

Use of Parabolic Equation Wide-Angle for calculation of Path Loss in Indoor Environment

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Abstract — This paper proposes a model to calculate the propagation path loss in an indoor environment using parabolic equation wide angles relative to paraxial direction of propagation, resolving it using the Mixed Fourier Transform, and comparing the results with UWB model and Wall and Floor Propagation Losses Model. A campaign of measurements was carried out in two environments at frequencies of 900 MHz and 2.4 GHz. The average error in the Parabolic Equation Method is 4.64 dB and 4.24 dB and it is 3.94 dB and 2.88 dB for the ground floor and first floor, respectively for the two environments.

Index Terms — Indoor; Fourier; Parabolic.

I. INTRODUCTION

Electromagnetic field prediction models for indoor and urban environments have several applications including wireless channel characterization. The characterization of path loss in indoor environments has been the subject of extensive research and many models have been proposed to make accurate predictions. Statistical models are easy to obtain when a lot of measurement data is available, but their validity is limited to the category of buildings they represent [1].

The characterization of path loss in indoor environments has been the subject of extensive research and many models have been proposed to make accurate predictions. Statistical models are easy to obtain when a lot of measurement data is available, but their validity is limited to the category of buildings they represent [2].

Studies show that there is no linear relationship between the radio wave attenuation and number of floors in multistoried buildings. The reasons are the reflection between buildings and the diffraction produced by the windows. The buildings used for the measurements campaigns have many walls and floors that have to be taken into account for efficient calculation of the path loss, and the Wall and Floor Propagation Losses Model does this. Hybrid methods combined with deterministic models and stochastic models show good precision. Specifically, the UWB Model [3] and Wall and Floor Propagation Losses Model [4] will be used to make a comparison with the model proposed in this work.

Method is that it requires less computing effort than full elliptical methods. The model presented in this work is based on the Parabolic Equation Method for the path loss calculation. Our implementation handles wide angles relative to the paraxial propagation direction (up to 90°). It uses mixed Fourier transform and considers the impedance boundary conditions.

To validate the proposed model, a measurement campaign was carried out at the Amazon Institute of Superior Studies (IESAM – Belem – PA - Brazil), using a frequency of 900 MHz, and at the Laboratory of Electric Engineering and Computation (LEEC) of

the Federal University of Para, using a WLAN frequency of 2.4 GHz, and a bandwidth of 22 MHz. The results obtained were compared with two models existing in the literature. A complex refractive index was considered for all the materials present in the buildings and furniture located inside the environments studied.

This paper is organized as it follows: the section II shows the theoretical method; section III describes the environment; in section IV is presented the path loss calculates parabolic equation and measured; the path loss models are shown in the section V; in section VI is presented the results; and section VII, the conclusion.

II. THE THEORETICAL METHOD

The two-dimensional scalar wave equation can written as [6]

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} + k^2 n^2 \psi = 0 \quad (1)$$

where k is the wave number and n the refractive index. Following Levy [6], we choose x as the paraxial direction and replace the function $\psi(x, z)$ by $e^{ikx}u(x, z)$ in (1), factored into two equations for computing the forward and backward propagation waves and solved giving the propagation in the forward or positive direction, using the operator by Feit and Fleck leads to the result [2] – [6]

$$\frac{\partial u}{\partial x} - i\sqrt{k^2 + \frac{\partial^2}{\partial z^2}}u - ik(n-2)u = 0 \quad (2)$$

Equation (2) is the wide-angle parabolic equation used in this paper [6].

The mixed Fourier transform was introduced as a rigorous method to incorporate surface impedance into split-step solutions of the parabolic wave equation. We follow the standard procedure to solve (2) using Mixed Fourier Transform and *split-step* [7],

$$\begin{aligned} u(x + \Delta x, z) = & e^{ik(n-1)\Delta x/2} \\ & \left[\frac{2}{\pi} F_s \left\{ \frac{\alpha}{\alpha^2 + p^2} e^{i\Delta x(\sqrt{k^2 - p^2} - k)} U(x, p) \right\} + \right. \\ & - \frac{2}{\pi} F_c \left\{ \frac{p}{\alpha^2 + p^2} e^{i\Delta x(\sqrt{k^2 - p^2} - k)} U(x, p) \right\} + \\ & \left. + e^{i\Delta x(\sqrt{k^2 - \alpha^2} - k)} e^{-\alpha z} K(x) \right] \end{aligned} \quad (3)$$

where

$$U(x, p) = \alpha F_s \left\{ e^{ik(n-1)\Delta x/2} u(x, z) \right\} - p F_c \left\{ e^{ik(n-1)\Delta x/2} u(x, z) \right\} \quad (7)$$

III. DESCRIPTION OF THE ENVIRONMENT

Different geometric structures and materials (walls of brickwork and PVC, doors of wood, iron and formic acid, and windows in glass and aluminum, steel in the elevators, etc.) in the buildings were considered, since they interfere in the propagation of the electromagnetic wave, causing losses in the received signal, when compared to the transmitted signal.

The IESAM was one of the five story buildings used for a measurement campaign. The building used as the test environment has corridors, computer science laboratories, laboratories for experimental work, classrooms, bathrooms, etc.

The other test environment was the LEEC. This environment was composed of a building with 2 floors, not inhabited, so that just the materials used in its construction were considered.

IV. PATH LOSS CALCULATES PARABOLIC EQUATION AND EXPERIMENTALLY RESULTS

The simulation of wave propagation in the first building used for the campaign of measurements, the IESAM, used a vertically polarized plane wave at 900 MHz as a source for the parabolic equation algorithm. The walls are built of bricks, the slabs are made of concrete, the doors for the 1st to 4th floors are made of wood and the ground floor is made of aluminum. All the windows are made of aluminum and glass.

The measurement setup consists of a transmitter system, composed of a sweeping generator (model HP 83752A), an amplifier (ZHL - 42W) and an antenna (monopole, with gain of 3 dBi). During the measurement campaign, the transmitter set was located at the end of the corridor on the ground floor.

The receiver system is composed of a receiving antenna (monopole, gain of 2.5 dBi), a spectrum analyzer (HP 8593E), a LNA amplifier, an AD-DA acquisition board (LAB JACK U12), a computer for data storage, and a prototype of a vehicle with a 5th wheel, that allows measurement of the distance traveled by the receiver system [8]. The mobile receiver system traveled the corridors of all 5 floors of the building, measuring and storing the signal received and the distance traveled by the system. The receiver antenna is linked to the spectrum analyzer, measuring the level of the signal received. The prototype of a vehicle with a 5th wheel measures the distance traveled by the system. The intensity of the signal measured by the spectrum analyzer and the signal measured by the prototype is sent to the computer through the converter board [8]. The data stored during the measurement campaign are treated and processed for subsequent use. In this paper, the simulation results are presented for the ground floor and first floor of IESAM so a better comparison could be made between the two buildings.

For the other building, the LEEC, a vertically polarized plane wave in line-of-sight (LOS) in the corridor, at 2.4 GHz was used. During the measurement campaign, the points where the measurement would be made were initially marked on the ground: 21 points on the first floor and 25 on the ground floor. After this, an access point was positioned at the entrance to the corridor on the ground floor. A notebook connected to the internal antenna and external antenna (6.0 dBi gain) was used as

receiver for calls, connected to a protocol analyzer. Another notebook with the same characteristics as the first, on a pushcart (that traveled the two floors of the building in the study), measured the received power at each point. The walls of the environment were brick and PVC. The access point is located at the beginning of the corridor.

Only the dimensions of length and width of the studied environments were considered. A FORTRAN program was implemented to simulate (3).

The refractive index is given by the following expression [9]

$$n = \left[\epsilon_r + \frac{i\sigma}{2\pi f \epsilon_0} \right]^{1/2} \quad (4)$$

where ϵ_r is the relative permittivity, σ is the conductivity (S/m), f is the frequency (Hz) and ϵ_0 is the permittivity in the vacuum (F/m). The path loss is calculated by [10]

$$L(\text{dB}) = 36,57 + 20\log_{10} f + 20\log_{10} |u_0| - 20\log_{10} |u| - G_T - G_R \quad (5)$$

where u_0 is the field in the distance of reference d_0 , u is the received field, f is the frequency in GHz, and G_T and G_R are the transmitter and receiving antennas gain in dB, respectively.

Due the differences in the electric characteristics between all the existing materials, it is necessary to use the values of the electromagnetic medium parameters for each of the materials in the building. Table I shows the values of relative permittivity, conductivity and path loss of the materials used.

TABLE I. RELATIVE PERMITTIVITY, CONDUCTIVITY AND PATH LOSS OF THE MATERIALS

Materials	Relative Permittivity	Conductivity (S/m)	Path Loss (dB)
Brick wall (900MHz)[11]	-	-	1.3
Brick wall (2.4 GHz)[12]	5.20	0.01	2.4
Concrete floor (900 Hz)[11]	-	-	4.9
Concrete floor (2.4 GHz)[13]	-	-	6.9
Wood [12]	3.00	0.00	-
Formic [12]	5.00	0.00	-
PVC [12, 14]	2.26	0.00	1.43
Iron [12,15]	12.00	1.03×10^7	-
Paviflex [16]	3.00	1.00×10^{-6}	-

V. PATH LOSS MODELS

To test the efficacy and accuracy of the proposed method, the forward-propagating waves calculated by this algorithm are compared to some models existing in the literature.

A. UWB Model

After finding the path loss through the proposed method, a comparison was made with the UWB model, and the model is described by the following equation [3]:

$$PL(dB) = PL_0 + 10m \log(d) + \chi(0, \sigma) \quad (6)$$

where, PL_0 , is the reference path loss at 1 m distance, m the path loss exponent, d the distance, χ a normally distributed variable which describes the spreading of the measured values around the mean path loss with the standard deviation σ , also called shadowing factor.

B. Wall and Floor Propagation Losses Model

The three main mechanisms of radio propagation are attributed to reflection, diffraction, and dispersion. These three effects cause distortions in the radio signal that suffers attenuation due to losses in its propagation. Common effects on the buildings that do not appear in free field are losses through the walls, roofs, and floors. This effect, together with the multipath and diffraction caused by the corners, is very difficult to evaluate, and there are many publications about mathematical models of indoor radio propagation.

The propagation losses value is given in the equation, where the effect of the losses due to multipath effect is added [4]:

$$L(dB) = L_0 + 10m \log(d) + \sum K_i F_i + \sum I_j W_j \quad (7)$$

where L_0 = power losses (dB) at a distance of 1m (40.2 dB at 2.4 GHz frequency), m = attenuation variation index with the distance ($m = 2$), d = distance between transmitter and receiver, K_i = number of floors of kind i in the propagation path, F_i = attenuation of one floor of kind i , I_j = number of walls of kind j in the propagation path, W_j = attenuation factor of one wall of kind j .

VI. RESULTS

The Figs. 1 at 4 show the slow fading component of the path loss, in dB, versus distance, in meter, for the calculation using Parabolic Equation Method (PE), UWB model, Wall and Floor Propagation Losses Model and the experimental results, in the IESAM and LEEC floors. The Figs. 1 and 2, and Figs. 3 and 4 show that the Parabolic Equation Method predicts the effects of refraction and diffraction, which does not occur with the other two models. In Parabolic Equation Method can be done the path loss map for any environment studied and it shows the path loss variation point by point and this variation is a consequence of the refraction and diffraction. It is observed a good agreement between Parabolic Equation Method with the experimental data and also with the models. The figures still show the effect of the influence of the number of floors among the transmitter antenna and receiving antenna in the path loss.

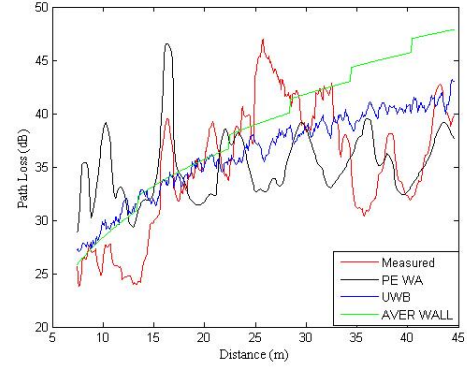


Figure1: Path loss versus distance in the Ground-floor (IESAM)

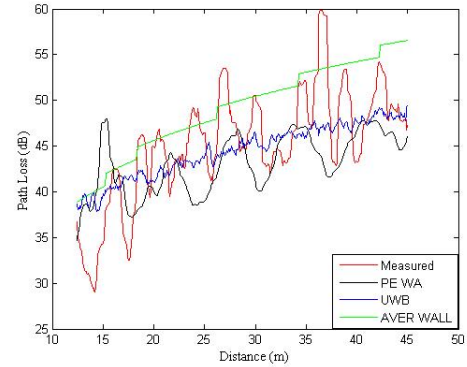


Figure2: Path loss versus distance in the First floor (IESAM)

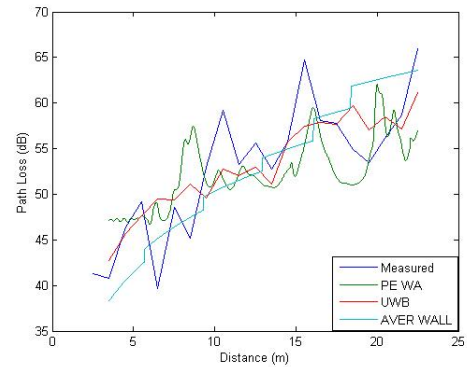


Figure3: Path loss versus distance in the Ground-floor (LEEC)

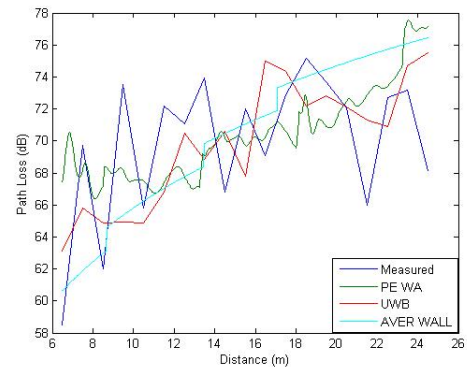


Figure 4: Path loss versus distance in the First floor (LEEC)

Table II shows the average error, standard deviation and RMS error for the two buildings; for the LEEC, average error for the

ground floor and first floor is less than ± 0.5 dB for the models used.

TABLE II. CALCULATION OF AVERAGE ERROR, STANDARD DEVIATION AND RMS ERROR FOR THE IESAM AND LEEC

Floor	Model	Average Error (dB)	Standard Deviation (dB)	RMS Error (dB)
Ground floor (IESAM)	PE WA	4.64	3.72	5.95
	UWB	5.32	3.51	6.38
	AVER WALL	4.66	3.12	5.61
First floor (IESAM)	PE WA	4.24	2.77	5.06
	UWB	3.75	2.30	4.40
	AVER WALL	4.88	3.37	5.93
Ground floor (LEEC)	PE WA	3.94	3.30	5.10
	UWB	3.27	2.32	4.01
	AVER WALL	3.97	3.05	5.00
First floor (LEEC)	PE WA	2.88	2.09	3.56
	UWB	3.10	2.57	4.03
	AVER WALL	3.25	2.53	4.12

VII. CONCLUSION

In this paper, a deterministic method, the Parabolic Equation Method, was used for the study of the path loss in an indoor environment. In the applied model, the complex refractive index was considered, which increases the precision of the model. This work shows that the Parabolic Equation Method can be applied to electromagnetic wave propagation in an indoor environment. The model was applied for wide angles relative to the paraxial propagation direction (up to 90°), and the principle of the Fourier/split-step method to solve the Parabolic Equation was introduced.

An advantage of the Parabolic Equation Method is the reduction of the computational effort in relation to the similar techniques of the full elliptical methods.

In future studies, the coverage of wireless communication.

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