An Adaptive Beam Tracing for Visual Simulation of Ray Propagation in Wireless Communications Systems

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Abstract: In this paper, an adaptive beam tracing method with revised subdivision technique is proposed, in which the beam is generated by a set of three rays. According to reflection and/or refraction of the rays on the buildings and/or ground, additional rays are generated adaptively and the beam is subdivided efficiently and automatically. After generation of the set of beams, we transform the electromagnetic wave propagation data into volume data. Then one can visualize the data of propagation with reflection, refraction and interaction in full three dimensional space at any viewpoint by the so-called ray casting algorithm, which is one of the most useful methods in computer graphics(CG).

1. Introduction

Due to the multiple interference between the surrounding buildings, urban propagation environment of electromagnetic waves has become more complicated, and it would be difficult to install base station antenna in a proper site for micro- or pico-cellular systems of wireless communication networks[1, 2, 3]. For personal communication services (PCS) applications and wireless LAN, UHF and higher frequency band are mainly used. The propagation characteristics for such bands depend largely upon the local constituents and material of the structure nearby. Therefore, in order to study the propagation characteristics, and to install the base station antennas efficiently, one may need to know more detail of the surrounding environment of the cell or section of a service station.

Various groups have proposed site specific propagation prediction methods for PCS application[4, 5, 6], and their main tool is ray tracing technique. Since ray can propagate by bouncing (reflection), diffraction, diffusion and their combination, possible ray paths from a base station antenna to a subscriber are uncountable, even for a simple site configuration. Accordingly, one has to select somehow the rays which give us dominant contribution to the receiving signal.

In the previous paper, our group has discussed about ray tracing method, which would be the preferable way for path loss prediction in rather irregular geometry bounded by surrounding buildings[7]. Although the method is applicable to any altitude in the three dimensional space, it is very hard to apply in full three dimension because of the limited computational time. Furthermore, in the case of tracing rays only, there always exists space between the rays, and the propagation in such space cannot be calculated. Therefore, it is difficult for ordinary ray tracing method to calculate propagation correctly for a complex environment as an urban area of many reflections.

In order to visualize the propagation in three dimensional space, a beam tracing method with subdivision technique has been proposed by our group, in which the beam is generated by a set of three rays[8]. According to reflection and/or refraction of the rays on the buildings and/or ground, additional rays are generated adaptively and the beam is subdivided automatically. After generation of the set of beams, we transform the electromagnetic wave propagation data into volume data. Then one can visualize the data of propagation with reflection, refraction and interaction in full three dimensional space at any viewpoint by the so-called ray casting algorithm[9], which is one of the most useful methods in computer graphics(CG).

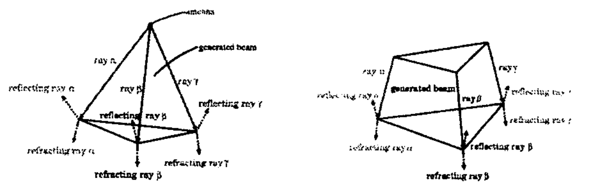
However, it is seen that the numbers of rays and beams may become huge, since the procedure subdivides the beams recursively. Therefore in order to decrease rays and beams, in this paper we propose a revised subdivision algorithm of beams. By the revised subdivision, the additional rays are generated recursively, but the beam is not subdivided recursively. Therefore, the numbers of the additionally generated rays and beams are less than the previously proposed method so that it will take lower computational cost.

2. Revised Adaptive Beam Tracing for Ray Propagation

2.1 Outline

In this paper, a concept of the CG beam tracing method[10] is introduced, in which reflection and refraction are traced by a set of polyhedric beams instead of rays only. Hereby all region, where the electromagnetic wave propagates, can be fully covered with the beams.

In order to generate beams efficiently, we define a beam as a triangular pyramid or a truncated triangular pyramid, which are formulated by three rays tracing the propagation (see Figure 1). Also not for including the region where the wave does not propagate, the beams are adaptively subdivided according to the situation of the rays. After generation of the set of beams, we transform the propagation into volume data, so that CG images can be generated by the ray casting algorithm, which represent propagation with reflection, refraction and interaction from any viewpoint.



(a) rays from the antenna (b) rays from the object

Figure 1: Definition of a beam by a set of three neighbor rays

The proposed method consists of the following steps:

Step 1: Computation of the wave propagation
- Generation of beams by tracing rays from the antenna
- Subdivision of beams by addition of rays

Step 2: Transformation of propagation data into volume data

Step 3: Rendering of volume data by the ray casting algorithm

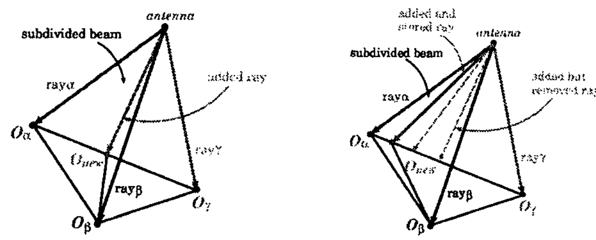
Steps 1-3 are independent each other, so that we can generate any precision of volume data from the same set of beams, and generate any size of images from the full or partial volume data from any viewpoint. Consequently, by the proposed method we can visualize the propagation in full three dimensional space with low computational cost.

2.2 Definition of Beams by Adaptive Beam Tracing

The initial rays are defined radially and equiangularly from the given antenna to the space. It is noted that the number of rays should be many enough to cover the objective space. Each ray has information on (1) neighbor rays, (2) position of starting point and endpoint, (3) accumulated propagating distance between the antenna and the starting point of the ray, and (4) accumulated relative permittivity from the antenna to the starting point. Among the rays, we select three rays α, β and γ, which are neighbor each other. For each ray, we obtain the nearest object from the starting point, which the ray intersects. This calculation is similar to one in the CG ray tracing method[11]. According to the relative permittivity of the object, reflection and/or refraction rays are generated and traced repeatedly if necessary (see Figure 1).

Let O_α, O_β and O_γ be intersected objects for the rays α, β and γ, respectively. Then, in order to represent a region of propagation, a beam (polyhedron) is defined which is surrounded by the rays α, β, γ, the objects O_α, O_β, O_γ, and starting points/plane of the rays. However, if there are any objects within the beam region, the beam does not represent the exact propagation. In such cases, the beam should be subdivided. For each beam region, we check whether the beam is needed to be subdivided or not. Concretely, conditions of subdividing beam are: (1) O_α, O_β and O_γ are not same, (2) propagation distance between three rays is greater than the given threshold, or, (3) distance between the intersection points on O_α, O_β and O_γ is greater than the given threshold. Additionally, a maximum subdividing times of each condition is set in order to avoid to subdivide the beams infinitely.

When the beam is judged to be subdivied, in the previously proposed method[8] a new ray is defined according to the situation of the original three rays α, β and γ2), and the information on neighbor rays is updated. By the updated information, the beam is subdivided into two beams. By repeating this procedure until all sets of three rays do not satisfy the above conditions (a)-(c), we obtain a set of beams, which represents the region where the electromagnetic wave propagates.



(a) method by [8] (b) proposed method

Figure 2: Subdivision of beam

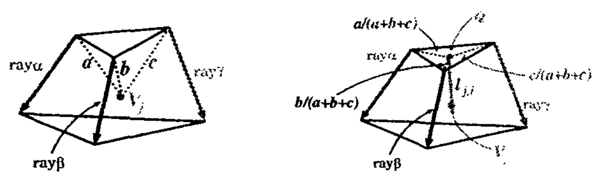
However, it is seen that the numbers of rays and beams may become huge, since the procedure subdivides the beams recursively. In order to decrease rays and beams, in this paper we propose the following revised subdivision algorithm of beams:

When the beam is judged to be subdived, two of the three rays are selected to be subdivided. Then, additional rays are generated repeatedly at the middle between one of the selected two rays and the lastly defined additional ray, until the latest generated ray intersects either objects which the selected two rays intersect. In the proposed method, the additional rays are generated recursively, but the beam is not subdivided recursively. In addition, since all the generated rays except the latest one are not used for subdivision of beams, they can be removed (see Figure 2). Therefore, the numbers of the additionally generated rays and beams are less than the previously proposed method so that it will take lower computational cost.

2.3 Transformation of Propagation Data into Volume Data

It is seen that the beams generated in the previous section sometimes overlap in the same region because of reflection and/or refracion of the rays. In order ot visualize the situation of propagation efficiently, in this section a set of volume data of the electric power will be transformed from the beams.

In the first place, define a set of voxels $\{V_j\}$ as the objective space.In the second place, for each voxel obtain a subset of beams in which the voxel exists. Suppose that the voxel V_j exists in the beam $B_i^{(N)}$ having a set of three rays α, β and γ. Here $B_i^{(N)}$ is assumed to be generated after N times of reflections and/or refractions. Then, a ray through V_j can be approximated by the rays α, β and γ (see Figure 3).



(a) starting points of rays and the voxel

(b) calculation of $l_{j,i}$

Figure 3: Approximation of ray through V_j

Since the rays α, β and γ have the accumulated distance from the antenna, respectively, the accumulated distance d_Q can be calculated between the antenna and the starting point Q of the obtained ray through V_j. From d_Q and the distance $l_{j,i}$ between Q and V_j, for $B_i^{(N)}$ the accumulated distance $d_{j,i}$ between the antenna and V_j can be approximately obtained by the following:

$$d_{j,i} = d_Q + l_{j,i}. \quad (1)$$

From Eq.(1), the amplitude $C_{j,i}^{(N)}$ at V_j for $B_i^{(N)}$ can be calculated by the followings:

$$C_{j,i}^{(0)} = \frac{\lambda_i}{4\pi d_{j,i}} e^{-jk_1 d_{j,i}} \sqrt{G_{ti} P_{ti}}, \quad \text{(for direct wave)} \quad (2)$$

$$C_{j,i}^{(N)} = \frac{\lambda_i R}{4\pi d_{j,i}} e^{-jk_1 d_{j,i}} \sqrt{G_{ti} P_{ti}}, \quad \text{(for reflection)} \quad (3)$$

$$C_{j,i}^{(N)} = \frac{\lambda_i T}{4\pi d_{j,i}} e^{-jk_1 d_Q + k_2 l_{j,i}} \sqrt{G_{ti} P_{ti}}, \quad \text{(for refraction)} \quad (4)$$

where $N = 1, 2, 3, \ldots$. Here,

$$R = \frac{1}{2}\left\{ \frac{\varepsilon_r \cos\theta - \sqrt{\varepsilon_r - \sin^2\theta}}{\varepsilon_r \cos\theta + \sqrt{\varepsilon_r - \sin^2\theta}} + \frac{\cos\theta - \sqrt{\varepsilon_r - \sin^2\theta}}{\cos\theta + \sqrt{\varepsilon_r - \sin^2\theta}} \right\}, \quad (5)$$

$$T = \frac{1}{2}\left\{ \frac{2\sqrt{\varepsilon_r}\cos\theta}{\varepsilon_r \cos\theta + \sqrt{\varepsilon_r - \sin^2\theta}} + \frac{2\cos\theta}{\cos\theta + \sqrt{\varepsilon_r - \sin^2\theta}} \right\}, \quad (6)$$

where λ_i is wavelength of B_i, P_{ti} is power of the antenna, G_{ti} is gain of the antenna, k_1 is wave number in vacuum, k_2 is wave number of the object, θ is angle between the obtained ray and the normal vector at Q, and ε_r relative permittivity.

From Eq.(2), (3) and (4), the electric power P_j at V_j can be obtained by

$$P_j = \left| \sum_n \sum_i C_{j,i}^{(n)} \right|^2. \quad (7)$$

It is noted that the interval and number of voxels can be defined in consideration of accuracy of approximation and computational cost. For example, if intersection of waves should be visualized, then the interval of voxels must be very close. In this case, a part of space will be only transformed from the beams.

2.4 Rendering of Propagation Data

In order to visualize the volume data, we use the so-called ray-casting method combined with the CG ray tracing method, which is one of rendering algorithms being suitable to such spatial data.

It is noted that by the ray casting algorithm we can visualize and accentuate any amplitude of the P_j from any viewpoint, so that the visualization makes us understand the situation easily.

3. Simulation

Figure 4 shows a panoramic view of the propagation in the urban space around the Tokyo Metropolitan Office in Shinjuku, Tokyo, Japan. The CG image with 600 × 800 pixels is generated by the proposed method under P_t = 20mW and G_t = 1 with 1.9GHz frequency. Also 8,400,000(= 400 × 300 × 70) voxels are defined in the object space 800m×600m×140m. Here it is assumed that $\varepsilon_r = 15 - j0.3\lambda$. Each pixel shows the electric power from 0 to 50mW. From the image it is shown that reflection and shadowing are represented.

For the situation, a set of 960 initial beams with 482 rays is defined. After generation process, we have 2,880 beams with 2,764 rays including the initial ones, while we have 44,241 beams with 43,763 rays by the previously proposed subdivision. Under UltraSPARC IIi 440MHz system, It takes 104.81 seconds for generation of the rays and beams while it takes 1,270.44 seconds for the generation by the previous method.

Figure 4: Generated image by the proposed method

The computation of transformation of the beams to volume data depends on both numbers of voxels and beams strongly. In the other example, it takes 7206.43 seconds by the proposed method under 6,339 beams and 2,000,000 voxels, while it takes 10080.52 seconds by the previous method under 10,881 beams and 2,000,000 voxels. Consequently, it is seen that the proposed revised subdivision algorithm is very useful for decreasing the computational cost, so that it can be applied to more complex urban space than the previous method.

4. Conclusion

In this paper, we have proposed a visual simulation method for high frequency electromagnetic wave propagation with reflections and refractions by tracing beam region generated and subdivided adaptively. In the case of tracing rays only, there always exists space between the rays, and the propagation in such space cannot be calculated. Therefore, it is difficult for the ordinary ray tracing method to calculate propagation correctly in a complex environment as an urban area having many reflections and refractions. It is noted that our method is able to calculate propagation more efficiently than the previously proposed method because of smaller number of beams by the adaptive generation and subdivision of beams.

Each step in the proposed method is independent each other, so that we can generate any precision of volume data from the same set of beams, and generate any size of images from the full or partial volume data from any viewpoint. Consequently, by the proposed method we can visualize the propagation in full three dimensional space with low computational cost.

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