A Novel 3D Ray-tracing Acceleration Technique Based on Kd-tree Algorithm for Radio Propagation Prediction in Complex Indoor Environment

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Abstract— This paper presents a new 3D ray tracing acceleration technique based on the kd-tree algorithm for predicting the radio coverage in complex indoor environment. For each ray emitted from the transmitter, all the valid ray propagation paths can be searched for by the hybrid ray tracing model which combines the shooting and bouncing ray (SBR) and the image method. The kd-tree algorithm is mainly used to accelerate the intersection test of ray tracing. In addition, the receiver power strength can be calculated based on geometrical optics (GO) and uniform theory of diffraction (UTD). As expected, the proposed method performs higher superiority than the conventional ray tracing model in terms of computational efficiency. Meanwhile, it also shows good agreement with measurements and the Winprop's simulated results with respect to computational accuracy.

1. INTRODUCTION

With the rapid spread of wireless communication technology, the efficient and accurate indoor propagation model becomes a topic of most concern in designing and deploying communication systems.

Many radio propagation models were developed over the past decades for indoor environments, particularly site-specific models [2], which are based on electromagnetic wave propagation theory. Among of those site-specific models, the ray tracing models are the most widely used, such as the image method [2, 3], shooting and bouncing ray (SBR) method [1, 2] and the hybrid method (SBR/image) [2, 4, 5]. The image method is accurate, but suffers from inefficiency when the environment is complex. The SBR method is efficient but the accuracy is not stable. Because it needs to introduce a receiving sphere, while the size of it is of great importance to the calculation accuracy. Hybrid method combines the image and SBR method, performing both the advantages of such two methods. However, when applied to the complex and convoluted indoor environment, ray tracing models still face the problem of computational inefficiency.

The purpose of this study is to introduce a new three dimensional (3D) ray tracing acceleration technique based on kd-tree algorithm [6, 7] for predicting radio coverage in complex indoor environment. The proposed method is based on the hybrid ray tracing model and the kd-tree technique. In addition, the precedence of the proposed acceleration method is proved by comparing with the measured data, commercial maturity software Winprop and the conventional ray-tracing technique in terms of computational accuracy and efficiency.

2. THE IMPLEMENTATION OF PROPOSED METHOD

Ray tracing models are vastly applied in radio propagation prediction. One of the biggest challenges of ray tracing is the computational burden of overload ray-object intersection test. Therefore, to overcome this drawback, the proposed method introduces a well-known acceleration intersection technique, namely, kd-tree algorithm. The following subsections focus on describing the details of how to search for the radio propagation paths and finally the whole ray tracing procedure is presented.

2.1. Searching for Propagation Paths

The highly important step of ray tracing is to search for the valid radio propagation paths between transmitter and receiver, which is the most time consuming and the most challenging part. In order to improve the efficiency of finding propagation paths, both the hybrid ray tracing model and kd-tree technique are adopted.

2.1.1. The Hybrid Ray Tracing Model

The hybrid model which combines SBR and image method is recommended as follows. The SBR method is used to quickly identify all possible propagation paths from transmitter to receiver.

Each propagation path is composed of a series of face ID intersecting with the ray and the type of propagation mechanism (reflection or transmission) on this face. Tracking each ray, when it intersects with an obstacle, it will be transmitted and reflected generating two new rays. For the new ray, continue to search for the intersected face. The above process is repeated until it reaches the set maximum reflection, transmission times. So far all propagation paths corresponding to the ray have been obtained and recorded. Among of these paths attained by the SBR model, there exist some paths through which it cannot reach the receiving point from the emitter. Therefore, it is necessary to apply the image method to determine the effectiveness of propagation paths. For each possible path, on the basis of recorded information, all the mirror points relevant to every interacted face are calculated respectively. Based on these mirror points, we can search for the exact point of intersection and judge whether the path is legal. At this point, all valid propagation paths have been acquired via the hybrid model.

2.1.2. Acceleration Technique — Kd-tree Algorithm

Traditional intersection test needs to judge whether the ray intersects with all the faces one by one in the whole scene space. For ease of understanding, a simple 2D scenario is illustrated in Figure 1(a), the a, b, c, d, e triangles represent different faces of obstacles and a signal ray is plotted as red line. Traditional way requires to test all the a, b, c, d, e faces whether intersecting with the ray. When the simulated environment is complex, it takes plenty of time.

The kd-tree algorithm can get through such inefficiency of above traditional intersection test. The implementation of kd-tree [6] is described as follows with the help of illustration in Figure 1. The symbols s_0, s_1, s_2, s_3 denote the space related to internal node and n_0, n_1, n_2, n_3, n_4 denote the smallest subspace related to leaf node in the tree.

2.1.2.1. Construction of Kd-tree

The construction of kd-tree is based on space partition. Firstly, a bounding box representing the whole original space is generated for the goal scenario. It is corresponding to the root node in the tree as s_0 in Figure 1(b). Then the best split plane can be selected based on ray tracing costs estimation model, the most widely used greedy surface area strategy (SAH) [6]. As plotted in Figure 1(a), the split_plane0 is namely the best split plane corresponding to the space s_0. According to the split plane, the original space s_0 is divided into two subspace s_1, s_2 (in Figure 1(a)) and at the same time the root node s_0 generates two child nodes s_1, s_2 (in Figure 1(b)). For the new subspace, we go on to search for its optimal split plane and then generate new child nodes. The above operation is recursive until it meets construction terminal condition, then there is no need to continue space subdivision directly generating a leaf node. After all, the complete and optimal kd-tree can be constructed corresponding to the simulated environment, as illustrated in Figure 1(b). It must emphasize that the kd-tree is only constructed once for a given scenario and it is independent of the position of transmitter and receiver, so it is ease of application.

2.1.2.2. Traversing of Kd-tree

After the kd-tree is constructed, starting from the root node to traversal the tree. For internal node of kd-tree as s_0 in Figure 1(b), according to the position relationship between the ray and the split plane split_plane0 (in Figure 1(a)) of space s_0, the nearer child node s_1 to the ray is acquired to continue traversing while the faster child node s_2 is recorded and pushed back into stack. If the current node is not a leaf node, it is required to keep searching for its child node. For the finally

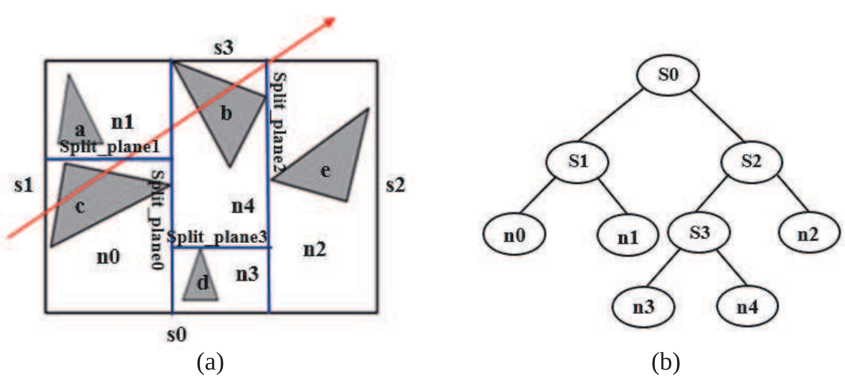


Figure 1: (a) The space division of 2D scene. (b) The corresponding constructed kd-tree.

obtained leaf node n_0, the ray is just only to test whether intersecting with faces in it. Generally it can find a valid intersection face. Otherwise, the traversal procedure is repeated by pushing up the top node in stack.

After fully understanding the features of kd-tree algorithm, based on its spatial division and traversal criterion, we can generally find a smaller subspace of the scene which is the nearest to the ray and then it is only to judge whether the ray intersects with faces in this subspace. As a result, the number of intersection test dramatically reduces. As illustrated in Figure 1, for the emitted geometrical-optics ray, it needs five times of intersection test by the means of traditional way but only one time by applying the kd-tree algorithm. It adequately shows the advantage of kd-tree algorithm in terms of acceleration intersection test for ray tracing.

2.2. Ray Tracing Procedure

In Figure 2, a general flowchart of the proposed method is presented. It is composed of three important phases: modeling, searching for path and calculating.

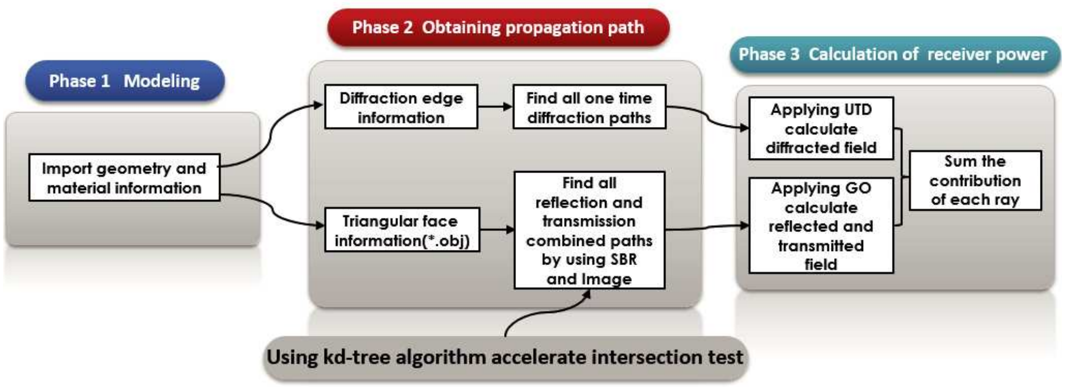


Figure 2: Procedure of the proposed ray tracing model.

Firstly, the original input geometry and material information files are converted and combined to generate the edge information file and triangular face information file conformed to requirement. Secondly, all possible reflection and transmission combined propagation paths are searched for by using the SBR method and then all the valid paths can be picked out by applying the image method. Furthermore, one time diffraction propagation paths must be considered for the indoor object edge. Lastly, after all the paths are determined, tracking the path and employing the GO and UTD theoretical formulas [8, 9] to calculate the final receiver power strength. Moreover, it is valuable to note that the introduction of kd-tree algorithm is used to accelerate the intersection test of ray tracing.

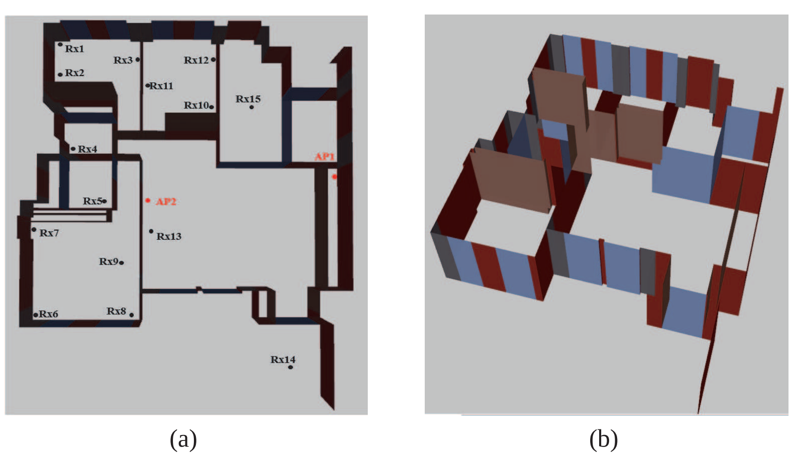
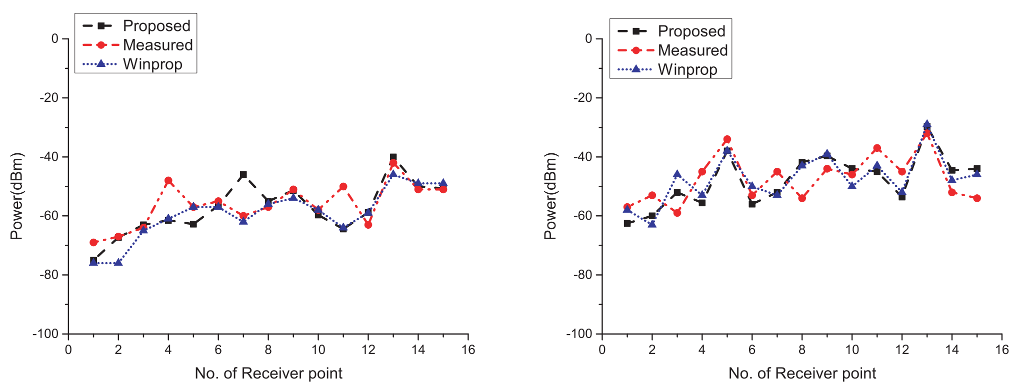


Figure 3: Illustration of simulated house environment. (a) 2D diagram. (b) 3D contour structure.

3. COMPARISON OF NUMERICAL RESULTS

In order to demonstrate the accuracy and efficiency of the proposed acceleration ray tracing model, the simulated results is not only compared with the measurements and the commercial software Winrpop but also the conventional ray tracing model. A complex indoor simulated environment, a household room, is total of about 140 square meters and composed of three bedrooms, two halls and two bathrooms, as illustrated in Figure 3. Figure 3(a) is two dimension (2D) simplified diagram of the simulated household environment, while Figure 3(b) is three dimension (3D) graphic of the house contour structure. In Figure 3(a), symbol AP1, AP2 represent transmitters (Tx) and Rx1, Rx2, ..., Rx15 represent receivers (Rx). The result are taken by moving one Tx to two different position (AP1 (12.1, 9.5, 0.5), AP2 (5.3, 8.5, 0.4)) while keeping 15 Rx steady in the simulation household environment. Different Tx represents different scenarios and they all use a same transmitting antenna, which is isotropic, the power is 18 dBm and the frequency is 2.4 GHZ.

The simulation has been separately done for 2 scenarios as presented in Figure 3(a). The received power obtained by the proposed method is compared to the measurements and Winprop in terms of computational accuracy, which are plotted in Figure 4. It can be observed that the proposed method shows good performance and agreement not only with measurements but also the Winprop simulated result. However, there still exists slight difference in a certain receiver points. By analysis, it may be primarily caused by the subtle difference between simulation and actual measurement environment. Because the simulation modeling environment actually skips some difficult-to-model indoor objects which make a non-negligible contribution to the overall computed field strength at the receiver. Furthermore, in order to demonstrate the efficiency, the proposed technique has also been compared with the conventional ray tracing (CRT), which in this paper is namely the hybrid model as stated in Section 2.1.1 but without any acceleration technique. Figure 5 shows a comparison, which is one Tx corresponding to one Rx based on computational time, considering 15 different receiver points in 2 different scenarios as presented in Figure 3(a). Hence, it can be



(a) (b)

Figure 4: Comparison of measured data, Winprop and the proposed method. (a) AP1. (b) AP2.

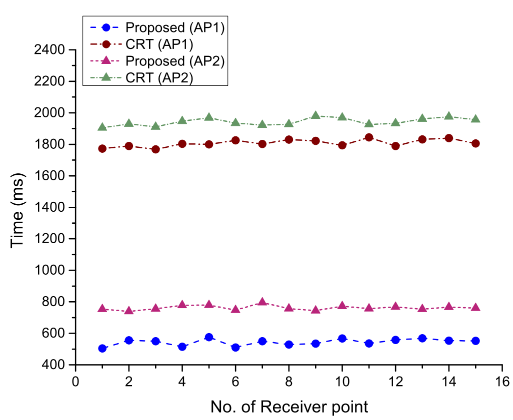


Figure 5: Comparison between the proposed method and conventional ray tracing model based on computational time in terms of 15 receiver points in 2 different scenarios (AP1, AP2).

found that the proposed method gives obviously higher computational efficiency than the CRT. Therefore, it can be summarized that the proposed acceleration ray-tracing technique based on the kd-tree algorithm shows high superiority in terms of both computational accuracy and efficiency.

4. CONCLUSION

In this study, a sophisticated 3D ray tracing acceleration technique based on kd-tree algorithm has been implemented and can be applied to complex indoor environment radio prediction. The proposed method is based on the hybrid ray tracing model and the kd-tree technique. The kd-tree algorithm is applied to accelerate the intersection test of ray tracing by tremendously reducing the number of intersection test. The precedence and reliability of the proposed acceleration method are confirmed by comparing the simulated results with measurements, commercial maturity software Winprop in terms of computational accuracy and at the same time comparing with the the conventional ray-tracing technique in terms of computational efficiency, respectively. The achievement of this study will facilitate the deployment of personal communication systems in complex indoor environment. Moreover, our future work will be concentrated on applying the proposed method to outdoor or indoor-outdoor collaboration radio coverage prediction.

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