss prediction, in spite of many technical problems for developing a practical tool of transmission loss prediction in urban environment.
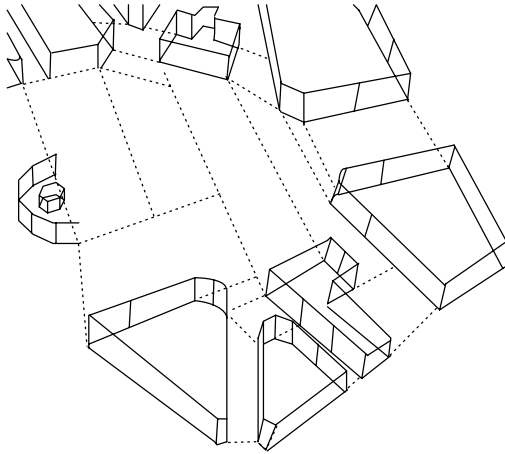
FIGURE 1: Simplified urban area comprising wall and road surfaces.

FIGURE 2: Closed 3D surface representation of a building group.

In a sense, radiosity is the complement of ray-tracing method based on geometrical optics in physical optics. Ray-tracing techniques excel in the simulation of point sources, specular reflections, and refraction effects. Radiosity accurately models area sources, diffuse reflections, and realistic shadows. In urban environments, there are many irregularities such as windows, balconies, stucco, and so forth in the outside building walls, which are comparable with the wavelengths of mobile communication (about 16.7 cm for 1.8 GHz). Thus multiple reflection and diffraction might occur inside or on the surfaces of irregularities, and rendering those reflections resemble the diffuse type in macroscopic perspective. Under such circumstances, the diffuse reflection model is more efficiently employed than the specular reflection model [5]. Therefore we can suppose that real building walls can be thought as the macroscopic diffuse rough surfaces, the radio wave propagation simplified to the electromagnetic scattering problem that can be suitably solved by radiosity approach.

The fine theoretical models have to be computationally efficient and of easy software implement for complicated transmission scenario. In other words, software implement of a model is as important as the theoretical modeling method. Different from ray-tracing methods, there are many available numerical algorithms and effective programming techniques that can be directly used for the relative software development.

In radiosity, the city environments are composed of wall and road surfaces, each of which is discretized into a mesh of elements. To simplify the radiosity calculation, this model makes the following assumptions in modeling an urban environment: (1) all surfaces are the ideal diffuse and opaque rough surfaces (Lambertian) [6]; (2) each element has a uniform power density distribution. Although none of these assumptions represents fundamental constraints for radiosity theory, they make solving the radiosity equation a computationally tractable problem for a personal computer (PC). Optical five-times rule has been used by illumination engineers for nearly a century. Murdoch investigated this problem as part of a theoretical study in illumination engineering
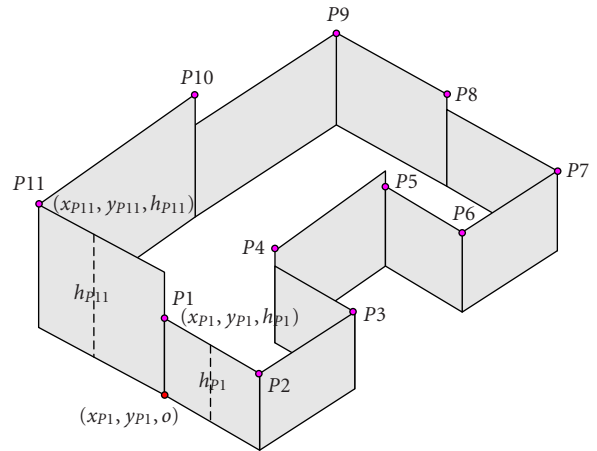
[7]. He demonstrated that modeling a Lambertian luminous rectangle as a point source results in worst-case illuminance prediction errors of less than ±1 percent if the distance from the illuminated point to the rectangle is at least five-times its maximum projected width. There have been several other detailed studies concerning form factor calculation errors [8]. Although there is no firm consensus on the topic, it appears that the five-times rule can be applied to radiosity calculations and used as the consequent simplification under which we are justified in modeling an emitting surface element as a point source. We should keep in mind that this does not limit the applicability of the simplified approach. If the five-times rule is violated for any two surface elements, we can always subdivide the emitting surface element until the rule is satisfied for each subdivided area.

2. 3D PROPAGATION MODEL

2.1. Simplified urban environment

In a static macrocellular or microcellular channel, the received signal is composed of energy, which has been reflected or scattered by buildings. Additional scatterers such as trees and lampposts also contribute to the received signal, but these are mostly secondary effects, which can be neglected [9]. Thus, the data required for a propagation model would consist of the geometrical and the electrical characteristics of buildings and road surfaces. A planiform environment is assumed where urban terrain is flat and every building has an effective height above terrain level (or road level). The original geometrical data can be acquired from city map with building height by means of some graph scanning and preprocessing tools, or directly from topographical database of local government.

Based on the opinion of radiosity and as the next simplification, we can think that, every building group comprises the closed external vertical walls that are rectangular and usually have different height, and whole road area between building groups (e.g., streets, squares and parks, etc.) pieces together with horizontal quadrilateral boards as shown in Figures 1 and 2. In radiosity equation, there are only the
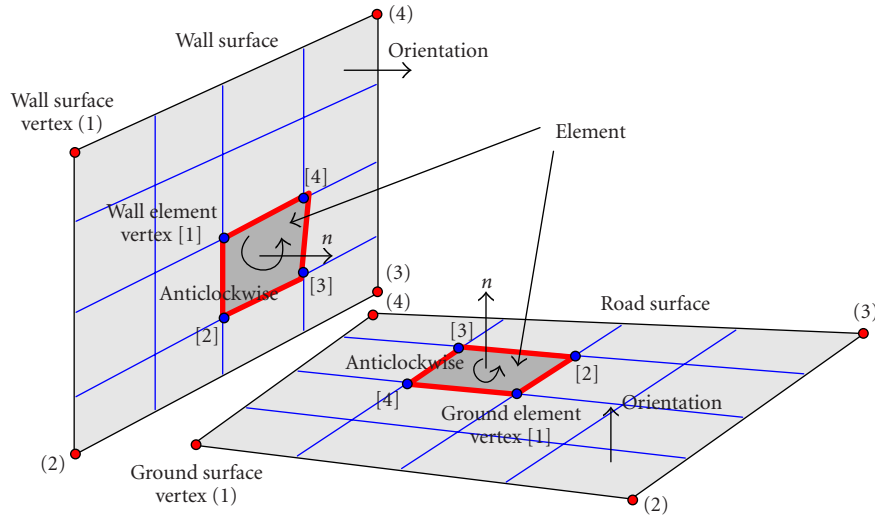
FIGURE 3: Quadrilateral mesh representation of wall and road surfaces.

contributions from the outward surfaces of external vertical walls and upward surfaces of road horizontal quadrilaterals. So it means that the inward and downward surfaces of walls and roads can be ignored in the following discussion, and the finite element naming, mesh subdividing and database constructing are uniquely pointed at the outward and upward surfaces.

Consecutively, the building structures and other obstructions in the streets are complicated, which makes it difficult to determine the dielectric constants and electrical characteristics of the building surfaces strictly and exactly. In fact, most of outside building walls are constructed with bricks and concrete for the typical European city. Hence the same electrical characteristics are supposed for the wall surfaces of building group, and the wall's reflectance of outside surfaces is fixed to 0.7 in terms of comparison between classical examples and radiosity calculations [10]. Additionally, the road areas between building groups are also thought as ideal diffuse and opaque rough surfaces, and 0.3 is adopted as the reflectance of road surfaces.

2.2. City information database

A city information database is constructed to facilitate storage and retrieval of the required building group and road data. In above section, the city environments are simplified as the aggregate of wall and road surfaces. The contours of building groups comprise the closed rectangular wall surfaces with the outward orientation, and the road areas consist of the quadrilateral surfaces with the upward orientation as shown in Figures 2 and 3. The reflectance of wall's and road's surfaces, according to the material or user specification, is designated for each wall of building structure and road area in the database.

As the typical practice, we focus on Vienna city. Because there is not any available governmental topographical database, we get the original geometrical data (location and size of building groups and roads) from 1/2000-scaled Vienna map with building height by means of Autodesk's Auto-

CAD 2000. Exact wall height of building groups is used when available, otherwise the wall is assigned a height of $3.8N + 2$ m , where N is the number of floors in the building [9]. An important and mostly forgotten parameter in radio propagation prediction is the accuracy of city information database, and it depends on the accuracy of the original city map and graph digitalization from city map to DXF file of AutoCAD 2000. Compared with the accuracy of the original city map, the second effect of graph preprocess can be neglected.

The complete city map is too large, and it is not easy to do some processing with PC. Therefore firstly we must divide the city map into some pages whose size depends on your graph-input equipment (scanner or digital camera) and computer's power. In general, we can fix the page's size to A4 $(210 \times 295$ mm$)$, and the Vienna city map can be divided up into about 60 pages. Using the graph input and processing tools, we can manually convert the city map pages into the AutoCAD 2000 DXF files that are composed of wall's 3D polylines, road's quadrilaterals, and arrowheaded 4-vertex 3D polylines of transmitting (thick) and receiving (thin) antennae. The anticlockwise vertex's numbering and the surface's orientating of surfaces and elements are represented in Figure 2, and the Graph file format used for establishing the DXF file is listed in [11].

In radiosity approach, each surface is discretized into a mesh of elements as shown in Figure 3. The accuracy of power density and graph soft shadow calculations mostly depend on the underlying mesh of elements used to represent each wall's or road's surface. If the mesh is too coarse, there maybe excessive calculation errors. By contrast, the cost in terms of memory requirements and execution times quickly becomes unmanageable. It is also inefficient because there is no reason to finely mesh the surface where the change in power density is relatively constant. This clarifies the need to choose an appropriately space mesh of elements. On the other hand, entering superfluous vertexes by hand are obviously impractical for meshing. Hence we need to develop a tool that will allow us to predict the cause-and-effect

relationship between element meshes and simulation results. RadioPower for Windows is just the tool [11]. Dxf2Dat is the data preprocessing module of RadioPower prediction system. It can find out the geographical data about walls, roads and antennae in the chosen urban area from the prepared DXF file, dissect the building and road surfaces according to the meshing factor, and then output the processed instance file automatically.

The city information database is composed of some instance files produced by Dxf2Dat module. The prediction system simulates the complex 3D urban environments as a two-level hierarchy of objects. A hierarchical representation allows us to model one map page as an instance. We can scale, rotate, and translate these instances as required to position them individually in the city map.

2.3. Equivalence of transmitter and receiving point

Applying optical five-times rule and Lambertian surface to radiosity calculation, a transmitter can be simplified as an oriented point source that has the radiation pattern of cosine function if the maximum dimension of a transmitter is less than five times its distance from a receiving element. In order to model antenna's radiation patterns, we can think the transmitting antenna as the combination of several oriented point sources. Because the size of equivalent transmitting antenna does not have direct relation with radiosity calculation, we can choose them only in the opinion of 3D graph display and process. In conclusion, the transmitting antennae are approximately shaped into an eight-arris cylinder with eight square elements whose width and reflectance are 0.1 m, and zero, respectively.

There are two kinds of antennae in our experiments: the omnidirectional $\lambda/2$-dipole antenna and the 65° half-power beamwidth 16 dB gain antenna (Eurocell Panel 732382). For the omnidirectional $\lambda/2$-dipole antenna, the power pattern is simulated by ideal diffuse patterns of eight square elements in above cylinder, and the radiation power density values of eight square elements are set to 1. However, for the 65° half-power beamwidth 16 dB gain antenna, the directional element of antenna cylinder is enough for simulating the main lobe, but 16 dB gain must be counted in calculation. For the simulation of antenna subsidiary lobs, two surfaces neighboring the directional element can be used. Therefore, the radiation power density of the directivity element is adjusted to 39.81 (16 dB), the radiation power density values of two neighboring elements are kept still on 1, and the values for other five elements are set to zero.

In urban environments, the power density distribution of all wall and road surfaces can be acquired through one-time solution of radiosity equation. In general, the power density in streets and alleys can be substituted with the power density of adjacent wall and road surfaces. But for special cases, we can put some points into the chosen space. In our calculation, each receiving point is equivalent to a cube with six square surfaces whose width and reflectance is 0.1 m and one, respectively. Whereas for the power density of chosen receiving point, we must sum the received power density values of six square surfaces.

2.4. Transmission loss calculation

Suppose there are n elements, that is, the sum of all wall-surface elements, road-surface elements, and elements of equivalent transmitters and receiving points, and each element is a quadrilateral Lambertian plane and has a uniform power density distribution in the urban environment. The radiosity equation for all the elements E_1 through E_n can be expressed as a set of n simultaneous linear equations:

$$
\begin{bmatrix} B_{o1} \\ B_{o2} \\ \vdots \\ B_{on} \end{bmatrix} = \begin{bmatrix} 1 - \rho_1 F_{11} & -\rho_1 F_{12} & \cdots & -\rho_1 F_{1n} \\ -\rho_2 F_{21} & 1 - \rho_2 F_{22} & \cdots & -\rho_2 F_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ -\rho_n F_{n1} & -\rho_n F_{n2} & \cdots & 1 - \rho_n F_{nn} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_n \end{bmatrix}
$$

(1)

Where B_i is the final power density of element E_i, B_{oi} is the initial power density of element E_i, ρ_i is the reflectance of element E_i, and F_{ij} is the form factor that indicates the fraction of power emitted by E_i that is received by E_j.

Excepting the elements of transmitting antennae, the initial power densities of elements have zero values. If we set some transmitting antennae in the streets and on the tops of buildings in the urban environment, the initial power densities of elements for omnidirectional $\lambda/2$-dipole antenna and 65° half-power beamwidth 16 dB gain (referred to as half-wave dipole) antenna can be expressed separately as

$$
B_{oi} = \begin{cases} 1, & \text{antenna cylinder,} \\ 0, & \text{other elements,} \end{cases}
$$

$$
B_{oi} = \begin{cases} 39.81, & \text{directional element of antenna,} \\ 1, & \text{adjacent directional element,} \\ 0, & \text{other elements.} \end{cases}
$$

(2)

The reflectance values of elements are given by

$$
\rho_i = \begin{cases} 0.7, & \text{walls,} \\ 0.3, & \text{roads,} \\ 1, & \text{each receiving cube,} \\ 0, & \text{each antenna cylinder.} \end{cases}
$$

(3)

The equation set above can be solved properly with the progressive refinement radiosity algorithm based on iterative technique of Jacobi and Gauss-Seidel, and the method converges very quickly [12, 13].

The form factor F_{ij} between two elements is defined as the dimensionless fraction of electromagnetic power from element E_i to element E_j. Applying optical five-times rule, the simplified form factor is given by

$$
F_{ij} \approx \int_{A_j} \frac{\cos \theta_i \cos \theta_j}{\pi r^2} H_{ij} dA_j.
$$

(4)

A_j and dA_j are the area and the differential area of elements E_j, respectively, θ_i and θ_j are the directions of the center point of element E_i and differential element dE_j in E_j, respectively, and γ is the distance between two elements E_i

and dE_j. The term H_{ij} accounts for the possible occlusion of each point of element E_j as seen from center point of element E_i, and is given by

$$H_{ij} = \begin{cases} 1, & \text{if } E_i \text{ and } dE_j \text{ are visible to each other,} \\ 0, & \text{otherwise.} \end{cases} \quad (5)$$

We can use the adaptive meshing technique to surface dissection of walls and roads, and ensure that five-times rule is satisfied for most calculations of simplified form factors.

The reciprocal form factor F_{ji} can be obtained by the reciprocity relation

$$F_{ji} = \frac{A_i}{A_j} F_{ij}. \quad (6)$$

Where A_i is the area of elements E_i. This equation can halve the integration calculation cost of form factors.

The cubic tetrahedron algorithm is used for numerical integration calculation of the form factor [8], and a resolution of 142×142 cells for this algorithm provides a reasonable trade-off between execution speed and minimization of aliasing artifacts [14]. Therefore the form factor of the projected element E_j can be determined simply by summing the delta form factors of those cells it covers:

$$F_{ij} \approx \sum \delta F_{\text{covered}}. \quad (7)$$

Where $\delta F_{\text{covered}}$ refers to the delta form factors of those cells covered by the projection of E_j onto one or more of the cubic tetrahedron faces.

Based on the theoretical analysis mentioned above, the radiant power density of every element surface (B_i; $i = 1, 2, \ldots, n$) can be gained in the urban environment it describes through solving (1), and the power density distribution is uniform within each element. Transmission loss of wall (or road) surfaces can be defined as the ratio of power densities between the surface of wall (or road) element and the surface of omnidirectional $\lambda/2$-dipole antenna. Because we have set the average power density of omnidirectional $\lambda/2$-dipole antenna one, the transmission loss of wall (or road) surfaces is expressed as

$$\text{Transmission loss (dB)} = 10^* \log (B_i). \quad (8)$$

For the special interesting receiving points put in streets that were represented by six elements (B_{i+j}; $j = 0, 1, 2, \ldots, 5$), the transmission loss is given by

$$\text{Transmission loss (dB)} = 10^* \log \left(\sum_{j=0}^{5} B_{i+j} \right). \quad (9)$$

By radiosity approach, the power density distribution all over the surfaces of walls and roads under urban environment can be simulated through one time of calculation. Making use of (8) and (9), the 3D power density distribution map can be expediently converted into 3D transmission loss distribution map.
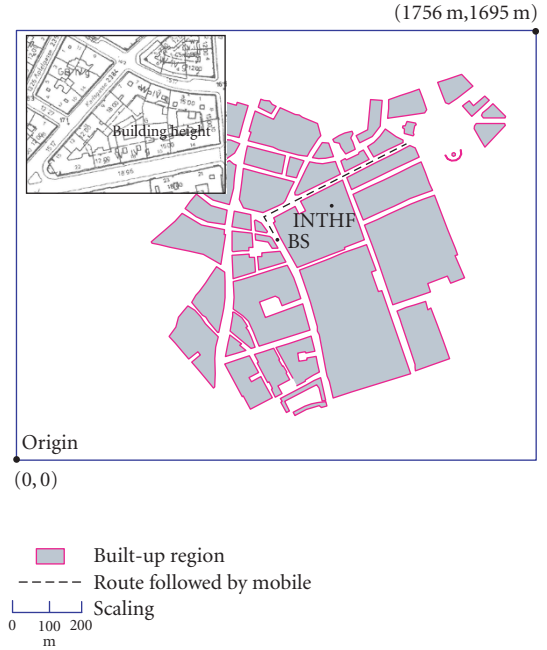

FIGURE 4: Simplified map of measurement site and base station location.

3. EXPERIMENTAL VERIFICATION

3.1. Experiment with RadioPower for Windows 1.10

The transmission loss prediction tool, named RadioPower for Windows, has been developed with MS VC++ 5.0 under Windows 9X/NT/2000 [11]. Based on object-oriented programming, it uses 3D propagation model based on radiosity approach and advanced techniques of 3D graphical meshing and processing, and allows predicting average transmission loss distribution in both urban and indoor environments quickly and accurately. If your PC has 512 MB memory and a powerful Pentium 1 k CPU, RadioPower allows to process the entire 3D map data of a European city, and to simulate and visualize the average transmission loss distribution over all the outside surfaces and the interesting points at one time with acceptable time consumption and engineering precision. Following prediction results are acquired through this system.

To evaluate the 3D propagation model in this project, simulation of the average propagation loss distribution should be made under the same condition with the measurement. As a typical sample, we have realized the simulation of average transmission loss distribution in the whole urban environment of Vienna's fourth district around Department of Electronic Engineering and Information Technique, Vienna University of Technology (DEEIT-VUT). The map pages of Vienna district number 4 are scanned from the 1/2000-scaled Vienna city map with building height, and most of buildings were constructed with bricks and concrete in this area.

Figure 4 represents the corresponding simplified map of measurement site, and in that, the location of base station (BS), the route (short dashed black line, which includes

TABLE 1: Comparison between meshing factor and time consumption.

Meshing	Calculation parameters		
factor	Elements	Convergence	Elapsed time
10 m	6255	1.0E-10	0:04:40
8 m	9787	1.0E-10	0:06:36
5 m	24 263	1.0E-10	0:14:24
3 m	67 778	1.0E-10	0:37:01
1.5 m	268 492	1.0E-10	2:19:28

TABLE 2: Comparison between convergence and time consumption.

Meshing	Calculation parameters		
factor	Elements	Convergence	Elapsed time
8 m	9787	1.0E-06	0:01:53
8 m	9787	1.0E-08	0:03:59
8 m	9787	1.0E-10	0:06:36
8 m	9787	1.0E-12	0:09:14

LOS and NLOS points) followed by mobile station (MS). Moreover, the transmitting antenna (Eurocell Panel 732382, 1800 MHz) was located 6 m above road level, and kept 5 m away from the wicket of DEEIT-VUT main building, and antenna's direction is assigned to the starting point of MS route. For the receiving antenna (half-wave dipole, 1800 MHz) of MS, the height is 1.5 m, and its route is also kept about 5 m away from the building group.

Quantifying the errors in transmission loss predictions for complex urban environments is more problematic. Various technical committees have attempted to develop guidelines for validating (or at least comparing) the prediction accuracy of transmission loss design and analysis software programs, but it remains an outstanding problem. Regardlessly, it is reasonable to assume that the transmission loss prediction errors in complex urban environments will depend mostly on the measure of mesh subdivision (meshing factors) and the accuracy of radiosity calculations (convergence) for the environment.

In general, the meshing factors and the convergence are smaller, the prediction accuracy is higher, but the cost of memory requirements and execution times becomes excessive quickly. Tables 1 and 2 display the comparisons between meshing factor, elements, and time consumption, and between convergence and time consumption of RadioPower prediction system running under MS Windows 98 on a standard PC with P-II 350 MHz CPU and 128 M RAM, respectively. Making a comprehensive consideration, the moderate values of meshing factor and convergence, 8 m and 1.0E-12 are adopted for analysis and verification. Subsequent figures refer to demonstration and visualization of RadioPower system under the above specification conditions.

Transmission loss distribution over all surfaces in measurement site is shown in Figure 5. The color coordinates are displayed at right side of window, and that value changes linearly from 0 dB (bottom) to 100 dB (top) those can be changed by RadioPower menu configuration command.
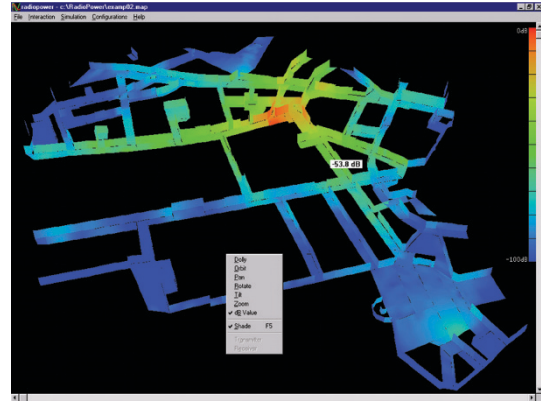

FIGURE 5: Transmission loss distribution over all surfaces.

In any graph display mode of RadioPower, you can press the right key of mouse to activate the interaction menu, then choose the needed commands (Pan, Rotate, Zoom, dB-Value, Shade, ...) to process your image. In this way, you can check the displaying contents at any place in 3D graph, either in shade or normal modes, such as mesh construction, antenna position, reflectance, transmission loss, and so forth.

3.2. Measurement of average propagation loss

The narrowband measurements under the same condition with the prediction were made in order to validate the 3D model. The transmitter was installed at an auto tail, and located at the BS point as showed in Figure 4. Transmitting antenna was directional antenna (Eurocell Panel 732382) with gains of 18.1 dBi at 1800 MHz, and the transmitter power was +27 dBm. The receiver was an Advantest spectrum analyzer with a half-wave dipole antenna (2.1 dBi, 1800 MHz). The respective receiver was controlled by a laptop computer via GPIB bus and was mounted on a trolley. We performed measurements along the fixed route (Figure 4). Samples of the instantaneous power were taken at every $\lambda/4$. The local mean power values are determined by calculating the arithmetical averages over a measurement length of 6λ, and that is a reasonable way to calculate local means in urban environment [15].

3.3. Comparison between results

Figure 6 shows the plot of the predicted transmission losses versus measurements for the special receiving points, and in that, the broken line marked asterisk denotes the measured values, and the the broken line marked diamond, the broken line marked triangle, and the broken line marked fork denote the predicted values of the special receiving points, and their nearest road and wall surface points separately. Figure 7 represents the result comparison between different reflectance values, and the broken line marked triangle and the broken line marked fork denote the predicted results that wall (and road) reflectance values are 0.2 and 0.9, respectively.
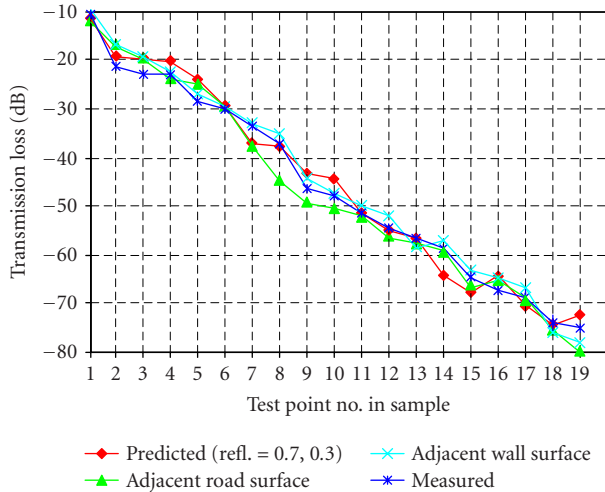
FIGURE 6: Comparison of measured and predicted results.

FIGURE 7: Result comparison of different reflectance values.

Comparison between the predicted results and the data actually measured previously, demonstrate good coincidence both in LOS and NLOS environments (less than 5 dB standard deviation of the error), which is an indication of the validity of 3D propagation model and algorithms. From Figure 5, it is clear that the predicted values of wall and road surfaces adjacent the special receiving points are closed to the measured values. Therefore, the transmission loss distribution in streets and alleys can be substituted with the corresponding distribution at wall (or road) surfaces. Moreover from Figure 6, it is correct to choose 0.7 and 0.3 as the wall and road reflectance values, respectively.

4. CONCLUSION

In this paper, a practical 3D transmission loss prediction method is presented, using a new 3D propagation model based on radiosity and a simplified city information database. Preprocess and selection of different mesh sizes allow for a very fast, but still accurate large-area prediction in urban radio propagation environments. Under the working environment of PC, this prediction method permits to process the entire 3D map data of a typical European city, and simulate and visualize the average transmission loss distribution over all the outside surfaces and the interesting points at one time with acceptable time consumption and engineering precision. Time consumption is much lower than other prediction methods based on ray-tracing algorithms.

Narrowband validation measurements give excellent agreement in urban environments.

As a future work, it would be interesting to improve the 3D radiosity propagation model and algorithms in the matters of antenna patterns, polarization, and non-Lambertian reflections, and to assess the prediction method and system at both multiantennae and mobile indoor environments.
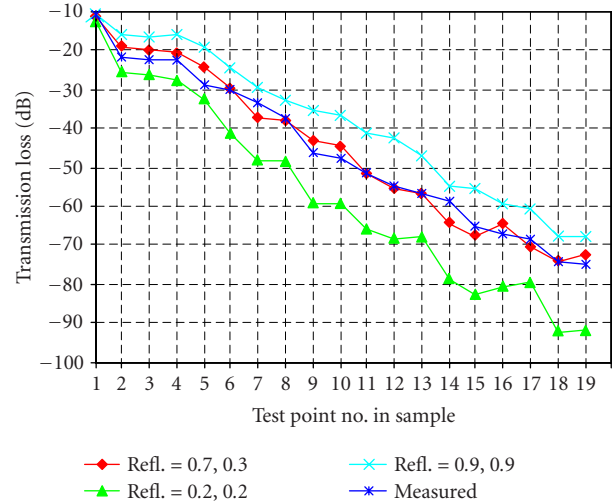
REFERENCES

[1] M. Levoy and P. Hanrahan, "Light field rendering," in *Proc. 23rd Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '96)*, pp. 31–42, ACM Press, New Orleans, La, USA, August 1996.

[2] M. F. Cohen, J. R. Wallace, and P. Hanrahan, *Radiosity and Realistic Image Synthesis*, Academic Press, San Diego, Calif, USA, 1993.

[3] C. Kloch, G. Liang, J. B. Andersen, G. F. Pedersen, and H. L. Bertoni, "Comparison of measured and predicted time dispersion and direction of arrival for multipath in a small cell environment," *IEEE Trans. Antennas and Propagation*, vol. 49, no. 9, pp. 1254–1263, 2001.

[4] C. Kloch and J. B. Andersen, "Radiosity—an approach to determine the effect of rough surface scattering in mobile scenarios," in *Proc. IEEE Antennas and Propagation Society International Symposium (APSIS '97), IEEE Digest*, vol. 2, pp. 890–893, Montreal, Quebec, Canada, July 1997.

[5] K.-F. Tsang, W.-S. Chan, D. Jing, K. Kang, S.-Y. Yuen, and W.-X. Zhang, "Radiosity method: a new propagation model for microcellular communication," in *Proc. IEEE Antennas and Propagation Society International Symposium (APSIS '98)*, vol. 4, pp. 2228–2231, Atlanta, Ga, USA, June 1998.

[6] P. Moon and D. E. Spencer, *The Photic Field*, MIT Press, Cambridge, Mass, USA, 1981.

[7] J. B. Murdoch, "Inverse square law approximation of illuminance," *Journal of the Illuminating Engineering Society*, vol. 11, no. 2, pp. 96–106, 1981.

[8] J. C. Beran-Koehn and M. J. Pavicic, "Delta form factor calculation for the cubic tetrahedral algorithm," in *Graphics Gems III*, pp. 324–328, Academic Press, San Diego, Calif, USA, 1992.

[9] K. R. Schaubach, N. J. Davis, and T. S. Rappaport, "A ray tracing method for predicting path loss and delay spread in microcellular environments," in *IEEE 42nd Vehicular Technology Conference (VTC '92)*, vol. 2, pp. 932–935, Denver, Colo, USA, May 1992.

[10] G. Papagiannakis, G. L'Hoste, A. Foni, and N. Magnenat-Thalmann, "Real-time photo realistic simulation of complex heritage edifices," in *Proc. 7th International Conference on Virtual Systems and Multimedia (VSMM '01)*, vol. 2, pp. 218–227, Berkeley, Calif, USA, October 2001.

[11] L. Ming, *A tool for power-density prediction of radio propagation in urban environments*, Doctoral thesis, Institute of Communications and Radio-Frequency Engineering, Vienna University of Technology, Vienna, Austria, July 2002.

[12] M. E. Cohen, S. E. Chen, J. R. Wallace, and D. P. Greenberg, "A progressive refinement approach to fast radiosity image generation," *Computer Graphics*, vol. 22, no. 4, pp. 75–84, 1988.

[13] M. Shao and N. I. Badler, "Analysis and acceleration of progressive refinement radiosity method," in *Proc. 4th Eurographics Workshop on Rendering*, pp. 14–16, Paris, France, June 1993.

[14] I. Ashdown, *Radiosity: A Programmer's Perspective*, John Wiley & Sons, New York, NY, USA, 1994.

[15] R. Gahleitner, "Wave propagation into urban building at 900 and 1800 MHz," COST 231 TD(93) 92, European Commission/Cost Telecommunications, Grimstad, May 1993.

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