Least Squares Optimization for Forest Propagation Augmented by Rainfall/Snowfall, Frequency, and Polarization Effects

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***Abstract*— The general path loss model parameters for forest propagation environment are optimized using the least squares technique. The resulting model is verified by comparison with measured data where acceptable agreement is observed. The direct wave, vegetation effect, and rainfall/snowfall contribute to the wave propagation in a forest. The average rain rate that will probably be exceeded for at most 0.01% of the year (i.e., $R_{0.01\%}$) is computed using real measured data in Jordan. Based on that, rainfall attenuation rate is computed and analyzed for varying frequencies and for both horizontal and vertical polarizations.**

Keywords*— *Optimization, Fading, Rainfall, Snowfall, Forest, Polarization, Vegetation

I. INTRODUCTION

Communications in forest area includes military and police communications, fire and rescue services, emergency services, security, and private mobile radio systems. Thus, the performance of the propagation prediction model needs to be evaluated for services that involve different frequencies. On the other hand, the forest environment and weather conditions have considerable effect on the propagation and fading of wireless signals.

The forest was modeled with a dielectric slab [1] in order to predict wave attenuation. The diffraction theory was used to describe the terrain effects of the forest [2]. Empirical model was applied to wooden urban area [3]. Trees were described by a statistical model to analyze wave attenuation [4]. Trees and buildings were modeled using the theory of diffraction for satellite mobile communications [5]. The fast-fading associated with radiation from a cellular base station was found to be Rician distributed [6]. The fading due to wind and rain in a forest was approximated by a Rician distribution function [7]. The propagation loss in a forest was modeled by an empirical model [8]. It is worth noting here that the path loss models for vegetation channels are well covered by the open literature. A review on wave propagation in rain conditions is available in [9]. In general, theoretical models are more accurate than empirical models. However, theoretical models are sophisticated and not user friendly. Alternatively, the empirical path loss models for forest environment are attractive for the prediction of radio-channel behavior. As far as the author knows, research work on weather effects on the propagation in forest areas is inadequate.

The snowfall is either dry or wet depending on the liquid water content. The dry snow has negligible dielectric losses [10]. On the other hand, attenuation of wet snowfall is comparable to rain showers with big raindrops [11]. Thus, losses of the wave due to wet snowfall may be represented by rainfall propagation losses, whereas dry snowfall losses may be neglected. In general, accurate modeling helps in providing: reliable communication systems, lower-cost equipment, and decreased operating power which further reduces the possible adverse effects on the ecological system [12].

This paper presents a least squares optimized model augmented by rainfall losses and polarization effects, for wireless signals in forest area at varying frequencies. The model is also valid for wet snowfall conditions since wet snowfall has comparable effect to rain showers. The loss associated with dry snowfall is negligible, and thus the model for this case can be used without rain attenuation. The optimized empirical model was able to accurately predict the attenuation in the forest environment with RMSE of only 4.5 dB.

II. LOSSES DUE TO RAINFALL/ SNOWFALL

The path loss PL in a forest area [13],

$$PL = -L_t + G_t - L_0 - L_G - L_V - L_R + G_r - L_r \quad (1)$$

where L_t , L_r are the transmitter and receiver feeder losses, G_t , G_r are gains of the transmitting and receiving antennas, L_0 is free space propagation loss, L_G is ground loss, L_V is vegetation loss, and L_R denotes rainfall /snowfall losses.

For a uniform rain attenuation rate, the rain attenuation in dB for a distance r_r through rain is:

$$L_R = \gamma(r)\, r_r\,,\ \gamma = a R^b \quad (2)$$

Where γ is the specific rain attenuation in dB/km [8], R is the rain rate in mm/hr, and the parameters a and b can be found from ITU-R Recommendation P.838 [14] for horizontal and vertical polarizations.

Using Fig. 1, if the rain cell covers the whole wireless channel in the forest, then r_r and the foliage attenuation distance r_f are expressed as:

$$r_r = \sqrt{(h_b - h_m)^2 + d^2} \quad (3)$$

$$r_f = h_{foliage} \sqrt{d^2 + (h_b - h_m)^2} \,/\, (h_b - h_m) \quad (4)$$

where $h_{foliage}$ is the average foliage height of the trees, d is the distance between the transmitter and receiver, h_b is the transmitter antenna height, and h_m is the receiver antenna height, all in measured meters.

From the above analysis, the frequency, length of path through rain cell, wave polarization, and rainfall rate affect rain fade quantity. The direct wave is attenuated as it travels through the foliage layer of the forest.

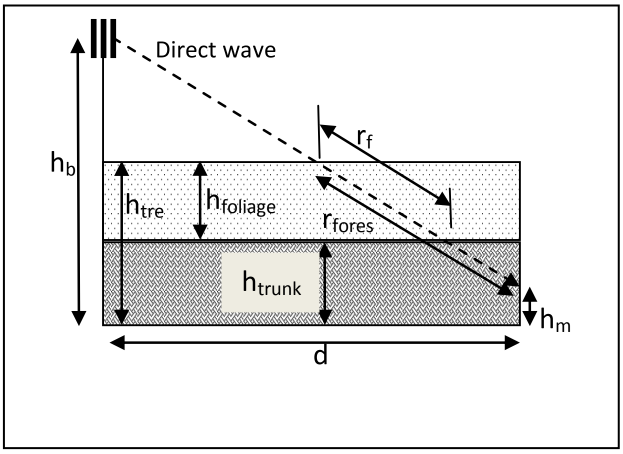

Fig. 1. Graphical representation of the direct-wave propagation through the foliage and trunk layers of the forest.

For reliable radio communication system, the rain rate value $R_{0.01\%}$ is considered, which indicates a rain rate value that will probably be exceeded for at most 0.01% of the year. The following model is based on the Rice-Holmberg model [15] where the value of $R_{0.01\%}$ is computed, from the average annual rainfall R_Y, by:

$$R_{0.01\%} = \frac{1}{0.03}\left[\ln(0.03\frac{R_Y\beta}{\Delta t})\right], \Delta t \ = \ 0.876\ hrs \qquad (5)$$

β is a parameter related to the convective rain portion, and is defined as the ratio of convectional rainfall and thunderstorm rainfall to the total rainfall accumulation. The value β=27.7% for Jordan is estimated from the data given in [16].

Using equation (5), the average value of $R_{0.01\%}$ for Jordan is 22.9 mm/hr. This computed value, based on real measurements in Jordan, agrees with the ITU recommended value of 22 mm/hr [17]. Based on these values of $R_{0.01\%}$ and using equation (2), the specific rain attenuation in Jordan is computed and shown in Fig. 2 for both horizontal and vertical polarizations. The computation considers frequency range that extends up to 1000 GHz. It is seen from this figure that the horizontal polarization has a little higher attenuation than the vertical polarization for frequencies lower than 100 GHz, but after 100 GHz, the difference becomes negligible.

In order to characterize the difference between polarizations, the relative difference of attenuation rates vs. frequency is shown in Fig. 3. The relative difference is defined here as the difference between the attenuation rate of horizontal polarization γ_H and vertical polarization γ_V divided by their average, i.e., $(\gamma_H-\gamma_V)/(\gamma_H+\gamma_V)/2$. Figure 3 shows that the relative difference fluctuates until 23 GHz, and then it decreases monotonically towards the 100 GHz frequency. Observe that the wavelength decreases after 23 GHz towards the raindrop size. For wavelengths larger (smaller frequencies) than raindrop size, the wave "distinguishes" the non-spherical shapes of the raindrops, where horizontal dimension is larger than the vertical dimension. This may explain why horizontally polarized wave is more attenuated by rainfall than vertically polarized wave.

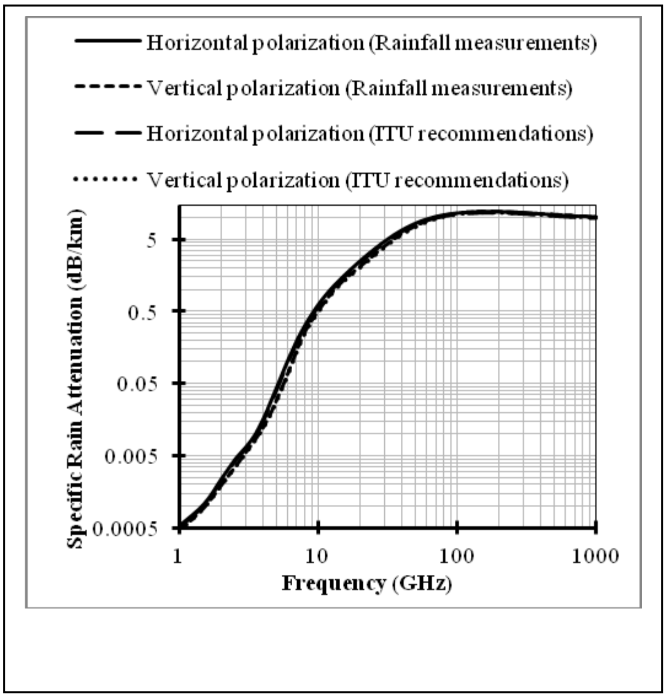

Fig. 2. Attenuation rate vs. frequency in Jordan for horizontal and vertical polarizations.

The difference between the attenuation rate of horizontal polarization γ_H and vertical polarization γ_V vs. attenuation rate of vertical polarization in Jordan is depicted in Fig. 4. The quantity $\gamma_H - \gamma_V$ is used since γ_H is in general higher than γ_V. Also, equation (2) shows that the attenuation rate γ increases with the rain rate. Accordingly, Fig. 4 along with equation (2) reveals that the rainfall attenuation depends on the polarization. The straight line fitting gives the following relationship: $\gamma_H - \gamma_V = 0.1812\ \gamma_V$.

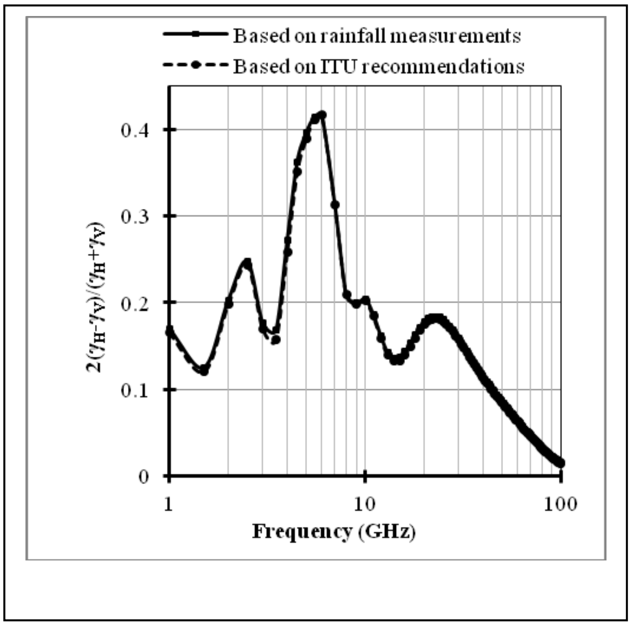

Fig. 3: Relative difference between rain attenuation rates of horizontal and vertical polarizations in Jordan.

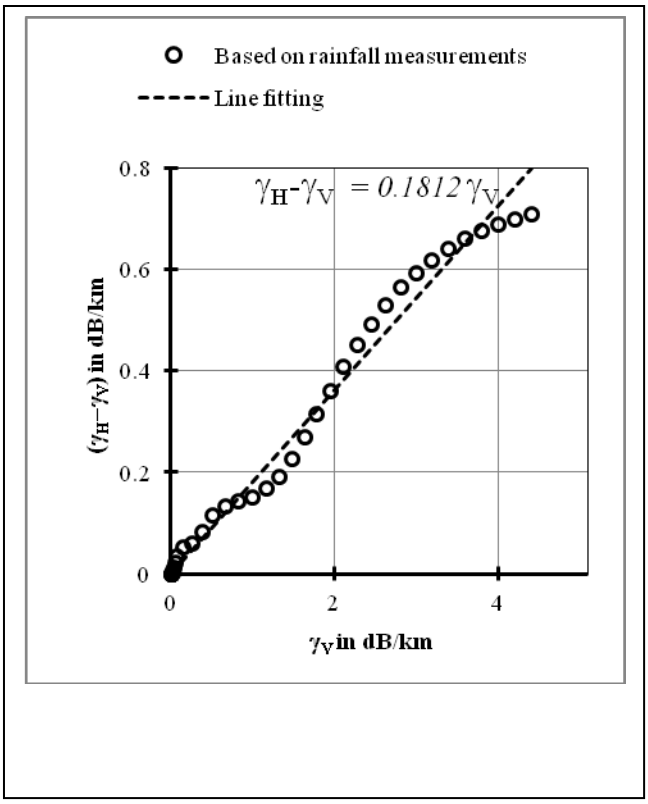

Fig. 4: Excess attenuation rate of horizontal over vertical polarization vs. attenuation rate of vertical polarization, and its straight line curve fitting.

III. FOREST OPTIMIZED MODEL

A series of experimental propagation path loss measurements and modeling in forests were conducted at the VHF and UHF frequencies using the general expression [18]:

$$L_{Forest} = K + A \log(d) + B\, d \quad (6)$$

Where L_{Forest} is the propagation path loss in dB, K, A and B are parameters to be determined based on the measured data, and d is the distance in kilometers between the transmitter and receiver.

The model in this paper will be based on equation (6), and least squares method gives the optimum values of the parameters:

$$L_{Forest} = -97.79 - 32.33 \log(d) + 0.1832\, d \quad (7)$$

To this point, equation (7) doesn't involve frequency dependence of the loss. In order to take in the frequency dependence, the forest path loss is computed for different frequencies using the lateral wave ITU-R model integrated with the free space loss model [19], as shown in Fig. 5. From the logarithmic curve fitting, the frequency dependence is: $-15.65\ln(f) = -15.65\ln(10)\log(f) = -36\log(f)$, where f is the frequency in MHz. Inserting the frequency dependence and rain loss L_R correction factors, (7) becomes:

$$L_{Forest} = -97.79 - 32.33 log(d) + 0.1832d \\ -36\, log(f\ /92.1) + aR^b r_r \quad (8)$$

IV. COMPUTED LOSSES

The Root Mean Square Error (RMSE) formula, $RMSE = \sqrt{\sum_{i=1}^{N}(P_{mi} - P_{ri})^2 / (N-1)}$, will be used in this paper to quantify the accuracy of path loss models as compared with reference measured data. P_{mi} , P_{ri} are the measured and model predicted path loss amounts, respectively, at distance point i for a total of N data samples. As per reference [20], acceptable values of root mean square error (RMSE) should not exceed 8 dB. The reference measured data of path loss [21] were obtained in a forest at an operating frequency of 92.1 MHz, transmitter antenna gain 9.54 dB, and radiated power 2.5 kW from transmitting antenna at a height of 130 m. The receiving antenna was a dipole with height of 0.5 m and gain of 1.76 dB. Microsoft Excel computer programs were utilized in this paper in order to numerically evaluate the new model predicted results.

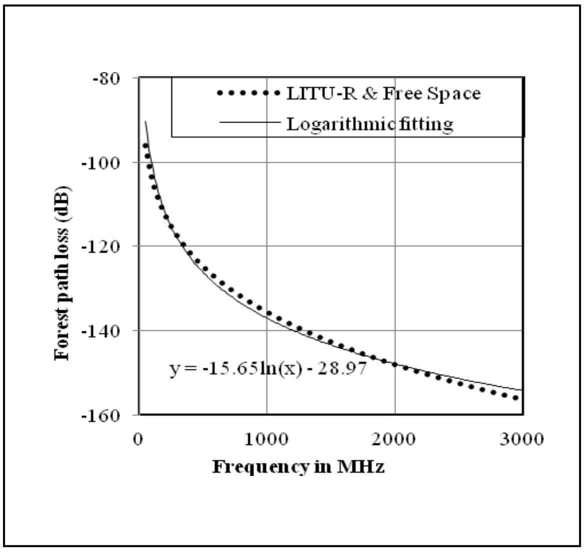

Fig. 5: Frequency dependence of the forest path loss and its logarithmic curve fitting.

The optimized model equations presented in the previous Section were used to evaluate the path loss in the forest. For comparison purposes, the free space path loss was also used to find the path loss associated with the direct wave. Note that the ground reflection is negligible due to the presence of the scrubs and grasses layer on the ground under the trees. This scrubs layer attenuates and absorbs the wave as it passes through it. Thus, the principal contributors to the received signal, in a forest with scrubs and small plants on the ground, are the direct wave, vegetation effect, and rainfall as shown in Fig. 6. The measured data [21] are in excellent agreement with the optimized model predictions. The RMSE of the optimized model is only 4.5 dB with reference to the measured data. Over and above that, the figure confirms the fact that the vegetation has significant effect on wave propagation in the forest, where the vegetation attenuation is greater than 20 dB even for small distances. Moreover, Fig. 6 reveals that the vegetation effect saturates after a distance of about 20 km from the transmitter. This may be explained by the fact that the lateral wave has dominant effect in the VHF and UHF frequency bands [22]. Notice that the ratio of the lateral wave magnitude to the direct wave at the free space-foliage interface increases for larger distances due to the increasing angle of incidence at the larger distances. The angle of incidence is the angle subtended between the direction normal to the interface and the direction of the incident direct wave.

V. CONCLUSIONS

This paper presents a least squares optimized model for propagation in forest with scrubs covering the ground under the trees. The model allows for varying frequencies. Rainfall and snowfall are considered for both horizontal and vertical wave polarizations.

The results computed by the new model agree well with the measurements where the root mean square error (RMSE) is only 4.5 dB. For comparison reasons, the direct ray path loss and vegetation loss are calculated and compared with the optimized model path loss. The results show that vegetation has significant and important effect on the propagation phenomenon.

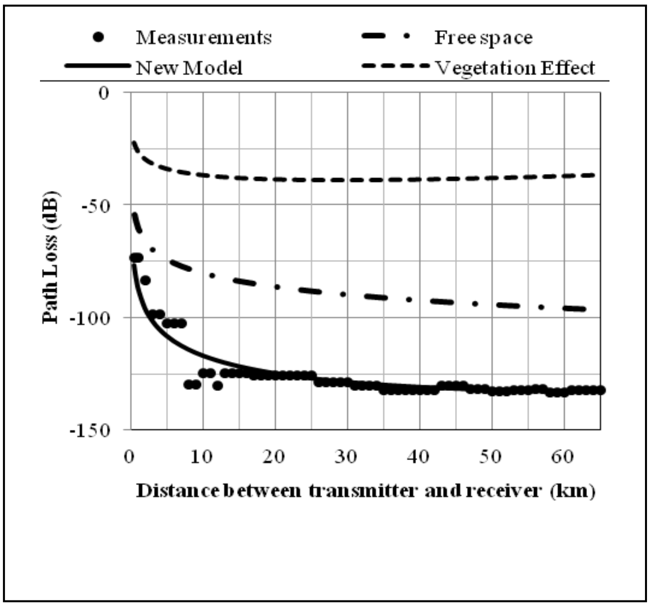

Fig. 6: Computed total path loss and measured path loss as well as free space loss and vegetation loss at 92.1 MHz in forest area.

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