Indoor Wireless Channel Modeling for UWB Communications Using Finite Difference Time Domain Method

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Abstract

In this paper, a two-dimensional (2-D) transverse magnetic (TM) mode of finite difference time domain (FDTD) method is used to simulate the indoor radio wave propagation and model the path loss of an ultra wideband (UWB) channel. The modulated Gaussian pulse satisfied the UWB signal definition and the Federal Communications Commission (FCC) indoor limit spectral mask is used as the UWB excitation signal. The propagation of electric field at each example time step is demonstrated. The power delay profiles along the specific distances are shown. The free space path loss obtained from the FDTD method is shown and verified by comparing with that obtained from the extension of Friis' transmission formula. After that, we evaluate the path loss effect with our proposed model in an indoor environment. Our proposed model is a room structure, which consists of gypsum board, plywood door, 3 metallic cabinets, brick and dry concrete walls. The line-of-sight (LOS) and obstructed (OBS) environments are considered. Furthermore, these obtained data model the path loss by using the regression model. The probability density function (PDF) and cumulative distribution function (CDF) of fading are illustrated. From the results, we can see that the FDTD simulation is convenient and flexible for the site-specific and statistical models of the UWB indoor radio wave propagation.

Keyword: ultra wideband (UWB), finite difference time domain (FDTD) method, channel model, power delay profile, path loss.

1. 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]. UWB technology is different from other radio frequency (RF) technologies. Instead of using a narrow carrier frequency, UWB transmits pulses with power spectral density (PSD) in the range of the ultra wide frequency spectrum. The Federal Communications Commission (FCC) [2] in US specified that UWB pulses have 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 PSD of the UWB signal is considered to be noise for other communication systems because its power spectrum is below the FCC part 15 noise limit. The UWB receiver collects the power of the received signal to rebuild the pulse. Therefore, UWB radio technology can coexist with other RF technologies without interference.

Indoor radio communications have become more and more important recently, which several researchers report wideband impulse response measurement [3]. Such data is useful to predict the maximum allowable data rates, which depend on the intersymbol interference (ISI), and in the exploration of such techniques as diversity and equalization. The effective design, assessment and installation of radio communication in the indoor environment require the accurate characterization of radio wave propagation. Therefore, it is also important to consider the propagation behavior in the 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 an alternative method for modeling the channel. Although the FDTD method requires more computer resources compared with the ray tracing technique, the simulation of indoor environment requires less computer resources than that of the outdoor environment. Furthermore, the FDTD method can compute the scattered fields more accurately compared with the ray tracing technique for complex lossy structures with finite dimensions encountered in the indoor environment. Therefore, the FDTD method is usually used to model a site-specific narrow band indoor channel [7], [8]. For the UWB communication, several statistical channel models based on measurements are reported in [9]-[11]. There is much research that used the FDTD method to model the UWB channel [12], [13]. However, there is no consideration about the UWB signal satisfying FCC regulation.

In this paper, the two-dimensional (2-D) transverse magnetic (TM) mode of the FDTD method, satisfying the numerical stability condition [14] and with perfectly matched layer absorbing boundary condition (PML ABC) [15], is used to simulate the indoor radio wave propagation and model the path loss of UWB channel. The modulated Gaussian pulse satisfying the UWB signal definition and FCC indoor limit spectral mask [16] is used as the UWB excitation signal. The free space path loss obtained from the FDTD method is shown and verified by comparing with that obtained from the extension of Friis' transmission formula [17], [18], which has high accuracy for the UWB channel [19], [20]. After that, we evaluate the path loss effect with our proposed model in the indoor environment. Our proposed model is a room structure, which consists of gypsum board, plywood door, 3 metallic cabinets, brick and dry concrete walls. The line-of-sight (LOS) and obstructed (OBS) environments are considered. Furthermore, these obtained data model the path loss by using the regression model. The probability density function (PDF) and cumulative distribution function (CDF) of fading are illustrated.

This paper is organized as follows. In section 2, the FDTD method used in this paper is reviewed. Next, the indoor UWB channel is modeled in section 3. Finally, the conclusions are discussed in section 4.

2. FDTD Method

2.1 Finite Difference Equations

The 2-D TM mode of finite difference equations are directly derived from Maxwell's curl equations in the time domain. Maxwell's curl equation can be written as [21]:

$$\mu\frac{\partial\vec{H}}{\partial t} = -\nabla\times\vec{E} \tag{1}$$

$$\varepsilon\frac{\partial\vec{E}}{\partial t} = \nabla\times\vec{H} \tag{2}$$

where H is the magnetic field, E is the electric field, μ is the magnetic permeability and ε is the electric permittivity.

To obtain discrete approximation of the continuous partial differential equations, the centered difference approximation is used on both the time and space first-order partial difference. The entire computation domain is the collection of all unit cells. The dimensions of the unit cell along x and y directions are Δx and Δy, respectively. The node with subscript indices i and j corresponds to node number in the 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 of finite difference equations is described as follows [5]-[6]:

$$H_x\Big|_{i,j}^{n+1/2} = H_x\Big|_{i,j}^{n-1/2} + \left(\frac{\Delta t}{\mu_{i,j}}\right)\left(\frac{E_z\Big|_{i,j-1/2}^{n} - E_z\Big|_{i,j+1/2}^{n}}{\Delta y}\right) \quad (3)$$

$$H_y\Big|_{i,j}^{n+1/2} = H_y\Big|_{i,j}^{n-1/2} + \left(\frac{\Delta t}{\mu_{i,j}}\right)\left(\frac{E_z\Big|_{i+1/2,j}^{n} - E_z\Big|_{i-1/2,j}^{n}}{\Delta x}\right) \quad (4)$$

$$E_z\Big|_{i,j}^{n+1} = C_a\Big|_{i,j} E_z\Big|_{i,j}^{n-1} + C_b\Big|_{i,j}\left(\frac{H_y\Big|_{i+1/2,j}^{n+1/2} - H_y\Big|_{i-1/2,j}^{n+1/2}}{\Delta x} + \frac{H_x\Big|_{i,j-1/2}^{n+1/2} - H_x\Big|_{i,j+1/2}^{n+1/2}}{\Delta y}\right) \quad (5)$$

The electric field updating coefficients at node $(i,\ j)$ are given by:

$$C_a\Big|_{i,j} = \frac{1 - \dfrac{\sigma_{i,j}\Delta t}{2\varepsilon_{i,j}}}{1 + \dfrac{\sigma_{i,j}\Delta t}{2\varepsilon_{i,j}}} \quad (6)$$

$$C_b\Big|_{i,j} = \frac{\dfrac{\Delta t}{\varepsilon_{i,j}}}{1 + \dfrac{\sigma_{i,j}\Delta t}{2\varepsilon_{i,j}}} \quad (7)$$

where the parameter σ is the electric conductivity.

The maximum time step is limited by the stability restriction of the finite difference equation. The numerical stability condition of 2-D FDTD is specified as [14]:

$$\Delta t \le \frac{1}{c\sqrt{\dfrac{1}{\Delta x^2} + \dfrac{1}{\Delta y^2}}} \quad (8)$$

where c is the velocity of light in free space.

In this paper, the magic time step condition is used to obtain the minimum numerical error. The magic time step condition is defined as:

$$\Delta t = \frac{1}{c\sqrt{\dfrac{1}{\Delta x^2} + \dfrac{1}{\Delta y^2}}} \quad (9)$$

2.2 UWB Excitation Signal

The modulated Gaussian pulse satisfies the UWB signal definition and the FCC indoor limit spectral mask is used as the UWB excitation signal V_S. The expression of this pulse is [7]:

$$V_s\Big|^{n} = Ae^{-[(n-n_o)\Delta t/d]^2}\sin[2\pi f_c(n-n_o)\Delta t] \quad (10)$$

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 n_0 is the delayed time step.

2.3 Perfectly Matched Layer Absorbing Boundary Condition (PML ABC) Treatment

The tangential field components on the 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 [15]. The PML, ABC can effectively absorb propagation wave by using nonphysical lossy media adjacent to the outer grid boundaries backed by perfectly conducting walls. The field components are split into two subcomponents. The electric and magnetic losses, σ_e and σ_h, inside the PML medium are specified by satisfying the PML impedance-matching condition as follows:

$$\frac{\sigma_e}{\varepsilon} = \frac{\sigma_h}{\mu} \quad (11)$$

After the specification of electric and magnetic losses, electromagnetic waves inside the PML medium are rapidly attenuated. The explicit exponentially difference file-updating equations are used to replace the conventional FDTD algorithm.

The electric loss inside the PML region is assumed to increase with depth from zero at $\rho = 0$ to a maximum value of $\sigma_{\max}$ at $\rho = \delta$ by the quadratic ramping:

$$\sigma_e(\rho) = \sigma_{\max}\left(\frac{\rho}{\delta}\right)^2 \quad (12)$$

where $\sigma_{\max}$ is chosen to bound the PML reflection coefficient. The PML reflection coefficient at normal incident has the following expression:

$$R(0) = e^{-2\sigma_{\max}\delta/(3\varepsilon c)} \quad (13)$$

3. Modeling of Indoor UWB Channel

We evaluate the path loss effect with our proposed model in the indoor environment. Our proposed model is a room structure with the excitation signal located at point S. The dimension of this room is shown in Fig. 1. The room consists of gypsum board, a plywood door, 3 metallic cabinets, brick and dry concrete walls. The metallic cabinet is assumed to be a perfect conductor. The electromagnetic properties of other materials are listed in Table 1 [16].

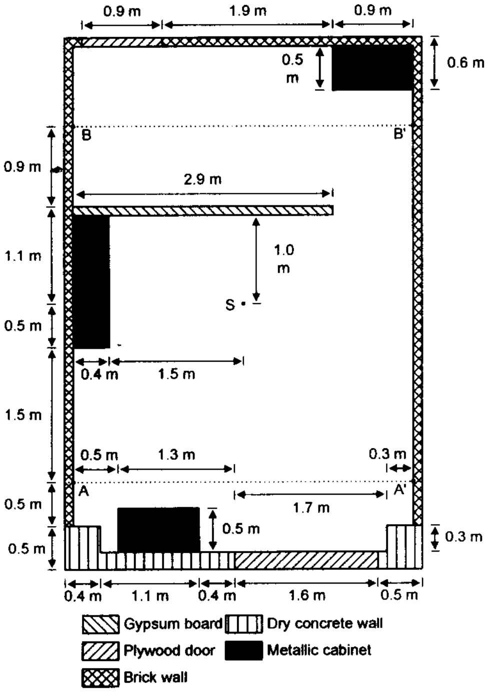

Fig.1 Dimension of room indoor environment.

Table 1 Electromagnetic properties of different materials.

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

Subsequently, the 2-D TM mode of FDTD simulation is used to model this structure. 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 the edges of the simulation boundary. The dimension of total lattice is 873×1273 cells. The time interval of each time step is $\Delta t = 11.79$ ps, which satisfies the numerical stability condition. The total time steps of this simulation are $N = 10000$. 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. These signal parameters are the maximum amplitude and average power optimizations with bit rate of 110 Mbps [21]. The UWB excitation signal in the time domain and its radiated PSD compared with FCC indoor limit spectral mask are shown in Fig. 2 and 3, respectively.

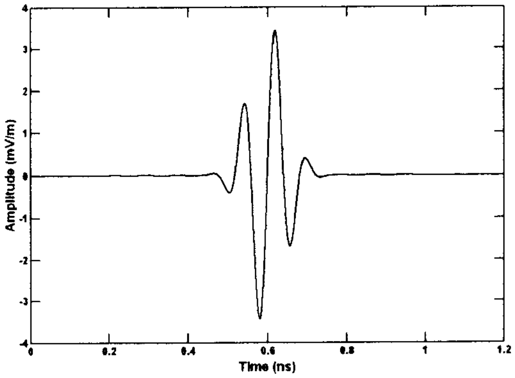

Fig. 2 UWB excitation signal in time domain

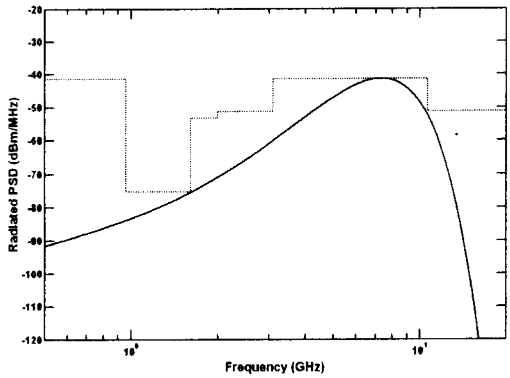

Fig. 3 Radiated PSD of UWB excitation signal compared with FCC indoor limit spectral mask

From the FDTD simulation, we can observe the characteristics of the electromagnetic field propagation in each time step. Figures 4 to 7 show the electric field patterns at example time steps of $n = 500$, 1000, 1500 and 2000, respectively. As seen in Fig. 4, the electromagnetic wave is excited at point S and propagates with circular wavefront. It reflects at the top gypsum board and diffracts to the other side. From other figures, we can see the propagation mechanisms of the electromagnetic wave, such as reflection, diffraction and scattering, occur in this indoor environment.

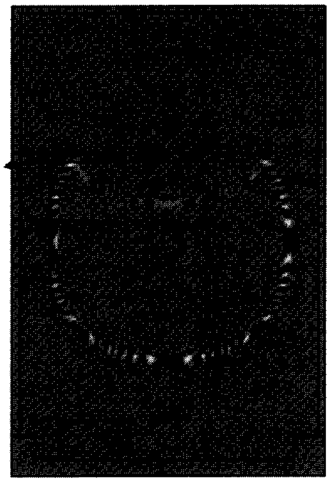

Fig. 4 Electric field pattern at time step of $n = 500$.

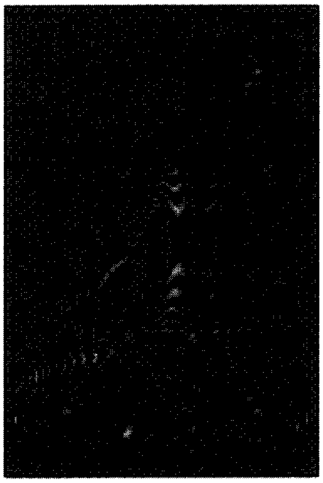

Fig. 5 Electric field pattern at time step of $n = 1000$.

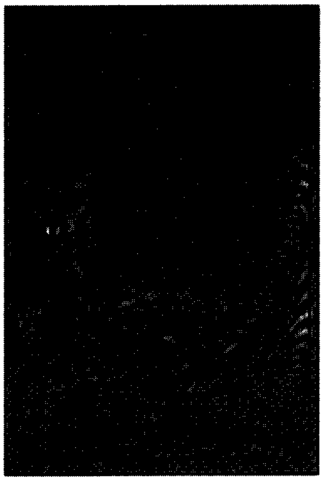

Fig. 6 Electric field pattern at time step of $n = 1500$.

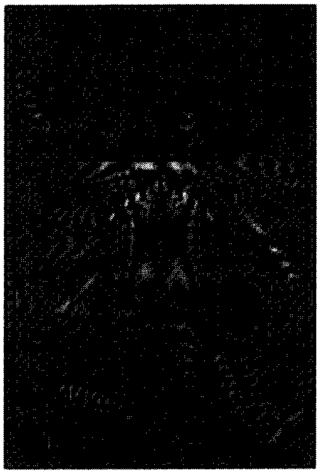

Fig. 7 Electric field pattern at time step of $n = 2000$.

After that, the distance along AA' and BB' in Fig. 1 are considered. Figures 8 and 9 show the power delay profile along AA' and BB', respectively. The distance along AA' is the line-of-sight (LOS) environment, while the distance along BB' is the obstructed (OBS) environment. We can clearly see the characteristic of fading along AA' and BB'. These data are used to model the channel.

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

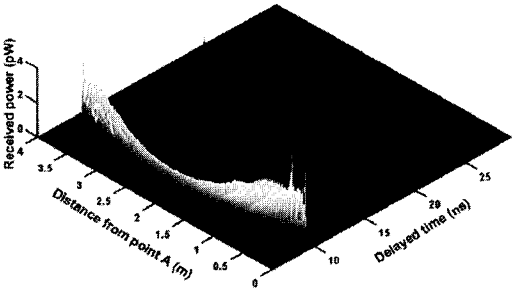

Fig. 8 Power delay profile along AA'.

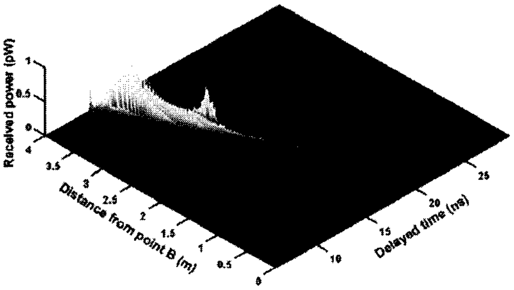

Fig. 9 Power delay profile along BB'.

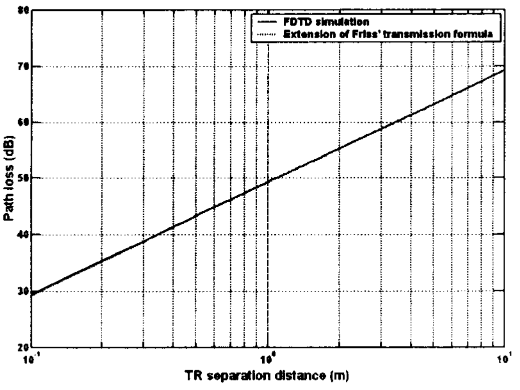

Fig. 10 Free space path loss obtained from FDTD simulation compared with that obtained from Friis' transmission formula.

Subsequently, the two areas, Area #1 and Area #2, as shown in Fig. 11, are considered for the LOS and OBS environments, respectively. The path loss of both considered areas is modeled by using the regression model. The PDF and CDF of fading are illustrated.

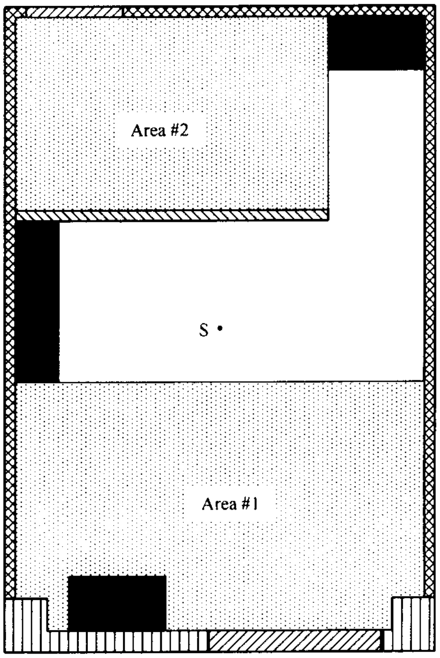

Fig. 11 Area #1 and Area #2 that are used to consider LOS and OBS, respectively.

For modeling the path loss, the linear regression model based on log-distance path loss model [22] is used. The model can be realized by curve fitting on a scatter plot of obtained path loss and then the path loss exponent n is derived from:

$$PL(d) = \overline{PL}(1) + 10n\log(d) + X_{\sigma} \qquad (14)$$

where $PL(d)$ is the path loss in dB at the TR separation distance of d, $\overline{PL}(1)$ is the average large-scale path loss at 1 m TR separation distance, X_{σ} is the shadowing fading parameter with the 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 the UWB signal propagation in Area #1 and Area #2.

Figure 12 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 points 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. 13. The 207,861 data points are used to model the path loss. For this area, the model parameters are $\overline{PL}(1) = 64.79$ dB and $n = 0.35$.

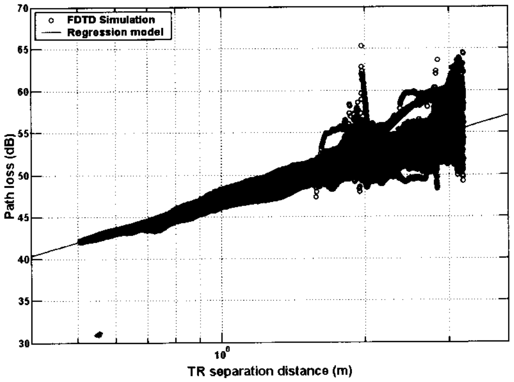

Fig. 12 Scatter plot of the path loss obtained from FDTD simulation and regression model in Area #1.

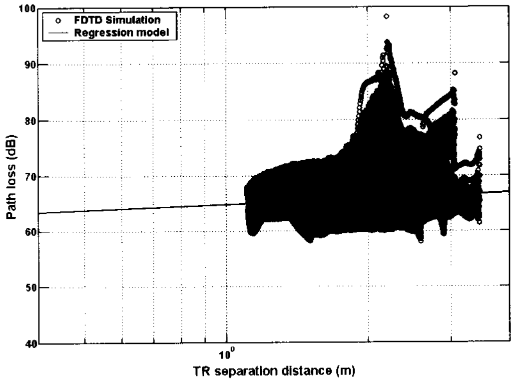

Fig. 13 Scatter plot of the path loss obtained from FDTD simulation and regression model in Area #2.

For considering the fading parameter X_σ, the statistic model is used. The PDF and CDF of fading are evaluated. Figure 14 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. 15. 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 the OBS environment, fluctuates more than that in Area #1, which is the LOS environment.

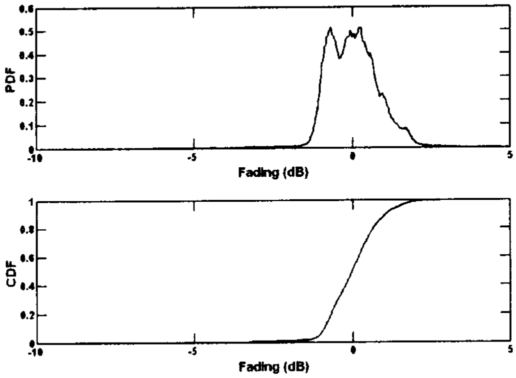

Fig. 14 PDF and CDF of fading in Area #1.

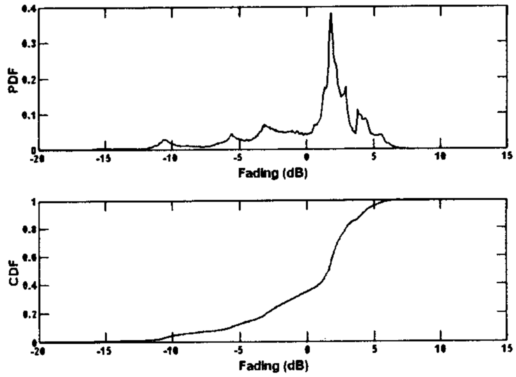

Fig. 15 PDF and CDF of fading in Area #2.

4. Conclusion

In this paper, a 2-D TM mode of FDTD method is used to simulate the indoor radio wave propagation. It is flexible to model a UWB channel of different environment according to the desired accuracy by setting the cell size. The free space path loss obtained from the FDTD method is verified with that obtained from the extension of Friis' transmission formula. By using the FDTD method, numerous data points can be obtained for modeling the path loss. 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 understanding of the UWB channel model of a specific environment is essential for the link budget. Therefore, this FDTD method provides a highly flexible and convenient tool for modeling the UWB channel.

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