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Implementation of 3-D Ray Tracing Propagation Model for Indoor Wireless Communication

Satvir Singh Sidhu[1], Arun Khosla[2] & Ashita Sharma[3]

[1]*Department of ECE, SBS College of Engineering & Technology, Ferozepur, Punjab, India*

[2, 3]*Department of ECE, National Institute of Technology, Jalandhar, Punjab, India*

(E-mail: satvir15@gmail.com, arun.khosla@gmail.com, ashita_sharma1986@yahoo.co.in)

Abstract: Wireless and mobile broadband communication systems are planned to operate at the mm-wave band, due to the spectrum availability and wider bandwidth requirements. It is important to characterize the radio propagation channel to ensure satisfactory performance of a wireless communication system. This paper classifies the propagation models and discusses the importance of indoor propagation modeling and concentrates on the development of MATLAB code for the ray tracing propagation model because of its practical appeal and its applicability to any environment.

Keywords: Wireless communication, propagation models, ray tracing technique, MATLAB.

1. INTRODUCTION

Wireless communications is a rapidly growing segment of the communications industry with the potential to provide high-speed, high-quality information exchange between portable devices located anywhere in the world. The performance of a wireless communication system is strongly dependent on the propagation channel. Site measurements are costly, therefore, propagation models have been developed as a suitable low-cost alternative that describes the channel behavior and ensure satisfactory performance of a wireless communication system or provide a prediction of the effective coverage [1,2,4,5]. A propagation model is a set of mathematical expressions, diagrams, and algorithms used to represent the radio characteristics of a given environment.

The propagation models can be classified into two major classes: (1) statistical models and (2) site-specific propagation models [4,5,10]. Various statistical/empirical propagation models exist for outdoor and indoor propagation scenario that relies on measurement data [9]. For outdoor scenario, the existing empirical models are Okumura-Hata model, Walfisch-Ikegami model, Longley Rice model, Durkin's model, PCS extension to Hata model [1]. For indoor scenario, the existing empirical models are International Telecommunication Union (ITU) Indoor propagation model, Log distance path loss model, Log normal shadowing model, Ericsson multiple breakpoint model, Attenuation factor model [2].

All the empirical based radio propagation models are applicable to a specific application, i.e., a model specific for one application cannot be applied to any other application and these models lack the generality and rigor of a basic theoretical formulation. So there is a need to develop site-specific/deterministic models which may be applied to different environments without affecting the accuracy that are based on electromagnetic-wave propagation theory. The understanding of indoor radio propagation is important in the design and layout of mobile data and voice systems because the characteristics of a multipath channel in indoor communication are strongly dependent on the physical environment, e.g., layout of the building, construction material, type of the building etc.

In theory, the ultimate details of propagation in a certain environment could be obtained by solving Maxwell's equations with boundary conditions that express the physical properties of the walls and other structures that scatter the radio waves. From a practical view point, this is impossible as in complex environments specifying details with accuracy smaller than the wavelength is a severe problem. To overcome this, approximation models, i.e., ray tracing technique (site-specific model) has been emerged as the dominant method to predict propagation in such environments due to its practical appeal and accuracy [12,13]. Moreover, ray tracing provides a vision to wireless network managers to see the effect of signals as they bounce off of walls within the building. It makes empirical models obsolete for both network planning and optimization in an indoor environment.

There has been considerable interest in the last two decades in propagation prediction for indoor environments, due to the extended use of indoor wireless communication for a large variety of applications [8,11]. Research on ray tracing for indoor propagation has also been reported in [4-15]. This paper presents a software application (developed in MATLAB environment) incorporating ray tracing algorithm with finite detailing to simulate and predict the radio propagation in the indoor radio channel from the layout of the floor plan.

2. RAY TRACING

Ray tracing (site-specific) model uses the theory of Geometrical Optics (GO) to treat reflection and transmission on plane surfaces. Geometrical optics is based on the so-called ray approximation, which assumes that the wavelength is sufficiently small as compared to the dimensions of the obstacles in the environment. These high frequency radio waves behave in a ray like fashion like light waves. Therefore signal propagation can be modelled as ray propagation. Rays may be launched from a transmitter location and interaction of the rays with partitions within buildings modelled using reflection and transmission theory based on Fermat's principle which states that of all the possible paths from one point (transmitter) to another point (receiver) after reflection or transmission through walls that satisfy the boundary conditions, a ray takes the path which requires the shortest time and that happens only when angle of incidence is equal to the angle of reflection or transmission.

Two types of methods employed in ray tracing models are (1) image method [10] and (2) brute force ray launching method [7]. Brute Force method relies on ray shooting where a transmitter shoots rays in all directions. The ray tracing is accomplished by an exhaustive search of a ray tree accounting for the decomposition of the ray at each planar intersection. For each ray, we need to check each partition which is accompanied by a cubic bounding box, so actual intersection calculations are done only if the ray passes through it. Therefore this method requires numerous ray-object intersection tests and extensive data arrays for ray tracing. Considerable requirements on the computer operating platform are necessary for implementing this method. On the other hand, image method relies on the method of images, which associates virtual sources with every obstacle and gauge their effect on transmission. So Image method based ray tracing model has been used for implementation due to its practical appeal and less computational complexity.

2.1. Algorithm

A detailed geometrical description of the building is taken under consideration. This geometry must be in three-dimensional coordinates and non-planar surfaces must be broken down into planar segments before they can be inputted to the model. The steps involved in the developed framework are as shown in Figure 1.

The first three blocks of the flow chart corresponds to the three types of databases needed to run the simulation completely – building database, electromagnetic parameter database, and receiver database [14]. The building database also known as floor plan file gives relative location of the

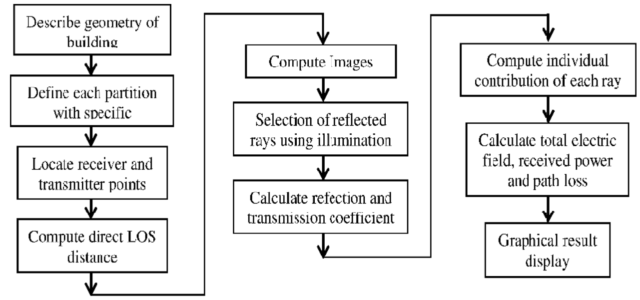

Figure 1: Flow Chart for Ray Tracing Model Implementation

walls within the building and is written in the array editor of MATLAB. Each column in the floor plan file represents a finite square plane, e.g., a wall, a floor, a ceiling, a counter top, or a window A plane surface can be entered starting from the leftmost coordinates of its vertices and then proceeding counter clockwise whereas electromagnetic parameter database is used to model the effect of the building details on the ray path. Each wall and partition must have its electromagnetic properties like real and complex permittivity, conductivity, and dielectric constant that are used to calculate the reflection and transmission coefficients. Each column in this file represents the properties of the corresponding finite plane. The receiver database contains the coordinates of the receiver points. The first column represents the location of the first receiver in *x*, *y* and *z* coordinates, with respect to the building database coordinate system. Multiple receiving locations can be defined or a grid of receiver locations can be made, so that the algorithm described here can be applied to each receiving point so as to display graphically the distribution of path loss along the sampling area. This description acts as input to the following geometric and electromagnetic engines.

The position of the transmitter is specified as a point in a 3-D coordinate system that is given as the input. In an indoor environment, signal rays arriving at the receiver can be line of sight (LOS) signals and reflection signals from walls, partitions, ceilings, floors and tables etc. Next three blocks (fifth, sixth and seventh) refers to the geometrical engine of the model that computes the different paths between transmitter and receiver using the data given in the above four blocks. First, the model determines if a line-of-sight path exists, and if so computes the distance taken by the LOS path and calculates the electric field strength.

Usually, a maximum number N_{max} often called reflection order is prescribed. This geometric "ray tracing" core is by far the most critical and time consuming part of the ray tracing procedure. It includes the formation of image tree, to find location of reflection point and the selection of those reflected rays that contribute in the field strength calculated at the receiver using illumination zone concept.

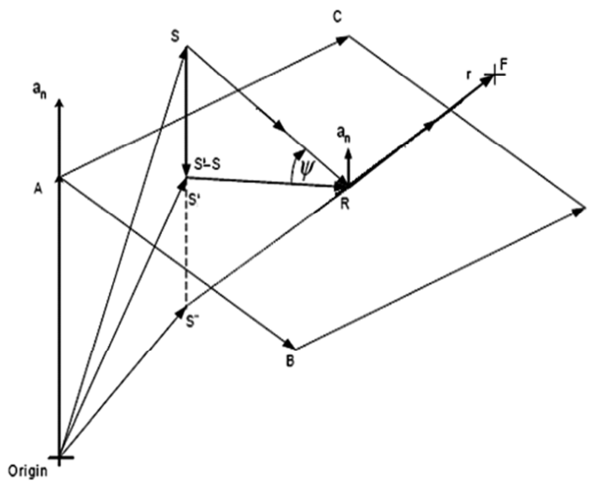

Figure 2: First Order Reflection

MATLAB code can be instructed to process just the LOS ray, or the LOS and all the rays that reach the receiver after one reflection or the LOS and all one and two-reflection rays etc. For single reflection propagation, a calculation is made to determine the position of the normal line's end point from the transmitter, *T*, to a wall shown by a plane in Fig.2. The distance from *T* to wall is then doubled and the point at the end of the doubled line is called an *image* (*T*''). By this the images of a source object in all the planes can be generated. These images then serve as objects for a second round of reflections, and so forth. If there are *N* reflecting planes then there are *N* first-order, i.e., one-reflection, images of a source, $N(N-1)$ two-reflection images, $N(N-1)(N-2)$ three-reflection image, etc. The images can thus be arranged as a tree graph known as image tree that consists of nodes and branches and has a layered structure. Each node of the tree represents an object of the scenario (a building wall, intervening walls, a wedge, the receiver antenna) whereas each branch represents LOS connection between two nodes/objects, the first branching is *N*-fold and all the later ones are $N-1$ fold. The root node corresponds to the transmitter antenna and each layer corresponds to the reflection order [6].

The single-reflection propagation path can then be obtained by connecting the source point (T), reflection point (*R*) and receiver point (*F*). Location of the reflection point *R* on plane *P* is determined by finding out the image of the source point in the plane, namely *T*'', then the intersection of the plane *P* and the vector from *T*'' to *F* is the location of the reflection point *R*. The plane is defined as [3]

$$P = A + sB + tC \tag{1}$$

where *A* corresponds to the distance of the plane from origin given by [0 0 *z*], *B* and *C* corresponds to [*x* 0 0] and [0 *y* 0] respectively in case of ceiling, s and t are the spatial co-ordinates. The perpendicular projection point of T on the plane, namely *T*' is calculated, and the relationship between T and *T*' is given by

$$T = T' + u'a_n \tag{2}$$

where *u*' is the displacement along the unit vector as shown in Figure 2 and an is unit vector normal to the plane expressed as

$$a_n = \frac{B \times C}{|B \times C|} \tag{3}$$

Other position vectors can be expressed as

$$T' = A + s'B + t'C \tag{4}$$

Substitute (4) into (2),

$$T = A + s'B + t'C + u'a_n \tag{5}$$

$$T - A = s'B + t'C + u'a_n \tag{6}$$

Rearrange Equation (5) in matrix form:

$$\begin{bmatrix} s' \\ t' \\ u' \end{bmatrix} = \begin{bmatrix} B_x & C_x & a_{nx} \\ B_y & C_y & a_{ny} \\ B_z & C_z & a_{nz} \end{bmatrix} \begin{bmatrix} T_x - A_x \\ T_y - A_y \\ T_z - A_z \end{bmatrix} \tag{7}$$

When (7) is solved for *u*', substitute into (2) to calculate the position vector *T*'. The image of the source point in the plane can be expressed as

$$T'' = T + 2(T'' - T) \tag{8}$$

The position of *R* can be expressed as

$$R = T'' + u''(F - T'') \tag{9}$$

$$R = A + s''B + t''C \tag{10}$$

Rearrange (9) and (10),

$$s''B + t''C + u''(T'' - F) = T'' - A \tag{11}$$

Equation (11) expressed in matrix form is

$$\begin{bmatrix} s'' \\ t'' \\ u'' \end{bmatrix} = \begin{bmatrix} B_x & C_x & T''_x - F_x \\ B_y & C_y & T''_y - F_y \\ B_z & C_z & T''_z - F_z \end{bmatrix}' \begin{bmatrix} T''_x - A_x \\ T''_y - A_y \\ T''_z - A_z \end{bmatrix} \tag{12}$$

Then substitute *u*'' into (9) to find the reflection point *R*. This process is repeated for every wall or partition encountered in the scenario. After finding out all the rays, illumination zone concept is used because the algorithm starts by assuming the walls as infinite planes that is not true as the real walls are finite-size panels on these infinite planes. By applying the limits of finite size panel on the location of reflection point, the number of images gets reduced.

Last four blocks correspond to the electromagnetic engine of the model that uses the file produced by the geometric engine and the electromagnetic parameters database file to determine the entire signal's strength. It computes the electromagnetic propagations along each path by taking into account the transmitter-emitted field, free space path loss, and the reflections, etc. experienced by the ray. The backtracking procedure determines the path of each ray by starting from the corresponding leaf of an image tree, traversing the tree upwards to the root node, and applying the appropriate geometrical optic rules at each traversed node used to find the field at all of the receivers. Reflections and transmissions through partitions are accounted for by applying the Fresnel Reflection Coefficients. The polarization of the wave relative to the interface determines whether the perpendicular or parallel Fresnel Reflection Coefficients (Γ) are used [2] that is given by

$$\Gamma = \frac{\sin\theta_i - a\sqrt{\varepsilon_r - \cos^2\theta_i}}{\sin\theta_i + a\sqrt{\varepsilon_r - \cos^2\theta_i}} \tag{13}$$

Where ε_r is relative dielectric constant, a is $1/\varepsilon_r$ or 1 for vertical or horizontal polarization respectively and ε_i is the incidence angle. The field vector is multiplied by the appropriate coefficients. Multiple reflection signal strength at the receiver for i^{th} ray is given by [7]:

$$E_i = \frac{(T_1T_2 \ldots\ldots T_m)(\Gamma_1\Gamma_2 \ldots\ldots\ldots\ldots \Gamma_m)E_s e^{-j2\pi(l_1+l_2+\ldots\ldots\ldots\ldots\ldots l_{m+1})/\lambda}}{(l_1+l_2+\ldots\ldots\ldots\ldots\ldots l_{m+1})} \tag{14}$$

where E_i : Multiple reflection signal strength at Receiver

$l_1 + l_2 + \ldots + l_k$: Total reflection distance, k any positive integer

$\Gamma_1, \Gamma_2, \ldots, \Gamma_m$: Reflection coefficients at reflection points 1, 2,…, m

$T_1, T_2, \ldots, T_m$: Transmission coefficients at each wall or partition 1, 2,…, n

The resulting field vector at the receiver position is composed of the fields for each of the n rays arriving at the receiver. Total electric field strength $\mathbf{E_T}$ is given by the vector sum of field strength calculated by each ray.

$$\mathbf{E_T} = \sum_{i=1}^{n} E_i \tag{15}$$

Once field strength is calculated, different parameters like received power, path loss are calculated by applying the appropriate formulas.

4. CONCLUSION AND FURTHER SCOPE

Ray tracing model based on 3-D geometry and the image method is implemented in MATLAB to demonstrate radio wave propagation in an indoor scenario. Three different scenarios are created to see the effect of the construction material, layout and type of the building on the electric field strength that is the vector sum of direct, refracted, first order reflected and second order reflected fields (or fewer) at the receiver. The simulation result shows the surface is smooth due to the dominant direct field in the area close to the source point, and then the surface contains ripples due to interferences between direct and reflected fields and shows the variation in the field strength for different scenarios.

The implemented model for 3-D ray tracing still needs some improvements. This model can be augmented to include diffraction because around the corners of a room inside the buildings, there may be a significant power loss due to diffraction. To validate the site-specific ray tracing model, the simulated data must be compared with the site measurements. Agilent E6474A Wireless Network Optimization Application for indoor wireless systems can be used as the drive test equipment. This model can be integrated with suitable optimization techniques to optimize the number and location of the transmitters.

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