Modeling of Indoor UWB Channel by Using Finite Difference Time Domain Method

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Abstract— **In this paper, a two-dimensional (2-D) transverse magnetic (TM) mode finite difference time domain (FDTD) method is used to simulate the indoor radio wave propagation and model the indoor ultra wideband (UWB) channel. The modulated Gaussian pulse, which is satisfied the UWB signal definition and Federal Communications Commission (FCC) indoor limit spectral mask, is used as the UWB excitation signal. The free space path loss obtained by using FDTD method is shown and verified by comparing with that obtained by using Friis' transmission formula. After that, the path loss in example indoor environment is evaluated. The line-of-sight (LOS) and obstructed (OBS) environments are considered. Furthermore, these obtained data are modeled the path loss by using regression model. The probability density function (PDF) and cumulative distribution function (CDF) of fading are evaluated. The results are discussed in the conclusion.**

I. INTRODUCTION

Recently, ultra wideband (UWB) radio technology has become an important topic for microwave communication because of its low cost and low power consumption potentials [1]. The UWB technology is different from other radio frequency (RF) technologies. Instead of using narrow carrier frequency, the UWB transmits pulses with power spectral density (PSD) in the range of ultra wide frequency spectrum. The Federal Communications Commission (FCC) [2] specified that UWB signal has a frequency spectrum ranging from 3.1 GHz to 10.6 GHz. The FCC defined the UWB signal as those which have a fractional bandwidth equal to or greater than 0.20, or occupied bandwidth equal to or greater than 500 MHz.

The power density of UWB signal is considered to be the noise for other communication systems because its power spectrum is below the FCC part 15 noise limit. The UWB receiver collects the power of received signal to rebuild the pulse. Therefore, the UWB radio technology can coexist with other RF technologies without interference.

The indoor radio communications have become more and more interesting in recent time, which several researchers report the wideband impulse response measurement [3]. Such data is useful to predict the maximum allowable data rates in order to the intersymbol interference and in the exploration of such techniques as diversity and equalization. The effective design, assessment and installation of radio communication in indoor environment require the accurate characterization of radio wave propagation. Therefore, it is also important to consider the propagation behavior in indoor environment.

A ray tracing technique has been demonstrated to be promising for indoor radio propagation [4]. A finite difference time domain (FDTD) method [5], [6] is the alternative method for modeling channel. Although the FDTD method requires more computer resources compared with the ray tracing technique, the simulation of indoor environment requires the computer resources less than that of outdoor environment. Furthermore, the FDTD method can be calculated the scattered fields more accurately compared with ray tracing technique for complex lossy structures with finite dimensions encountered in indoor environment. Therefore, the FDTD method is usually used to model the narrow band channel [7], [8]. For UWB communications, there are many researches that used the FDTD method to model the channel [9], [10]. However, there is no consideration about path loss model with FCC regulation of UWB signal.

In this paper, the two-dimensional (2-D) transverse magnetic (TM) mode FDTD method, which is satisfied the numerical stability condition [11] and with perfectly matched layer absorbing boundary condition (PML ABC) [12], is used to simulate the indoor radio wave propagation and model the indoor UWB channel. The modulated Gaussian pulse, which is satisfied the UWB signal definition and FCC indoor limit spectral mask [13], is used as the UWB excitation signal. The free space path loss obtained by using FDTD method is shown and verified by comparing with that obtained by using Friis' transmission formula [14]. which has the high accuracy for UWB channel [15]. After that, the path loss in example indoor environment is evaluated. The line-of-sight (LOS) and obstructed (OBS) environments are considered. Furthermore, these obtained data are modeled the path loss by using regression model. The probability density function (PDF) and cumulative distribution function (CDF) of fading are evaluated.

II. FDTD METHODS

The 2-D TM mode finite difference equations are directly derived from Maxwell's curl equations in time domain. To obtain discrete approximation of continuous partial differential equations, the centered difference approximation is used on both time and space first-order partial difference. The entire computation domain is the collection of all the unit cells. The dimensions of unit cell along x and y directions are Δx and Δy, respectively. The node with subscript indices i and j corresponds to the node number in x and y directions. The time step is indicated with the superscript index n. The time interval of each time step is Δt. After simple arrangement, the 2-D TM mode finite difference equations are described as [5],[6]

$$\begin{aligned} H_x\big|_{i,j}^{n+\frac{1}{2}} &= H_x\big|_{i,j}^{n-1/2} \\ &\quad + \left(\frac{\Delta t}{\mu_{i,j}}\right)\left(\frac{E_z\big|_{i,j-\frac{1}{2}}^{n} - E_z\big|_{i,j+\frac{1}{2}}^{n}}{\Delta y}\right), \end{aligned} \tag{1}$$

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

$$\begin{aligned} E_z\big|_{i,j}^{n+1} &= C_{\mathrm{a}}\big|_{i,j} E_z\big|_{i,j}^{n-1} \\ &\quad + C_{\mathrm{b}}\big|_{i,j}\left(\frac{H_y\big|_{i+\frac{1}{2},j}^{n+\frac{1}{2}} - H_y\big|_{i-\frac{1}{2},j}^{n+\frac{1}{2}}}{\Delta x}\right. \\ &\quad \left. + \frac{H_x\big|_{i,j-\frac{1}{2}}^{n+\frac{1}{2}} - H_x\big|_{i,j+\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta y}\right), \end{aligned} \tag{3}$$

with the electric field updating coefficients at node (i,j) are given by

$$C_{\mathrm{a}}\big|_{i,j} = \left(1 - \frac{\sigma_{i,j}\Delta t}{2\varepsilon_{i,j}}\right) \Big/ \left(1 + \frac{\sigma_{i,j}\Delta t}{2\varepsilon_{i,j}}\right), \tag{4}$$

$$C_{\mathrm{b}}\big|_{i,j} = \left(\frac{\Delta t}{\varepsilon_{i,j}}\right) \Big/ \left(1 + \frac{\sigma_{i,j}\Delta t}{2\varepsilon_{i,j}}\right), \tag{5}$$

where H is the magnetic field, E is the electric field, μ is the magnetic permeability, ε is the electric permittivity and σ is the electric conductivity. The maximum time step is limited by stability restriction of finite difference equation [11].

The modulated Gaussian pulse, which is satisfied the UWB signal definition and FCC indoor limit spectral mask, is used as the UWB excitation signal V_{S}. The expression of this pulse is [7]

$$V_{\mathrm{S}}\big|^{n} = Ae^{-[(n-n_0)\Delta t/d]^2}\sin[2\pi f_{\mathrm{c}}(n-n_0)\Delta t], \tag{6}$$

where A is the maximum amplitude of envelope signal, f_{c} is the carrier frequency, d is the $1/e$ characteristic decay time and n_0 is the delayed time step.

The tangential field components on four mesh walls must be specified in such a way that outgoing waves are not reflected. The FDTD simulation in this paper uses the PML ABC [12].

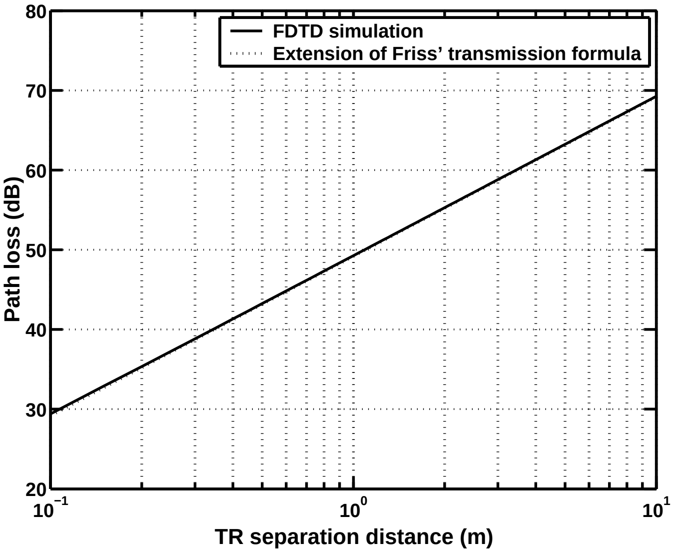

Fig. 1. Free space path loss obtained from FDTD simulation compared with that obtained from Friis' transmission formula.

TABLE I

ELECTROMAGNETIC PROPERTIES OF DIFFERENT MATERIALS.

Material	Electromagnetic property
Gypsum board	$\varepsilon_{\mathrm{r}} = 2.80$, $\sigma = 0.15$
Plywood door	$\varepsilon_{\mathrm{r}} = 2.88$, $\sigma = 0.21$
Brick wall	$\varepsilon_{\mathrm{r}} = 3.30$, $\sigma = 0.11$
Dry concrete wall	$\varepsilon_{\mathrm{r}} = 5.00$, $\sigma = 0.70$

III. UWB CHANNEL MODEL

In this section, the path loss obtained from FDTD method is modeled. First, the 2-D TM FDTD simulation is done in the free space environment. The cell sizes in x and y directions are $\Delta x = \Delta y = 0.005$ m. The PML ABC with 16 layers is used to reduce the reflection error at edges. The time interval of each time step is $\Delta t = 11.79$ ps, which is satisfied the numerical stability condition. For UWB excitation signal, the parameters of modulated Gaussian signal, which is satisfied the UWB signal definition and indoor limit spectral mask, are $f_{\mathrm{c}} = 7.34$ GHz, $d = 0.11$ ns and $A = 0.27$ V. These signal parameters are the maximum amplitude and average power optimizations with bit rate of 100 Mbps [13].

Figure 1 shows the free space path loss obtained from FDTD simulation compared with that obtained from Friis' transmission formula along transmitter-receiver (TR) separation distance 0.1 to 10 m. From the figure, the path loss obtained from FDTD simulation coincides very well with that obtained from Friis' transmission formula. There is root mean square (RMS) error only 0.13 dB. This verifies that FDTD simulation can be modeled the path loss of UWB channel.

Subsequently, the FDTD simulation is done in the room structure with excitation signal located at point S. The dimension of this room is shown in Fig. 2. The room consists of gypsum board, plywood door, metallic cabinet, brick and dry concrete walls. The metallic cabinet is assumed to be the perfect

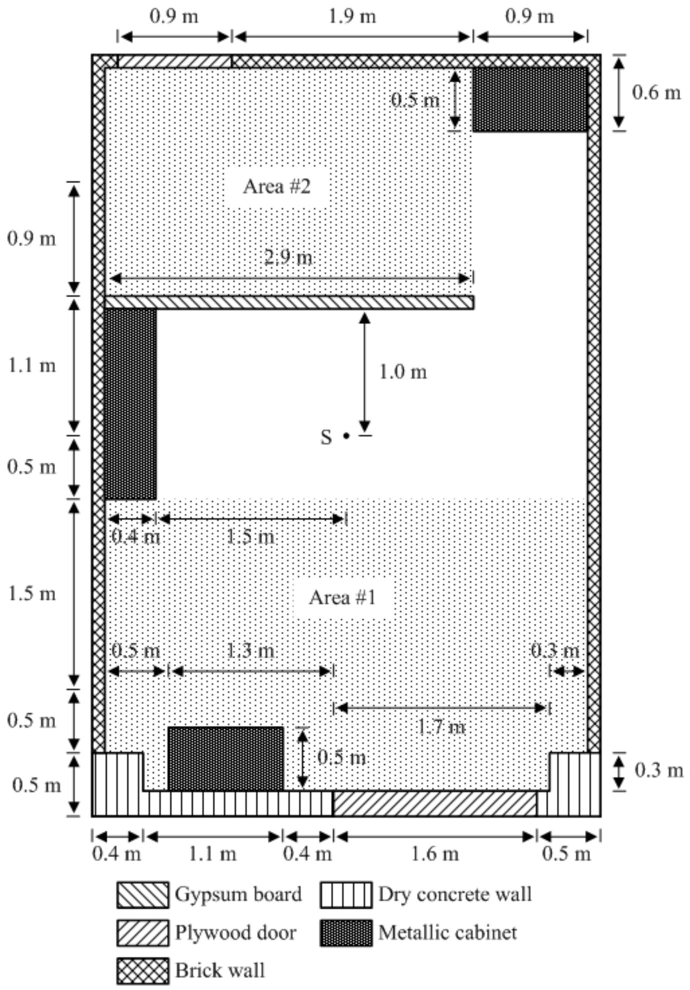

Fig. 2. Layout of room environment.

conductor. The electromagnetic properties of other materials are listed in Table 1 [4]. The two areas, Area #1 and Area #2, as shown in Fig. 2 are considered for LOS and OBS environments, respectively. The UWB path loss of both considered areas in dB at note (i, j) can be evaluated by using

$$PL|_{i,j} = 10\log\left[\frac{\sum_n \left(V_\mathrm{S}|^n\right)^2}{\sum_n \left(V_\mathrm{R}|^n_{i,j}\right)^2}\right], \tag{7}$$

where V_R is the received signal.

The TR separation distance d at node (i, j) is computed by using

$$d = \sqrt{\left[(i - i_\mathrm{S})\Delta x\right]^2 + \left[(j - j_\mathrm{S})\Delta y\right]^2}, \tag{8}$$

where $(i_\mathrm{S}, j_\mathrm{S})$ is the node of UWB excitation signal.

For modeling path loss, the linear regression model based on log-distance path loss model [16] is used. The model can be realized by curve fitting on a scatter plot of obtained path loss and then derived the path loss exponent n from

$$PL(d) = \overline{PL}(1) + 10n\log(d) + X_\sigma, \tag{9}$$

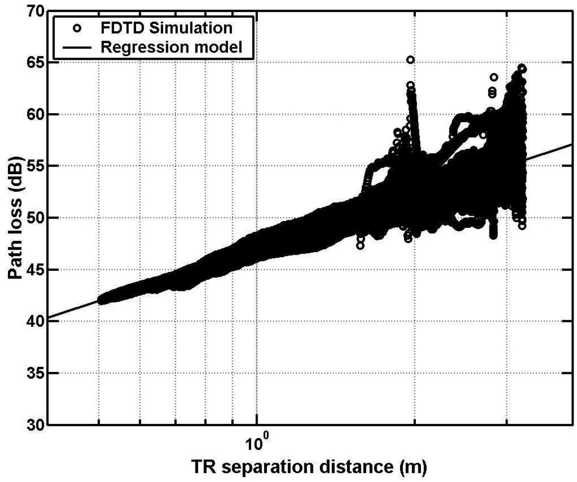

Fig. 3. Scatter plot of path loss obtained from FDTD simulation and regression model in Area #1.

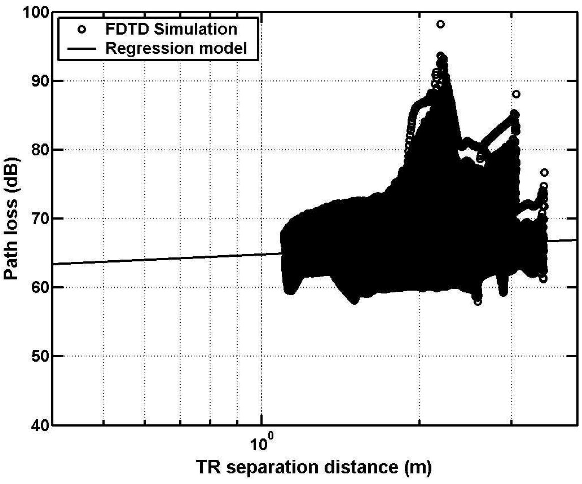

Fig. 4. Scatter plot of the path loss obtained from FDTD simulation and regression model in Area #2.

where $PL(d)$ is the path loss in dB at TR separation distance of d (m), $\overline{PL}(1)$ is the average large-scale path loss at TR separation distance is 1 m, X_σ is the fading parameter with standard deviation of σ in dB. When plotted on a log-distance graph, the path loss model is a straight line and n can be determined from the slope of $10n$ dB per decade. The value n and σ depend on the specific propagation environment. The main objective of this simulation is to determine $\overline{PL}(1)$, n and X_σ of UWB signal propagation in Area #1 and Area #2.

Figure 3 shows the scatter plot of path loss obtained from FDTD simulation and regression model in Area #1, which is the LOS environment. The 323,081 data are used to model the path loss. For this area, the model parameters are $\overline{PL}(1) = 47.00$ dB and $n = 1.68$. The scatter plot of path loss obtained from FDTD simulation and regression model in Area #2, which is the OBS environment, is shown in Fig. 4. The 207,861 data are

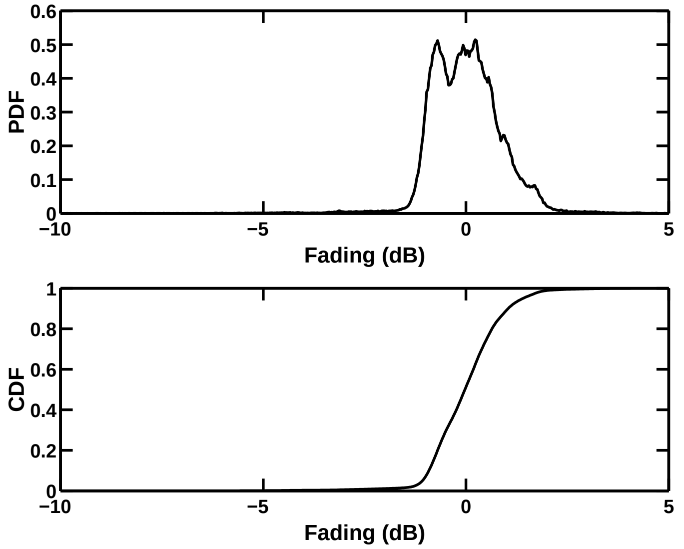

Fig. 5. PDF and CDF of fading in Area #1.

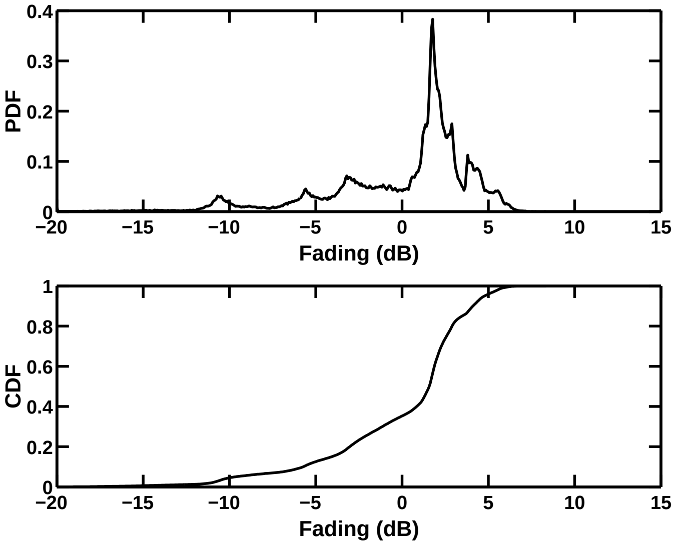

Fig. 6. PDF and CDF of fading in Area #2.

used to model the path loss. For this area, the model parameters are $\overline{PL}(1) = 64.79$ dB and $n = 0.35$.

For considering the fading parameter X_σ, the statistic model is used. The PDF and CDF of fading are evaluated. Figure 5 shows the PDF and CDF of fading in Area #1. The statistic parameters of this area are the standard deviation of $\sigma = 0.86$ dB and zero mean. The PDF and CDF of fading in Area #2 are shown in Fig. 6. The statistic parameters of this area are the standard deviation of $\sigma = 4.21$ dB and zero mean. We can see that the fading in Area #2, which is OBS environment, is more fluctuate than that in Area #1, which is LOS environment.

IV. CONCLUSION

In this paper, the 2-D TM mode FDTD method is used to simulate the indoor radio wave propagation and model the path loss of UWB channel. The free space path loss obtained by FDTD method is verified with that obtain by Friis' transmission formula. By using FDTD method, the numerous data can be obtained for modeling indoor UWB channel. It is flexible to model the different environment according to desire accuracy by setting cell size. This simulation can be applied to arbitrary bandwidths or types of UWB signals. In order to develop a reliable UWB product for WPAN applications, a good understand of UWB channel model of specific environment is essential for link budget. Therefore, FDTD method provides a high flexible and convenient tool for modeling UWB channel.

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