Segmentation Technique with ADI-FDTD for EM Propagation Modeling in Electrically Large Structure

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***Abstract*—This paper deals with the electromagnetic (EM) wave propagation modeling in complex tunnel environments. We propose a novel segmented alternating direction implicit finite difference time domain (S-ADI-FDTD) method for modeling the electromagnetic wave propagation inside an electrically large tunnel. The proposed S-ADI-FDTD method reduces the computational redundancy by dividing the problem space into segments. It also allows use of larger cells in each segment. To validate this method, we simulate the propagation in real tunnels and compare the results with the published experimental data. The comparisons reveal that the proposed S-ADI-FDTD method can predict the fields most accurately in real, large tunnels at longer ranges.**

***Keywords*— FDTD; ADI-FDTD; segmented-ADI FDTD; path loss; EM propagation; tunnels.**

I. INTRODUCTION

New developments in wireless communications has led to design and deployment of wireless sensor networks (WSN) for the monitoring and assessment of civil infrastructure such as tunnels, bridges etc and also for communication within mining tunnels. For Wireless Sensor Networks to work inside tunnels, it is important to understand the radio wave propagation characteristics, such as path loss, Impulse response etc within the complex propagation environments in which they will be deployed. The Path Loss enables determination of the critical parameters such as maximum distance, transmit power and receiver sensitivity for wireless communications and impulse response provides information on wideband characteristics [1-3]. Traditionally, the radio wave propagation inside tunnels was obtained by modelling the tunnel as a large waveguide. It has been established by Zhang [3] that there are two propagation regions in a tunnel. Other methods that have been commonly employed to model radio wave propagation in tunnels are modal analysis, geometrical optics and the parabolic equation (PE) approximation.

The conventional modal theory of electromagnetic (EM) propagation in conducting tunnels can not accurately predict the near distance path loss. The modal analysis and the geometrical optics methods cannot be used to solve for the fields in real tunnels due to their limitations [6-8]. In the modal approach, the tunnel is considered to be a waveguide that has one dominant mode and infinite number of higher order modes, which is not always applicable to real tunnel environments with arbitrary geometries. Further, it is difficult to determine eigen functions for real tunnels [7]. The geometrical optics method approximates the field as direct, reflected and refracted rays and becomes difficult to trace rays for problems with a longer range because of the large number of reflected waves. In addition, the GO method fails completely in caustic regions. The standard parabolic equation approximation method can be employed to accurately model electromagnetic fields in tunnels but limited for waves which travel within ±15º to the axis of propagation [6].

There is considerable literature on the use of parabolic equation approximation for radio wave propagation in tunnels e.g., Martelly and Janaswamy [1], Popov and Zhu [8] and Noori et al. [7]. Some authors have employed Crank Nicolson method due to the fact that it is stable for any discretization in the transverse plane or along the propagation axis [6]. However, the Crank Nicolson method requires the solution of sets of simultaneous equations that may become too large to efficiently solve for problems with dense meshes [1]. The alternating direction implicit (ADI) technique can address the problem of computational efficiency and has been used extensively in electromagnetics to directly solve for Maxwell's equation using the FDTD method [13].

The standard FDTD technique has also has been used extensively for modelling radio wave propagation in indoor environments [14-15]. When FDTD method is applied to model electrically large problems at microwave frequencies, its computational demands in terms of memory and central processing unit (CPU) execution time becomes excessive. To ease the computational burden when solving large problems using FDTD, the non-uniform FDTD technique was considered [16]. Most recently, research has been focussed on parallel computation for FDTD method using the message passing interface (MPI) [9]. A modified 3-D FDTD method was proposed for addressing the large problems [10]. Most recently, a new method known as Segmented Finite Difference Time Domain (S-FDTD) method was introduced for reducing the computational requirements and to enhance the feasibility of solving electrically large problems on a standard personal computer [4]. But in the Segmented FDTD method (S-FDTD), the cell size in every segment has to be small due to the CFL stability constraint, and hence for solving for electrically large problems, such as propagation in tunnels, the S-FDTD can be computationally ineffective. In this paper, we propose a novel

Segmented Alternating Direction Implicit Finite Difference Time Domain (S-ADI FDTD) method which can overcome the limitations of S-FDTD method and reduce the computational burden when solving for electromagnetic fields inside a large tunnel. In the proposed Segmented ADI FDTD (S-ADI FDTD) method, bigger cell sizes can be used since the method is not constrained by CFL stability condition. Thus, the proposed S-ADI FDTD method can ease the computational load and improves the feasibility of running large scale numerical electromagnetic problems on a standard PC.

In this paper, we propose the two dimensional S-ADI FDTD method to predict the radio wave propagation inside electrically large tunnels. Our simulated results obtained using the proposed S-ADI FDTD method for wave propagation inside large tunnels compare well with available experimental data. The paper is organised as follows: the proposed S-ADI FDTD method is presented in section II. A comparison of the simulation results with published measured data is provided in section III, and conclusions are given in section IV.

II. Segmented ADI FDTD (S-ADI FDTD) Method

A. Standard FDTD Method

It is well known that the standard finite difference time domain (FDTD) method is a very useful numerical simulation tool for solving problems related to electromagnetism. However, as the standard FDTD method is based on an explicit finite difference algorithm, the Courant-Friedrich-Levy (CFL) stability condition must be satisfied. Therefore, a maximum time step size is limited by the minimum cell size in a computational domain. As a result, a small time step size creates a significant increase in calculation time. Solving for electrically large problems using standard FDTD method requires a large amount of computational resources. It is almost impossible to perform a full 3D tunnel simulation using the conventional FDTD method since the computational cost can be overwhelming even on a cluster. To circumvent these problems, here we propose a novel Segmented ADI FDTD (S-ADI FDTD) method for use in large tunnels.

B. ADI-FDTD Method

The alternating direction implicit finite difference time domain (ADI FDTD) algorithms are split step methods, rather than leapfrog schemes, and they are unconditionally stable for simulating Maxwell's equations on a regular orthogonal mesh. Since maximum time step size is not limited by minimum cell size in computational domain, hence it can analyse objects having finer variations compared with wavelength. In this method, the electromagnetic field components are arranged on the cells in the same way as that of the conventional FDTD method. The calculation for one discrete time step is shown below using two procedures for the ADI FDTD method for TM_z waves:

First procedure:

$$H_x^{n+1/2}(i,j+1/2) = H_x^{n}(i,j+1/2) - \frac{\Delta t}{\mu_0 \Delta y}.\frac{1}{\kappa_{my}} \left\{E_z^{n}(i,j+1) - E_z^{n}(i,j)\right\} - (\frac{\Delta t}{\mu_0}) \times \Psi_{hxy}^{n+1/2}(i,j) \tag{1a}$$

$$H_y^{n+1/2}(i+1/2,j) = H_y^{n}(i+1/2,j) + \frac{\Delta t}{\mu_0 \Delta x}.\frac{1}{\kappa_{mx}} \left\{E_z^{n+1/2}(i+1,j) - E_z^{n+1/2}(i,j)\right\} - (\frac{\Delta t}{\mu_0}) \times \Psi_{hyx}^{n+1/2}(i,j) \tag{1b}$$

$$\begin{aligned} E_z^{n+1/2}(i,j) &= \frac{\varepsilon_z}{\varepsilon_z + \sigma_z^e \Delta t} E_z^{n}(i,j) \\ &+ \frac{\Delta t}{\varepsilon_z + \sigma_z^e \Delta t}.\frac{1}{\kappa_{ex}}.\frac{1}{\Delta x}\left\{H_y^{n+1/2}(i+1/2,j) - H_y^{n+1/2}(i-1/2,j)\right\} \\ &- \frac{\Delta t}{\varepsilon_z + \sigma_z^e \Delta t}.\frac{1}{\kappa_{ex}}.\frac{1}{\Delta x}\left\{H_x^{n}(i,j+1/2) - H_x^{n}(i,j-1/2)\right\} \\ &+ \frac{\Delta t}{\varepsilon_z + \sigma_z^e \Delta t} \times \Psi_{ezy}^{n+1/2}(i,j) - \frac{\Delta t}{\varepsilon_z + \sigma_z^e \Delta t} \times \Psi_{ezx}^{n+1/2}(i,j) \end{aligned} \tag{1c}$$

Sub-step 2:

$$H_x^{n+1}(i,j+1/2) = H_x^{n+1/2}(i,j+1/2) - \frac{\Delta t}{\mu_0 \Delta y}.\frac{1}{\kappa_{my}} \left\{E_z^{n+1}(i,j+1) - E_z^{n+1}(i,j)\right\} - (\frac{\Delta t}{\mu_0}) \times \Psi_{hxy}^{n+1}(i,j) \tag{2a}$$

$$H_y^{n+1}(i+1/2,j) = H_y^{n+1/2}(i+1/2,j) + \frac{\Delta t}{\mu_0 \Delta x}.\frac{1}{\kappa_{mx}} \left\{E_z^{n+1/2}(i+1,j) - E_z^{n+1/2}(i,j)\right\} - (\frac{\Delta t}{\mu_0}) \times \Psi_{hyx}^{n+1}(i,j) \tag{2b}$$

$$\begin{aligned} E_z^{n+1}(i,j) &= \frac{\varepsilon_z}{\varepsilon_z + \sigma_z^e \Delta t} E_z^{n+1/2}(i,j) \\ &+ \frac{\Delta t}{\varepsilon_z + \sigma_z^e \Delta t}.\frac{1}{\kappa_{ex}}.\frac{1}{\Delta x}\left\{H_y^{n+1/2}(i+1/2,j) - H_y^{n+1/2}(i-1/2,j)\right\} \\ &- \frac{\Delta t}{\varepsilon_z + \sigma_z^e \Delta t}.\frac{1}{\kappa_{ex}}.\frac{1}{\Delta x}\left\{H_x^{n+1}(i,j+1/2) - H_x^{n+1}(i,j-1/2)\right\} \\ &+ \frac{\Delta t}{\varepsilon_z + \sigma_z^e \Delta t} \times \Psi_{ezy}^{n+1}(i,j) - \frac{\Delta t}{\varepsilon_z + \sigma_z^e \Delta t} \times \Psi_{ezx}^{n+1}(i,j) \end{aligned} \tag{2c}$$

where, H is the magnetic field and E is the electric field in a discrete grid sampled with a spatial step of Δ. The updating coefficients include the properties of the different media inside the chosen environment. Ψ_{hxy}, Ψ_{hyx}, Ψ_{ezx}, Ψ_{ezy} are discrete variables with non zero values only in some CPML regions and are necessary to implement the absorbing boundary. In the first procedure, (1a) and (1b) cannot be used for direct numerical calculation. Thus by eliminating $H_y^{n+1/2}$ components using equation (1a) and (1b), simultaneous linear equations are obtained that result in the tri-diagonal matrix form. Similarly by eliminating H_x^{n+1} components from equation (2a) and (2b), the simultaneous equations are obtained that lead to the tri-diagonal matrix, resulting in lower computational burden.

C. *Proposed Segmented ADI-FDTD (S-ADI-FDTD) Method*

The major limitation of ADI-FDTD method is that it requires the solution of sets of the simultaneous equations that may become too large to efficiently solve for problems with dense mesh. So segmented ADI-FDTD (S-ADI-FDTD) method is proposed to solve larger problems as it requires less time compared to conventional ADI-FDTD method. The following procedures are applied to realize the S-ADI-FDTD algorithm that is also illustrated in Fig. 1.

1) Start the conventional ADI FDTD iteration in segment one with the signal source S0.
2) When the segment one reaches its steady state at each unit cell on the interface one, save these for use at the next segment.
3) Save signals of length one wavelength (i.e., one cycle in time domain) from each unit cell recorded at the interfaces, then form the interface array source S1. Note that the extraction of the array source must take place at the same sampling point in time; otherwise, phase information will be lost. The reason for solving one complete wavelength of samples is to maintain the signal wave continuity.
4) Synchronously propagate the extracted interface array source at each corresponding unit cell in segment two.

Follow the same steps to complete the simulations in segments 2, 3, 4 and up to n for the large problems.

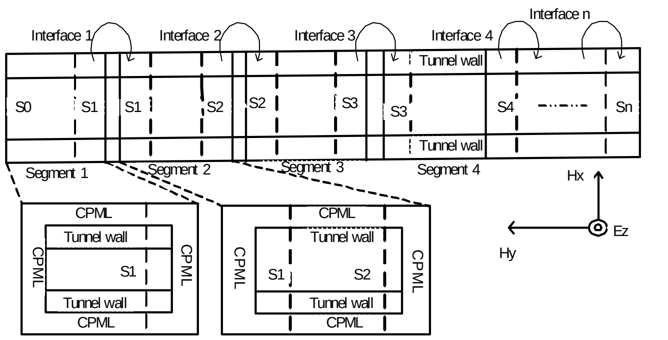


Fig. 1. Segmented problem space in S-ADI-FDTD simulation

III. NUMERICAL ANALYSIS

We consider a tunnel of width w meters and height h meters which is surrounded by a lossy non-magnetic homogeneous medium with relative permittivity ε_r and conductivity σ. The origin of the tunnel-coordinate system is arranged to be at the middle of the tunnel cross section. For the tunnel whose cross-sectional dimensions are sufficiently larger than a free space wavelength λ, different types numerical models have been proposed to predict the propagation loss. At first, we consider the case of real tunnels and compare S-ADI FDTD simulations with published measured data. The first example chosen is a coal mine tunnel. The straight tunnel is having w=4m and h=3.5 m and the material parameters for this tunnel ε_r =10 and σ=0.01S/m and the operating frequency is 900 MHz. Fig.2 shows the path loss as a function of axial distance and compares with the measured data provided by Y.P. Zhang [3].

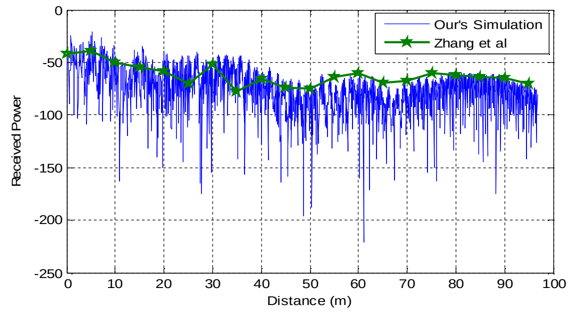
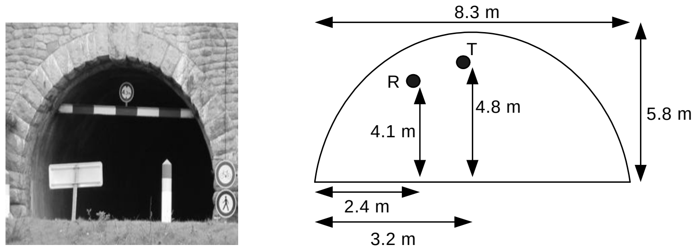


Fig. 2: Predicted Received Power inside the Tunnel

But using the FDTD method to get results, it takes couple of days and needs huge memory. Instead of using conventional FDTD method if we use S-FDTD and S-ADI-FDTD methods, it reduces computational time and memory. In second example, we consider the Roux tunnel in Ardeche region France studied in the published work of E. Masson [5]. This tunnel is perfectly straight and has a length of 3.336 km (Fig. 3(a)). The transverse section is semicircular and has a diameter of 8.3 m. the maximum height is 5.8 m at the centre of the tunnel. The cross sectional view of this tunnel is shown in Fig.3(b).



(a) (b)

Fig.3. (a) Roux Tunnel, (b) The profile of the Roux Tunnel

The material parameters for this tunnel ε_r =2.5 and σ=0.05S/m. The predicted path loss of this tunnel at 2.4GHz using segment FDTD and S-ADI FDTD are shown in the Fig.4.

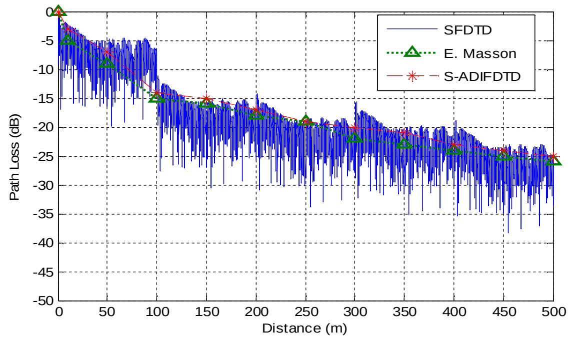


Fig. 4: Predicted Received Power inside the Tunnel

For the same tunnel using same parameters at different frequencies (5.8 GHz), using the segmented ADI FDTD (S-ADI FDTD) method, the predicted path loss is given in the Fig.

5. Both simulated and measured results are coincidence. But in this case the segment ADI FDTD (S-ADI FDTD) method takes less time to predict the path loss.

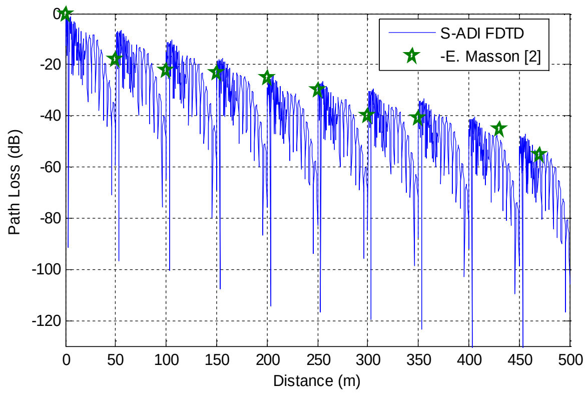


Fig.5. Simulated and Measured Path Loss versus distance

IV. USAGE OF CPU TIME

Table 1 summarizes the performance of the proposed S-ADI FDTD method in terms of computational time usage. Obviously, for a certain time scheme, an optimal (in terms of computational performance) segment size exists. The relationship between the total CPU execution time and segment size can be calculated as

$$\text{Total\_CPU\_Time} = n.\ dt.\ N$$

Where n is the number of time steps (iterations) for each segment to reach its steady state, dt is the CPU time required for each single time step (iteration) in the segment, and N is the number of segments into which the problem space is divided. To maintain the stability of the S- ADI FDTD in the tunnel example we have discussed, Fig. 6 shows the total CPU time requirements.

Table 1 Complex Tunnel Model Performance Comparisons using S-ADI FDTD

Segmentation	CPU Times (hrs)
250m × 2 segment	28.646
125m × 4 segment	22.590
50m × 10 segment	8.745
25m × 20 segment	4.877
10m × 50 segment	3.860
5m × 100 segment	3.350

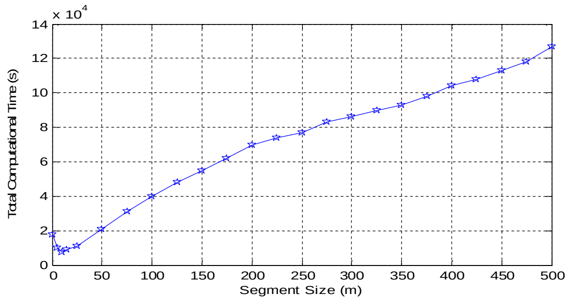


Fig. 6 Total computational time for the tunnel model by the S- ADI FDTD method

V. CONCLUSION

In conclusion, by reducing the segment size and taking the stability issue into consideration, with no additional modifications to the ADI-FDTD implementation , the proposed techniques allows the CPU execution time to increase only linearly with the number of segments instead of exponentially increase as seen in a conventional FDTD. In the case of actual tunnels, our segment ADI-FDTD (S-ADI-FDTD) approach compare well with published experimental data for the Massif Central tunnel. Future work will use the segmented ADI-FDTD (S-ADI-FDTD) to study the cases of curved and branching tunnels with rough surfaces as well as making comparisons to experimental data.

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