Theoretical Investigation of Foliage Effects on Path Loss for Residential Environments

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Abstract - A mobile communications system depends on the propagation loss due to the environment between the transmitter and the mobile receiver located at the street level. A theoretical model is proposed to include the effects of trees as well as buildings/houses on the propagation in residential environments. As in past models, the rows of building/houses are modeled as diffracting cylinders lying on the earth, but now the canopies of the trees adjacent to and above the building/houses are included in the model. The building/houses are represented as absorbing screens and the trees as phase screens. The phase screen properties are found by representing the trees as a time-invariant ensemble of leaves (discs) and branches (cylinders) all having a prescribed location and orientation statistics. The mean field at the aperture of the absorbing screen depends on the mean field in the canopy, which is calculated using the discrete scattering theory of Foldy and Lax.

I. Introduction

Operation of mobile communications system such as a Cellular Telephone or a Personal Communications System (PCS) depends on many important parameters. One of these parameters is the propagation loss due to the environment between the transmitter and the mobile receiver located at the street level. In a residential area, the environment is not only composed of building/houses but also of trees which are adjacent to and above the building/houses. In the past, the effects of trees in the propagation loss in a residential area has been considered empirically.

A theoretical model is proposed to include the effects of trees as well as buildings on the propagation in residential environments. As in past models, the rows or blocks of buildings/houses are viewed as diffracting cylinders lying on the earth [1], [2], but now the canopy of the trees adjacent to and above the buildings/houses are included. The buildings/houses are represented by absorbing screens [1], [2] and the trees as partially absorbing phase screens. The field at the aperture of the absorbing screen depends on the mean field going through the tree due to a plane wave incident. Physical optics is then used to evaluate the diffracting fields at the last absorbing screen-tree combination by using the multiple Kirchhoff-Huygens integration for each absorbing half screen-tree configuration. In order to find the properties of the phase screen, trees are represented as a time-invariant ensemble of leaves and branches all having a prescribed location and orientation statistics. Leaves are modelled as flat, circular, lossy-dielectric discs; and branches as finitely-long, circular, lossy-dielectric cylinders. The mean field in the canopy is calculated using the discrete scattering theory of Foldy and Lax [3], [4], [5]. By solving the mean wave equation for the mean scattered field propagating through a tree we find the wave propagation constant. This propagation constant has a real and imaginary part. We note that the horizontally and vertically polarized waves propagate independently that is without any depolarization. From the wave propagation constant the imaginary part corresponds to the specific attenuation of the tree, but it is important to recognize that the overall propagation loss through building/houses with trees is very much dependent of the real part as well as the imaginary part of the wave propagation constant in the trees. Finally, it is important to mention that the trees are modelled both with and without leaves to simulate winter and summer. The shape of the trees are modelled as been triangular and elliptical. Results are presented to show the effects of the various parameters.

II. Tree Modeling

The tree is modelled as a discrete random ensemble of branches and leaves all having prescribed orientation and location statistics. Because of the randomness associated within the medium of discrete scatterers, the wave behavior in a tree is better represented by modern stochastic models [3], [4], [5], [6]. Such models provide the basis to compute the mean field and the propagation constant in the tree.

The model was first developed by Foldy [3] and later extended by Lax [4], Twersky [5], and Lang [6]. The leaves are modelled as randomly positioned flat-circular lossy dielectric disks and the branches as randomly positioned finitely-long lossy dielectric cylinders. It is assumed that the thin-cylinders and the flat-circular disks are distributed uniformly in azimuthal coordinates, and the probability densities for the azimuthal coordinate ϕ and the θ coordinate are independent for the leaves as well as for the

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branches.

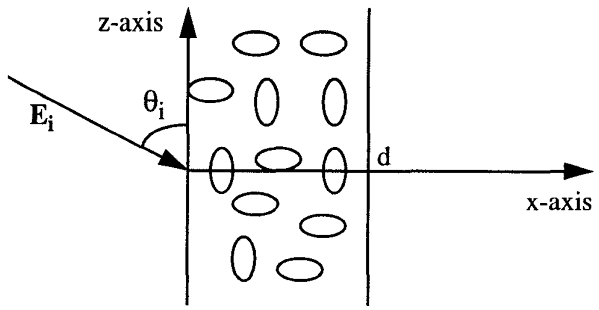

Figure 1. Slab Geometry with Incident Plane Wave

As shown in Figure 1, we have three-layered medium with free space for x<0 and x>d having a free space permeability μ_0 and permeability ε_0. In the region 0<x<d, we consider N identical scatterers contained within the slab of volume V with a constant density ρ. Each scatterer has a volume V_p, a relative dielectric constant ε_p. A free space background medium is assumed in the slab. The interface between the slab and free space is considered smooth.

The equation for the mean field in the canopy has been derived by using the multiple scattering theory of Foldy-Lax [3], [4]. The Foldy [3] approximation assumes that the total field incident on a scatterer is equal to the mean field. In our analysis we have assumed the contributions from the incoherent field are small compared to the mean field or the coherent field. So, by assuming a unit amplitude plane wave, having a direction **i** (**i** is a unit vector) and polarization **q** (**h**=horizontal or **v**=vertical) incident upon the slab, the mean wave in the slab has the form

$$\langle \mathbf{E_q}(x\ ,\ z\ )\rangle = \widehat{\mathbf{q}}\ e^{\ i\ \kappa x - i\ k_o z\ \cos\ \theta_i}$$

where the ensemble average over **E** is expressed as <E>, and the propagation constant to the first order of approximation κ (x-direction) is given by

$$\kappa = \kappa^0 + \kappa^1$$

$$\kappa^0 = \kappa_{xo} \qquad and \qquad \kappa^1 = \kappa_r^1 + i\ \kappa_i^1 = \frac{2\ \pi\ \rho}{\kappa_{xo}}\langle f_{qq}\rangle$$

consequently

$$\kappa = k_{xo} + \frac{2\pi\,\rho}{k_{xo}}\langle f_{qq}\rangle$$

where, $k_{x0} = k_0 \sin(\theta_\iota)$. Here, k_0 is the free space propagation constant, θ_ι is the angle of incidence with respect to the z-axis as shown in Figure 1, ρ as was said before is the density of scatterers, $< f_{qq} >$ is the average of the forward scattering amplitude over the scatterers orientation. The forward scattering amplitude f_{qq} has been calculated using the quasi-static approximation in the low-frequency regime (Rayleigh) for a leaf and a branch. It is important to note that because of the assumed azimuthal symmetry of the scatterers, the mean waves of the vertical and horizontal polarization do not couple, therefore no depolarization effects occurs at the level of the mean wave. Also, it is important to mention that the propagation constant can not be calculated to a higher accuracy than to the first order, since the mean equation in the medium has also been found to this accuracy

In general, the wave propagation constant in the medium κ has a real and an imaginary part, as a consequence, the imaginary part gives us the specific attenuation in nepers per meter or alternatively in dB per meter. The specific attenuation (dB/m) is given by.

$$\alpha \approx 8.686\ \mathrm{Im}\ (\ \kappa\ )$$

A. Numerical Results

Before we compute the specific attenuation for a tree as a function of incident angle, we require the relative dielectric constant, the angular probability density distribution, the density, and the dimensions of the leaves and branches. For our numerical calculations, we have used as the relative dielectric constant for the leaves 26 + i 7 [7] and for the branches 20 + i 7 [8], as the density for the leaves $\rho_l = 350\ /\ m^3$ and for the branches $\rho_b = 2\ /\ m^3$, as the leaf (circular-thin disk) radius 5cm and leaf thickness 0.5mm, as the branch (thin-circular cylinder) radius 1.6cm and branch length 50cm. The probability density in the azimuthal coordinate ϕ is uniformly distributed from 0^0 to 360^0 for the leaves and branches. The probability density in the θ coordinate is more vegetation type dependent, for the branches and leaves we have considered to be uniformly distributed

$$p_\theta(\theta) = \frac{1}{\theta_2 - \theta_1}$$

where, for leaves $\theta_2 = 180^0$ and $\theta_1 = 0^0$, and for branches $\theta_2 = 60^0$ and $\theta_1 = 0^0$. It is important to note that the relative dielectric constants of the leaves and branches are frequency dependent [7], [8].

Figure 2, shows a plot of tree specific attenuation versus frequency for both polarizations. It is seen that the specific attenuation for vertical polarization is higher than for horizontal polarization. The reason lies in the statistical distribution of leaves and branches in reference to the angle of incidence (90 degrees) of the incident plane wave. Figure 3, shows a plot of specific attenuation for branches and leaves versus frequency for both polarizations, here, one can see that the branch specific attenuation for the vertical polarization have a higher loss than for the horizontal polarization, this is due to the distributions given in our example where the branches are more vertical than horizontal. In Figure 4, we observe the specific attenuation versus the angle dependence of the incident plane wave with the slab interface for both polarization.

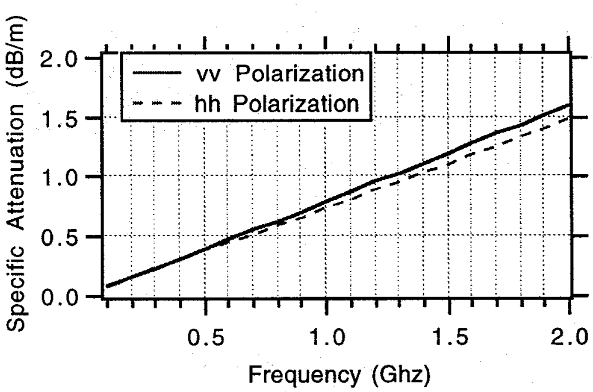

Figure 2. Tree Specific Attenuation with 90 deg.Incident Plane Wave

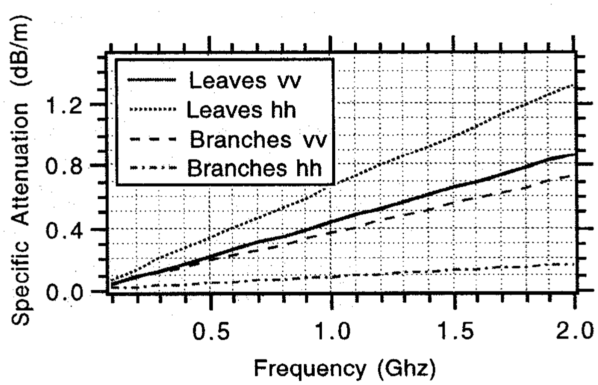

Figure 3. Branches & Leaves Specific Attenuation with 90 deg. Incident Plane Wave

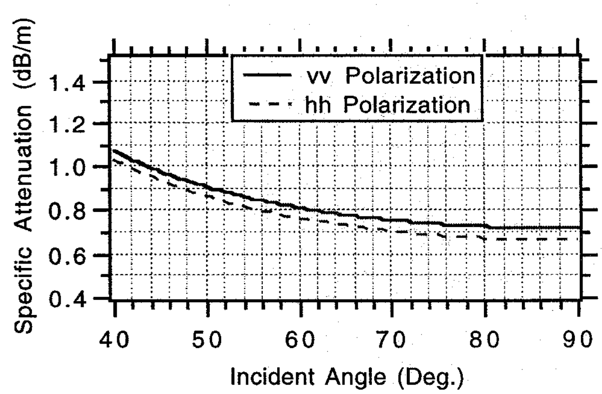

Figure 4. Tree Specific Attenuation vs Incident Plane Wave Angle at 900Mhz

III. Multiple Buildings and Trees Formulation

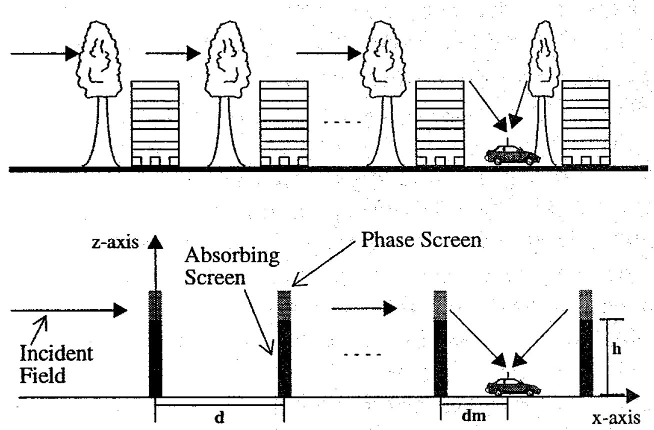

Figure 5. Geometry of the Problem

Extending the approach of Walfisch and Bertoni [1], a theoretical approach is introduced to account trees in the propagation loss in residential areas. As in past models [1], [2], the building/houses are modelled as absorbing screens, but now the trees are adjacent to and above the building/houses and are modelled as partially absorbing phase screens.

Physical optics (PO) is used to compute the fields diffracted by a series of absorbing/phase screens as shown in Figure 5. The absorbing/phase screens lie in the x-z-plane, the distance separation between screens is d, the origin coincides with the first screen, the phase screens are located above and to the left of the absorbing screens. A unit amplitude time harmonic ($exp\ (-iwt)$)plane wave with horizontal polarization (y-axis) is incident on to the first absorbing/phase screen. Using PO and the far field approximation [9], we write the mean field $<E_y(x,z)>$ at a distance

d due to the mean field $<E_y(x_n', z_n')>$ at the aperture of the last absorbing/phase screen n as

$$\langle E_y(x,z) \rangle = -\frac{k_{xo}}{2}\sqrt{\frac{2}{\pi k_o}}\, e^{-i\frac{\pi}{4}} \times$$
$$\times \int_h^\infty \langle E_y(x'_n, z'_n) \rangle \frac{e^{i k_o \rho}}{\sqrt{\rho}}\, dz'_n$$

where, h is the height of the absorbing screen, and $<E_y(x_n', z_n')>$ is the mean field at the aperture of the n absorbing/phase screen and is given by

$$\langle E_y(x'_n, z'_n) \rangle = e^{i w(z'_n)(\kappa - k_{xo})} E_y(x'_n, z'_n)$$

where $w(z'_n)$ is the width of the tree at different heights, κ is the mean wave propagation constant in the tree given in section II, and

$$\rho = \sqrt{x^2 + (z - z'_n)^2}$$

We note that the mean field $<E_y(x_n', z_n')>$ at the aperture of the n absorbing/phase screen is composed of two terms, the first term is the partial absorbing phase screen due to the tree, and the second term is the field from aperture n-1 to aperture n without considering a tree in between. The phase screen approach assumes that the strength of the random medium (tree) is strong enough to cause a phase modulation to the exit wave from the random medium (tree).

In general, the integral of the mean field $<E_y(x,z)>$ equation can not be carried out in a close form due to the phase screen term in $< E_y(x_n', z_n') >$. Therefore, we resort to numerical methods keeping in mind the need for reasonable accuracy and realistic computational time. In developing a numerical approach as in [1], it is necessary to convert the continuous integration into a sum of terms, where each term represents an approximation to the integral over a small interval. In addition, the sum must be finite which means that the field must be artificially limited in the z-plane. However, an abrupt truncation of the field will result in strong reflections from the non-physical upper boundary. A practical approach to this problem is to add an absorbing region above the maximum altitude of interest where the field is attenuated smoothly to zero, in the calculations we have used an absorber Hamming window in the absorbing region. The mean field could be re-written as

$$\langle E_y(x,z) \rangle = \int_h^\infty A_n(x'_n, z'_n)\, e^{i\phi(z'_n)}\, dz'_n$$

where

$$A(x'_n, z'_n) = -\frac{k_{xo}}{2}\sqrt{\frac{2}{\pi k_o}}\, e^{-i\frac{\pi}{4}} \times$$
$$\times \langle E_y(x'_n, z'_n) \rangle e^{-i k_{zo} z'_n}$$

and

$$\phi(z'_n) = -k_{zo} z'_n + k_o \rho$$

where $k_{zo} = k_0 \cos(\theta_t)$. Now, by using the first two terms of a Taylor series expansion for A (x_n', z_n') and for $\Phi(z_n')$ and integrating over the interval $m\Delta < z' < (m+1)\Delta$ in a close form as in [1], we find the solution of the mean field $<E_y(x,z)>$.

A. Numerical Results

All the results that follows are base on a normal incident plane wave of unit amplitude at 900Mhz, with a distance separation between buildings of 50m, with a building height of 8m, and with a 20m distance from the last building to the mobile unit. The trees are modelled as having a triangular and elliptical shape. The triangular tree has a height of 4m above the building and a base of 4m of width at the left side of the top of the building. The elliptical tree has a center at the top of the building and 2m to the left of the building, with a radius of 4m in the z-direction and radius of 2m in the x-direction. The physical and electrical characteristics of a tree are given in section II.

We first discuss the results of a single building with a single triangular tree. In Figure 6 we plot the power loss relative to free space as a function of height due to, a diffracting building only, a diffracting building/tree, a diffracting building/tree with the attenuation effect on the propagation constant not equal to zero ($\kappa^1_r = 0$), and a diffracting building/tree with the phase effect on the propagation constant not equal to zero ($\kappa^1_i = 0$). As seen in Figure 6 the overall propagation loss through a building/tree configuration is very much dependent of the *real* and the *imaginary* part of the propagation constant (first order approximation) in the tree. The imaginary part of the propagation constant (first order approximation) in the tree attenuates the signal down to its lowest level, instead the real part sometimes enhance the signal depending how strong the phase is relative to 2π. The effect of trees on the propagation loss is like that of a lense where focusing and de-focusing effects occurs. Also note that the difference in propagation loss due to the diffracting effect of a building/tree configuration and a building only at 1.8m height is around 2.6dB. We note that this loss is very much dependent on the type of tree.

In Figure 7, we plot the power loss relative to free space loss as a function of height for 20 rows of buildings/trees. As before, we have used the same type of tree but now with an elliptical shape instead of a triangular shape. We observe that as the signal propagates pass more rows, a larger difference occurs between the loss due to diffracting effects past buildings/trees as compare to buildings only. In this particular case, the difference in the propagation loss for a horizontal polarized incident plane wave at the mobile height (1.8m) is around 6dB (for a vertical polarized incident plane wave at 1.8m height is around 8dB).

In Figure 8, we see the effect of trees with leaves (summer) and without leaves (winter) on the propagation loss in a residential area (20 rows of buildings/trees).

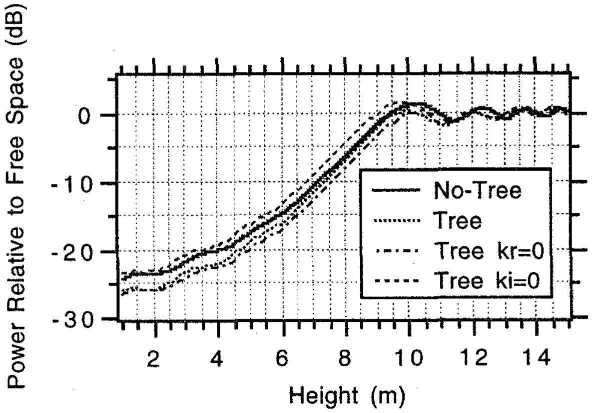

Figure 6. Power Relative to Free Space for One Building/Tree (Triangular) at 900Mhz (Horizontal Polarization)

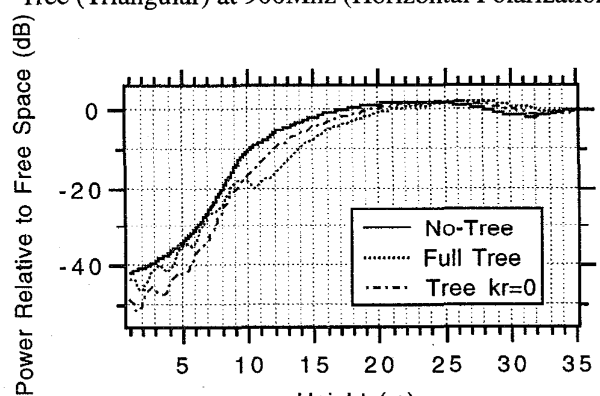

Figure 7. Power Relative to Free Space for 20 Buildings/Trees (Elliptical) at 900Mhz (Horizontal Polarization)

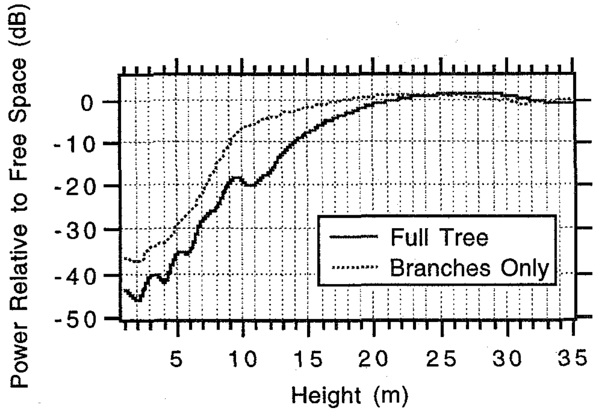

Figure 8. Power Relative to Free Space for 20 Buildings/Trees (Elliptical) with/without leaves at 900Mhz

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