Indoor Propagation Modeling for UWB Communications Using LOD-FDTD Method

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***Abstract*—This paper deals with electromagnetic channel modelling in typical indoor environments. We employ the sub-band locally one dimensional finite difference time domain (S-LOD-FDTD) method. We predict sub-band channel impulse responses, power delay profiles and path loss. The numerical results obtained using LOD-FDTD method is compared with the results obtained ADI-FDTD as well as with the published measured data in the literature. Numerical analysis provides the improvement of the proposed method over conventional FDTD and ADI-FDTD method for indoor propagation modeling.**

***Index Terms* — EM propagation, LOD-FDTD, FDTD, ultra wideband (UWB), path loss, channels Model.**

I. Introduction

Ultra wideband (UWB) wireless communication has been the subject of extensive research and increasing interest over recent years for communication system due to its potential applications and unique capabilities. More specifically, UWB communication is very popular for certain short range applications including indoor communications systems, home networks, cordless phones, high speed local area networks, and security sensors in wireless communications [1]. The prime advantages of UWB communication are increased bandwidth and the possibility of frequency reuse in personal communication networks. However, the performance of EM propagation inside indoor environment is affected due to reflection, refraction and diffraction of radio waves created by structures of the environment, and the subsequent interference of multiple rays at a particular point. For system operating between 10 and 100 GHz the wavelengths (3 cm to 3 mm) are small in terms of the dimensions of the walls and objects, while they are large in terms of the surface roughness dimension of indoor materials. However, the installation, assessment and effective design for EM propagation in the indoor environment need the correct characterization of radio wave propagation. Accurate prediction of radio propagation behavior is very important and crucial to system design. Therefore, Due to reducing link lengths and higher data rate, the UWB systems need sophisticated propagation models [2].

There are many types of propagation model have been proposed for indoor environments [3]. One of the common methods is ray racing technique which can be distinguished in ray launching and ray imaging techniques. But in ray tracing technique, new image sources are developed from exact sources in the current reflection or transmission depth for all planes. However, its accuracy is reduced in complex environment where too many reflections require to be computed. Another method is the geometrical optics which 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. For the UWB system, some statistical channel models based on measurements are proposed [3]. A finite difference time domain (FDTD) method is also used as an alternative method for modeling EM propagation in the UWB communications [4]-[6]. But the FDTD method is usually used for modeling narrow band indoor channel. Moreover, the computational efficiency of the explicit FDTD method for UWB propagation modeling is restricted by the CFL stability conditions which impose a maximum limit on the time step size depending on the spatial mesh size. Therefore, the FDTD method needs excess computer resources for the simulation of indoor environment. To overcome the CFL limitation, the unconditionally stable FDTD based on alternating direction implicit (ADI) has been developed [7]. However, the ADI-FDTD method still suffers for CFLN limitation and may not provide efficient performance for EM propagation modeling in UWB communications. CFLN is defined by $\Delta t/\Delta t_{CFL}$ where Δt_{CFL} is determined from CFL condition. To avoid problem with CFLN, locally one dimensional FDTD was proposed [8]-[10].

The locally one dimensional finite-difference time-domain (LOD-FDTD) method is a new implicit FDTD scheme that can effectively solve problems related to electromagnetic wave propagation [8]. Unlike the standard FDTD method, LOD-FDTD method does not require satisfying the CFL stability constraint. Hence, in LOD-FDTD method, maximum time step size is not limited by the minimum cell size within the computational domain, which enables it to simulate the indoor environment with higher computational efficiency.

In this paper, we apply for the first time LOD-FDTD method to analyze electromagnetic wave propagation inside an indoor environment. We present the formulation for generalized 2-D TM_z LOD-FDTD with CPML in detail.

Numerical results obtained using LOD-FDTD are provided compared with the results obtained using other methods to validate the technique for modeling the EM propagation for UWB communications.

II. Theory

A. LOD-FDTD Method

It is well known that the standard finite difference time domain (FDTD) method needs to satisfy the Courant-Friedrichs-Lewy stability condition. As a result, a small time step size creates a significant increase in calculation time. To alleviate the problems, implicit FDTD such as a locally one dimensional (LOD) FDTD method was proposed [9]. The locally one dimensional finite-difference time-domain (LOD-FDTD) algorithm [9] is a split step method, rather than a leapfrog scheme. They are unconditionally stable 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:

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

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

where, E , H are the magnetic, electric field in a discrete grid sampled with a spatial step of Δ. 1(a) and 1(b) cannot be used for direct numerical calculation. Using equation 1(a) and 1(b), simultaneous linear equations are obtained that result in the tri-diagonal matrix form. Placing (1b) in (1a) yields

$$\begin{aligned} &-\alpha_{y1}E_z|^{n+1/2}_{i-1,\,j} \\ &+(1+2\alpha_{y1})E_z|^{n+1/2}_{i,\,j} - \alpha_{y1}E_z|^{n+1/2}_{i+1,\,j} \\ &= E_z|^{n}_{i,\,j} + \alpha_{e1}\times\left(H_y|^{n}_{i+1/2,\,j} - H_y|^{n}_{i-1/2,\,j}\right) \\ &+\alpha_{y1}\times\{(E_z|^{n}_{i+1,\,j} - E_z|^{n}_{i,\,j}) - (E_z|^{n}_{i,\,j} - E_z|^{n}_{i-1,\,j})\} \\ &+\alpha_{e1}\times\left(H_y|^{n}_{i+1/2,\,j} - H_y|^{n}_{i-1/2,\,j}\right) \end{aligned} \quad (2)$$

where, $\alpha_{e1} = \Delta t / 2\varepsilon\Delta x$,

$\alpha_{y1} = \Delta t^2 / 4\mu\varepsilon\Delta x^2$

Similarly, the equations for second step can be obtained. Equation of sub-step 1 and 2 are solved by using Peaceman-Rachford method [11]. Fig.1 shows the placement of the electric and magnetic field in 2-D LOD-FDTD method in order to explain the calculation step.

B. CPML Absorbing Boundary Conditions for LOD-FDTD

The accuracy of LOD-FDTD method can be changed if proper boundary condition for the intermediate plan *n+1/2* is not considered.

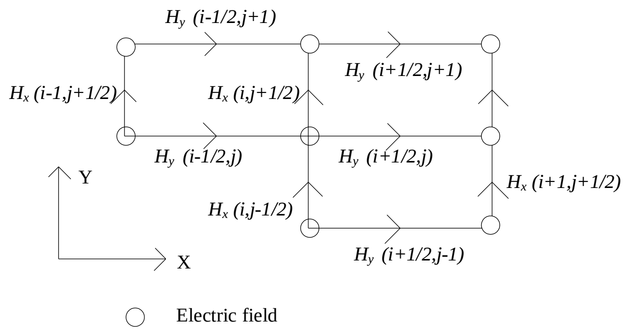

Fig.1. Placement of electric and magnetic field in case of the 2-D LOD-FDTD method.

Because, the *n* and *n+1* plane are physical planes and the intermediate *n+1/2* plane is considered a virtual plane. By adding 1(a) and 1(b), we could write the intermediate plane in terms of the physical planes, and then the resultant equation can only be satisfied if the boundary values are known for each propagation step. So, we consider same boundary conditions for the intermediate plane as the physical plane and then the overall accuracy will be first order. For brevity, in this paper we provide only one step for the explanation of the method for LOD-FDTD CPML. The electric and magnetic fields in the first simulation step of the LOD-FDTD CPML method are given as:

Sub-step 1:

$$\begin{aligned} H_x|^{n+1/2}_{i,\,j+1/2} &= C_{hxh}\times H_x|^{n}_{i,\,j+1/2} \\ &+ C_{hxez}\times\{(E_z|^{n+1/2}_{i,\,j+1} - E_z|^{n+1/2}_{i,\,j}) \\ &+ (E_z|^{n}_{i,\,j+1} - E_z|^{n}_{i,\,j})\} + C_{\psi hxy}\times\psi_{hxy} \end{aligned} \quad 3(a)$$

$$\begin{aligned} E_z|^{n+1/2}_{i,\,j} &= C_{eze}\times E_z|^{n}_{i,\,j} \\ &+ C_{ezhx}\times\{(H_x|^{n+1/2}_{i,\,j+1/2} - H_x|^{n+1/2}_{i,\,j-1/2}) \\ &+ (H_x|^{n}_{i,\,j+1/2} - H_x|^{n}_{i,\,j-1/2})\} \\ &+ C_{\psi ezy}(i,\,j)\times\psi_{ezy} \end{aligned} \quad 3(b)$$

where, $C_{hxh} = (4\mu_x - \sigma^m_x\Delta t)/(k(j)(4\mu_x + \sigma^m_x\Delta t))$

$C_{hxez} = -2\Delta t/(\Delta y(4\mu_x + \sigma^m_x\Delta t))$

$C_{eze} = (4\varepsilon_z - \sigma^e_z\Delta t)/(4\varepsilon_z + \sigma^e_z\Delta t)$

$$C_{ezhx} = -2\Delta t / (\Delta y(4\varepsilon_z + \sigma_z^e \Delta t))$$

$\psi_{hy}, \psi_{hyx}, \psi_{ezx}$ and ψ_{ezy} are discrete variables those have non-zero values only in some CPML regions and are necessary to implement the absorbing boundary. In order to avoid reflections between the computational domain and the CPML boundary due to the discontinuities, and the losses due to the CPML must be zero at the computational domain interface.

III. Numerical Results

We consider a 2-D indoor propagation scenario [4] as shown in Fig. 2, the 2-D LOD-FDTD is used to model this structure. The cell sizes in x and y directions are λ/10 and the CFLN is 2. The CPML ABC with 8 layers is used to reduce reflection error. For the UWB excitation signal, the parameters of modulated Gaussian signal satisfying the UWB signal definition and FCC indoor limit spectral mask are f_c=7.34 GHz, d=0.11 ns, n_0=50 and A=3.76 mV/m, respectively. The expression for the UWB signal is given below.

$$V_s(n) = Ae^{-[(n-n_0)\Delta t/d]^2}[\sin 2\pi f_c(n-n_0)\Delta t]$$

Where, *A* is the maximum amplitude of the envelope signal, f_c is the carrier frequency, *d* is the 1/e characteristic decay time and Δt is the delayed time step. The electromagnetic properties of the different materials of the indoor environments are shown in following table.

TABLE I
ELECTROMAGNETIC PROPERTIES OF DIFFERENT MATERIALS

Material	**Electromagnetic property**
Desk	ε_r =2.80, σ = 0.15
Plywood door	ε_r =2.88, σ = 0.21
Brick wall	ε_r =3.30, σ = 0.11
Shelf	ε_r =5.00, σ = 0.70

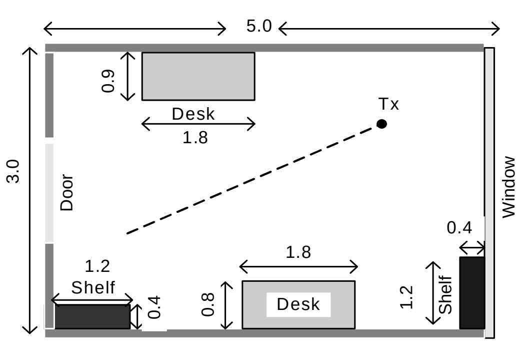

Fig.2. Indoor scenario for LOD FDTD simulation (units in m)

Fig. 3-5 show the results obtained for received electric field (E_z component) close to desk and door.

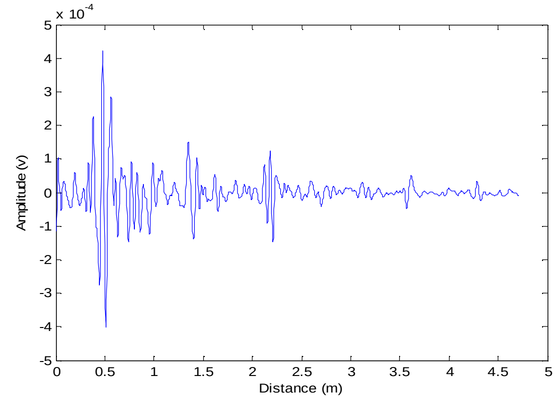

Fig.3. Electric field time response near desk1

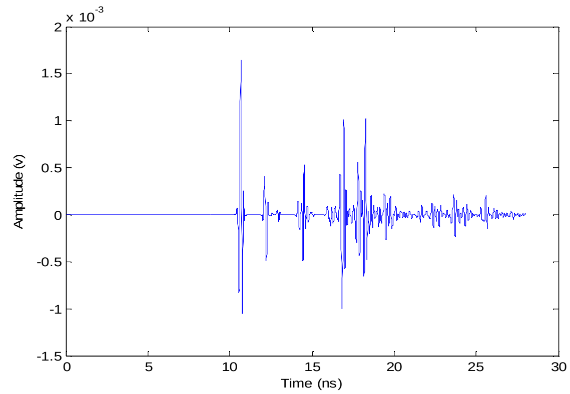

Fig.4. Electric field time response near window

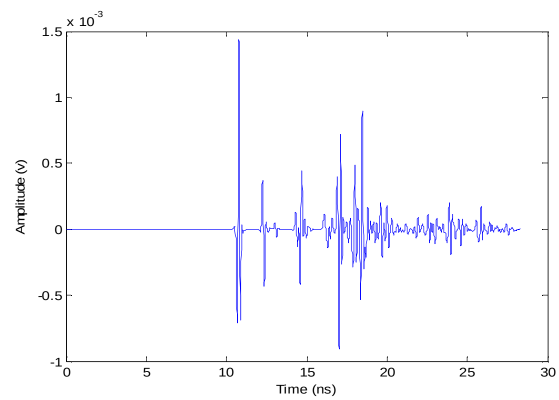

Fig.5. Electric field time response close to door

In this paper, we also predict the channel impulse response, power delay profile and path loss those are described below.

A. Channel Impulse Response

The sub band LOD-FDTD method has been proposed in [5], where the choice on the number of sub bands is also analysed. The sub band LOD-FDTD model used in this paper, takes into account the material dispersions at different frequencies, the whole UWB is divided into eight sub bands with 1 GHz bandwidth. Each sub band is simulated separately and a combination technique is used to recover the overall channel impulse response (CIR) [4], [5]. At each sub band, the frequency dependent material properties are obtained from measurement [5]. The complex Gaussian monocycles with different pulse width are used for the excitation signal according to the centre frequency of each sub-band. Fig. 6 shows the channel impulse responses at different sub-bands. It clearly shows that the CIRs are considerably different at different sub-bands, which is caused by both the change of channel behaviour introduced by the material dispersion, and antenna pattern variations at different frequencies.

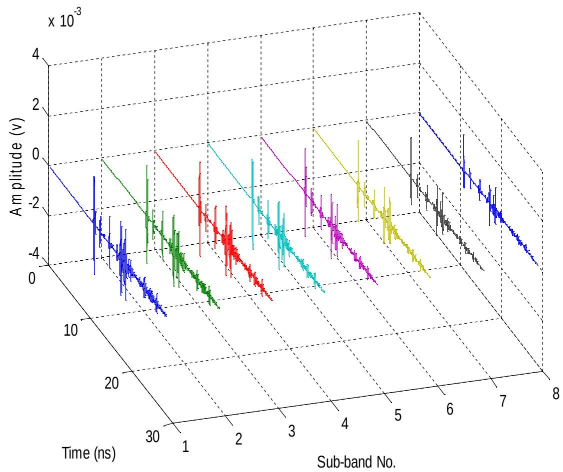

Fig.6. Time domain CIRs at 3 m to TX at different sub bands

B. Power Delay Profile

The power delay profiles (PDPs) for different base station antenna are calculated from the combined time domain signal. Fig. 7 shows the PDPs at 3m to the transmitter and a threshold of -23dB for detecting the MCs.

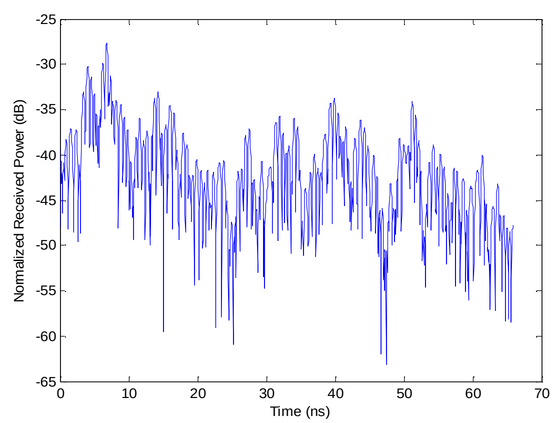

Fig.7. PDPs calculated from combined time domain CIRs at 3 m to TX for different base station antenna cases.

It can be seen that the PDP vary with different shape antenna, which indicates that the pattern distortions at higher frequencies can cause the overall reduction of the number of received MCs.

C. Path Loss

Fig. 8 shows the calculated path loss obtained from from LOD-FDTD compared with that obtained from literature. Fig.8 shows that the predicted propagation path loss obtained using LOD-FDTD agrees well with results obtained by FDTD and ADI-FDTD methods as well as with the published measured data [4]. This verifies that the LOD-FDTD method can be used to model the path loss of UWB communication.

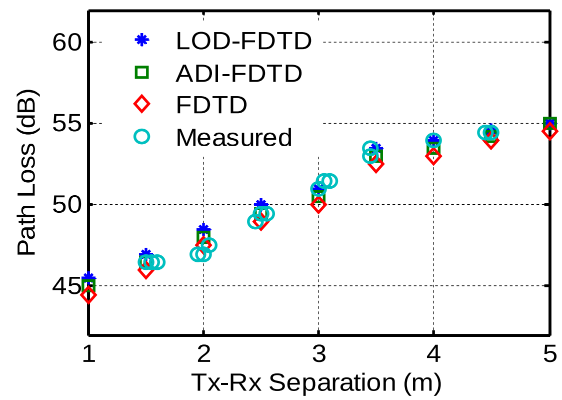

Fig.8. Path loss at 1 to 5 m to the transmitter to receiver.

To compare computational performances between LOD-FDTD and FDTD methods, we discuss the computation time and memory usage for computing the path loss of the indoor environment. Table II shows comparison of the execution time and CPU memory usage of the LOD-FDTD and FDTD method for calculating the path loss of the indoor environment. The execution time refers to the time it takes MATLAB to perform the one Backslash command and multiplied by the number of loops.

TABLE II
COMPARISON OF COMPUTER RESOURCES FOR CALCULATION PATH LOSS USING LOD-FDTD AND FDTD

	Δt=CFLN×Δt_{CFL} (ps)	CPU Time (s)	Memory (KB)
LOD-FDTD	(8×1.5)=12	143	925
FDTD	1.5	558	970

It can be observed from the Table II that the LOD-FDTD method requires less computational time compared to FDTD method when used for calculating the path loss. This may be due to lesser number arithmetic operations required for LOD-FDTD.

IV. CONCLUSION

In this paper, we propose LOD-FDTD method for propagation prediction inside the indoor environment for

UWB communication. The prediction agrees well with the published measured result. The path loss predictions inside indoor environment can help in the design of wireless links. The proposed technique allows efficient execution time at higher CFLN. The proposed method can also be extended for electromagnetic modeling of more complex indoor environment.

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