MODIFIED 2D FINITE-DIFFERENCE TIME-DOMAIN TECHNIQUE FOR TUNNEL PATH LOSS PREDICTION

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ABSTRACT

To effectively deploy wireless sensor networks (WSNs) for monitoring and assessing the condition of tunnels, a Propagation Path Loss (PL) Model, which describes the power loss versus distance between the transmitter and the receiver in a specific environment, is required. For most of the existing propagation measurements conducted in tunnels, the antennas have been positioned along the central axis of a tunnel. However this is not representative of most infrastructure monitoring applications where the wireless sensor nodes will be mounted on the walls of the tunnel. In this paper, the results obtained from conducting close-to-wall measurements at 868MHz and 2.45GHz in a curved arched-shaped tunnel are presented along with predictions made using a newly proposed Modified 2D Finite-Difference Time-Domain (FDTD) method. During our measurements, the antennas are always maintained at a height of 2m. However the antenna distance to the tunnel wall is varied. By having the PL model as a guideline, we are able to determine the critical parameters for wireless communication in a tunnel, such as maximum communication distance, transmit power and receiver sensitivity.

1. INTRODUCTION

Having knowledge of the Path Loss (PL) versus distance characteristic for the infrastructure scenarios being considered, enables us to predict the likely maximum communication range between wireless sensor nodes for any particular wireless sensor parameters, specifically the receiver sensitivity and transmit power. This avoids having to go and repeat propagation tests if nodes with different characteristics are deployed in the future. In addition the PL models can be used to perform estimates of the signal power to interference power ratio. The determination of appropriate PL models enables effective WSN deployment, for example, to monitor and assess deformation in tunnels.

The increase of path loss with distance varies generally between 20 dB per decade for free space conditions and may exceed 50 dB per decade for NLOS simulation with very high building densities [2]. In [3], Zhang further concluded that there are two propagation regions in a tunnel. The initial region exhibits path losses similar to that seen in free space followed by a region where the path loss gets worse more gradually since they act like oversized wave guides.

By directly solving Maxwell's equations in the time domain, the Finite-Difference Time-Domain (FDTD) method [1] fully accounts for the effects of reflection, refraction and diffraction in a model. The medium constitutive relation is incorporated into the exact solution of Maxwell's formulations. The advantages of the FDTD method are its accuracy and providing a complete solution for the signal coverage information throughout a defined problem space. Therefore it is well suited to the studies of the Electromagnetic propagation characteristic in a complex environment.

Note that the FDTD requires memory to store the basic unit elements of the model and also demands iterations in time in order to update the fields along the propagation direction. In other words, excessively large computational power in terms of CPU execution time and memory usage are often needed for conventional FDTD approaches to large-scale problems. In this paper, we are going to present our field measurements for side mounted antennas and then propose the Modified 2D FDTD tunnel model for the PL predictions.

The paper is organised as follows. The measurement equipment, procedures and the geometry of the investigated tunnel are introduced in Section 2. Measurement results and analysis follows in Section 3, while in Section 4, the Modified 2D FDTD model is presented along with simulation results and comparisons with measured results. Finally, Section 5 draws our conclusions.

2. FIELD MEASUREMENT SETUP

Our measurements are conducted at 868MHz and 2.45GHz within the Aldwych underground railway tunnel in London, which is 3.6m in diameter and 3.2m from the track bed to the crown. Figure 1 gives a cross-sectional view of the tunnel. The side mounted transmitter was positioned close the tunnel wall at the height of 2m(Y_s), 0.05m (X_S) away from the wall and oriented vertically to the tunnel base. The use of a vertical antenna is to limit intrusion into the tunnel. Here we represent the side located transmitter position as T (X_s,Y_s,Z_0). The receiver position is represented as R (x,Y_s,z), where z is the distance along the tunnel from reference point Z_0. For reference and comparison purposes, we also used a 2m transmit antenna mounted at the centre line of the tunnel.

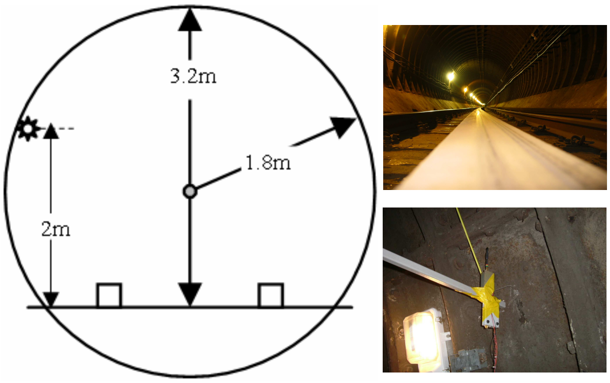


Figure 1: Aldwych Cross-Sectional View and Transmitter Position

At the receiver, the signal power is measured using a portable spectrum analyzer (SA) (Anritsu MS2721A) which is connected to a dipole antenna via a 10m low-loss coaxial cable. At the transmitter, AtlanTech ANS3-0800-001 (800~1200MHz) and AtlanTech ANS3-2000-001 (2000~3000MHz) battery powered signal generators are used. In addition, a Mini-Circuits power amplifier (PA) is used to increase the transmit power and a dipole antenna having an appropriate centre frequency is connected directly to the PA. The accuracy of this measurement setup has been validated in our plane earth measurements performed in [4]. Figure 2 illustrates the 2D plan view of the tunnel while on the right hand side, two small circles represent the positions of the center transmitter and the side transmitter antennas.

Two different measurement techniques are applied as will now be described:

a. A Low Resolution (LR) Technique, where measurements are conducted at intervals of 2m, 5m and 10m depending upon the transmitter to receiver separation and the operating frequency. At each measurement position, the transmitter is moved randomly within a 1 square meter area while 100 samples are recorded. By using this technique, the fading due to multipath can be averaged out allowing the mean path loss to be estimated.
b. A High Resolution (HR) Technique, in which, the receiver is moved slowly and continuously along the tunnel while the received signal strength is recorded using a sampling interval of 0.5s. This method provides us with detailed PL information against distance. In contrast to the LR method the measurement results still exhibit signal fading. It is

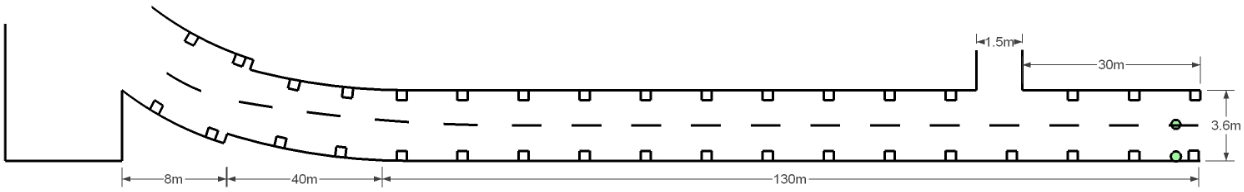


Figure 2: Aldwych 2D Geometry Plan and Transmitter Position

	Set	Tx	Rx	Measurements
i	Centre to Centre (C-C): both transmitter and receiver are deployed at equal distance (noted as Xc) to both side walls	(X_c,Y_s,Z_0)	(X_c,Y_s,z)	LR & HR
ii	Side to Centre (S-C)	(X_s,Y_s,Z_0)	(X_c,Y_s,z)	LR & HR
iii	Side to Same Side 2cm (S-SS 2cm): receiver is 2cm away from the wall with transmitter mounted (noted as Wall S)	(X_s,Y_s,Z_0)	(X_{iii},Y_s,z)	LR
iv	Side to Same Side 11cm (S-SS 11cm): receiver is 11cm away from Wall S	(X_s,Y_s,Z_0)	(X_{iv},Y_s,z)	HR
v	Side to Opposite Side 2cm (S-OS 2cm): receiver is 2cm away from the wall opposite to Wall S	(X_s,Y_s,Z_0)	(X_v,Y_s,z)	LR
vi	Side to Opposite Side 11cm (S-OS 11cm): receiver is 11cm away from the wall opposite to Wall S	(X_s,Y_s,Z_0)	(X_{vi},Y_s,z)	HR

Table 1: Six Sets of Measurements

not possible to take measurements at 2cm from the tunnel sides with any accuracy owing to flanges that protrude by about 10cm and other obstructions on the tunnel wall. Consequently, to obtain accurate results at closer spacings e.g., 1~2cm, the LR technique is more suitable.

For each frequency, we carried out six sets of measurements, which are described in Table 1. Appropriate measurement techniques are applied in each set of measurements.

3. FIELD MEASUREMENTS RESULTS AND ANALYSIS

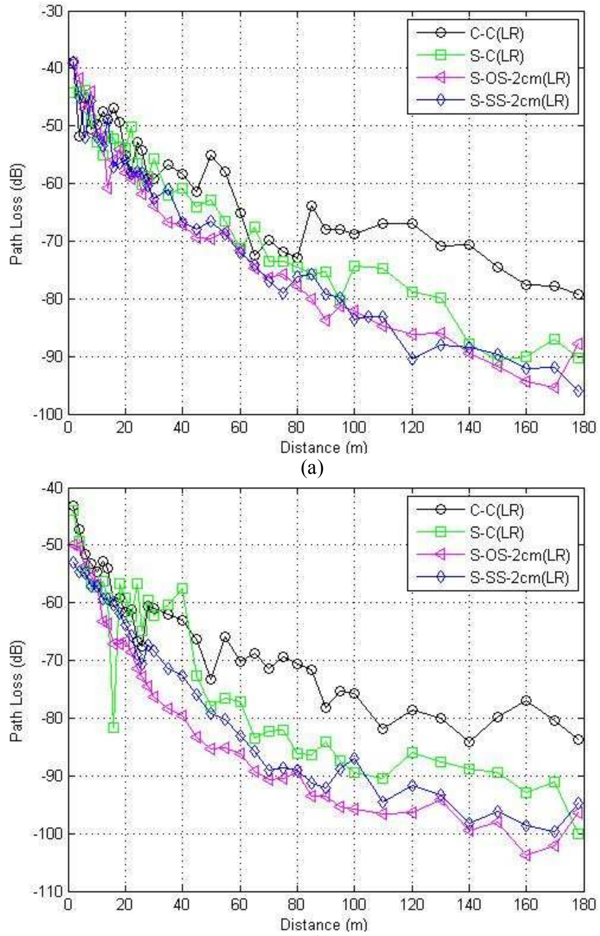
The PL is defined differently in various contexts. To avoid confusion, here we define our PL model in dB as:

$$PL_{(dB)} = P_{Tx(dBm)} + G_{Tx(dB)} + G_{Rx(dB)} - P_{Rx(dBm)} + P_{cable\_loss(dB)}, \quad (1)$$

where P_{Tx} is the transmit power; P_{Rx} is the receive power; P_{cable_loss} is the coaxial cable loss, which adds 1.5dB loss at 868MHz and 2.0 dB loss at 2.45GHz; G_{Tx} and G_{Rx} are the transmit and receive antenna gain respectively (both are 2 dB).

From the LR measurements presented in Figure 3, in general, it can be seen that the PL increases more rapidly in the near region than in the far region of the tunnel. The PL worsens with side mounted antennas, specifically in the order C-C, S-C, S-SS, S-OS. In another words, more transmit power is needed using side mounted antennas to achieve the same coverage as for the C-C case. In terms of the transmit frequencies, 868MHz has a better performance than 2.45GHz. This is owing to the fact that diffraction losses will be greater at 2.45GHz due to the smaller wave length, i.e., 12cm compared with 35cm. Comparisons between the LR and the HR techniques for the C-C scenario at 868MHz and 2.45GHz have shown close agreement.

As can been seen in Table 1, the S-SS and the S-OS scenarios have been investigated for receive antenna to wall spacings of 2cm and 11cm. From the measurement results shown in Figure 4, it can be seen that in general the 11cm spacing performs better than does the 2cm spacing. In other words, the close-to-wall scenario at the receive antenna gives a worse overall performance. Note that for clarity, we only plotted one fifteenth of the samples collected from the HR measurements. We also added the offsets of +60dB, +30dB, 0dB and -30dB for Figure 4(a), (b), (c) and (d) respectively in order to conserve space. The detailed close-to-wall investigations will be presented in [5].



(a)

(b)

Figure 3: PL Performance Comparison at Different Antenna Positions: a. 868MHz; b. 2.45GHz

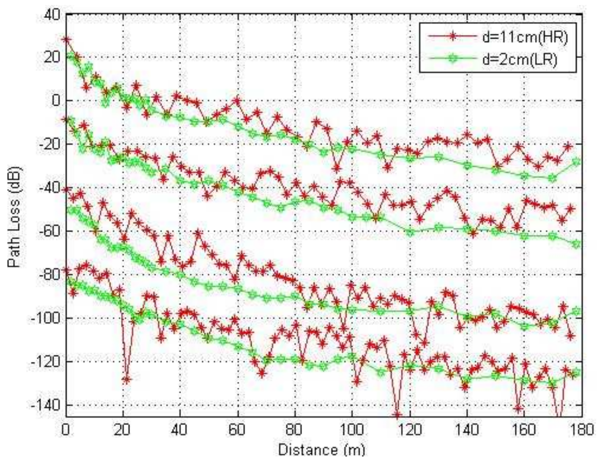


Figure 4: 2cm vs. 11cm Close-To-Wall Antenna Position Comparisons (from top down): a. (S-OS-2cm) vs. (S-OS-11cm) at 868MHz; b. (S-SS-2cm) vs. (S-SS-11cm) at 868MHz; c. (S-OS-2cm) vs. (S-OS-11cm) at 2.45GHz; d. (S-SS-2cm) vs. (S-SS-11cm) at 2.45GHz

4. MODIFIED 2D FDTD TUNNEL MODEL

The conventional FDTD method proposed by Yee [1] has been serving the EM modeling community for more than 40 years. Although a huge amount of effort has been dedicated to improve this method, the conventional FDTD is stable and it is straight forward to implement. These issues are of fundamental importance for the large-scale EM simulation required in our situation. The truth is that it is almost impossible to implement a full 3D tunnel model using the conventional FDTD method as the computational cost is overwhelming to any regular computer.

Consequently, the problem has become how can we convert a 3D tunnel model into a realistic 2D FDTD simulation, i.e., removing the computational burden while at the same time preserving the factors that shape the radio propagation characteristics. This has lead to our proposing the Modified 2D FDTD Method.

Based on the current understanding, it is known that transmit frequency, antenna position, tunnel diameter, building material and course are the main factors which affect radio propagation in a tunnel. The 2D tunnel structure used in the FDTD simulations is that shown in the plan of the Aldwych tunnel given in Figure 1. Figure 5 illustrates the layout of the model in our simulation, where the TM $\left(E_z, H_x, H_y\right)$ mode in the conventional 2D FDTD method is used according to our measurement setup.

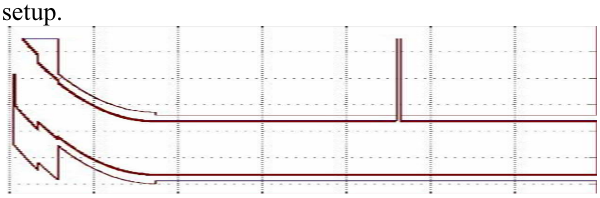


Figure 5: Modified 2D FDTD Tunnel Structure.

The unit cell sizes are 1.73cm at 868MHz and 0.61cm at 2.45GHz in order to maintain accuracy. The Cast Iron lining is represented as $(\varepsilon_r = 1.0, \mu_r = 1.0, \sigma = 20\times 10^3)$.

Previously we have shown that by applying the correction factor (CF) in Eqn. (2), we are able to achieve a close match between 2D FDTD simulation results and those due to a full 3D free space model or plane earth

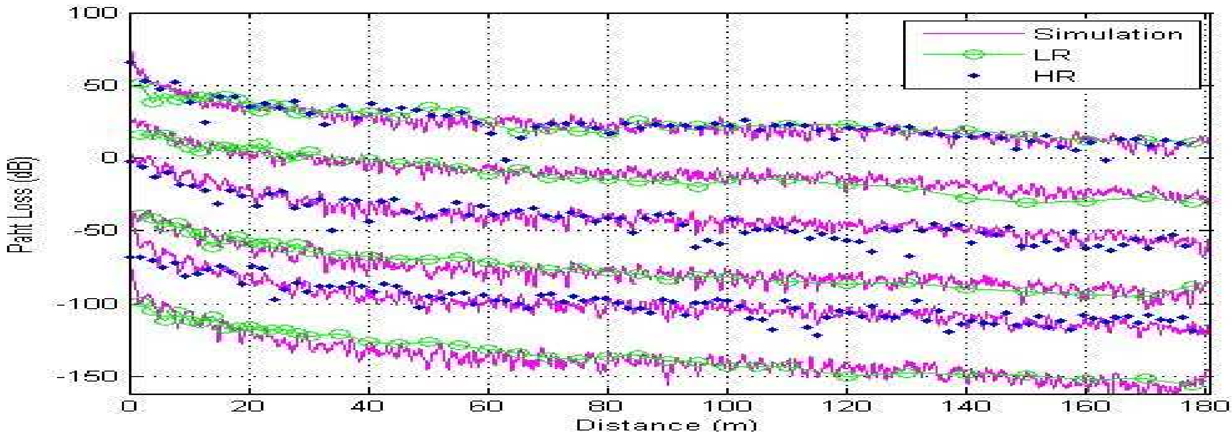


Figure 6: 868MHz (from top down): a. C-C (+90dB Offset); b. S-C (+60dB Offset); c S-OS 2cm (+30dB Offset); d. S-OS 11cm (0dB Offset); e. S-SS 2cm (-30dB Offset); f. S-SS 11cm (-60dB Offset).

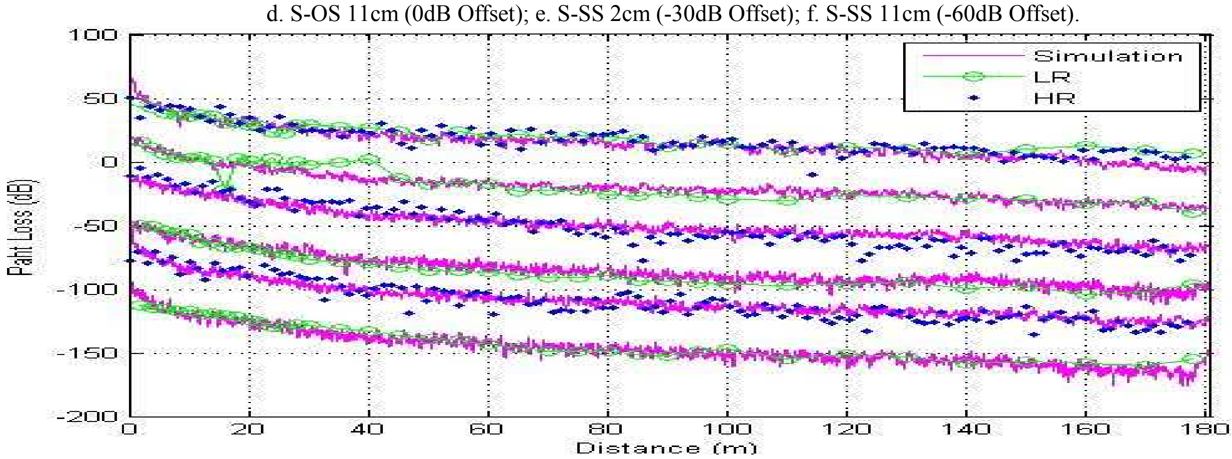


Figure 7: 2.45GHz (from top down): a. C-C (+90dB Offset); b. S-C (+60dB Offset); c S-OS 2cm (+30dB Offset); d. S-OS 11cm (0dB Offset); e. S-SS 2cm (-30dB Offset); f. S-SS 11cm (-60dB Offset).

mode [6].

$$CF_{(dB)} = 10\log_{10}(R) + 10\log_{10}(f) - 23.2123, \quad (2)$$

where R is the distance between the transmitter and the receiver in m and f is the signal frequency in MHz.

We assume that the CF for the Modified 2D FDTD tunnel model is also of the same form, i.e.,

$$CF_{(dB)} = a\log_{10}(R) + b\log_{10}(f) + c, \quad (3)$$

where a, b, and c are the unknown variables. By comparing the difference between the initial simulation results from the conventional 2D TM FDTD method and the measurement data in the C-C scenario at both 868MHz and 2.45GHz, the following CF is determined:

$$CF_{(dB)} = 20\log_{10}(R) + 8\log_{10}(f) - 19.2123. \quad (4)$$

The Modified 2D FDTD tunnel PL predictions are obtained by using the CF to modify the 2D FDTD simulation data. A close correspondence between the measurement results and our simulation results can be seen in Figure 6 and Figure 7, which demonstrates that the newly proposed CF is acceptable for correcting conventional 2D FDTD results to represent measurements conducted in a full 3D environment.

The simulation has a very high resolution compared with the measurements, i.e., of the order of 10^4 samples in the simulation, $10^2 \sim 10^3$ in the HR measurements and much less in the LR measurements. The average Root mean square (rms) error between the simulation and measurement results for all 6 scenarios at each frequency are shown in the 2nd column in Table 2. By applying a window filter, the simulation results are reduced to the same resolution as the measurements. This second comparison shows a much reduced rms error as shown in the 3rd column. In reality, we are interested in quantifying the prediction error for the mean path loss. Consequently to remove the fading effects, we applied window filters with an averaging window size up to 100 samples both to the simulation and to the measurement data. As a result, the rms error is further reduced as shown in the 4th column of Table 2.

	1st	2nd	3rd
868MHz	5.965	3.6441	1.546
2.45GHz	6.174	3.9055	1.877

Table 2: Comparisons of RMS Error (dB) for the Modified 2D FDTD Tunnel Model

There are several issues that we want to address in terms of the rms errors. From the simulation aspect, the total number of time steps for the FDTD iteration is not large enough to cover the multipath effect at the far end, therefore we may expect larger errors occurring toward the far end. Also we are effectively dealing with a 2D environment rather than 3D, thus due to the lack of one dimension, we may expect reduced fading than in the full 3D radio propagation environment.

Our 2D FDTD simulation was performed on a 3.46GHz, 8GB RAM, Dell Precision PWS 380 computer. The current simulation time for 868MHz is approximately 15 hours and 90 hours for 2.45GHz, which can be later reduced by 70% after using the Segmented FDTD method as proposed in [7].

5. CONCLUSIONS

Within a specific tunnel environment, the PL worsens with side mounted antennas, this applies both to the receiver and transmitter ends. The PL also becomes worse when the transmit frequency is increased. The Modified 2D FDTD Tunnel Model has shown reasonable accuracy, especially for the overall mean PL values.

As part of our future work, we are targeting different construction materials, e.g. concrete, different diameter, e.g., 5m, and different tunnel courses when the transmitter is deployed on the side wall. Since there are basically two sets of information involved in the FDTD simulation, i.e., field strength and phase, it should also be possible to investigate signal angle of arrival in a tunnel environment.

6. REFERENCES

[1] K.S. Yee, Numerical Solution of Initial Boundary Value Problems involving Maxwell's Equations in Isotropic Media, IEEE Trans. Antennas Propagat., vol. 14, No. 3, pp. 302-307, May 1966.

[2] D.J. Cichon, and T. Kurner, *COST Telecommunications – COST Action 231 Digital Mobile Radio Towards Future Generation Systems Final Report*, Chapter 4, Propagation Prediction Models, COST 231 TD(95), pp. 190-195, Sept. 2005.

[3] Y.P. Zhang, Novel Model for Propagation Loss Prediction in Tunnels, IEEE, Trans. Vehicular Technol., vol. 52, No. 5, pp. 1308-1314, Sept. 2003.

[4] M. Lin, Y. Wu, I.J. Wassell, Wireless Sensor Network: Water Distribution Monitoring System. 7th IEEE Radio & Wireless Symposium, Jan. 2008.

[5] Y. Wu, M. Lin, and I.J. Wassell, Investigation of Close-to-Wall Wireless Sensor Deployment using 2D Finite-Difference Time-Domain Modelling, 2nd International Conference on Wireless Communication in Underground and Confined Areas (To Appear), Aug. 2008.

[6] Y. Wu, M. Lin, I.J. Wassell, Path Loss Estimation in 3D Environments using a Modified 2D Finite-Difference Time-Domain Technique, 7th International Conference on Computation in Electromagnetics, Apr. 2008.

[7] Yan Wu, Ian Wassell, Introduction to the Segmented Finite-Difference Time-Domain Method. 13th Biennial IEEE Conference on Electromagnetic Field Computation (CEFC 2008), May 2008.