Mobile Radio Propagation along Mixed Paths in Forest Environment using Parabolic Equation

João F. de Souza, Fátima N. B. Magno, Zínia A. Valente, Jessé C. Costa, Gervásio P. S. Cavalcante

Universidade Federal do Pará, furtado@ufpa.br, fnbm@ufpa.br, zinia@ufpa.br, jesse@ufpa.br, gervasio@ufpa.br

Abstract

This paper calculates the propagation loss in mixed-path mobile communication using parabolic equation method. The implicit finite differences scheme of the Crank-Nicolson type is applied in order to get the solution of the parabolic equation. The propagation is considered in 15^0 in the direction paraxial and the complex refractive index was considered what increases its precision. To validate the method, a radio propagation measurement campaign was carried out, in the county of Benfica, near the city of Belém, State of Pará. The frequency used was 900 MHz. The results were compared to the simulations made with the proposed method, which presented the best performance comparing to others works in literature. The loss predicted by this method had a mean error of 3.40 dB and standard deviation of 2.75 dB in relation to the measured data.

1. Introduction

For line-of-sight communication, cellular communication in particular current interest centers on radio-link performance, and how it is affected by wave attenuation, fading and co-channel interference. When vegetation, such as a forest, lies along the path of a radio performance is affected by strong multiscattering effects and imposes stringent constraints on system design. Therefore, accurate modeling of wave propagation behavior through foliage has attracted significant attentions in recent years for its applications in many civilian and military problems. The most important effect introduced by the forest is the excess signal attenuation (or path-loss) in addition to that due to free space propagation [1] - [3].

Several methods to model vegetation for propagation analysis have been presented in literature. Empirical and deterministic models are available, mainly aimed at characterizing the effects of vegetation and calculation of path loss. The empiric model are based in simple and direct formulas, very easy to apply, but on the other hand these models provide poor local-specific precision and they cannot predict parameters of the broad band of the communication channel. The deterministic models follow physical principles of propagation of electromagnetic waves - most popular they are ray tracing and the numerical solution of the equations of Maxwell.

One of the most reliable and widely methods is the Parabolic Equation (PE) Method, initially developed for the study of underwater acoustics problems and later on extended to tropospheric propagation. It has been proved that like troposphere parabolic equation in vegetation. The biggest advantage to using the PE method is that it gives a full-wave solution for the field in the presence of range-dependent environments. This method supplies an excellent combination of precision and efficiency for many problems of electromagnetic waves propagation [4].

The method presented in this paper is based on the parabolic equation (PE) using the finite difference scheme of Crank-Nicolson to calculate the path loss in a forest environment. A complex refractive index was considered in the studied environment and the propagation angle was considered in 15^0 in the direction paraxial. In this formulation the backscattered field was neglected.

To validate the proposed method a measurement campaign was carried out in a mixed path in forest environment in Benfica, Belém – Pará. The frequency used was 900 MHz. The results of the simulation through the proposed method had been compared with the experimental data and models of Blomquist-Ladell's method, Multiray' s model and Okumura-Hata' s model.

This work is organized as it follows: the problem formulation, the parabolic equation (PE) method and the finite difference scheme of Crank-Nicolson, is described in section 2; the path loss models are shown in the section 3; the section 4 shows the results and the section 5, the conclusion.

2. Problem Formulation

Assuming propagation to be predominantly along the axis and the paraxial cone with a narrow-angle, θ as shown in Figure 1, the 2-D Parabolic Equation can be derived from the Helmholtz equation in Cartesian coordinates by factoring out a fast varying phase term in the direction. In case where the propagation medium is homogeneous with refractive index n, the field component Ψ satisfies the two-dimensional scalar wave equation given by

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

where k is the wave number in vacuum. In general, the refractive index varies with direction x and height z. In the case of small variations of this index, (1) it can be used as a good approach. Considering the electric field component (E) as solution of (1), we introduce it as the reduced function associated with the paraxial direction x [5]

$$E(x,z) = e^{-jkx} \psi(x,z) \tag{2}$$

The importance of using this reduced function is that it is of slow variation in the direction of the propagation of the energy at angles close to the paraxial direction, which is convenient for property numerical.

The scalar wave equation in terms of electric filed component E is

$$\frac{\partial^2 E}{\partial z^2} + \frac{\partial^2 E}{\partial x^2} + 2jk\frac{\partial E}{\partial x} + k^2(n^2 - 1)E = 0 \tag{3}$$

In the general case, the term n^2 is a variable depending on the index of refraction of the atmosphere and the surface roughness, but for free-space without boundaries $n^2 = 1$. Equation (1) is factored into two equations for computing the forward and backward propagation waves [6], [7],

$$\frac{\partial}{\partial x} = -ik(1-Q)E \quad \text{and} \quad \frac{\partial}{\partial x} = -ik(1+Q)E \tag{4a – 4b}$$

where $Q = \sqrt{\dfrac{1}{k^2}\dfrac{\partial^2}{\partial z} + n^2(x,z)}$.

In this case only one piece is solved giving the propagation in the forward or positive direction.

Using the first order Taylor series and substituting in (4a) we have a standard parabolic equation (SPE) given by [8]

$$\frac{\partial^2 E}{\partial z^2}(x,z) + 2ik\frac{\partial E}{\partial x}(x,z) + k^2(n^2(x,z) - 1)E(x,z) = 0 \tag{5}$$
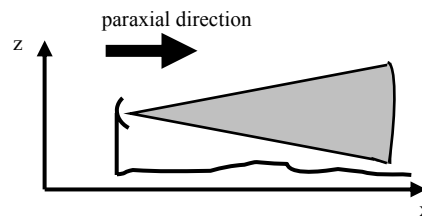

Figure. 1. Paraxial propagation at angles close to the horizontal

In order to solve the Parabolic Equation numerically, (5) can be expressed using finite differences. This is done using the Crank–Nicholson scheme, which permits the modeling of arbitrary boundaries [8]. In this scheme the Parabolic Equation is written using finite differences, which are centered, on a point midway between two successive planes of field points. Using in (5) the equation for the central

finite-difference approximation of the first-order derivative and second-order derivative, where the midpoint to advance the solution from range x_{m-1} to range x_m is $\xi_m = \dfrac{x_{m-1} + x_m}{2}$, $E_j^m = E(x_m, z_j)$, $b = 4ik\dfrac{\Delta z^2}{\Delta x}$ and $a_j^m = k^2\left(n^2\left(\xi_m, z_j\right) - 1\right)\Delta z^2$, it is obtained

$$E_j^m\left(-2 + b + a_j^m\right) + E_{j+1}^m + E_{j-1}^m = E_j^{m-1}\left(2 + b - a_j^m\right) - E_{j+1}^{m-1} - E_{j-1}^{m-1} \tag{6}$$

for $j=1,..., N-1$. the solution of (6) it is not found explicitly, however it is found implicitly, because it is necessary to invert the matrix to obtain E for the range x_m. This is the implicit finite difference scheme of Crank – Nicolson type [8].

3. Path loss models

To test the efficacy and accuracy of the proposed method, the forward-propagating waves calculated by this algorithm are compared with a measurement campaign and path-loss predictions for some classical models in the literature as described below.

3.1. Blomquist-Ladell's Method

This method considers the free-space loss (L_0), plane-earth loss (L_p), and knife-edge loss (L_k) combined to give the total loss (L) as follows [9]:

$$L = L_0 + \left[\left(L_P - L_0\right)^2 + L_D^2\right]^{1/2} \approx L_0 + L_D \tag{7}$$

where

$$\begin{aligned} L_0 &= -147.56 - 10\log G_T - 10\log G_R + 20\log f + 20\log d \\ L_D &= -10\log G_T - 10\log G_R - 20\log h_T - 20\log h_R + 40\log d \end{aligned} \tag{8}$$

where f, G_T and G_R was described in (8), h_T and h_R are the transmitter and mobile receiver height and d is the distance between the transmitter and mobile receiver. The model applies to frequencies within the range 30 – 900 MHz and distances 5 – 22 km range.

3.2. Multirays's Model

The modeling of structures with abrupt relief discontinuity can be analyzed by the diffraction and/or reflection in environment components. The multirays's model, based on the study of the diffraction in a knife-edge, it can be used to model that structure type.

3.2.1. The Two Rays Model

Figure 2 shows the geometry of the propagation environment studied where two knife-edges are considered. The first is located in point A and the second in point B associated with the first and second discontinuity of the forest, respectively. Also, it is showed the situation where only two rays are considered as the most important components of the received field [10].
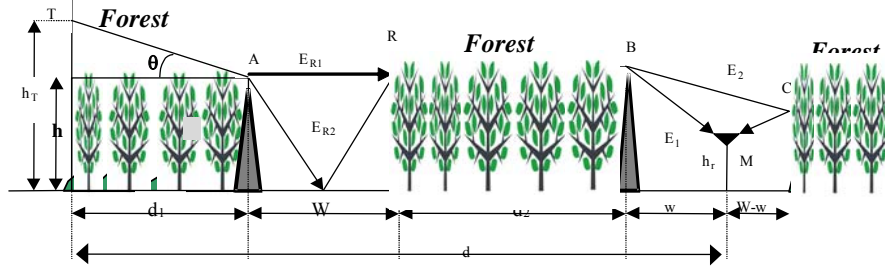
Figure. 2. Geometry of the model (lateral view of the forest)

The mobile receiver field can be calculated as follows [10]:

$$E_{mobile} = 0.225 \cdot \frac{\sqrt{30 \cdot P_T \cdot G_T}}{d} \cdot \frac{(d_2 + w)}{(d_1 + W)} \cdot \sqrt{5 + \left(\frac{R_{ROAD}}{v_R}\right)^2} \cdot \sqrt{\frac{\left(\frac{1}{v_{BM}}\right)^2 + \left(\frac{R_{FOREST}}{v_{BCM}}\right)^2}{\left(\frac{1}{v'_{BM}}\right)^2 + \left(\frac{R_{FOREST}}{v'_{BCM}}\right)^2}} \tag{9}$$

where R_{FOREST} and R_{ROAD} are the Fresnel reflection coefficient at forest and road; and v_R, v_{BM}, v_{BCM}, v'_{BM} and v'_{BCM} are the Fresnel parameters.   .

From (9) we can obtain the path loss

$$L = 20 \log\left(\frac{E_{mobile}}{E_0}\right) \tag{10}$$

3.3. Okumura-Hata's Model

Okumura's predictions of median path loss are usually calculated using Hata's approximations for urban areas, suburban areas, and open areas. The prediction for suburban areas (village or highway scattered with trees and houses, some obstacles near the mobile but not very congested) is calculated as follows [11]

$$L_{dB} = A + B \log R - C \tag{11}$$

where

$$\begin{aligned}
A &= 69.55 + 26.16 \log f_c - 13.82 \log h_T \\
B &= 44.9 - 6.55 \log h_T \\
C &= 2\left(\log\left(\frac{f_c}{28}\right)\right)^2 + 5.4
\end{aligned} \qquad , \tag{12}$$

R is the great circle distance between base station and mobile and f_c is the carrier frequency. The model is valid only for 150 MHz $\leq f_c \leq$ 1500 MHz, 30 m $\leq h_T \leq$ 200 m, and $R >$ 1 km.

4. Results

The measurement environment is showed in Figure 3. The measurements were taken in a covered by radio signal transmitted by fixed station in the surroundings of Belém, state of Pará in a town called Benfica. The transmitted signal was at 900 MHz, using a collinear antenna in a twelve-height tower. The transmitter was installed on a building of the ANATEL (Agencia Nacional de Tele*comunicações*). The mobile receiver has traveled along a 5.6 km road inside a forest at a speed of approximately 30 km/h. The measurement results were recorded for off line processing. The map of measurement environment (Figure 3a) indicates the transmitter position, and the path of mobile receiver unit in road. Figure 3b shows a view of the road crossing forest.

(a) Map of Benfica road inside forest   (b) Benfica road

Fig. 3. Measurement environment

A plane wave vertically polarized in 900 MHz was transmitted for simulation using the parabolic equation method. The paraxial direction (Figure 1) was chosen, with approach for small angles, up to 15^0. Also was considered only the dimensions of length and width of vegetation and road in studied environments. The refractive index was considered complex as given by [12]. A FORTRAN program was developed to simulate (6). In order to compare the Parabolic Equation method with measured data and the path los models the electric field given by (6) was introduced in (13) to obtain the path loss.

$$L(dB) = 36,57 + 20\log_{10} f + 20\log_{10}|E_0| - 20\log_{10}|E| - G_T - G_R \qquad (13)$$

where E_0 is the field in the distance of reference (d_0), E 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 [13].

The parameters showed in the Table 1 were used to simulate the models considered.

Table 1. Parameters used in the models

Parameters	Symbols	Values
Frequency	f	900 MHz
Average height forest	h	12 m
Transmitter height	h_T	12 m
Mobile receiver height	h_R	3 m
Transmitter antenna gain	G_T	2.14 dB
Receiver antenna gain	G_R	2.14 dB
Transmitted power	P_T	30 dBm
Road – paved, width	W	12 m
Vehicle position	w	7.75 m
Forest relative permittivity [10]	ε_F	1.1

Parameters	Symbols	Values
Forest conductivity [10]	σ_F	0.1 mS/m
Road relative permittivity [10]	ε_R	2.7
Road conductivity [10]	σ_R	40 mS/m
Width of the first forest	d_1	1500m
Width of the second forest	d_2	2500m
Transmitter distance range	d	500 to 5600 m

The Figure 4 shows the path loss, in decibels, as a function of distance d, in meters, in the representative case. This result is compared with the model proposed by Cavalcante et all, called Multirays, with the Blomquist-Ladell's Method, with the Okumura-Hata's Model, and with the measured. In the Figure 4 we can observe a best fit to the experimental data by proposed method in this work.
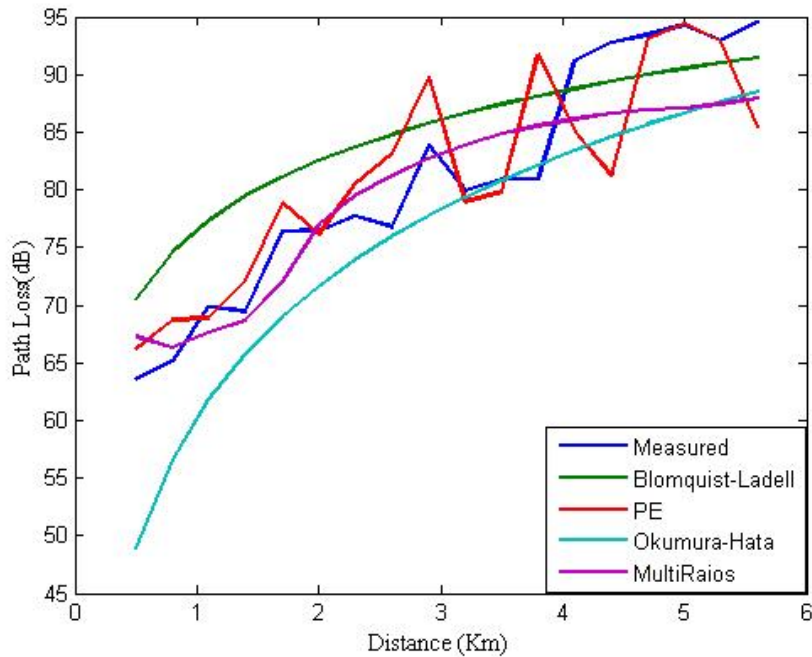

Figure 4. Path loss with distance of the theoretical and experimental results

The Table 2 shows the average error, standard deviation and rms error for several models, compared with the measured, for the test environment studied.

Table 2. Average error, standard deviation and rms error

Model	Average error (dB)	Standard deviation (dB)	Rms error (dB)
PE method	3.40	2.75	4.37
Blomquist-Ladell [9]	5.51	3.08	6.31
Multirays [10]	3.86	2.17	4.43
Okumura-Hata [11]	5.71	4.15	7.06

5. Conclusion

Several theoretical and experimental models exist for to compute the path loss propagation in wireless communications, and each characterizes the environment with different view. In mixed-path, the shadowing, the scattering and the absorption caused for the vegetation can cause a significant path loss, which increases with the frequency.

This work shows that parabolic equation method can be applied to the electromagnetic waves propagation in forest environment. The principle of the domain decomposition technique for parabolic equation was introduced. Good agreements between the measured and simulated results through of parabolic equation method are also achieved. The limitations of the standard parabolic equation approximation are due to its bad behavior at large propagation angles.

An advantage of the parabolic equation method is the reduction of the computational time in relation to the similar techniques found in the literature. This is due to the fact that the problem is reduced to a tridiagonal system and the method to solve such system is the implicit finite differences scheme of the Crank-Nicolson type. This is a method stable unconditionally, what allows the change of the parameters of the middle without gets lost the stability. The adopted methodology allows the incorporation of new elements in geometric ways different with their respective properties electric.

Actually, we are made simulation increasing the angle of propagation with the paraxial direction, for 1.8 GHz that will be applied for this and other environments.

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