Modelling of Electromagnetic Propagation Characteristics in Indoor Wireless Communication Systems Using the LOD-FDTD method

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***Abstract*—Wireless technologies has been attracting much attention due to its wide application. Thus it is important to predict the electromagnetic propagation characterization precisely. Full-wave time-domain electromagnetic methods are usually effective in rigorously modelling and evaluating wireless channels. However, their computational expenditures are expensive, when dealing with electrically large size problems consisting of fine structures. Thus, in this paper, a rigorous full-wave numerical solution, via the locally one-direction finite difference time domain (LOD-FDTD) method for lossy media, which reduces computational time by removing the Courant-Friedrich-Levy (CFL) stability condition, is applied to characterize the wireless channel. By comparing the simulation results with the conventional FDTD, the proposed method demonstrates both good simulation efficiency and high accuracy. Post-processing of the simulation results lead to effective channel characterization with path loss exponent and probability distribution of path loss**.

I. Introduction

There have been many demands for studying electromagnetic propagation characterization of wireless communication systems. To ensure accurate propagation prediction and optimal realization of a wireless system, it is very important to find an efficient and accurate way to model the propagation environments which may include buildings walls, furniture, human body and *etc*. Although experimental approaches are reliable and close to reality, they can be very expensive due to the requirement for special equipment and setup, and in many cases, it is impossible to pre-set the needed testing environment.

Fortunately, recent progress in the Finite-Difference-Time-Domain (FDTD) method [1] has provided an alternate choice other than experiments for accurately simulating wireless channels [2-4]. However, due to the Courant-Friedrich-Levy (CFL) stability condition [1], which imposes an upper limit on the time step size, it often takes long computational time in simulating electrically large size structures containing fine structures.

In this paper, the locally one-direction finite-difference time-domain (LOD-FDTD) method for lossy media, which removes the Courant Friedrich Levy (CFL) condition and allows the use of large time step in comparison with the conventional FDTD method [5-6], is successfully implemented for studying an indoor wireless channel. As demonstrated, the proposed equation maintains both good simulation efficiency and accuracy. After post-processing the simulation results, pulse wave propagation characteristics are captured including path loss exponent and probability distribution of path loss.

II. Formulation

Consider an isotropic and lossy medium with permittivity of ε, permeability of μ and conductivity of σ; the time-dependent Maxwell's equation can be written in the following matrix form:

$$\frac{\partial V}{\partial t} + \sigma V = c(A+B)V \,, \tag{1}$$

where $V^n = [E_x^n, E_y^n, E_z^n, Z_0 H_x^n, Z_0 H_y^n, Z_0 H_z^n]$,

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \partial y \\ 0 & 0 & 0 & \partial z & 0 & 0 \\ 0 & 0 & 0 & 0 & \partial x & 0 \\ 0 & \partial z & 0 & 0 & 0 & 0 \\ 0 & 0 & \partial x & 0 & 0 & 0 \\ \partial y & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

and

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & -\partial z & 0 \\ 0 & 0 & 0 & 0 & 0 & -\partial x \\ 0 & 0 & 0 & -\partial y & 0 & 0 \\ 0 & 0 & -\partial y & 0 & 0 & 0 \\ -\partial z & 0 & 0 & 0 & 0 & 0 \\ 0 & -\partial x & 0 & 0 & 0 & 0 \end{bmatrix}. \tag{2}$$

By applying the Crank-Nicolson scheme to (1), we have

$$(I + \frac{\sigma\Delta t}{2} - \frac{c\Delta t}{2}A - \frac{c\Delta t}{2}B)V^{n+1} = (I - \frac{\sigma\Delta t}{2} + \frac{c\Delta t}{2}A + \frac{c\Delta t}{2}B)V^n \tag{3}$$

Equation (3) can be approximated by the following factorization:

$$(I+\frac{\sigma\Delta t}{4}-\frac{c\Delta t}{2}A)(I+\frac{\sigma\Delta t}{4}-\frac{c\Delta t}{2}B)V^{n+1} = (I-\frac{\sigma\Delta t}{4}+\frac{c\Delta t}{2}A)(I-\frac{\sigma\Delta t}{4}+\frac{c\Delta t}{2}B)V^{n} \quad (4)$$

In the LOD-FDTD method [6], (4) is solved in two steps

$$(I+\frac{\sigma\Delta t}{4}-\frac{c\Delta t}{2}A)V^{n+1/2}=(I-\frac{\sigma\Delta t}{4}+\frac{c\Delta t}{2}A)V^{n} \quad (5)$$

$$(I+\frac{\sigma\Delta t}{4}-\frac{c\Delta t}{2}B)V^{n+1}=(I-\frac{\sigma\Delta t}{4}+\frac{c\Delta t}{2}B)V^{n+1/2}. \quad (6)$$

Take $E_x^{n+1/2}$ for example, from (5), we have

$$(1+\frac{\sigma\Delta t}{4\varepsilon})E_x^{n+1/2}-\frac{\Delta t}{2\varepsilon}\partial y H_z^{n+1/2}=(1-\frac{\sigma\Delta t}{4\varepsilon})E_x^{n}+\frac{\Delta t}{2\varepsilon}\partial y H_z^{n} \quad (7)$$

$$H_z^{n+1/2}-\frac{\Delta t}{2\mu}\partial y E_x^{n+1/2}=H_z^{n}+\frac{\Delta t}{2\mu}\partial y E_x^{n} \quad (8)$$

Here we only consider about electric conductivity.

Substituting (8) into (7) yields the updating equations of $E_x^{n+1/2}$

$$(1+\frac{\sigma\Delta t}{4\varepsilon}-\frac{\Delta t^2}{4\mu\varepsilon}\partial_y^2)E_x^{n+1/2}=(1-\frac{\sigma\Delta t}{4\varepsilon}+\frac{\Delta t^2}{4\mu\varepsilon}\partial_y^2)E_x^{n}+\frac{\Delta t}{\varepsilon}\partial y H_z^{n} \quad (9)$$

As described in [7-8], in order to improve the computational efficiency, we can introduce some auxiliary quantities. For example, $e_x^{n+1/2}$ can be introduced into (9), and

$$(\frac{1}{2}+\frac{\sigma\Delta t}{8\varepsilon}-\frac{\Delta t^2}{8\mu\varepsilon}\partial_y^2)e_x^{n+1/2}=E_x^{n}+\frac{\Delta t}{2\varepsilon}\partial y H_z^{n} \quad (10)$$

where

$$e_x^{n+1/2}=E_x^{n+1/2}+E_x^{n} \quad (11)$$

For the other field components, their updating equations can be obtained in a similar manner.

To check on the accuracy of the proposed formula, a homogeneous cavity, filled with a lossy material with $\varepsilon_r = 4$, $\mu_r = 1$ and $\sigma = 0.05$ *S/m,* is chosen as the test case. A uniform mesh of $50\times 30\times 9$ with a cell size of 1*mm* is employed, and a current line source *Jz* with a Gaussian pulse waveform of *tw* = 150 *ps* and *tc* = 450 *ps* is placed from the bottom to the top at the cavity center. The observation point is located at the center of the computational domain.

For comparison, the cavity is computed with the conventional FDTD method with *CFLN*=1 and the proposed method with *CFLN*=1 and 5, respectively. Here, *CFLN* (Courant-Friedrich-Levy number) is the ratio of the time step to the CFL time step limit, i.e. $CFLN=\Delta t/\Delta t_{FDTD\_Max}$. To characterize the difference between the proposed method and the FDTD which is considered as the reference, the relative error is calculated by

$$e=\frac{|E_z(t)\text{-}E_z^{ref}(t)|}{Max|E_z^{ref}(t)|}\times 100\% \quad (12)$$

where $E_z(t)$ is the electric field value obtained with the proposed LOD-FDTD method, and $E_z^{ref}(t)$ is the electric field obtained with the FDTD method.

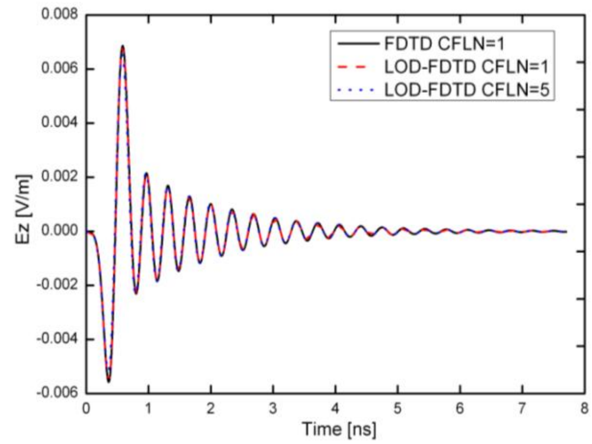

Fig.1.The Ez-component obtained with the conventional FDTD and the proposed method with *CFLN*=1 and 5.

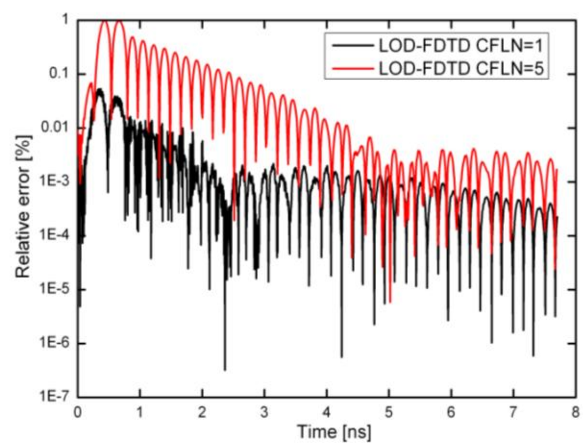

Fig.2. The relative errors of the proposed LOD-FDTD method with different *CFLN*s in reference to the FDTD results.

Fig.1 shows the computed electric field at the center of the computational domain. Fig.2 shows the relative errors of the proposed method. As can be seen, the proposed equations demonstrate high accuracy.

III. Numerical Results and Discussion

Simulations are carried out in a 3-D office as shown in Fig.3. The overall computational dimensions are $6\times 5\times 3$ m^3. The human body model is assumed to be made of homogenous human tissue liquid with $\varepsilon_r = 53.43$ and $\sigma = 0.76$ *S/m* [9]. The size of the body model is chose to be $1.61\times 0.30\times 1.78$ m^3. In the simulation, one sine-modulated Gaussian pulse $p(t)=\sin(2\pi ft)\exp(-((t\text{-}t_c)/t_w)^2)$, with f = 50 MHz, t_w = 15 *ns* and $t_c = 3t_w$, is applied in E_z at the transmitter point T_x, and the receiver position marked as R_x as denoted in Fig. 3. The space outside the room is considered as free space, which was then terminated with nine convolutional perfectly matched layers (CPML) [10].

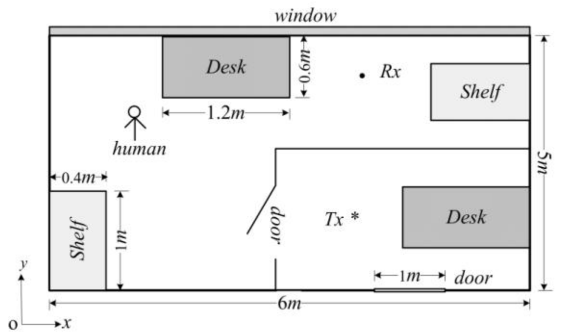

Fig.3. The floor plan of an office. The height is set to be 3*m* in the z-direction.

To save computational memory and reduce computational time, non-uniform meshes are employed. For the regions close to human body model, fine meshes $\Delta x = \Delta y = \Delta z = 1$ *cm* are used, while for the rest regions, coarse meshes $\Delta x = \Delta y = \Delta z = 4$ *cm* are applied. The slowly graded non-uniform meshes are employed between fine and coarse ones so as to reduce numerical reflections. As a result, the overall numerical mesh cells are 239 × 174 × 253. The simulation is carried on an Intel Pentium PC with 32 GB RAM. Fig.4 shows the time-dependent electric field E_z at the observation point R_x obtained with conventional FDTD method and the proposed method with *CFLN*=4. As shown in Table I, although the proposed formula uses more memory, it does consumes about 33.1% less CPU time with *CFLN* = 4 than the FDTD method.

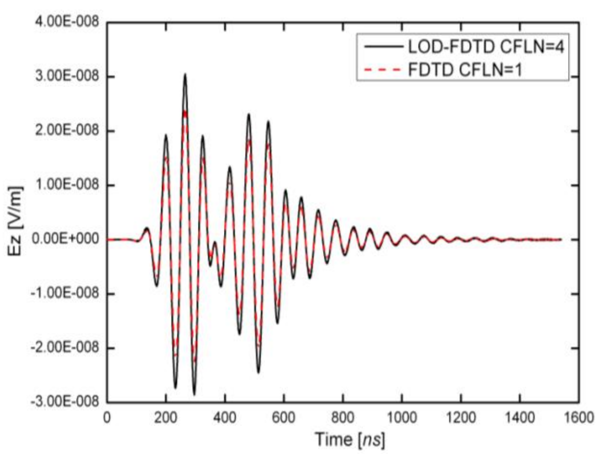

Fig.4 Time-dependent E_z recorded at R_x obtained with both FDTD and our proposed method with *CFLN*=4.

TABLE I

COMPARISON OF THE COMPUTATIONAL EXPENSES OF THE CONVENTIONAL FDTD AND THE PROPOSED LOD-FDTD METHOD

	FDTD	*LOD-FDTD*
CFLN	1	4
Memory (MB)	660	915
Number of steps	20,000	5,000
Total CPU time (seconds)	118,617	79,310

A simplified wireless channel model relating to the path loss with the transmitter-receiver separation distance is based on the following formula [11]:

$$PL(d) = F + 10n \log_{10} d + G \tag{13}$$

where F is a constant, d is the distance between transmitter and receiver. n, known as the path loss exponent (PLE), is a measure of how fast the signal energy decreases with d. The PLE plays an important role in the channel model and defines the signal fading of a given channel. G is a Gaussian variable in dB (a lognormal variable in linear scale).

The path loss is computed at 5602 sample grid points of a uniform mesh across the floor plan and shown in Fig. 5 (a) as a function of d. The mean values of path loss are also calculated for each fixed d value as plotted in Fig. 5 (b). The simulation results are used to extract the PLE, which is the slope of the best-fit lines.

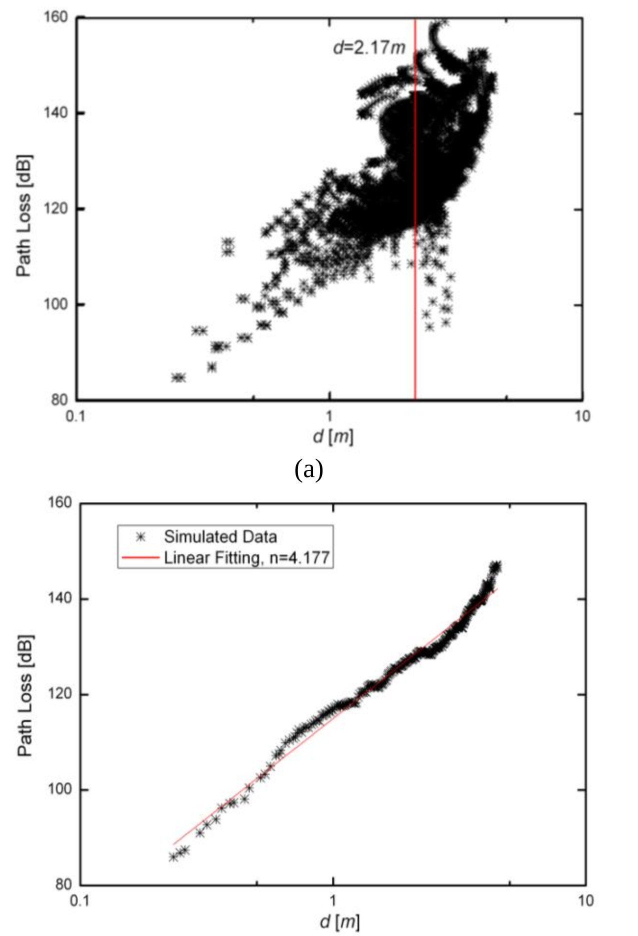

Fig.5. (a) Path loss computed at 5602 sample points, taken uniformly across the floor plan of Fig.3.The solid line represents a fixed d = 2.17*m*. (b) The mean values of path loss and path loss exponent best-fit line.

For a fixed d, for example, d = 2.17*m* as indicated by the solid line in Fig.5 (a), the probability density function (PDF) of path loss follows a Gaussian distribution. Figure 6 shows the results along with the best-fit Gaussian curves solved by the least mean-square method; there α_1 and α_2 represent the mean and the standard deviation of the associated normal random variable, respectively. As observed, the Gaussian distributions offer a good approximation to the distribution of path loss.

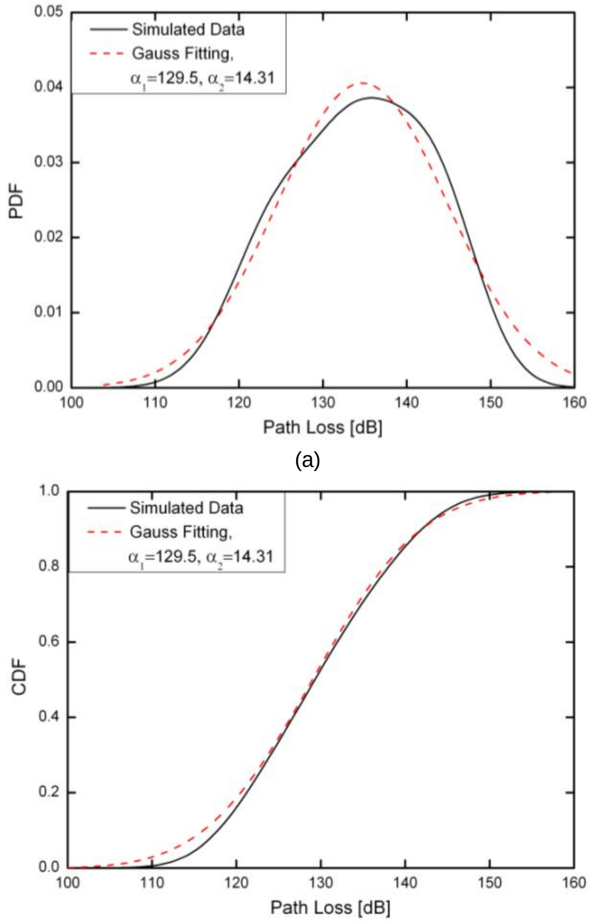

Fig.6. PDF and CDF for path loss (the transmitter and receivers are 2.17*m* apart). The best fit Gaussian models are also shown here: (a) for PDF and (b) for CDF.

IV. Conclusion

In this paper, a modified LOD-FDTD formulation for lossy media has been presented for modelling the wireless channel. By comparing the simulation results with the conventional FDTD, the proposed method is shown to have good simulation efficiency and accuracy. After post-processing the simulation results, propagation characteristics are captured such as path loss exponent and probability distribution of path loss.

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