PATH LOSS ESTIMATION IN 3D ENVIRONMENTS USING A MODIFIED 2D FINITE-DIFFERENCE TIME-DOMAIN TECHNIQUE

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Abstract: Interest has been growing regarding the use of Wireless Sensor Networks (WSNs) for monitoring and assessing the conditions of infrastructure such as tunnels, bridges and water supply systems. Therefore it is vitally important for us to understand the radio propagation characteristics, especially the Path Loss of these specific environments prior to the deployment of a WSN. The Finite-Difference Time-Domain (FDTD) technique using the Yee algorithm [1] is well-known for its ability to produce accurate predictions of received signal levels. However, when facing the challenges of large-scale systems e.g., nodes located in fire hydrants, tunnels, etc, the computational requirements of this technique become overwhelming, particularly for 3D simulations. In this paper, based on comparisons between conventional 2D FDTD simulations and existing analytical models of Free Space Path Loss and Plane Earth Path Loss, we propose a Modified 2D FDTD method. A unique path loss correction factor is determined. It converts a 3D signal source into an equivalent 2D source and provides path loss results which are identical to those of a full 3D model in both free space and plane earth scenarios.

I. Introduction

Having knowledge of the path loss versus distance characteristic of the scenarios at hand, we can predict the likely maximum communication range between wireless sensor nodes for any particular wireless sensor parameters, specifically the receiver sensitivity and transmit power. This will avoid having to go and repeat propagation tests if nodes with different characteristics are deployed in the future. In addition the path loss models can be used to perform estimates of the signal power to interference power ratio. By investigating the path loss model, an effective wireless sensor network (WSN) can be deployed to monitor and assess, for example, the leakage in local water distribution networks or the deformation in tunnels.

There are two conditions needed to convert a 3D FDTD into a 2D problem addressed in [2]: The property of the modeled structure and the property of the incident wave (signal source). To make the transformation from 3D into 2D realistic, we will have to handle these two issues separately. In this paper, we consider simple structures, specifically free space and plane earth models, which both satisfy Taflove's structural descriptions. Now addressing the second issue, we note that in a 3D environment, the wave from a point source spreads out in a spherical manner. In contrast, we observe that in a 2D plane, propagation occurs in a circular manner. We will now reveal the actual relationship between a 3D source and a 2D source in the FDTD technique.

II. Free Space Path Loss Model

We begin with the simplest model, i.e., the Free Space Model, which is the foundation of all other propagation models. The analytical formulation for free space path loss in decibels [3] can be expressed as:

$$PL_{FS}\left(dB\right) = 20\log_{10}\left(R/1000\right) + 20\log_{10} f + 32.4\,, \quad (1)$$

where R is the distance between the transmitter and the receiver in m and f is the signal frequency in MHz. Here we take TE mode (E_x, H_x, H_y) as an example. At a frequency of 868MHz, Figure 1 illustrates the discrepancy between a conventional 2D TE FDTD simulation and the corresponding analytical plot. We define the difference (in decibels i.e., dB) between our conventional 2D FDTD simulation and the analytical model as a variable - y:

$$y = a\log_{10} R + b \text{ and } b = n\log_{10} f + m\,, \quad (2)$$

where a, m and n are unknown variables. A series of discrepancy studies yielding results of the form shown in Figure 1 have been conducted at 12 different frequencies using conventional 2D TE FDTD simulations. The results are shown in Table 1. It can be seen from the second column of Table 1 that a has a constant value of 10. There are 12 simultaneous equations of b available to solve for n and m in Eqn. (2).

f (MHz)	y(TE)	y(TM)	Cell Size (m)
150	10.019log(*R*) - 1.4207	10.017log(*R*) - 1.4108	0.1000
290	10.020log(*R*) + 1.3686	10.020log(*R*) + 1.3688	0.0500
433	9.9896log(*R*) + 2.9039	9.9862log(*R*) + 2.8997	0.0346
650	9.9999log(*R*) + 4.6573	9.9902log(*R*) + 4.9789	0.0230
868	10.002log(*R*) + 5.9143	10.009log(*R*) + 6.2230	0.0173
1000	10.006log(*R*) + 6.8385	10.000log(*R*) + 6.8442	0.0150
1250	9.9920log(*R*) + 7.4185	10.005log(*R*) + 7.8127	0.0120
1500	9.9968log(*R*) + 8.6074	10.005log(*R*) + 8.6010	0.0100
1750	9.9958log(*R*) + 9.1254	10.010log(*R*) + 9.2779	0.0086
2000	10.007log(*R*) + 9.8557	9.9983log(*R*) + 9.8616	0.0075
2200	10.004log(*R*) + 9.9830	9.9726log(*R*) + 10.275	0.0068
2400	10.016log(*R*) + 10.545	9.9371log(*R*) + 10.709	0.0063

TABLE 1. DISCREPANCY STUDIES ON 2D TE & TM FDTD FREE SPACE MODEL

As a result, a path loss correction factor (CF) appropriate for 2D TE FDTD mode in free space is:

$$y = CF_{FSTE}\left(dB\right) = 10.0040\log_{10} R + 10.0006\log_{10} f - 23.3220\,. \quad (3)$$

By subtracting the path loss CFs from the results of a conventional 2D FDTD simulation at the corresponding distances, a Modified 2D FDTD technique is established. Figure 1 also shows that including the CF yields results that match the analytical results at 868MHz. Using the same approach, the CF of free space for our Modified 2D TM FDTD model has an almost identical formulation to that for the TE model:

$$y = CF_{FSTM}\left(dB\right) = 9.9959\log_{10} R + 9.9981\log_{10} f - 23.1850\,. \quad (4)$$

III. Plane Earth Path Loss Model

Above a flat reflecting ground (plane earth), the transmitter and the receiver antennas are located at the heights (in m) of h_t and h_r respectively. At the receiver antenna the resultant signal is the summation of a direct path and a reflected path from the ground. This is another fundamental model in radio communication and is known as the plane earth model. To further investigate our notion of a path loss correction factor, we moved on to consider this well-established propagation model. The analytical formulation for plane earth path loss model in decibels [3] can be expressed as:

$$PL_{PE} = 10\log_{10}\left\{\left(\frac{\lambda}{4\pi R}\right)^2\left|1+\rho\exp\left(jk\frac{2h_t h_r}{R}\right)\right|^2\right\}, \quad (5)$$

where ρ is the reflection coefficient for the reflected ray; k is the free space wavenumber $2\pi/\lambda$. For example, ρ in the TE model is expressed as:

$$\rho_{TE} = (\sin\psi-\sqrt{(\varepsilon_r - jx)-\cos^2\psi})\Big/(\sin\psi+\sqrt{(\varepsilon_r - jx)-\cos^2\psi}), \quad (6)$$

where $x=18\times10^9\delta/f$; ε_r is relative permittivity of the ground; δ is conductivity of the ground; ψ is the angle between the incident wave and the ground surface.

In our 2D FDTD simulation, we assume that the ground has the following physical constants of concrete: relative permittivity $\varepsilon_r=8.0$, relative permeability $\mu_r=1.0$ and conductivity $\delta=0.02\,S/m$. The height of the transmitter and the receiver antennas is initially set at 2m. Following the same procedures as used in the free space model investigation, we list our TE and TM 2D FDTD simulation results in Table 2.

f (MHz)	y(TE)	y(TM)	Cell size (m)
150	10.019log(*R*) + 0.4409	9.9588log(*R*) - 2.1393	0.1000
290	10.015log(*R*) + 2.0685	10.029log(*R*) + 0.9510	0.0500
433	10.090log(*R*) + 3.1939	10.063log(*R*) + 2.5601	0.0346
650	10.050log(*R*) + 4.9209	10.100log(*R*) + 5.0944	0.0230
868	9.9606log(*R*) + 6.2694	10.182log(*R*) + 6.2667	0.0173
1000	10.011log(*R*) + 6.6461	10.095log(*R*) + 7.0317	0.0150
1250	10.004log(*R*) + 8.0006	9.9094log(*R*) + 7.9927	0.0120
1500	10.117log(*R*) + 8.7553	10.123log(*R*) + 8.2680	0.0100
1750	10.110log(*R*) + 8.9352	10.066log(*R*) + 9.5545	0.0086
2000	10.138log(*R*) + 9.8690	10.115log(*R*) + 9.7922	0.0075
2200	10.215log(*R*) + 9.8539	9.9546log(*R*) + 10.591	0.0068
2400	10.183log(*R*) + 10.692	10.091log(*R*) + 10.490	0.0063

TABLE 2. DISCREPANCY STUDIES ON 2D TE & TM FDTD PLANE EARTH MODEL

The path loss CFs for the plane earth model for TM and TE modes are:

$$y = CF_{PETE}(dB) = 10.0761\log_{10} R + 10.0141\log_{10} f - 23.0748, \quad (7)$$

$$y = CF_{PETM}(dB) = 10.0572\log_{10} R + 9.9874\log_{10} f - 23.2673, \quad (8)$$

respectively. From the investigations conducted, we can see that all the four path loss CFs in Equations (3), (4), (7) and (8) are virtually identical, and also can be combined as the following CF to transform a simple structured 3D FDTD simulation into a modified 2D FDTD model:

$$CF_{PL}(dB) = 10\log_{10} R + 10\log_{10} f - 23.2123. \quad (9)$$

Furthermore, field measurements for the plane earth scenario have been conducted in a sports field. At each measurement position, the transmitter has been moved randomly within a 1 m^2 area while 100 samples are recorded. By applying this measurement strategy, the fading due to multipath can be averaged out allowing the mean path loss can be calculated. The measurement data is presented in Figure 2 and Figure 3 for comparison with the analytical and FDTD results. In both cases we observe a close correspondence between the results of the modified 2D FDTD simulations and the TE and TM analytical models.

IV. Conclusions

In conclusion, a discrepancy exists in both free space and plane earth scenarios owing to the use of a 2D FDTD model to represent a 3D environment. Consequently, the results from a conventional 2D FDTD need to be modified to accurately represent those produced by a 3D FDTD. However, in situations of practical interest, the simulation geometry gets more complicated. For example, consider the investigation of the path loss model appropriate for a wireless node located in a fire hydrant chamber with a cast iron lid. For the future, we are going to introduce a Modified 2D FDTD Path Loss Model of the fire hydrant link [4] and also for a tunnel environment.

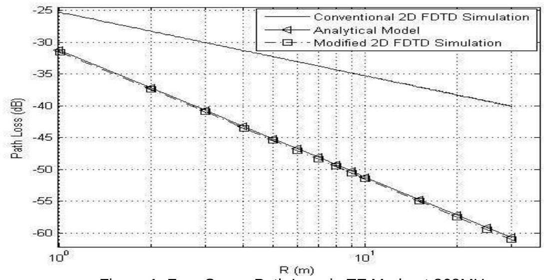

Figure 1. Free Space Path Loss in TE Mode at 868MHz.

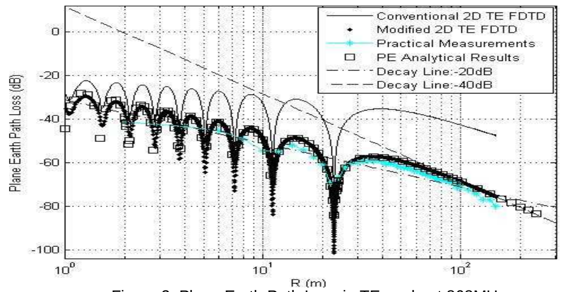

Figure 2. Plane Earth Path Loss in TE mode at 868MHz.

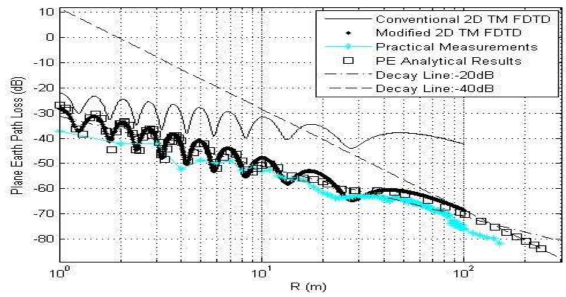

Figure 3. Plane Earth Path Loss in TM mode at 868MHz.

References

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