A Ray-Tracing Method Based on the Triangular Grid Approach and Application to Propagation Prediction in Urban Environments

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***Abstract*—This paper presents a fast ray-tracing procedure based on triangular division of the propagation environments. Unlike other accelerating methods that are mostly based on pre-establishment of visibility, this method does not require knowledge of the position information of the base station and/or receiving antennas and is thus more general. Although the triangulation is done in a two-dimensional (2-D) plane, this method is suitable for three-dimensional (3-D) simulations when a proper data structure for buildings is constructed. Validation results show good agreement between calculated and measured data from the European COST 231 project. The improvement in the computational efficiency is clearly demonstrated in examples.**

***Index Terms*—Mobile communication, prediction methods, ray tracing, urban propagation.**

I. Introduction

RADIO wave propagation models are necessary for the implementation of a mobile radio system. With the rapid growth of wireless communications, the cell sizes are getting smaller and site-specific propagation information is needed for the design of mobile systems. During the past decade, there were many proposed theoretical and measurement-based propagation models for microcells in urban environments. At first, some empirical or theoretical models (formulas) were developed as extensions of the models suitable for macrocells. Factors such as the heights of antennas and buildings, density of buildings, line-of-sight (LOS) or non-LOS propagations, geometry of the street grid, etc., are included [1]–[8]. A good review of these models can be found in [9]. Later on, propagation mechanisms were extensively investigated and the ray theory emerged as a highly promising procedure for providing accurate, site-specific means to obtain useful simulation results [10]–[12]. It should be noted that ray tracing can also serve as a starting point for statistical modeling of wireless channels [13]–[15]. According to the ray optics and the uniform theory of diffraction (UTD), propagation mechanisms may include direct LOS, reflected, transmitted, diffracted, scattered rays, and some combined rays, which complicates and in many realistic propagation environments, slows down the calculation procedure.

It was also found that simulating a realistic 3-D propagation environment using the standard shooting-and-bouncing ray (SBR) method presents a considerable challenge due to the geometric and physical complexity of the environments. It leads to the need for huge and often unavailable computation resources. To overcome this difficulty, simplified models were proposed to only include the contributions from main rays and/or to only consider the main geometric and physical characteristics of buildings and terrains. For example, walls with complex structures are approximated by uniform walls and the tops of buildings are assumed flat, etc. Also, in an urban environment, transmitted rays through buildings are assumed small and are hence neglected. Simplified ray-tracing models are useful, however, in providing reasonably accurate results for some propagation environments including, for example, the case when the base-station antenna is well below the average height of the buildings [16], [17]. In this case, the over-rooftop propagation is negligible and the lateral rays—including LOS, reflected, and diffracted rays—are the most important ones that need to be taken into account. Other approximations that may be used to improve accuracy include the calculation of the rooftop-diffracted rays as well as diffracted-reflected rays in the propagation model [1], [4], [18]–[21].

A more recent advanced simplified model is the vertical plane launch (VPL) model [22], [23]. The VPL technique employs the standard SBR method in the horizontal plane while using a deterministic approach to find the vertical displacement of the unfolded ray paths. This method is valid when the walls are vertical, and similar methods can be found in [24], [25]. Full 3-D ray-tracing methods have also been developed [26] and comparisons between different methods and their applicability can be found in [27]–[30].

Another approach in improving computational efficiency and accuracy of the ray-tracing-based methods is the application and development of geometric algorithms. Basically, the overhead of computation in the ray-tracing algorithm is related to the determination of the intersection of a ray and an object (a wall surface, a ground plane, or a wall edge, etc.) in the propagation environments. This geometric testing can consume more than 90% of CPU time for a naïve SBR algorithm [31]. Several techniques have been proposed to reduce the time spent on geometric testing using preprocessing of the propagation environments. Some methods in computational geometry and computer graphics, e.g., the bounding box method, can be used to reduce the number of intersection tests. Other methods using

Manuscript received June 28, 2001; revised December 19, 2001.

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Publisher Item Identifier S 0018-926X(02)05457-1.

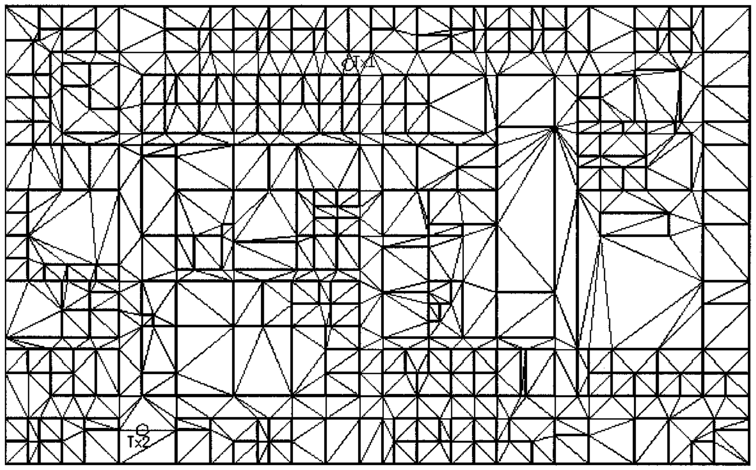


Fig. 1. Triangulation of the third floor of an office building and positions of two base stations.

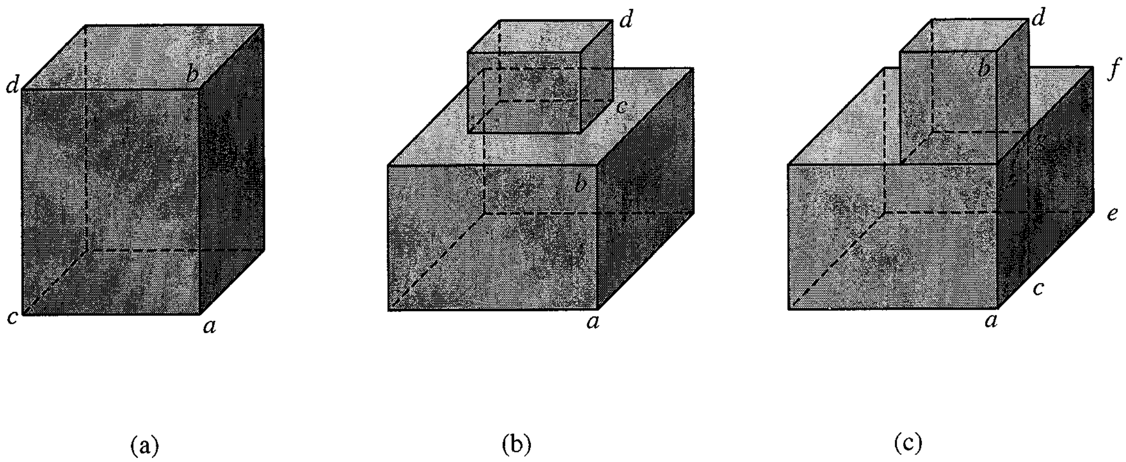


Fig. 2. Building models. (a) Simple building and (b) (c) stacked buildings.

visibility between transmit antenna (Tx)/receive antenna (Rx) and wall surfaces (edges) can reduce the number of candidate geometric objects to be tested [16], [26], [32]. These visibility-based methods are usually Tx- and/or Rx-specific and the preprocessing procedure needs to be repeated for each Tx and/or Rx position.

A fast ray-traversing algorithm developed in [33], based on uniform rectangular space division, is modified and applied to some environments, and higher efficiency is achieved over the visibility method [34]. Two-dimensional (2-D) results show that, on average, the computation time of the new method is 15% of that of the visibility method.

This paper is an elaboration and extension of the ideas presented in [35] for 2–D cases. Earlier calculations were extended to deal with 3-D urban environments while using the 2-D triangular grid method as described earlier. The new method is not Tx/Rx specific and can serve as a basis for many different ray-tracing approaches, e.g., VPL and over-rooftop models. The obtained 3-D simulation results were compared with experimental data from the European COST 231 project for Munich City in Germany [9]. It should be noted that a similar triangular grid method was briefly described in [36] for indoor environments.

II. Triangular Grid-Based Ray-Tracing Approach

The ray-tracing engine used in this paper is based on the 2-D ray-tracing algorithm proposed in [35]. The basic solution procedure was described earlier and simplified examples were used to illustrate its advantages and usefulness. In this paper, we will start by illustrating its computational efficiency advantage in a realistic propagation environment. A numerical experiment is carried out to compare results from the proposed method with those of the visibility method in an indoor office building as shown in Fig. 1. Two positions of base station antennas were selected, Tx1 and Tx2, as shown in Fig. 1. It may be seen from the figure that the numbers of edges visible to Tx1 and Tx2 are different and the numbers of edges visible to each edge in this case are also different.

To mimic an urban environment, only reflection rays are traced. For each Tx position, the visible edges are determined in the preprocess. The visible edges to each edge in the entire region are also predetermined. Three hundred and sixty rays are launched uniformly in all directions for each Tx and each ray is traced to 40 reflections. This large reflection number is selected to help include as many edges as possible with different numbers of visible edges. No reception test is included.

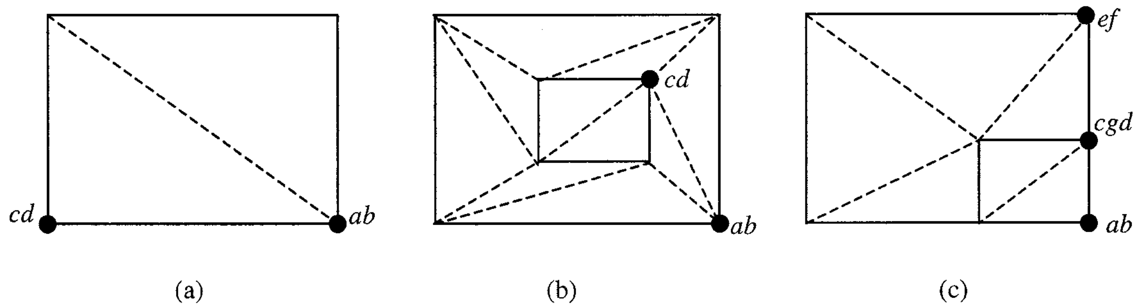


Fig. 3. 2-D representation of buildings in Fig. 2 and typical triangulations. (a) Simple building and (b) (c) stacked buildings.

The simulation results show that for Tx1, the CPU time ratio of this method over the visibility method is about 25%, while for Tx2, the ratio is 30%. These calculations, hence, show significant computational advantage of the proposed method.

III. 2-D Triangulation of Realistic Propagation Environments

A. 3-D Building Modeling

In the following calculations, it is assumed that all the buildings are stacked prisms with polygon cross-sections as shown in Fig. 2. These building geometries are projected onto a horizontal plane, i.e., x-y plane, as shown in Fig. 3. The projection of a vertical wall can be represented by two neighboring vertices in the 2-D plane. For example, wall $abdc$ in Fig. 2(a) may be represented by vertices ab and cd. A vertex is actually a vertical edge and has two heights associated with it. For example, vertex ab contains the heights of vertices a and b. For simplicity, the height of a is called the *ground height*, while the height of b is called the *vertex height*. It is assumed that the two vertex heights of a wall are identical. This means the rooftops of buildings are level-flat polygons. Special attention should be paid to the situation in Fig. 2(c). The walls $abdc$ and $cefg$ have a common vertex cgd in the 2-D plane. This suggests that in some cases we may need three parameters to represent the height information correctly, i.e., the heights of c, d and g. Fortunately, we can still use two parameters to deal with this situation. The first parameter is the ground height (height of c). The second is the larger value of the heights of vertices d and g. When the height information is needed for a wall, the vertex heights of the two vertices defining the wall are compared and the wall height is always equal to the smaller value of these two heights. For example, when we have to determine the height of wall $abdc$ in Fig. 2(c), we have two vertex heights of b and d. Since they have equal values, the wall height is equal to either the height of b or d. When we need the height of wall $cgfe$, we have two vertex heights of d and f. Since the height of f is less than the height of d, the wall height is considered equal to the height of f.

B. Triangulation

When all the buildings in a propagation environment are modeled and represented as described in the previous section (if there are buildings which cannot be presented in this way, approximation will be used), standard triangulation methods can be employed to triangulate the propagation region. (Commercial software or free codes on the Internet can be employed for the fast triangulation.) This paper uses the constrained triangulation of a planar straight-line graph (PSLG) so that a minimum number of dummy edges will be added. An outer boundary, which is usually a polygon, is also added to enclose the environment. A program developed by J. R. Shewchuk, *triangle.c* [37], is used for the triangulation of the resulting 2-D representation of the propagation domain.

IV. 2- and 3-D Lateral Ray-Tracing Algorithms

The basic ray-tracing algorithm for the 2-D case can be found in [35]. Here we give some more details regarding the data structure of the triangular grid and its extended use in modeling 3-D environments.

A. Data Structure of the Triangular Grid

After triangulation, the topological information is processed and stored into an array. The main entry of the array is a triangle. From a triangle, one can determine its vertices and the three neighboring triangles. The information of wall material for each edge in a triangle is also stored. In particular, the dummy edge (the nonwall edge) is characterized by a wall material index -1. Edge direction in a triangle is also included for the purpose of fast ray tracing.

B. Data Structure of the Ray Associated With the Triangular Grid

A ray can be represented by two vectors, one is the position vector $\boldsymbol{p}$, and the other is the direction vector $\boldsymbol{d}$, as shown in Fig. 4. A series of these vector pairs can represent a ray originating from a source point, reflected (or transmitted, diffracted) several times and then arriving at the field (observation) point.

For fast ray tracing based on the triangular grid, it is natural to associate a ray with an edge (for reflected and transmitted rays) or a vertex (for diffracted rays) in a triangle. Fig. 5 shows how a ray is related to an edge. For example, the ray in Fig. 5 is first related to edge E_1 and triangle T_2, denoted (E_1, T_2), then as it travels through the dummy edge e_2 and enters triangle T_3, it is related to (e_2, T_3), etc. This process may be represented in general terms as

$$(E_1, T_2) \rightarrow (e_2, T_3) \rightarrow (E_3, T_3) \rightarrow (e_2, T_2) \rightarrow (e_4, T_7) \\ \rightarrow (E_5, T_7) \ldots$$

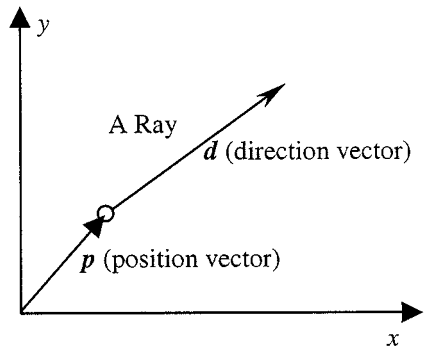


Fig. 4. Definition of a generic ray, located at $\boldsymbol{p}$ and pointed in direction $\boldsymbol{d}$.

This provides a natural data structure for a ray, in terms of class when using C++

```
class aRay{
        Vector Position, Direction;
        unsigned EdgeIndex, TriangleIndex;
        int WallMaterialIndex;
        ...
};
```

where WallMaterialIndex is used to characterize the wall material. It is set to -1 for the dummy edge and -2 for the outer boundary. Other information can be added to the aRay class in the realistic implementation. A list of class arrays can then represent a ray originating from a source point, reflected (or transmitted, diffracted) several times, and then arriving at a field point.

C. Initialization of a Ray

When a source point (antenna) Tx in position $\boldsymbol{p}_0$ is given, we first determine the triangle, T_0, containing it (Tx may be on an edge of a triangle). This is a typical planar point location problem and can be efficiently solved by standard algorithm, e.g., monotone subdivisions [38]. It should be noted that the triangular grid is itself a monotone subdivision and can thus be straightforwardly solved. Then a ray is launched from $\boldsymbol{p}_0$ in direction $\boldsymbol{d}_0$, see Fig. 6. This first ray segment is usually not related to any edge and is denoted $(-1, T_0)$.

To trace the ray, we have to determine the first edge that this ray will hit. This can be done by looking at the signs of two cross products of 2-D vectors. First, connect $\boldsymbol{p}_0$ to $\boldsymbol{V}_0$, the vertex opposite the edge e_0 in triangle T_0, then obtain a vector $\boldsymbol{p}_0\boldsymbol{V}_0$. Take the cross product of $\boldsymbol{d}_0$ (original direction) and $\boldsymbol{p}_0\boldsymbol{V}_0$, i.e., $a = \boldsymbol{d}_0 \times \boldsymbol{p}_0\boldsymbol{V}_0$. If $a > 0$, the ray will not hit the edge e_1. If $a < 0$, the ray will not hit e_2. Then, for the case $a < 0$ in Fig. 6, connect $\boldsymbol{p}_0$ to $\boldsymbol{V}_1$ and take the cross product, $b = \boldsymbol{d}_0 \times \boldsymbol{p}_0\boldsymbol{V}_1$. If $b > 0$, the ray will hit e_1; if $b < 0$, the ray will hit e_0. If $a = 0$ or $b = 0$, a vertex will be hit, which means a vertical wall edge is hit and diffraction will take place. Now we have a ray trajectory

$$(-1, T_0) \rightarrow (e_1, T_1) \rightarrow \cdots,$$

and the initialization of a ray is achieved.

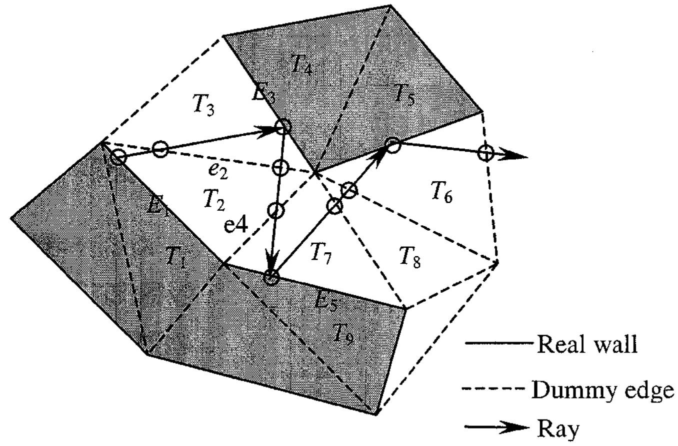


Fig. 5. Relationship between rays and edges in triangles.

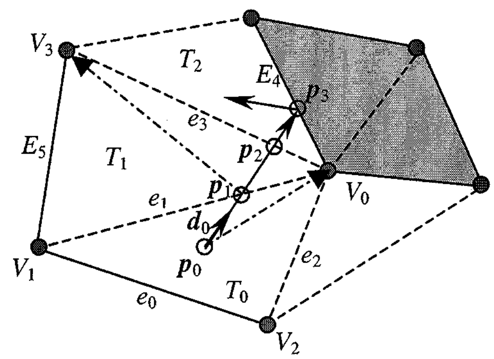


Fig. 6. Initialization of a ray and the determination of the first edge the ray will hit.

D. 2-D Ray-Tracing Procedure

The remaining part of the proposed ray-tracing procedure is a recursive approach. In Fig. 6, when we trace the ray further, i.e., to find the next edge to be hit, we only have to do one cross-product test. For example, to determine the intersection of the ray with the appropriate edge, connect $\boldsymbol{p}_1$ to the opposite vertex of $e_1, \boldsymbol{V}_3$, in triangle T_1 and calculate $c = \boldsymbol{d}_1 \times \boldsymbol{p}_1\boldsymbol{V}_3$. Here $\boldsymbol{d}_1$ is the direction vector of ray (e_1, T_1) and is equal to $\boldsymbol{d}_0$ since e_1 is a nonwall edge that did not cause reflection or diffraction of the incident ray. If $c > 0$, then edge e_3 will be hit; if $c < 0$, edge E_4 is hit; if $c = 0$, vertex V_3 is hit.

This test is equivalent to the test of calculating $c = \boldsymbol{d}_0 \times \boldsymbol{p}_0\boldsymbol{V}_3$ since no reflection or diffraction occurs. This leads to the fact that there is no need to calculate the position vector on a dummy edge. It is especially useful when a ray is traversing a large number of dummy edges and this will result in a significant saving in CPU time.

E. Reception Test and Diffraction

A ray is received by a receiving antenna when it hits the reception sphere (or circle, for 2-D cases). To determine if diffraction occurs, the two end points of the wall edge will serve as receiving points and will be tested if the ray hits the corresponding reception sphere. If yes, diffraction occurs.

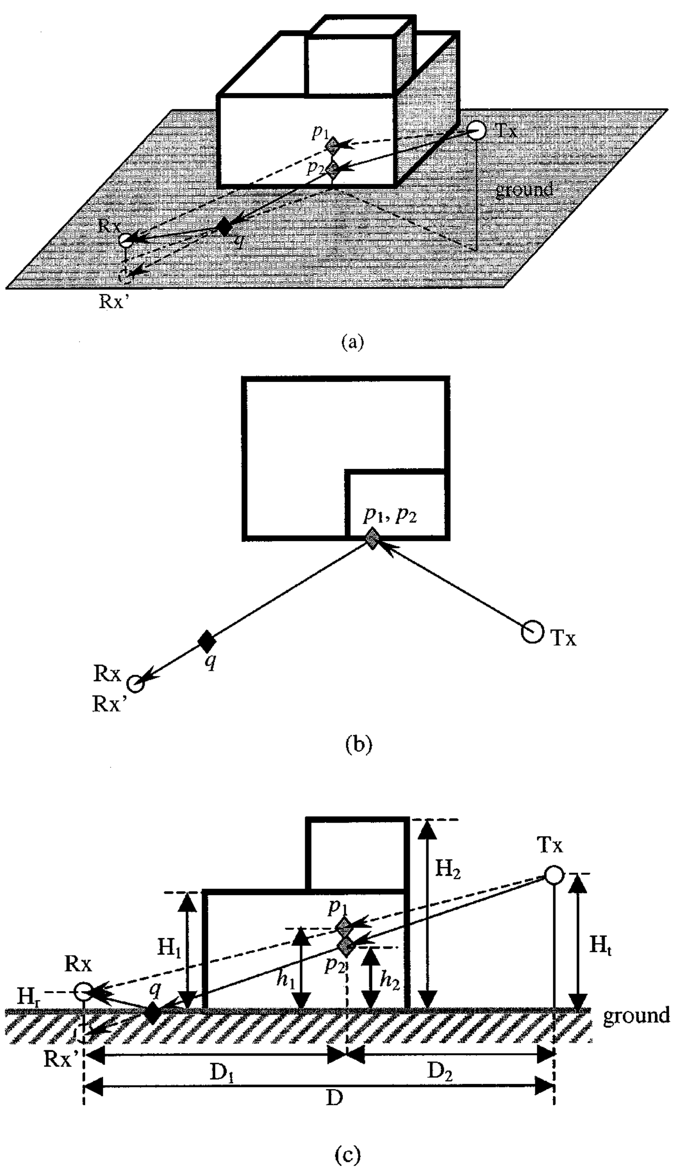


Fig. 7. Geometries of wall-and wall-ground-reflected rays. Rx' is teh image of Rx with respect to the ground plane. Tx-p_1-Rx is the wall-reflected ray and Tx-p_2-q-Rx is the wall-ground-reflected ray. (a) Perspective view of rays. (b) Top (projected) view of rays. (c) Unfolded rays.

F. 3-D Lateral Ray Tracing Based on the 2-D Triangle Grid

For the 3-D ray tracing, this paper proposes a simple method based on the 2-D method. Without loss of generality, we consider the lateral reflected ray tracing. Suppose we trace a 2-D ray and the ray is received by a receiving antenna. In this case, we have to determine the corresponding 3-D trajectory of this ray. The 3-D ray may not be a real ray because the heights of walls associated with it play a significant role. It is easy to calculate the hit point height on a vertical wall using the information of the 2-D ray. If the calculated height is larger than the height of the wall, the ray will not be reflected by the wall and no further action is needed. If the ray is valid (i.e., intercepted by the wall), the received field or power associated with the ray will be calculated. A 2-D ray may represent a 3-D ray which undergoes a ground reflection. This is due to the fact that the

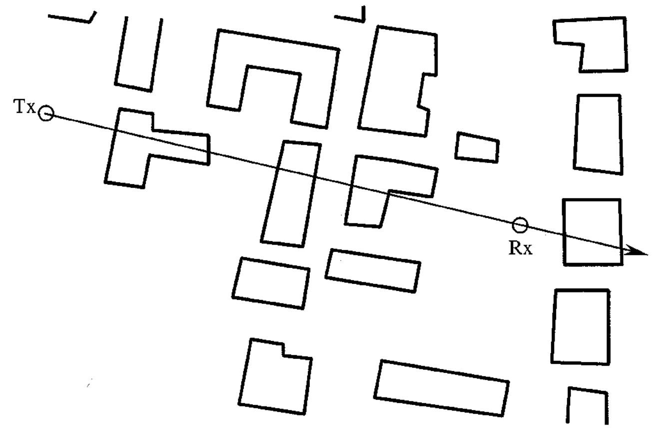


Fig. 8. Determination of over-rooftop rays.

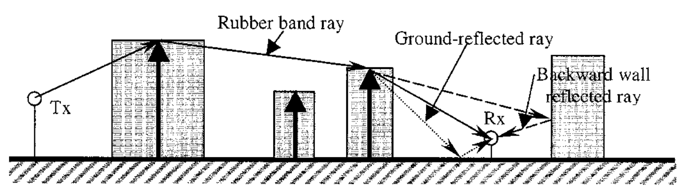


Fig. 9. Vertical profile used to determine the over rooftop rays. Buildings can be approximated by knife edges. Only main rays are shown and taken into account.

ground-reflected ray is the one traveling from the transmitter to the image of the receiver with respect to the ground, which is coincident with the receiver when projected to the horizontal plane, as shown in Fig. 7. Using the height information of vertical walls, we can also determine if a 2-D ray is a 3-D ray with ground reflection. For example, from the 2-D ray tracing, the unfolded ray lengths D, D_1 and D_2 are known (Fig. 7(c)). Then the heights of p_1 and p_2 can be calculated by

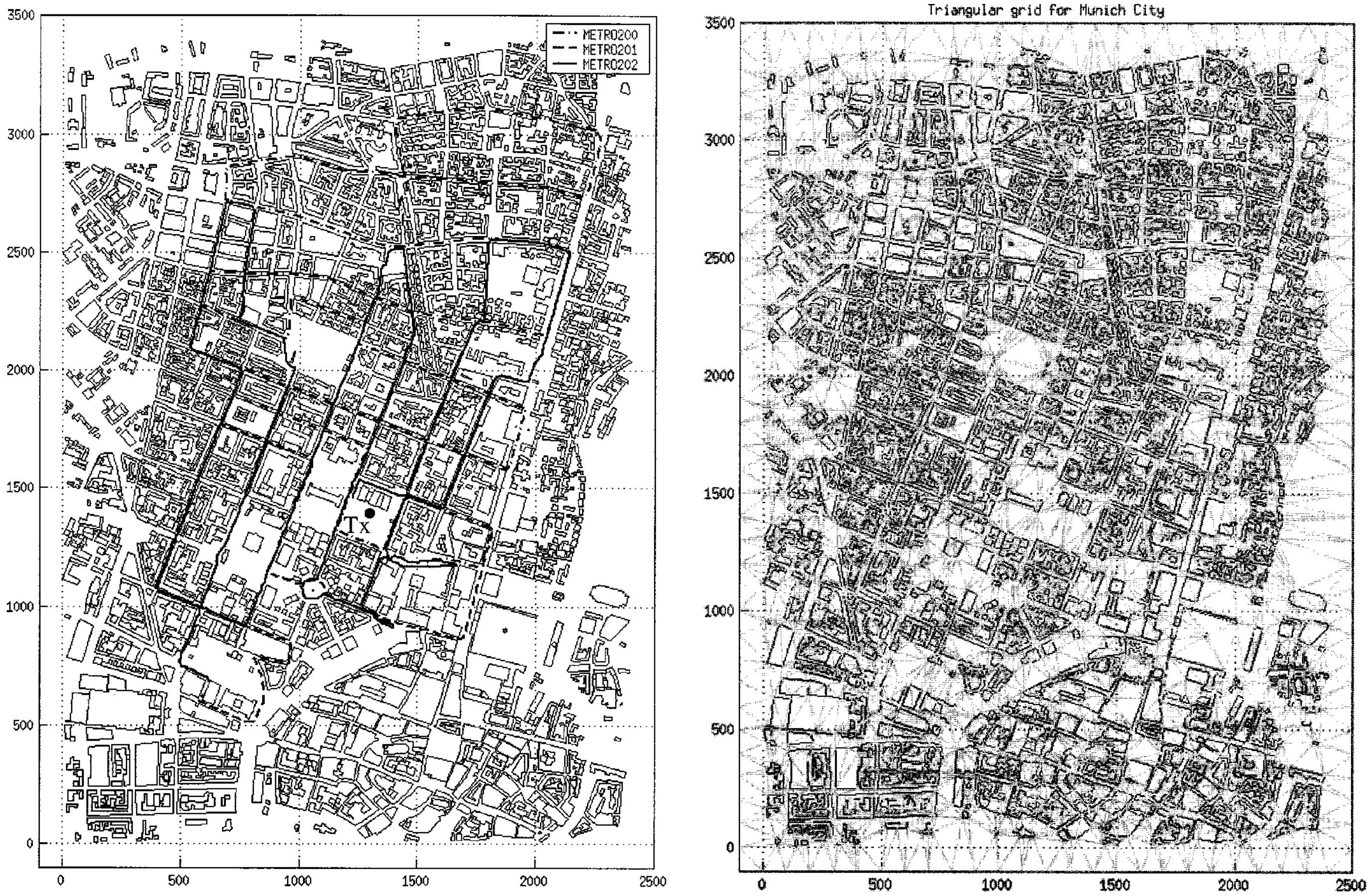
$$h_1 = H_r + (H_t - H_r)\frac{D_1}{D}$$
$$h_2 = -H_r + (H_t + H_r)\frac{D_1}{D}.$$

If $h_1(h_2)$ is greater than H_2, the height of the wall, the reflected ray is not valid.

The diffracted rays by the vertical edges can be traced in a similar manner.

V. Over-Rooftop Ray Tracing Algorithms

To calculate the over-rooftop rays, it is necessary to know the building profile cut by a vertical plane containing the transmitter and receiver. This can be done very efficiently by launching a ray from Tx to a receiving point using the 2-D ray-tracing method. Fig. 8 shows a ray launched from Tx, going through Rx, and hitting a series of edges, which determines the vertical building profile. Using the height information of edges, the building profile may then be constructed as shown in Fig. 9. Then the buildings are replaced by knife edges and the main rays are traced. The first ray is the "rubber band" ray that connects Tx and Rx. The second ray is the ground reflected ray, and the third one is the backward wall-reflected ray, as shown in Fig. 9.



(a) (b)

Fig. 10. (a) Building geometry of Munich City. Also shows three routes (i.e., METRO200, METRO201, and METRO202) used in the experimental measurements and the path losses along these routes were compared with the simulation results using the new ray-tracing method. Note that an outer boundary is added and many dummy edges are inserted in the triangular grid. All dimensions are in meters. b) The triangular grid used in the ray-tracing simulation.

VI. Simulation Results and Comparison With Experimental Data

In an attempt to verify the accuracy and computational efficiency of the proposed method, calculations were made for one of the propagation sites that was comprehensively studied by the European COST 231 working group. Experimental results for Munich City have been amply reported and hence used as the test case for our method.

Fig. 10(a) shows the top view of Munich City and Fig. 10(b) the triangular grid used in our simulation. In this test case, there are 2088 buildings and 17 445 walls. The transmitter position and the routes of measurement are also shown Fig. 10(a). These were determined through the measurement efforts established by the COST 231 working group. After triangulation, there are 31 156 triangles and 46 796 edges. Note that the original building database of Munich is in the form of vectors and was reformatted to fit our use.

Fig. 11 shows the comparison of the simulated and measured path losses for route METRO202. Table I gives a comprehensive comparison of our simulation results with several other results for all three routes (i.e., METRO200, METRO201, and METRO202, as shown in Fig. 10(a)) in Munich City. It can be seen that the proposed method provides results with very good accuracy as compared with others. The details of these models can be found in [9].

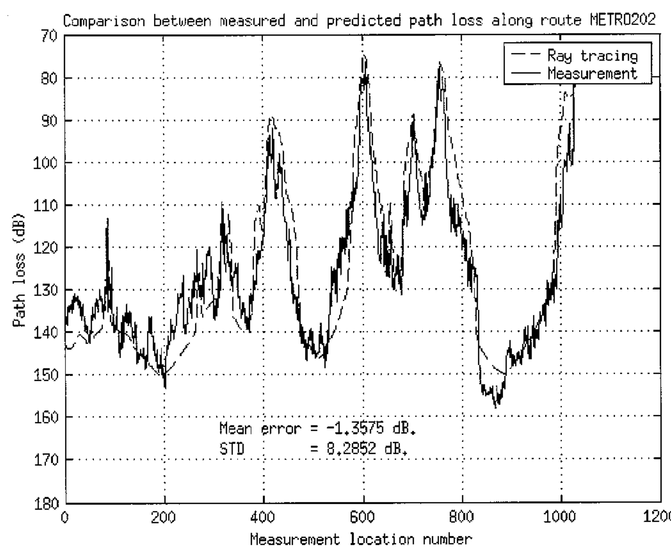


Fig. 11. Comparison with the measured path loss for Munich City.

The total ray-tracing time for all three routes is 3.47 s, running on a Sun Workstation Enterprise 420 R, 450 MHz. To compare the overall computational efficiency of our method, CPU time results were compared with those from a commercial software package ***WaveSight*** (http://www.wavecall.com/pre-

TABLE I
COMPARISON WITH OTHER SIMULATIONS

Prediction model	METRO200 (970 points)		METRO201 (355 points)		METRO202 (1031 points)		Average
	STD (dB)	mean (dB)	STD (dB)	mean (dB)	STD (dB)	mean (dB)	STD (dB)
Ericsson	6.7	0.3	7.1	2.3	7.5	1.4	7.1
CNET	6.9	-2.1	9.5	-3.6	5.6	-0.2	7.3
PTT (RT)	14.6	-6.1	15.5	-6.7	12.3	-1.1	14.1
PTT (TLM)	13.	0.8	21.7	6.7	12.9	6.5	16.1
COST-WI	7.7	10.8	5.9	15.4	7.3	16.3	7.0
Uni.-Valencia	8.7	0.2	7.0	-6.6	10.3	-7.4	8.7
CSELT	10.4	21.8	12.3	16.1	13.3	20.6	12.0
PTT (MCOR)	7.0	-3.3	6.2	-0.1	7.6	-1.1	6.9
Villa Griffone Lab	6.3	-1.7	10.9	-6.3	6.8	-5.5	8.0
Uni.-Karlsruhe	8.5	-4.3	9.1	2.4	8.6	-1.0	8.7
This paper	7.1	-2.6	6.2	-0.7	8.3	-1.4	7.2

diction.html). For this commercial software, the CPU time is 420 s on a Pentium II 266 for route METRO202, while our CPU time for the same route is 1.5 s. It is understood that calculations were made on different computers, but taking these differences into account (even in an approximate sense) it may be clearly observed that the proposed method provides significant advantages regarding the computational efficiency.

VII. CONCLUSION

In this paper, a computationally efficient propagation prediction model was presented. The approach is based on 2-D triangulation of the propagation environments and the use of straightforward vector algebra to determine the path of the propagation ray. Basically, the proposed method avoids the use of the usual time-consuming algorithms to determine the appropriate reflecting surfaces in the propagation path. It therefore provides significant advantage in computational efficiency. It is shown that although the triangulation is 2-D, it is possible to simulate 3-D environments using the proposed technique. This is accomplished by including additional information on the building heights and considering this information in the determination of true wall hits in the 3-D modeling case.

Accuracy and computational efficiency of the proposed method were evaluated by comparing simulation results with experimental data from the European COST 231 working project and with ray tracing using visibility for a realistic indoor environment. Excellent agreements were observed and considerable savings in CPU time were accomplished. Specifically, an average standard deviation of 7.2 dB was observed which is considered among the very lowest (ranging from 7.0 to 16.1 dB) of currently available techniques that used the same test site. CPU time ratio of the proposed method when compared with the visibility method [32] is about 25% to 30%. Comparing with one of the available commercial software packages, ***WaveSight***, that was used for the same measurement route in Munich City, the CPU time of the proposed method was 1.5 s (on a Sun Workstation, Enterprise 420 R) while the CPU time of the commercial package was reported to be 420 s (on a PC, Pentium II 266).

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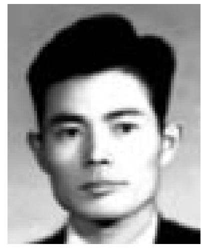

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