

Modeling and Simulation of Electromagnetic Wave Propagation Using a Hybrid of Ray-Tracing and FV/FDTD Method in Indoor Environment

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Abstract: Growing interest in providing and improving radio coverage for mobile phones and wireless LANs inside buildings has recently emerged. The need of such coverage appears mainly in office buildings, shopping malls in very complex environment. This project presents a hybrid technique based on combining ray tracing and finite volume/finite-difference time domain (FV/FDTD) methods for modeling of indoor radio wave propagation. Ray tracing is used to analyze wide area and FV/FDTD is used to study areas close to complex discontinuities where ray-based solutions are not sufficiently accurate. The hybrid technique ensures improved accuracy and practically in terms of computational resources at the same time since FV/FDTD is only applied to a small portion of the entire modeling environment. Examples of applying the method for studying indoor structures are given at 2GHz. Numerical results are compared with known exact solutions or results of full wave analysis or traditional ray model to demonstrate the accuracy, efficiency, and robustness of the novel method. Cumulative distributions of field envelope obtained from the hybrid method show close resemblance to Rayleigh distribution, which conforms to the reported measurement results.

Keywords: FV/FDTD method, ray tracing, geometrical optics (GO), UTD (universal theory of diffraction), indoor radio.

1. Introduction

Nowadays, due to increasing interest in wide-band applications like Wireless Local Area Networks (WLANS), the multimedia services require higher bit rate and so a larger bandwidth. Ray tracing techniques for predicting the wide-band channel behaviour. These asymptotic methods are fast and frequency unlimited, but for indoor propagation, this classical approach is not sufficient to model object of very small size and with complex forms. Hence, the FV/FDTD method which is based on solving Maxwell's equations in discrete time domain is considered. Ray tracing technique has been demonstrated to be promising for indoor radio propagation modelling. The paths of radio wave propagation between the transmitter and the receiver are determined through transmission, reflection, and diffraction mechanisms. The two general approaches used to calculate multipath propagations are (a) imaging approach and (b) ray-shooting technique.

Based on geometrical optics (GO) and the uniform theory of diffraction (UTD), ray-tracing method provides a relatively simple solution to indoor radio propagation. However, it is well known that GO provides good results for electrically large objects and UTD is rigorous only for perfectly conducting wedges. For complex lossy structures with finite dimensions encountered in indoor environment, ray tracing fails to predict correctly the scattered fields. In the complicated indoor communication environment, transmitting and receiving antennas are often inevitably installed close to these complex discontinuities, where no asymptotic solutions are available. By directly solving Maxwell's equations in the time domain, FV/FDTD method fully accounts for the effects of reflection, diffraction, and

radiation. The medium constitutive relation is automatically incorporated into the solution of Maxwell's equations. Therefore, it is well suited to study wave interactions in complex media. The advantages of the FV/FDTD method are its accuracy and that it simultaneously provides a complete solution for all points in the map, which can give signal coverage information throughout a given area. However, as a numerical analysis method, FV/FDTD method requires large amounts of memory to keep track of the solution at all locations. Application of accurate numerical analysis method to the entire modeling area is neither practical because of the computational resource required, nor is it necessary for open areas without many indoor objects.

In this paper, we present a hybrid technique based on combining ray tracing method with FV/FDTD method for more accurate modeling of radio wave propagation. The basic idea is to use ray tracing to analyze wide areas and FV/FDTD to study areas close to complex discontinuities, where ray-based solutions are not sufficiently accurate. The proposed hybrid method enables the study of effects of generic indoor structural features, furniture, inhomogeneity inside walls, and any objects that may have significant effect on signal coverage and statistics inside buildings. Signal intensity and phase at all points can be obtained in the FV/FDTD computation domain, which provides information of both long-term shadowing effect and short-term fading effect.

$$D(\varphi_i, \varphi_o, f) = \frac{E_{far}(\varphi_i, \varphi_o, f)}{E_{inc}^{plane wave}(P)} \quad (1)$$

2. Description of the Method

Two steps are needed for the hybrid method:

- 1)The scattering matrix of a structure is computed by using the FV/FDTD method.
- 2)The scattering matrix is included into an asymptotic approach as a generalized diffraction coefficient.

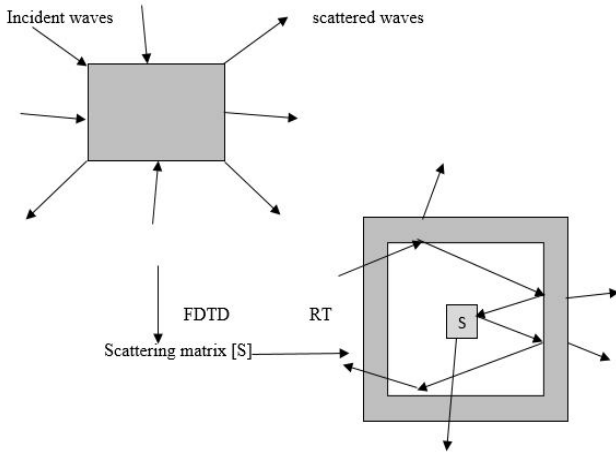


Figure 1: Basic principle of the hybrid technique.

2.1 Scattering matrix computation

The scattering matrix is computed by the FV/FDTD method. Figure 2 shows the different regions in the computational volume of the FV/FDTD method. We first illuminate the object with a pulsed plane wave. Following the principle of Huygens, a first surface is placed around the structure: the equivalent currents existing on this surface generate an incident field inside this Huygens box, in the region R1. In region R2, interactions happens between waves and the structure, the computed field gives the scattered field by the structure. Using Fourier transformation, we get the diffracted field in the near-field region in frequency domain. The main theory behind the application of hybrid method is to get far-field conditions of propagation.

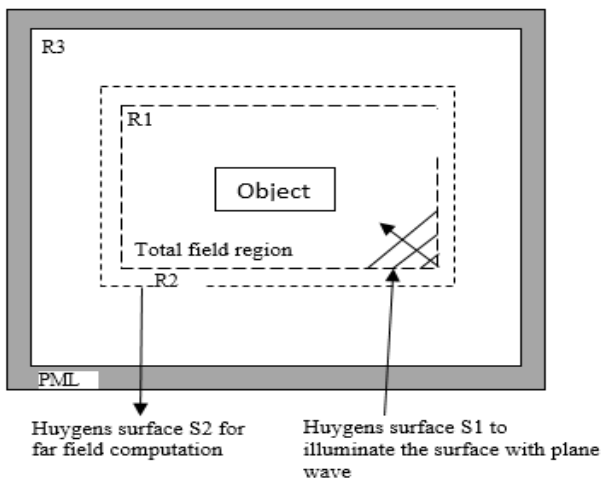


Figure 2: FV/FDTD computation.

So, another Huygens box S2 is placed around the first one; the equivalent electrical and magnetic currents radiate outside this second surface and, thanks to a near- to-far field

transformation, we obtain the diffracted far-field. After knowing the incident field at P, a scattering matrix can be deduced in frequency domain for a given frequency and angle of illumination. Diffraction coefficients for various angles of observation is given by

$$D(\varphi_i, \varphi_o, f) = \frac{E_{cor}(\varphi_i, \varphi_o, f)}{E_{inc}^{planewave}(P)} \quad (1)$$

Where φ_i and φ_o are angles incidence and observation calculated in relation to lines $\varphi_i=0$ and $\varphi_o=0$ respectively as shown in Figure 3.

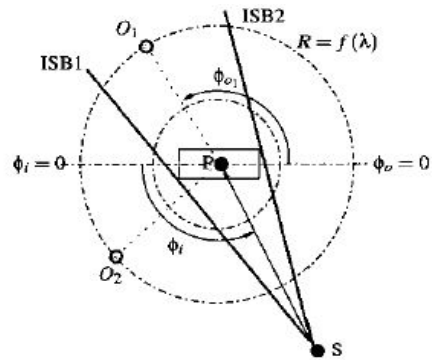


Figure 3: Scattering matrix computation

2.2 Correction of Scattering Matrix

Basic concept behind computation of the scattering matrix is based on Huygens's principle. According to it, the incident field is confined to the region R1 (Figure 2). In R1, the total field minus the incident field gives the computed field. The physical field will consequently be false when the observation's point is located inside the shadowed region. As a matter of fact, we have to compensate this error by adding a correcting component to the diffraction coefficient for the directions of interest (i.e. in the shadowed region). This component deals with the incident field at the observation's point. It clearly appears that this factor will depend on the emission's point, since the shadowed region change with the position of the source. More precisely, we found that this correcting component E_{cor} equals to

$$E_{cor}(r, s') = E_{inc}^{planewave}(P) \frac{\varphi(r)}{\varphi(s')} \quad (2)$$

Where r, s' are the distances respectively from the transmitter to the receiver and from the transmitter to the phase center, $\varphi(r), \varphi(s')$ are the 3D-Green functions equal to $\varphi(R) = \frac{e^{-jkr}}{r}$ with k the wave factor. In all the simulations presented below, we consider a 2-D propagation (x&y plane). The represented field is observed over circles centered on the structure with various radius (Fig. 3). As a consequence, we will have to use the 2D-Green functions equal to $\varphi_{2D}(R) = \varphi(R) F_{2D}$ where $F_{2D} = \sqrt{\frac{2}{\pi k \Delta z}}$ with Δz the computational spatial step in z direction of the FDTD method. In the Ray Tracing code, the object will now be replaced by its scattering matrix and viewed as a simple point of diffraction.

3. Combination of FV/FDTD and Ray-Tracing method

A perfect isotropic current source with a Gaussian envelope is used for the three methods. It avoids normalization problem and a TM polarized wave of center frequency 2GHz is used. The scattering matrix is computed using a FDTD code with perfectly matched layer as (PML) absorbing boundary conditions. In the FDTD code, we use square grid cells of side length of resolution $\frac{\lambda_0}{50}$ to minimize numerical errors, where λ_0 is the wavelength at 2GHz; the source is placed at distance 20λ from the structure. Four cases are studied: the first one corresponds to a simple finite metallic sheet; the others are smaller and more complex structures for which the UTD is not applicable.

3.1 Ray-Tracing method

The ray tracing is used first to cover the wide area with large scale and weak in homogeneity. Ray tubes are sent out from the transmitter. Each ray tube occupies a solid angle. The direction of each ray is determined by dividing the azimuth angle equally in. Objects are modeled as metallic sheets, square box (PEC) and other complex structures with predefined thickness, boundaries, dielectric constant, and loss tangent. Reflection and transmission coefficients for lossy dielectric slabs are derived and given in [4]. Starting from the source point, the algorithm follows the source ray direction and detects the closest object intersected by the ray. If an intersection has been detected, the program generates one transmitted ray and one reflected ray. The reflected ray is stored and the transmitted ray is traced in a similar fashion to source rays. This continues until the ray intensity falls below a specified threshold. Next, an already stored reflected ray is taken out and traced in the same way until all of the rays are exhausted. The program then generates a new source ray from the transmitter.

In the simulations, the ray termination threshold is defined with respect to the field strength at one wavelength from the transmitting antenna in free-space. To determine the total field at a given point, a reception sphere is constructed around the receiving point with radius $r = \lambda/2$. If the ray intersects the reception sphere, it contributes to the total field at the receiving point. Diffraction is also a propagation mechanism included in ray tracing. In indoor environment, most of the structures causing diffraction can be categorized into thick half plane such as doors, windows, and partitions, and right-angle wedge such as wall corner. When a diffracting edge is detected to be inside a ray tube, the ray tracing algorithm searches for any receiving points that have direct path to the diffracting edge. Diffracted field is then calculated and contributes to the total field at these receiving points. Diffracted rays are not traced further.

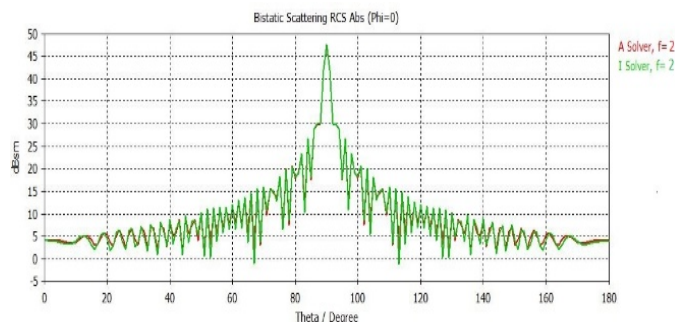


Figure 4: Asymptotic computation of the normalized total field at distance λ_0 around the λ_0 long metallic sheet

3.2 FV/FDTD Method

In the next step, the region to be studied by FDTD method [2], [3] is enclosed by a virtual box. The region inside the virtual box may contain inhomogeneity in construction materials, isolated objects, or any structural features that are of interest. Surface sources exciting the field inside the virtual box are found by ray tracing. Whenever a ray tube intersects the box, the intersection position, ray direction, and electric field are stored in a data file, which is subsequently used in the FV/FDTD method as the source excitation to analyze wave interaction with the structure enclosed in the box. Each region inside the virtual box needs to be treated separately by FDTD afterwards. It is assumed that the receiving points of interest are in the enclosed regions.

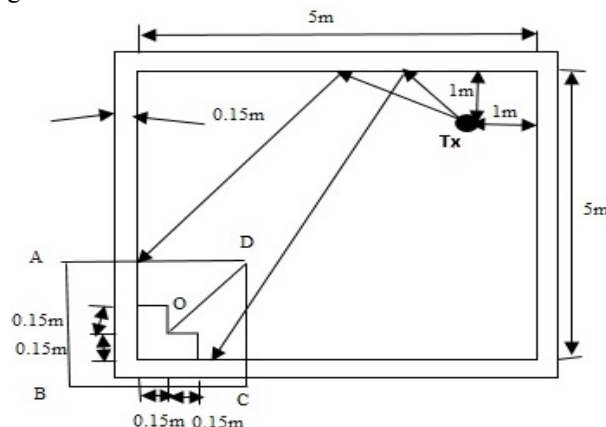


Figure 5: An L-shaped object at bottom left corner in a room

As an example, Figure 5 shows a 2-D environment with a transmitter. The area enclosed by the rectangle ABCD is the region of interest, which contains complex inhomogeneity while the rest of the area is quite open. The four sides of the rectangle are the incident planes providing interface between the intersecting rays and the FV/FDTD method. Reflected or scattered field emerging from the virtual box will interact with the outside environment. The actual computation domain of FDTD extends to, which is larger than rectangle, as shown in Figure 2. The shaded area is the scattered-field region, which is introduced to reduce parasitic waves generated by the source excitation method [4]. The area inside is the total-field region. It is given as;

$$\begin{aligned} E_{tot} &= E_{inc} + E_{sc} \\ H_{tot} &= H_{inc} + H_{sc} \end{aligned}$$

Where, subscriptions tot, scat, and inc denotes total, scattered, and incident components of electric and magnetic fields, respectively. In the total-field region, where the structure of interest is embedded, the algorithm operates on the total field. Incident wave is introduced along the interface between these two regions.

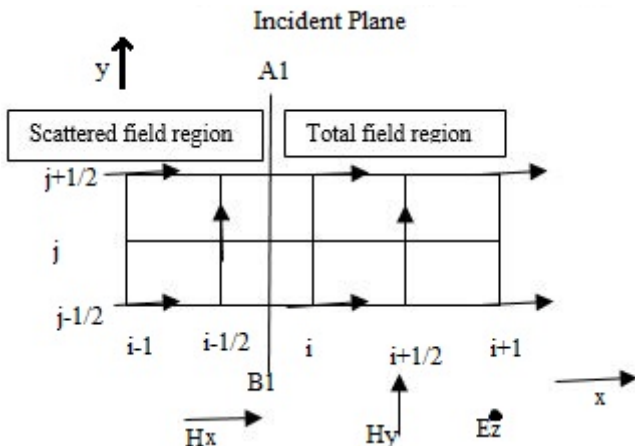


Figure 6: Source excitation.

The source excitation scheme is demonstrated in Figure 6, which shows field components around node (i, j) along incident plane A_1B_1 . The evaluation of $E_z(i, j)$ at time step $(n+1)$, denoted by $E_z^{n+1}(i, j)$, using the FDTD propagator requires knowledge of the preceding half time step values of $H_y(t - \frac{1}{2}\Delta t, j)$, $H_y(t + \frac{1}{2}\Delta t, j)$, $H_x(t, j - \frac{1}{2})$ and $H_x(t, j + \frac{1}{2})$. There is inconsistency if the FDTD propagator is applied blindly, because $E_z(t, j)$, $H_y(t + \frac{1}{2}\Delta t, j)$, $H_x(t, j - \frac{1}{2})$ and $H_x(t, j + \frac{1}{2})$ are in the total-field region while $H_y(t - \frac{1}{2}\Delta t, j)$ is in the scattered field region. The correct equation for updating $E_z(i, j)$ is given by Taflove [1] as

$$E_z^{n+1}(i, j) = E_z^{n,tot}(i, j) + \frac{\Delta t}{\epsilon_0 \Delta} \times \left[H_{y,tot}^{n+\frac{1}{2}}(i + \frac{1}{2}, j) - H_{y,scat}^{n+\frac{1}{2}}(i - \frac{1}{2}, j) + H_{x,tot}^{n+\frac{1}{2}}(i, j - \frac{1}{2}) - H_{x,tot}^{n+\frac{1}{2}}(i, j + \frac{1}{2}) \right] - \frac{\Delta t}{\mu_0 \Delta} H_{y,inc}^{n+\frac{1}{2}}(i - \frac{1}{2}, j) \quad (3)$$

where Δt and Δ are time and space increments of the FDTD propagator and ϵ_0 is the permittivity of free-space. $\Delta x = \Delta y = \Delta$ is assumed for simplicity. Similarly, the scatter field of H_y at node $(i-1/2, j)$

$$H_{y,scat}^{n+\frac{1}{2}}(i - \frac{1}{2}, j) = H_{y,scat}^{n-\frac{1}{2}}(i - \frac{1}{2}, j) + \frac{\Delta t}{\mu_0 \Delta} \times [E_z^{n,tot}(i, j) - E_z^{n,scat}(i - 1, j)] - \frac{\Delta t}{\mu_0 \Delta} E_z^{n,inc}(i, j) \quad (4)$$

where μ_0 is the permeability of free space. Therefore, both $E_z(i, j)$ and $H_y(i-1/2, j)$ components of the incident wave are required. With known incident ray direction and electric field, the incident magnetic fields can be readily calculated using plane wave model.

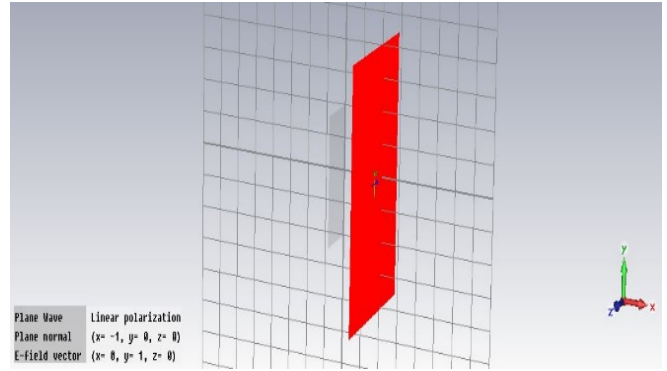


Figure 7: A metallic plate is given a plane wave excitation

Table 1: Standard Material specifications[7]

Material	Permittivity, ϵ_r
Wood	3.5
Paper	3
Glass	5.5
Brick	2.8
Concrete	9

4. Simulation Results

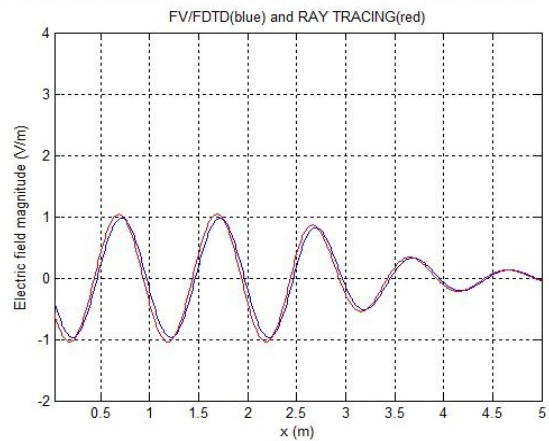


Figure 8: Comparison of FV/FDTD and Ray-Tracing 1D results for empty room.

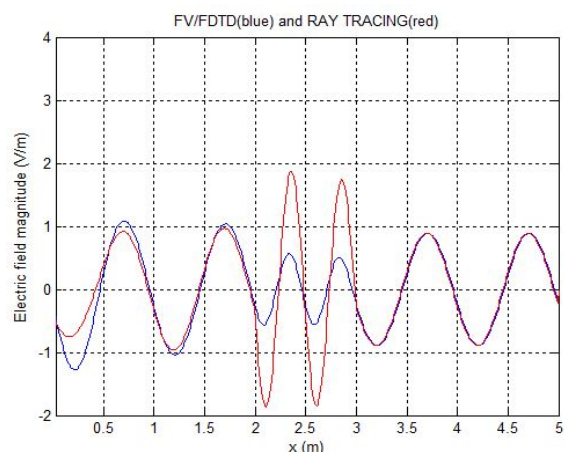


Figure 9: Comparison between FV/FDTD and Ray-Tracing 1D results for a metallic sheet.

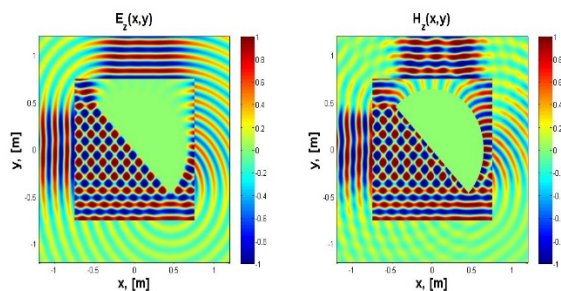


Figure 10: A 2D simulation of E_z and H_z field using FDTD.

5. Conclusion

In this paper, we presented a technique of combining the FV/FDTD and the Ray-Tracing methods to obtain the field diffracted in the far-field region for scatterers. We have illustrated the accuracy of this method for a finite metallic sheet, as well as for more complex structures. We found that the accuracy of the hybrid method depends on the form and the dimensions of the structures. Further, we want to extend this approach to the 3-D propagation modelling by calculating a library of diffraction coefficients for a variety of 3-D complex structures. Also an implementation of this approach keeping in an industrial terrain will be performed as the future work. Finally, our goal with the presented hybrid method is to evaluate the influence of small and complex structures on the channel modelling.

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Author Profile



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