Segmented Locally One Dimensional FDTD (S-LOD-FDTD) Method for EM Propagation Modeling in Large Complex Tunnel Environments

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Abstract —We propose a novel segmented locally one dimensional finite difference time domain (S-LOD-FDTD) method for modeling the electromagnetic wave propagation inside an electrically large tunnel. The proposed S-LOD-FDTD method reduces the computational redundancy by dividing the problem space into segments. 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 method can predict the fields accurately in real, large tunnels at longer ranges.

I. INTRODUCTION

Understanding the radio propagation characteristics, such as path loss, etc inside complex tunnel environments will help to deploy wireless monitoring and communication systems. The Path Loss enables determining the critical parameters such as maximum distance, transmit power and receiver sensitivity for wireless communication in a tunnel and impulse response provides information on wideband characteristics. Traditionally, the radio wave propagation inside tunnels was obtained by modeling the tunnel as a large waveguide. 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 [1]-[4]. The conventional modal theory of electromagnetic (EM) propagation in conducting tunnels can not accurately predict the near distance path loss. Particularly for obtaining fields in close-to- wall antenna deployment scenarios, the accuracy of prediction can be poor when using the conventional techniques. The modal analysis and the geometrical optics methods cannot be used to solve for the fields in real tunnels due to their limitations. 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 [5]-[6].

In this paper, we propose a novel segmented locally one dimensional finite difference time domain (S-LOD-FDTD) method which can overcome the limitations of other methods and reduce the computational burden when solving for electromagnetic fields inside a large tunnel. In the proposed Segmented LOD FDTD (S-LOD-FDTD) method, bigger cell sizes can be used since the method is not constrained by Courant-Friedrichs-Lewy (CFL) stability condition. Thus, the proposed method can ease the computational load and improves the feasibility of running large scale numerical electromagnetic problems on a standard PC.

II. LOD FDTD METHOD

The locally one dimensional finite-difference time-domain (LOD-FDTD) algorithm [7] is a split step method, rather than a leapfrog scheme. They are unconditionally stable for simulating Maxwell's equations on a regular orthogonal mesh and its maximum time step size is not limited by minimum cell size in computational domain. The calculation for one discrete time step is performed using two procedures for this method. The first procedure for TM_z waves is shown below.

Sub-step 1:

$$\begin{aligned}
H_y\big|_{i+1/2,\,j}^{n+1/2} &= H_y\big|_{i+1/2,\,j}^{n} \\
&+ \frac{\Delta t}{2\Delta x\mu}\times\left(E_z\big|_{i+1/2,\,j+1/2}^{n+1/2} - E_z\big|_{i-1/2,\,j+1/2}^{n+1/2}\right) \\
&+ \frac{\Delta t}{2\Delta x\mu}\times\left(E_z\big|_{i+1/2,\,j+1/2}^{n} - E_z\big|_{i-1/2,\,j+1/2}^{n}\right) \\
&+ \beta_{h1}(i+1/2,\,j)\psi_{hyx}\big|_{i+1/2,j}^{n}
\end{aligned}\tag{1}$$

and

$$\begin{aligned}
E_z\big|_{i+1/2,\,j+1/2}^{n+1/2} &= E_z\big|_{i+1/2,\,j+1/2}^{n} \\
&+ \frac{\Delta t}{2\varepsilon\Delta x}\times\left(H_y\big|_{i+1,\,j+1/2}^{n+1/2} - H_y\big|_{i,\,j+1/2}^{n+1/2}\right) \\
&+ \frac{\Delta t}{2\varepsilon\Delta x}\times\left(H_y\big|_{i+1,\,j+1/2}^{n} - H_y\big|_{i,\,j+1/2}^{n}\right) \\
&+ \beta_{e1}(i+1/2,\,j+1/2)\psi_{ezx}\big|_{i+1/2,j+1/2}^{n}
\end{aligned}\tag{2}$$

where, H is the magnetic field and E is the electric field in a discrete grid sampled with a spatial step of Δ. ψ terms are discrete variables with non zero values only in some CPML regions and are necessary to implement the absorbing boundary. In the first procedure, (1) and (2) cannot be used for direct numerical calculation. Using equation (1) and (2), simultaneous linear equations are obtained that result in the tri-diagonal matrix form.

III. PROPOSED SEGMENTED LOD FDTD (S-LOD-FDTD) METHOD

The major limitation of LOD 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 LOD FDTD (S-LOD-FDTD) method is proposed to solve larger problems as it requires less time compared to conventional LOD FDTD method. Fig. 1 illustrates the S-LOD-FDTD algorithm.

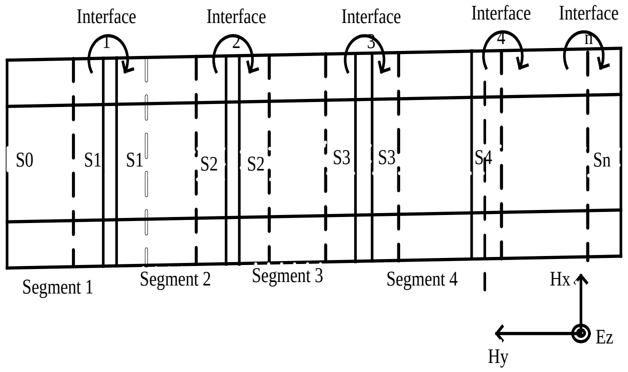
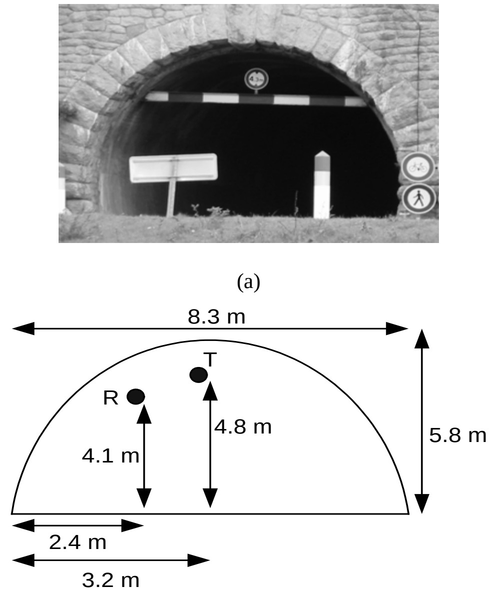


Fig. 1. Segmented problem space in S-LOD-FDTD simulation

IV. Comparison of Numerical Results With Experimental Data

We consider the Roux tunnel in Ardeche region France studied in the published work of E. Masson [2]. This tunnel is perfectly straight and has a length of 3.336 km (Fig. 2 (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. 2 (b).



(a)

(b)

Fig. 2. (a) Picture of 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 LOD FDTD compared with the measured data [2] is shown in fig. 3. Fig. 4 shows the comparison of the predicted path loss of different methods. This figure shows that the path loss obtained by the proposed method agrees well with other methods and measured data.

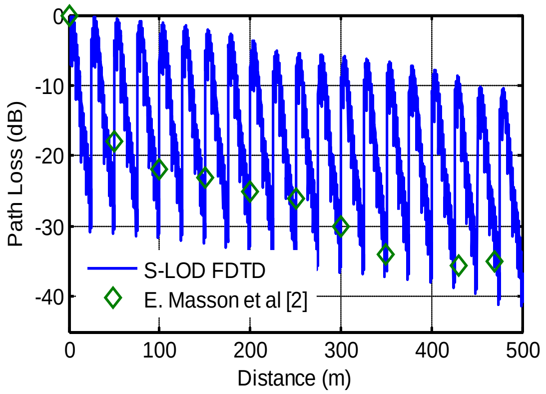


Fig. 3. Simulated and Measured Path Loss versus distance

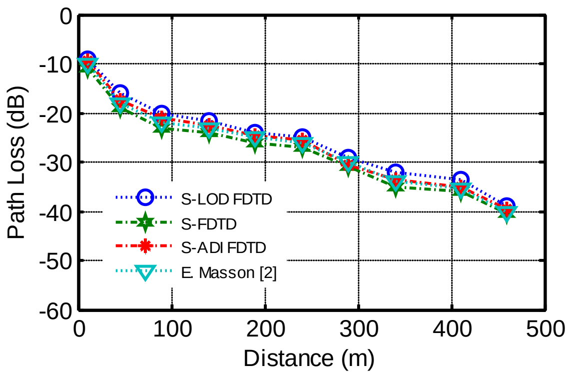


Fig. 4. Simulated and Measured Path Loss versus distance

V. Conclusions

Results obtained using S-LOD-FDTD method on Path Loss agrees reasonably well with measured data taken from literature. Path Loss predictions in complex environments help in the wireless link design. In future, we consider more complex environments for simulation using proposed S-LOD-FDTD method.

VI. References

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