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Simple Empirical Model for Long Distance Through-Foliage Propagation

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Abstract

A simple empirical model for long distance through-foliage propagation is presented. It comprises two parallel propagation mechanisms: direct transmission through a line of trees modelled by a simple linear transmission line; and along the free-space dominated forest top, modelled by simplified multiple-edge diffraction. The model is matched to recently published experiments by Hejselbaek *et al* over a long distance (2500m), demonstrating a fit that is not possible using other physics-based modelling.

1 Introduction

There is a long-standing need for accurate multipath propagation modeling for non-line-of-sight (NLOS) such as through-foliage propagation. Propagation modelling covers many different approaches, from empirical, e.g., [1, 2, 3, 4, 5] to analytic, e.g., [6, 7, 8], and numerical approaches, including, for example, in-computer antenna evaluation using ray tracing [9], and so on. Different techniques are applied for different frequencies and types of environments. The analysis for propagation through foliage, such as radiative energy transfer (RET) is not accurate despite its parameters being empirical. There are no fundamentally new approaches or mechanisms for through-foliage propagation presented in recent decades - most newer propagation papers are empirical approaches matching to recent measurements. These are nearly all for so-called 5G frequencies which are at much higher frequencies than considered here, and for much smaller distances, e.g., [10].

This paper discusses an empirical model for a large through-forest range propagation at $\sim$ 1GHz, by looking at two mechanisms: penetrative transmission directly through the randomly media af a foliage using the simplest linear transmission line; and a diffraction-based path over the top of the trees using multiple knife-edge diffraction. The model is checked against an extraordinary, recently-published experiment conducted in a typical forest terrain of Denmark over a range of 2500m [11]. We show here that this simple two-mechanism model can provide an accurate fit to the experimentally-found [11] dual-slope behaviour in a log-log scale. Over this large range of distances, the radiative energy transport (RET) model cannot be fitted well to the experimental data [12, 13]. Applications include terrestrial point-to-point, in particular for long-distance through-forest communications such as an Internet-of-Things system.

2 Propagation Model

Fig.1 depicts in-line trees between a transmitter and a receiver. For the model, the transmitter is considered to be located away from the trees for plane wave illumination, although this in not necessary in practice. Similarly, for simplicity of the model, there is no coupling between the paths.

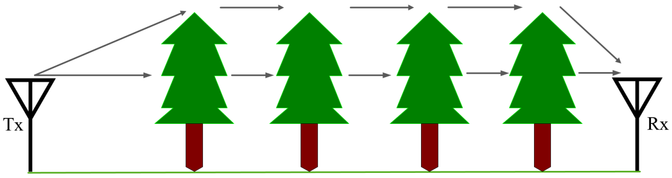

Figure 1. Through-foliage propagation. A line of trees are between a transmitter and receiver antenna.

The propagation model is illustrated in Fig.2. The transmission through forest is modelled by an M-layer lossy linear transmission line in parallel with the transmission over the trees modelled by multiple knife-edge diffraction where each tree is considered as an ideal absorbing baffle. These two transmission mechanisms are uncoupled for the sake of the model simplicity. Looking into the time domain behaviour would be an illuminating extension to this modelling.

For simplicity in the transmission line model, the thickness of the trees, d, and the free-space between them, d_0, are constant. The mean propagation constant for each tree is

$$\gamma_d = j\omega\sqrt{\mu_0\mu_d\varepsilon_0\varepsilon_d} \tag{1}$$

where the relative permeability of the dielectric (tree) is $\mu_d = 1$ and the complex relative permittivity is $\varepsilon_d = \varepsilon_d' - j\varepsilon_d''$. μ_0 and ε_0 are for free space, and ω is angular frequency. The transmitted power through the M layers is

$$P_{MLTL_{Trans}} = \frac{|E_0|^2\,|T|^2}{2\eta_0}. \tag{2}$$

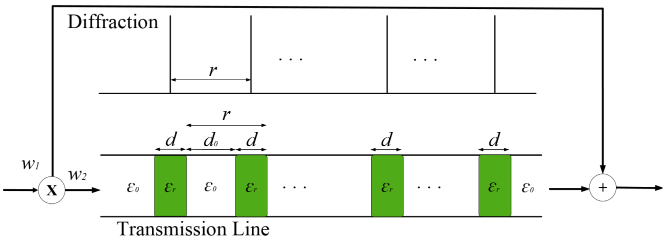

Figure 2. Long- distance through-foliage propagation model. The M-layer transmission line of in-line trees and the knife-edge diffraction over the top of the trees are modelled as independent. The receive power is a simple empirically weighted sum of these two mechanisms.

with $\eta_0 = \sqrt{\mu_0/\varepsilon_0} = 120\pi\,\Omega$. E_0 can be calculated from the experimental set-up, and T is the transmission coefficient (see [12, 14]).

The second mechanism is diffraction. The trees are considered as absorbing baffles with equal height and spacing r, where $r = d + d_0$. Therefore, the number of trees, N, between the transmitter and receiver is $N = M/2 = d_{total}/r$, where d_{total} is the distance between the transmitter and receiver. Therefore, the multiple knife-edge attenuation simplifies to an exact solution [15, 16] which is a constant (not frequency dependent) gain,

$$A_N = \frac{1}{N+1}, \tag{3}$$

and the diffracted power is calculated from

$$P_{D_N} = G^{(FS)}_{path} \cdot (A_N)^2, \tag{4}$$

where the free space path gain is $G^{(FS)}_{path} = (4\pi d_{total}/\lambda_0)^{-2}$.

Finally, The total received power is the weighted sum of these two mechanisms

$$P_{R_{total}} = W_1 P_{D_N} + W_2 P_{MLTL_{Trans}}. \tag{5}$$

where $W_1 = 1 - W_2$ and $W_2 < 0$.

3 Results and Discussions

The propagation model is examined using the measurement data conducted in a typical forest train at the frequency of 917.5MHz, published in [11]. The trees are predominantly fir (pine), oak, and beech [12]. The height of the transmitter and receiver are 1.5m. The transmitter power is 40dBm, and there are are 71 measurement locations along the path of total length 2580m. For this example, the tree thickness is considered as $d = r/4$. The real part of the complex relative permittivity is taken as unity for simplicity and because the reflected power is not of interest, - just the loss behaviour is the focus. Note that the thickness of the dielectric (tree) and its loss (imaginary part of the tree permittivity) can be interchanged for the same effect [12]. The empirical parameters of this model are just r, ε'' and W_2. The model can be fitted to the measurement data by considering, for example, $r = 1$m, $\varepsilon'' = 0.008$ and $W_2 = -70$dB, depicted in Fig.4. Further studies which are not presented here (see [12]) show that the dominant mechanism for the long distance is the diffraction path which depends on the spacing r (for fixed d). The transmission through the trees is dominant over the short distances, and depends on ε'' (or the thickness of the trees d).

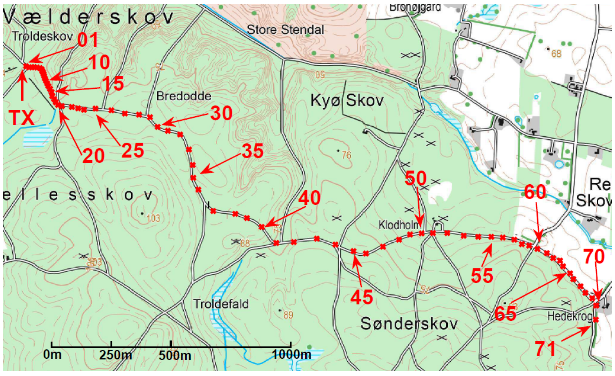

Figure 3. 71 measurement locations conducted in a typical forest terrain in Denmark [11].

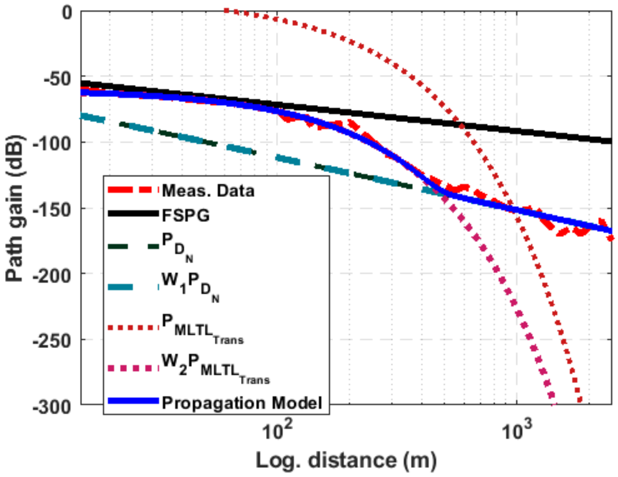

Figure 4. Our propagation model compared to the measured path gain in [11]. The distance scale is logarithmic, so the plot is log-log. The free space path gain ($FSPG$), P_{D_N}, $W_1 P_{D_N}$, $P_{MLTL_{Trans}}$ and $W_2 P_{MLTL_{Trans}}$ are also included.

The propagation model is compared to the RET model and the models presented in [11], for the distance range from 200m to 2580m, by calculating RMSE between the measured data and the predicted path gain in dB,

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(G^{(dB)}_{path_{m_i}} - G^{(dB)}_{path_{p_i}}\right)^2}{n}}\ [dB], \tag{6}$$

where n is the total number of measurements. The results are summarized in Table 1. The RMSE of our model with

Table 1. RMSE of through-forest propagation model.

Model	RMSE (dB)
Our propagation model [12]	4.6
Two–Ray+2×ITU-R P.2108-0 in [11] from 200m (Same height Tx and Rx)	7.6
ITU-R P.1546+2×ITU-R P.2108-0 in [11] from 200m (Same height Tx and Rx)	11.2
RET model	13
Polynomial regression (n=3)	4.5

three empirical parameters is 4.6dB, which for general interest, is close the fit of a 3rd degree polynomial function. It gives a better fit from the initial point to the furthest point of the measurement, from 15m to 2580m, relative to the models in [11] for the distance from 200m to 2580m. The RET model cannot be fitted well to experimental long distance propagation through foliage.

4 Conclusion

A simple empirical model for a long distance propagation through-forest with minimal parameters is presented. It uses parallel and uncoupled transmission mechanisms comprising a simple transmission line for the short distances, and the multiple knife-edge diffraction for long distances. The RMSE with a measurement [11] is 4.6dB, compatible to a fit of a 3rd degree polynomial function. The classical model for propagation through distributed scattering is the RET model, and this cannot be fitted to this through-forest propagation because there is an extra mechanism which dominates the long distance behaviour. This is here taken as a surface-wave like phenomena, modelled by the multiple diffraction across the tree tops. Investigating the wide band nature, i.e., time domain features, would be illuminating for further investigating these mechanisms.

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