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Characterization and Modeling of Vegetation Effects on UHF Propagation through a Long Forested Channel

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Abstract—In this paper, measurement, modeling and validation of existing models on the effect of nonhomogeneous vegetation on UHF radio-wave propagation through a long forested channel at frequency of 1835 MHz are reported. The paper focuses on vegetation attenuation measurement through a long forested channel of about 8 km long with mixed vegetation of different density. The measured data were fitted using exponential decay function, and a new model was proposed from the fitted curve. The new proposed model will take care of the limitation in vegetation depth posted by some existing models. Generic models, mainly modified exponential decay and analytical models were also fitted to the data and validated, while RMSE was used to determine the best model that describes the data. The evaluated data results show that all the models tested give significant errors which show that they are not suitable for long forested channel scenario. Though COST 235 has the least error (17.05 dB), the error is still significant because COST 235 could only account for vegetation attenuation of short distance scenario. Attenuation shows corresponding increase with increase in leaves thickness in the forested channel considered, which was due to complex permittivity of the leaves moisture content and the dielectric properties of the leaves saline water. The developed model and other results obtained in this study will help to improve prediction accuracy of the effects of vegetation attenuation in nonhomogeneous vegetation along forested channels and also help in establishing efficient UHF radio link budget for long forested channel scenario.

1. INTRODUCTION

A forest is characterized by vegetation of different canopies and components with different physical natures in terms of trees height, leaves pattern, leaves thickness, trunk sizes and number of branches which determine the rate of attenuation of radio-waves that propagate through it via scattering, absorption, refraction and diffraction of the waves. Trees in forest can exist in a group or a single tree and can be made up of mixed or homogeneous tree types resulting in different effects on radio-waves even at the same frequency by the same group of tree depending on the geometry of the link [1].

Over ten decades, forest in Africa countries particularly tropical rainforest regions have been the major sources of agriculture such as timbre, cash crops, fruits and oil palm plantations which serve as one of the major sources of Government revenues. The poor state of Africa economy and inadequate wireless network plan and link system necessitated the use of a single based-transmitting station for UHF link over some long distance forest, hence higher attenuation rate which results to poor or no reception of radio-waves inside forest.

The recent fall in crude oil price globally and the economic recession of some oil dependent Africa nations led to little improvement in commercial farming and increment in Agricultural products. To improve crops, disease and environmental monitoring and, to control crop growing conditions and

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automate agricultural processes, wireless transmission and reception networks are seen as enabling technology [2]. Implementation of quality UHF wireless networks in a very long and wide forest of some Africa regions particularly tropical rainforest regions requires accurate measurement, prediction and modeling of the impact of different vegetation on UHF radio-wave propagation through such long forested channel so as to enable adequate UHF wireless link budget planning and implementation for long and wide forested channel. In [3], further work was recommended on empirical modeling of propagation loss in forest, especially over larger forested depth.

With the advent of microcellular radio networks likely to be employed in third-generation mobile communication systems there is increased interest in propagation models that are able to provide location-specific predictions of channel parameters [4]. Many vegetation models have since been developed, but some of these models are range and frequencies-specific, hence do not perform well in all scenarios. In this paper, measurement, modeling and validation of existing models on the effect of inhomogeneous vegetation density on UHF radio-wave propagation through a long forested channel at frequency of 1835 MHz are reported.

The primary objective of this paper is to examine the additional attenuation caused by propagation of UHF radio-wave signal at frequency of 1835 MHz in a forest of long and wide vegetation depth with different vegetation components for the case where the transmitter is located outside the forest while the receiver is located at a different point within the forest. The major contribution of this paper is the development of vegetation attenuation model over a long forested channel of different vegetation type and its comparison with the existing models on long forested channel scenario.

2. EXISTING VEGETATION ATTENUATION MODELS

A traditional approach to modeling attenuation loss caused by propagation through vegetation is to assume that this loss increases exponentially with the distance through foliage [5]. A review of the models and data that can be used to predict the attenuation caused by propagation through, rather than over, groves of trees has indicated that the exponential-decay model, generally assumed applicable to such problems, is often inaccurate. In [6] an improved empirical algorithm, the modified exponential decay (MED) models developed to overcome some of the problems observed with the exponential decay algorithm were discussed.

A summary of vegetation attenuation models is presented in Equations (1) to (8). These models can be classified into empirical and analytical models. Amongst the empirical generic models widely used are the modified exponential decay (MED) models, such as Weissberger model [7] given in Equation (1), it is applicable in situations where propagation is likely to occur through a grove of tree rather than by diffraction over the top of trees;

$$L_W\,(\mathrm{dB}) = \begin{cases} 1.33 \times f^{0.284} d^{0.588} & 14\,\mathrm{m} < d \leq 400\,\mathrm{m} \\ 0.45 \times f^{0.284} d & 0\,\mathrm{m} \leq d < 14\,\mathrm{m} \end{cases} \tag{1}$$

F is frequency in GHz & d is the tree depth in meter.

ITU-R model [8, 9] was proposed for cases where either the transmitter or receiver is near a small grove of trees so that most of the signal propagates through trees;

$$L_{\text{ITU-R}} = 0.2 \times f^{0.3} d^{0.6} \tag{2}$$

f is frequency in MHz, and d is the tree depth in meter ($d < 400\,\mathrm{m}$).

COST 235 model [10] was proposed based on measurements made in millimeter wave frequencies through small grove of trees;

$$L_{\text{cost}}\,(\mathrm{dB}) = \begin{cases} 26.6 \times f^{-0.2} d^{0.5} & \text{out-of-leaf} \\ 15.6 \times f^{-0.09} d^{0.26} & \text{in-leaf} \end{cases} \tag{3}$$

f is the frequency in MHz, and d is the tree depth in meter ($d < 200\,\mathrm{m}$).

FITU-R model [11] was proposed through an optimization campaign carried out using data at 11.2 and 20 GHz as;

$$L_{\text{FITU-R}} = \begin{cases} 0.37 \times f^{0.18} d^{0.59} & \text{out-of-leaf} \\ 0.39 \times f^{0.39} d^{0.25} & \text{in-leaf} \end{cases} \tag{4}$$

f is the frequency in MHz, and d is the tree depth in meter ($d < 120$ m).

Gradient generic models, such as Maximum attenuation (MA) [12] was recommended by (ITU) for frequency range of 30 MHz–30 GHz using the excess maximum attenuation measured and the initial gradient of the attenuation curve as input parameters;

$$L_{MA} = A_m \left[1 - \exp\left(-\frac{R_o d}{A_m}\right)\right] \tag{5}$$

A_m is the maximum attenuation, R_o the initial gradient of the attenuation rate curve, and d the tree depth in meter.

The Non-Zero Gradient (NZG) model [13] was proposed to overcome the zero final gradient problem of the MA for frequencies above 5 GHz;

$$L_{\text{NZG}}\,(\text{dB}) = R_\alpha d \left(1 - \exp\left\{\frac{-(R_o - R_d)}{K} d\right\}\right) \tag{6}$$

d is the tree depth meter, and R_o and R_∞ are the initial and final specific attenuation offset in dB.

Dual Gradient (DG) model [13] was achieved by using antenna of different beam widths to accommodate the different in the received signal levels.

Analytical models are used to describe the propagation mechanisms through vegetation, and they require more detailed knowledge of the environment and hence, are computationally intensive which has led to their underutilization [2]. Examples are Radiative Energy Transfer (RET) model, which assumes the vegetation to be a statistically homogenous medium of scatterers and absorbers [14];

$$\begin{aligned}\frac{P_R}{P_{\max}} &= e^{-\tau} + \frac{\Delta\gamma^2 R}{4} \cdot \left\{\left[e^{-\tilde{\tau}} - e^{-\tau}\right] \cdot \bar{q}_M + e^{-\tau} \cdot \sum\nolimits_{m=1}^{M} \frac{1}{m!}(\alpha W_T)^m [\bar{q}_m - \bar{q}_m]\right\} \\ &+ \frac{\Delta\gamma^2 R}{2} \cdot \left\{-e^{-\bar{\tau}} \cdot \frac{1}{P_N} + \sum\nolimits_{K=\frac{N+1}{2}}^{N} \left[A_k e^{-\frac{\bar{\tau}}{s_k}} \sum\nolimits_{n=0}^{N} \frac{1}{1 - \frac{\mu_n}{s_k}}\right]\right\}\end{aligned} \tag{7}$$

P_R is the received power, $P_{\max}$ the signal strength received in absence of vegetation, $\Delta\gamma R$ the beam width of the forward scatter lobe, and m the order of the term, $\tau = (\sigma_a + \sigma_s)$. τ is the optical density and d the distance in metres, and σ_a and σ_s are the absorption and scattering cross-sections.

Wave Theory Based Model is believed to be more accurate for presenting the coherence effects of phase information [15];

$$E^s = \frac{e^{ikr}}{r} \sum\nolimits_{n=1}^{N} e^{i\emptyset_n} S_n \cdot E_o^i \tag{8}$$

N is the total number of scatterers, S_n the individual scattering matrix of the n-th scatterer, and $\emptyset_n$ the phase compensation accounting for the shifting of the phase reference.

Coherent wave propagation models based on Monte Carlo simulation of scattering from a realistic looking fractal tress were successfully used to obtain the statistics of wave propagation through foliage in [16] and [17].

3. EXPERIMENTAL SET-UP AND MEASUREMENT CAMPAIGN

Figure 1 illustrates the forest geometry and measurement configuration. The transmitter (Figure 2) is a fixed base transmitting station of Mobile Telecommunication Network (MTN) of TRX power class 2 with output power of 10 W, antenna gain of 18 dBi, and height of 100 m, operating at a frequency of 1835 MHz and located very close to the entrance of the forest along which the measurement campaign was carried out. The receiver in Figure 3 is a UHF field strength meter designed and constructed in [18] to receive mobile network signals at GSM frequency bands. It consist of the receiving and storage segments. The receiving segment consists of two high gain dipole antennas (7.5 dBi each), modem controller with MTN subscriber identification module, PIC 16F877A microcontroller, 12 V, 7.5 AH storage battery, charging unit and voltage controller, while the storage unit consists of DS 1307/series, HD44780U (LCD II), user interface (as button) indicator, memory card and PIC 8F452 microcontroller. The receiver system

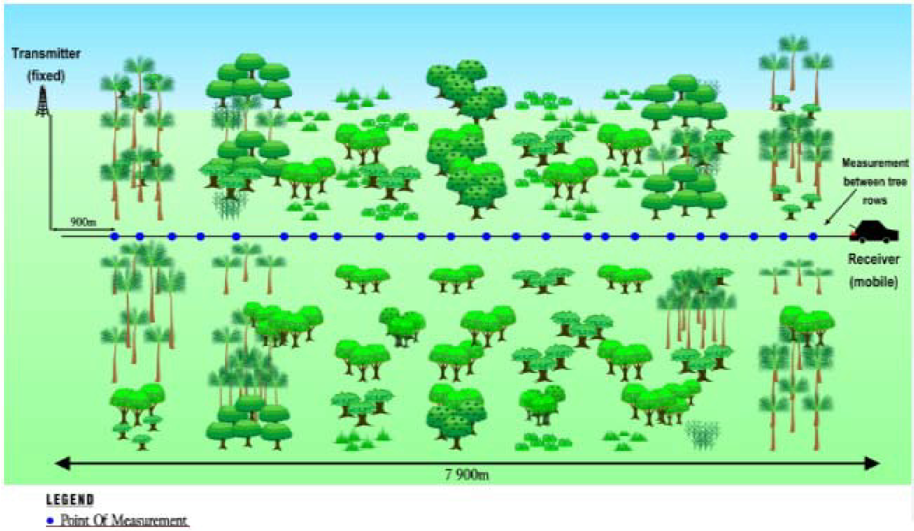
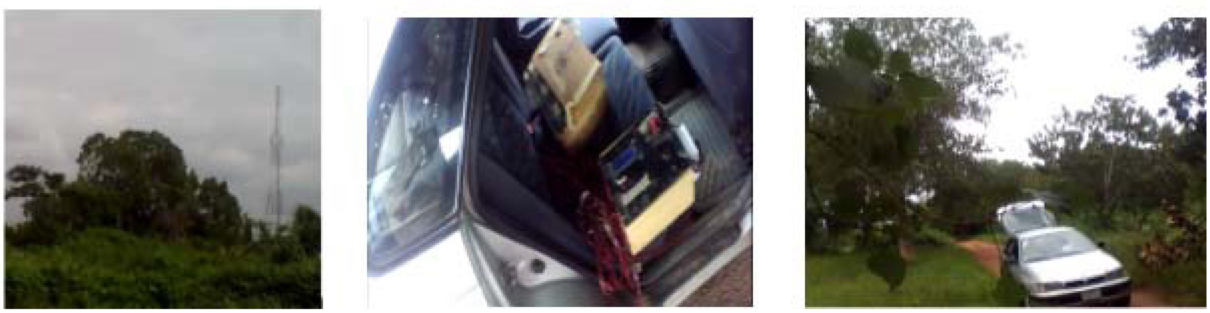


Figure 1. Forest geometry and measurement configuration.



(a) (b) (c)

Figure 2. Vegetation attenuation measurement campaign: (a) transmitter, (b) UHF field strength meter and, (c) measurement campaign into the forest.

operates in a similar pattern to mobile handset, and it receives the mobile network signal strength and convert it to numerical form in dB through a programming code embedded in the system. The system was calibrated using Standard GSP 810 spectrum analyzer that operates in the range of 10 kHz to 3G, and the comparison results show the same correlation coefficient up to one decimal place, which makes the instrument a benchmark UHF Signal receiver. The measurements were conducted along the forested path at the beginning, middle and end of a typical vegetation type. At every measured point, the vehicle stops for twenty minutes, while the receiver receives, logs and stores the signal strength every five minutes.

Some other measuring equipment such as GPS, tape rule and micrometer screw gauge were taken along for position identification, to measure trunk diameter and leave thickness of peculiar vegetation along the forest. There are different varieties of vegetation. The predominant ones along the forest are mango trees, Odan trees, maize plantation, palm trees, cashew plantation, big thick tress, Iya plant and grasses, but grasses and maize plantation were very short during the measurement campaign, and the areas covered by the grass and maize plantation were referred to as open field area. The vegetation was of different trunk diameters, leave thicknesses and densities, each dominating wide area of land along the forest, though cashew, mango, thick and palm are more predominant. Meanwhile there are background weeds under the forest vegetation. Measurements were conducted at some interval along the forest as depicted in Figure 1. Table 1 shows the characteristics of the varieties of vegetation in the selected forest area.

Table 1. Forest common vegetation and their characteristics.

Vegetation variety	Average Height (m)	Average Trunk diameter (m)	Average Leave thickness (m)
Mango	6.50	0.16	0.0010
Thick	14.20	1.19	0.0018
Odan	11.25	1.11	0.0011
Short legumes	1.50	0.01	0.0001
Iya	5.50	0.30	0.0012
Maize	2.50	0.25	0.0011
Palm tree	9.85	1.08	0.0015
Cashew	8.90	0.51	0.0012

4. RESULTS AND DISCUSSIONS

Figure 3 shows the results of the fitted curve of the data obtained from the measurement conducted along the long forested channel at different points away from the transmitter. The fitted curve, using exponential decay function, shows a corresponding increase in attenuation with increase in forest or vegetation distance into the forest. The deduced exponential decay model (DED model) (Equation (9)) obtained from the measured data will be useful henceforth for estimating vegetation attenuation through long inhomogeneous forested channel of different vegetation species and densities in which the transmitter is located outside the forest while the receiver position varies within the forest.

$$Att_{\text{data}} = 175.32 + (-63.79)e^{-d/3964.21} \quad 900\,\text{m} \leq d \leq 8000\,\text{m} \tag{9}$$

where d represents the distance into the vegetation.

Figure 4 shows the result of modified exponential decay and gradient models fitted to the data obtained from the measurements, while root mean square error (RMSE) criterion was used to estimate the best model that describes the data obtained from the measurement. It was observed that all the models tested gave significant errors which show that they are not suitable for long forested channel scenario. Though COST 235 has the least error (17.05 dB), the error is still significant because COST 235 could only account for vegetation attenuation of short distance scenario. MED model gives lesser error value in term of RMSE value than gradient (MA and NZG) models at the 1835 MHz frequency class considered. Fitu model gave the worst performance in this scenario, as a result of smaller values of its model parameters than that of COST 235. Likewise, the MA model parameters values A_l and α

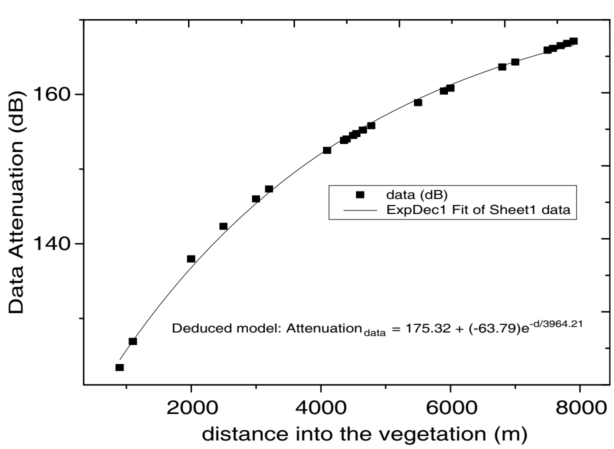


Figure 3. Fitted curve of attenuation along the long forested channel and the deduced model.

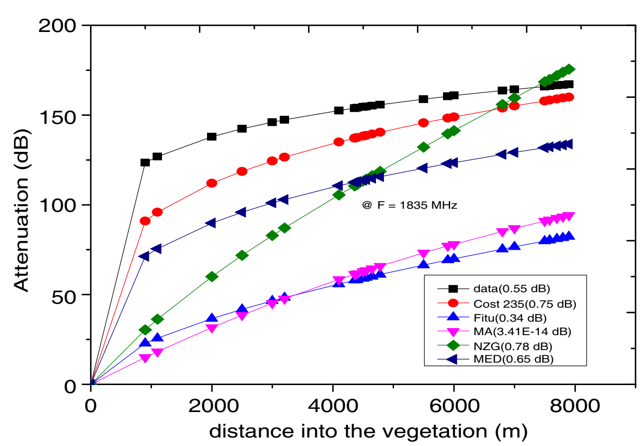


Figure 4. Comparison of vegetation attenuation models at 1835 MHz.

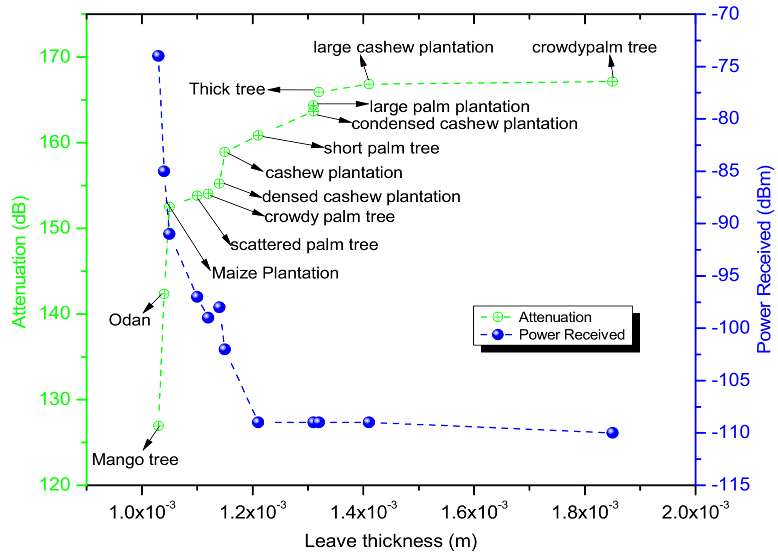


Figure 5. Power received, attenuation variations with forest vegetation leave thickness.

to be precise are vegetation species, which are not limited to vegetation species alone but also depend on vegetation characteristics, and other dependent parameters gave a poor performance in this case because the types of vegetation from which these factors were deduced are not available in the chosen forest. The problem associated with MA model led to the development of NZG whose error in this scenario though is significant but less significant than that of MA model.

Figure 5 shows variations in power received, attenuation and the vegetation leaves thickness, and the essence of this analysis is to predict the significant effect of vegetation leaves thickness on power received and its role on vegetation attenuation in a forested channel of mixed vegetation species. It was observed that there is significant reduction in the power received and significant increase in attenuation with corresponding increase in leave thickness of the forested channel under consideration, which is due to complex permittivity of the leaves moisture content and the dielectric properties of the leaves saline water. Thicker leaves have more moisture content than the lighter ones which reduces the permittivity of the transmitted signal, and eventually causes more attenuation of the transmitted signal, as it has also been justified in the results of leave — scattering predictions of microcells propagation established in [19] and [20].

5. CONCLUSION

This paper has presented the results of the measurement carried out along an inhomogeneous vegetation density of a long forested channel at a frequency of 1835 MHz. The aim of the study was to validate the existing models and determine which model is most suitable among the existing models for application in long forested channel scenario, and finally, to deduce a unique model from the data obtained which will be suitable for use, especially in a mixed vegetation through long forested channel. Some of the existing generic models have been fitted to the data. The results of the fitted models show that none of the models tested for validation is suitable for predicting vegetation attenuation in a long forested channel scenario. The inhomogeneity of the vegetation density leads to significant variations in the power received along the long forested channel from one location to the other. Likewise, variations in canopy structures, leaves thickness, vegetation trunk sizes along the forest are responsible for the significant variations observed in the signal attenuation. The long distance into the vegetation covered by the newly developed model will take care of the limitations in vegetation depth posted by some of the old generic models. Hence, further research work should be done on tree and leave scattering of UHF radio wave propagation in a long forest channel of nonhomogeneous vegetation density and mixed vegetation scenario. Moreover, the deduced model can also be revalidated through measurement in another tropical forest region.

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