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VEGETATION ATTENUATION MEASUREMENTS AND MODELING IN PLANTATIONS FOR WIRELESS SENSOR NETWORK PLANNING

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Abstract—As wireless communication moves from long to short ranges with considerably lower antenna heights, the need to understand and be able to predict the impact of vegetation on coverage and quality of wireless services has become very important. This paper focuses on vegetation attenuation measurements for frequencies in the range 0.4–7.2 GHz in mango and oil palm plantations to evaluate vegetation attenuation models for application in wireless sensor network planning and deployment in precision agriculture. Although a number of models have been proposed and evaluated for specific frequencies, results show that these models do not perform well when applied to different vegetation types or at different frequencies. A global assessment of the models using a broad range of frequencies shows that the COST 235 model gives more consistent results when there is vegetation in the propagation path. For grid-like plantation, the study shows that the RET model provides the best prediction of path loss for measurements between two rows of trees. However, taking into account

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the limited number of parameter values available for the RET model and the potential inaccuracy that may results from the use of a wrong parameter value, a sub-optimal model which combines the ITUR model with ground reflection does offer a more consistent prediction. The differences in the average values of RMS error between RET, ITUR and free space loss models when combined with ground reflection is less than 1.6 dB.

1. INTRODUCTION

Recently, there has been a significant expansion of land use for plantations such as oil palm, rubber and other commercially cultivated crops. To improve crops, diseases and environmental monitoring and, to control crop growing conditions and automate agricultural processes, wireless sensor network (WSN) is seen as the enabling technology. Wireless sensor devices are often battery powered small devices that transmit low power radio-waves for communication purposes. The implementation of wireless sensor networks in forested areas requires a better understanding of the impact of vegetation on radio-waves and the validation of existing models that will facilitate wide area WSN planning and deployment.

In general, trees can exist in a group or as a single tree and can be made up of mixed or homogeneous tree type resulting in different effects on radio-waves even at the same frequency by the same group of trees depending on the geometry of the link [1]. Vegetation in the transmission path has two main effects on radio-waves; attenuation and scattering. Attenuation increases fading whilst scattering reduces the signal-to-interference ratio (quality) of the received signal even at shallow vegetation depths. The studies reported in this paper focuses on managed plantations where only one tree type is planted.

Until recently, experimental studies of the impact of vegetation on radio-waves have been conducted on predominantly trees that grow in temperate climates. The International Telecommunications Union-Recommended (ITU-R) models and other recommended models for vegetation attenuation have been developed using mainly data from those studies. Examples include Savege et al. [1], Seville and Craig [2], COST 235 programme [3], and Shukla et al. [4]. The work by Shukla et al. [4, 5] led to the development of the current ITU-R 833.6 model [6] which is based on the Radiative Energy Transfer (RET) theory [7]. Measurement studies carried out in tropical environment have been reported in [8–11]. Although many researchers have considered contributions from ground reflections, in [12] for studies conducted in a palm plantation (similar to coconut trees) and rainforest, it has been shown that contributions from canopy reflection can also be significant. Further studies on oil palm plantation at 240 MHz and 700 MHz has led to the proposal of an optimized Lateral wave ITU-R model for frequencies up to 300 MHz for application in long range communications [9]. This model, however, does not apply at higher frequencies due to the absence of lateral waves. In addition, very few data points were measured within the transmission range of wireless sensor nodes. The modeling of signals through vegetation is also very important for remote sensing especially for application in forestry, environmental monitoring and agriculture [13]. Some studies have focused on using the vegetation signal attenuation properties to reduce electromagnetic pollution [14].

Very limited studies have been conducted at or close to frequencies in the Industrial, Scientific and Medical (ISM) or license free bands. Most commercially available wireless sensor devices operate in these bands, and their range is often expected to be below 200 m. To minimize energy usage, most of the components in a wireless sensor node are closely coupled, which means that for application in the agricultural environment, the antenna height is unlike to be higher than 3 m as most parameters that are monitored by the sensors are at, or close to, ground level. In [15], studies aimed at the planning and deployment of WSN in a forest environment has been carried out using ZigBee. A simple exponential power decay approach of computing attenuation based on the number of trees in the signal path has been proposed. Signal propagation mechanisms were not taken into account in the planning of the network, although aspects of the effects are encompassed in the power decay profile modeled. The study has shown that the maximum range for each WSN node in forested areas is limited to 90 m.

Most models published in open literature have been developed and optimized for specific frequencies or range of frequencies. Their performances when applied to different plant species, link set-ups, scenarios and frequencies are often inconsistent. In this paper, a database of vegetation attenuation measurements over a wide range of frequencies, from 400–7200 MHz in steps of 100 MHz, conducted in a mango plantation and an oil palm plantation has been used to evaluate vegetation attenuation models as part of a WSN deployment project to monitor plant growing conditions and possible plant diseases. The main contribution of this paper is the assessment of vegetation attenuation models over this wide range of carrier frequencies in tropical tree species and the identification of the model(s) that offer consistent accuracy in different scenarios and vegetation types over a wide range of frequencies. The paper emphasizes the fact that although some models may offer higher accuracies in a specific scenario, for a particular geometric set-up and frequency, their performances in other set-ups are too poor for application in a wide area wireless sensor network planning in agriculture where the vegetation components vary in sizes and hence, effects on radio-waves. The paper evaluates the performance of each model using the models' generic formulation to fit to the data and it is shown that the limited accuracy of most models is associated with the parameters values assigned. Overall, this study identifies the optimum model(s) that should be used to plan WSN in a wide range of areas.

This paper is organized as follows. Section 2 describes the experimental set-up and the measurements carried out. Details of the various vegetation attenuation models that have been evaluated are provide in Section 3. In Section 4, a discussion of the measurement observations is given together with the results of fitting the generic vegetation attenuation models to the measured data. This is followed in Section 5 by the assessment of the performances of the models based on the values published in open literature and the paper concludes with recommendations of the model(s) that should be used for wireless sensor network planning in plantations.

2. EXPERIMENTAL SET-UP AND MEASUREMENTS

Figure 1 illustrates the experimental measurement set-ups. The transmitter consisted of a signal generator (Agilent E8267D), power amplifier, and wideband horn antenna. The receiver consisted of a wideband horn antenna, low noise amplifier and spectrum analyzer (Agilent E4405B) that was connected to a computer for data logging. The noise floor of the spectrum analyzer was −70 dBm. The

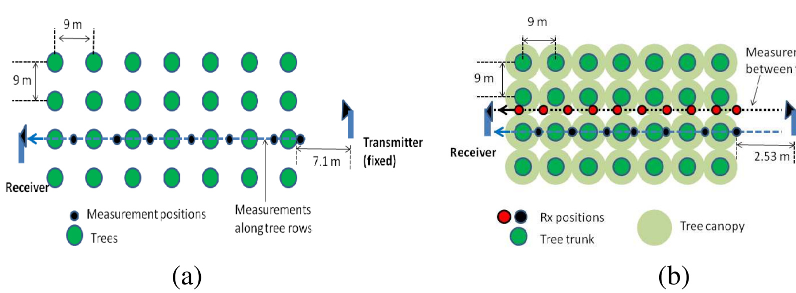


Figure 1. Vegetation geometry and measurement configurations: (a) mango plantation and, (b) palm plantation.

transmitted power and antenna gains used for the measurements are given in Table 1. The signal generator was configured to sweep across the band of interest in steps of 100 MHz with a dwell time of 5 s per frequency to allow multiple samples to be captured and also provide sufficient time for the system to settle. The spectrum analyzer and the signal generator were phase-locked to a common 10 MHz reference signal at the start of the measurement. During measurements, the spectrum analyzer span was set to cover the whole band of interest and the whole band was digitized. Post-processing software was used to filter out the received frequency component and its amplitude. All measured signals were calibrated to remove the system response.

The mango plantation covered an area of approximately 20 acres with the mango trees planted in rows that were 9 m apart. The tree had an average height of approximately 5 m and trunk diameter of between 20 cm and 30 cm. The grass was kept very short, and hence the only contributors to vegetation attenuation were the mango trees. The transmitting antenna height was 2.5 m, and measurements were conducted at four receiver antenna heights: 1.3 m, 1.7 m, 2.2 m and 2.6 m. Figure 2 shows photographs of the transmitter antenna set-

Table 1. Transmitted power and gains of the antennas used.

Frequency (GHz)	TX Power (dBm)	Transmitting Antenna Gain (dBi)	Receiving Antenna Gain (dBi)
0.4–1.4	31	≈ 5	≈ 4–6.5
1.5–7.2	25	4–11	≈ 7.0
0.4–7.2 (orchard)	25	≈ 5	≈ 4–6.5

(a) (b)

Figure 2. Experimental measurement set-up in (a) mango plantation — transmitter and, (b) oil palm plantation — receiver.

up in the mango plantation and the receiver in the palm plantation. Measurements were conducted on two rows of mango trees.

The palm tree trunks were approximately 3 m high with palm fronts extending for a further 5 m, although not all vertically. The trunk diameters varied from 60 cm to about 130 cm. Network outage due to shadowing effect is highly probably in this type of plantation. The transmitter antennas were mounted 2.53 m from the edge of the plantation. Measurements were conducted at a height of 2.6 m along a line of palm trees and also between two rows of palm trees in the direction of signal propagation. The propagation path for this second measurement was unobstructed by tree trunks but there were palm fronts that acted as a vegetation canopy at heights from 3 m and above.

3. SIGNAL ATTENUATION MODELS IN THE PRESENCE OF VEGETATION

A good survey of vegetation attenuation models is presented in [4, 5, 11]. The models can be classified into empirical and analytical models. These models are described in this paper for completeness. Empirical vegetation attenuation models developed using experimental data are convenient for their simplicity but they do not account for the geometry of the measurement nor distinguish between the modes of propagation. Most of the models, including deterministic models, do not take explicit vegetation density parameter. Amongst the empirical generic models widely used are the Modified Exponential Decay (MED), Maximum Attenuation (MA) and the Non-Zero Gradient (NZG) models.

The MED model is described by Equation (1);

$$Att_{MED} = X f^{Y} d^{Z} \tag{1}$$

where f is the frequency in megahertz (MHz), d the vegetation depth in metres, and X, Y and Z the model parameters. Applications of this model using data from a variety of studies have each resulted in different values of the parameters, X, Y and Z [3, 16, 17]. This has resulted in the model been known by different names. A summary of the parameter values and variants of the model are provided in Table 2.

The maximum attenuation (MA) model, recommended by International Telecommunications Union (ITU) for frequency range 30 MHz–30 GHz, uses the maximum excess attenuation (A_m) measured and the initial gradient (R) of the attenuation curve as input parameters to Equation (2);

$$Att_{MA} = A_m \left(1 - e^{\left(\frac{Rd}{A_m}\right)}\right) \tag{2}$$

where d is the vegetation depth in metres. It has a fixed final attenuation gradient. This model is recommended for cases where the transmitter is located outside and the receiver is located inside the vegetation. The parameter, A_m, has a frequency dependency of the form $A_m = A_L f^{\alpha}$. Recommended values of A_L and α have only been measured at frequencies in the range 900 to 2200 MHz. Two sets of values have been provided in ITU-R833.6 [6]; for frequency in the range 900–1800 MHz, $A_L = 0.18$ dB and $\alpha = 0.752$. For measurements conducted in Europe for frequency in the range 900–2200 MHz, $A_L = 1.15$ dB and $\alpha = 0.43$.

The Non-Zero Gradient (NZG) model, (3), was proposed to overcome the zero final gradient problem of the MA model for frequencies above 5 GHz [2]. The model requires an estimate of the initial gradient (R_0) and the final gradient (R_∞) of the attenuation curve, and the offset of the final gradient (κ). The parameter k is frequency dependent.

$$Att_{NZG} = R_\infty d + k\left\{1 - \exp\left(-\frac{R_0 - R_\infty}{k} d\right)\right\} \tag{3}$$

In contrast to the above models, analytical models can be used to describe the propagation mechanisms through vegetation. They require more detailed knowledge of the environment and hence, are also computationally intensive. This has led to their under utilization. One of the models is the Radiative Energy Transfer (RET) model which assumes the vegetation to be a statistically homogeneous medium of scatterers and absorbers [5, 7]. The model is described by Equation (8).

Table 2. Variants of the modified exponential decay model.

Model	Equation	Equation number
ITU-R	$Att_{ITUR} = 0.2 f^{0.3} d^{0.6}$, $d < 400$ m	(4)
Weissberger [17]	$Att_{WEIS} = \begin{cases} 1.33 f^{0.284} d^{0.588}, & 14\,\text{m} < d \leq 400\,\text{m} \\ 0.45 f^{0.284} d, & 0\,\text{m} < d \leq 14\,\text{m} \end{cases}$ Note that f is in GHz in this model.	(5)
COST 235	$Att_{COST} = \begin{cases} 26.6 f^{-0.2} d^{0.5}, & \text{out-of-leaf} \\ 15.6 f^{-0.009} d^{0.26}, & \text{in-leaf} \end{cases}$	(6)
FITU-R	$Att_{FITUR} = \begin{cases} 0.37 f^{0.18} d^{0.59}, & \text{out-of-leaf} \\ 0.39 f^{0.39} d^{0.25}, & \text{in-leaf} \end{cases}$	(7)

It is divided into three parts: the coherent component (I_{ri}), which decreases with vegetation depth due to scattering and absorption of the incident waves; the forward scatter lobe (I_1), and; the isotropic diffused scatter signal (I_2), that dominates at large vegetation depths.

$$\left.\begin{array}{ll}\frac{P_R}{P_{\max}} = e^{-\tau} & (l_n)\\ +\frac{\Delta\gamma_R^2}{4}\cdot\left\{\left[e^{-\hat{\tau}}-e^{-\tau}\right]\cdot\bar{q}_M+e^{-\tau}\cdot\sum\limits_{m=1}^{M}\frac{1}{m!}(\alpha W\tau)^m\left[\bar{q}_m-\bar{q}_M\right]\right\} & (l_1)\\ +\frac{\Delta\gamma_R^2}{2}\cdot\left\{-e^{-\hat{\tau}}\cdot\frac{1}{P_N}+\sum\limits_{k=\frac{N+1}{2}}^{N}\left[A_k e^{-\frac{\hat{\tau}}{s_k}}\cdot\sum\limits_{n=0}^{N}\frac{1}{1-\frac{\mu_n}{s_k}}\right]\right\} & (l_2)\end{array}\right\} \quad (8)$$

P_R is the received power, $P_{\max}$ is the signal strength received in the absence of vegetation, $\Delta\gamma_R$ is the beamwidth of the forward scatter lobe and m is the order of the term, $I_1 \cdot N$ in I_2 has to be an odd number larger than 1. The other parameters of the RET equations are defined as follows: $\tau = (\sigma_a + \sigma_s)\cdot d = \sigma_\tau \cdot d$; where τ defines the optical density and d is the distance in metres and, σ_a and σ_s are the absorption and scattering cross-sections.

$$\begin{aligned}\bar{q}_m &= \frac{4}{\Delta\gamma_R^2 + m\beta^2}\\ \mu_n &= -\cos\left(\frac{n\pi}{N}\right)\\ P_N &= \sin^2\left(\frac{\pi}{2N}\right)\\ P_n &= \sin\left(\frac{\pi}{N}\right)\cdot\sin\left(\frac{n\pi}{N}\right) \quad \text{for } n = 1, 2, \ldots, N-1\\ \hat{\tau} &= (1-\alpha W)\,\tau\\ \hat{W} &= \frac{(1-\alpha)\,W}{1-\alpha W}\end{aligned}$$

The I_2 component of the RET equation, which contains the attenuation coefficients S_k and the amplitude factors A_k can be determined numerically [7]. The attenuation coefficients S_k can be determined using Equation (9).

$$\frac{\hat{W}}{2}\cdot\sum_{n=0}^{N}\frac{P_n}{1-\frac{\mu_n}{s}} = 1 \quad (9)$$

Equation (9) will yield $N+1$ roots, for which $s_{0,\ldots,\frac{N}{2}} = -s_{N,\ldots,\frac{N+1}{2}}$ applies. The amplitude factors A_k are determined by a system of

Table 3. Selected values of RET parameters at 2.5 GHz.

Tree Type	α	β	**W**	σ_τ
Gingko	0.93	36.89	0.92	1.1
Plain American tree	0.74	23	0.95	0.486
Maple	0.95	45.34	0.71	0.73

linear equations given by:

$$\sum_{k=\frac{N+1}{2}}^{N} \frac{A_k}{1-\frac{\mu_n}{s_k}} = \frac{\delta_n}{P_N} \quad \text{for } n = \frac{N+1}{2} \quad \ldots . \quad N \tag{10}$$

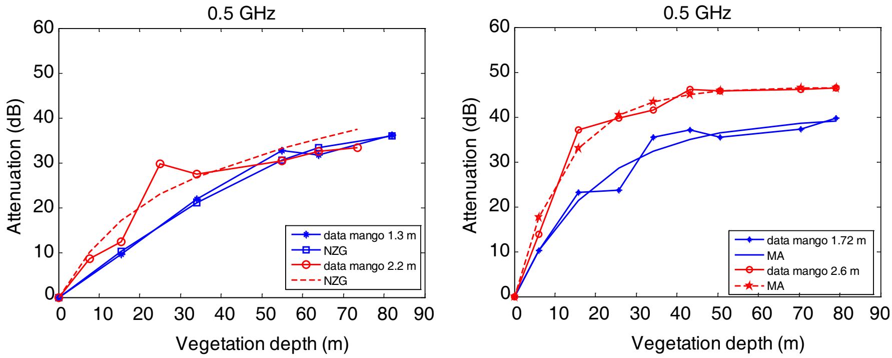
In the RET equations, the antenna beamwidth is assumed to be Gaussian and the resulting phase function beamwidth relates to the 3 dB beamwidth of the antenna ($\Delta\gamma_{3\,\mathrm{dB}}$) by $\Delta\gamma_R = 0.6 \cdot \Delta\gamma_{3\,\mathrm{dB}}$.

The implementation of the RET model requires 4 input parameters: α, β, σ_τ and W. These parameters vary according to the vegetation species, leaf condition, and frequency. Some of the parameters can be determined directly from specific vegetation characteristic whilst others can be estimated from measured vegetation attenuation curves. The fitted parameter values at specific frequencies and tree types are given in [6], however values for all frequencies at which the model applies do not yet exist. Some of the values for the parameters at 2.5 GHz, Table 3, provided in ITU-R 833.6 have been used to assess the performance of the model using measurements conducted in this research.

4. RESULTS AND DISCUSSIONS

Each generic model has been fitted to the data and the root mean square error (RMSE) criterion has been used to determine the best model that describes the data. Figure 3 shows two sets of measurement results at the same site but two locations in the mango plantation. The model with the smallest RMSE is plotted for each set of data. It is worth noting that the best-fit model in Figure 3(a) is the NZG model and in Figure 3(b) is the MA model. However the differences in the RMSE values between the two models in Figure 3(b) were less than 0.02 dB. The figures show that:

- there was a differences in vegetation density between the two locations illustrated by the slower rate of attenuation in Figure 3(a) which had smaller vegetation density. The maximum attenuation is higher at location 2 at similar vegetation depths;



(a) (b)

Figure 3. Vegetation attenuation of 500 MHz signal (mango plantation) at (a) location 1 and (b) location 2 for different antenna heights and best-fit model.

- greater attenuation is obtained for measurement at canopy height compared to measurements at trunk heights. This would be expected at higher frequencies where there are more branches, twigs and leaves. At high frequencies, the sizes of some of these vegetation components are comparable to the wavelength of the radio-waves resulting in greater attenuation. As a result the gap between the attenuation curves obtained at low and high antenna heights increases with frequency.

Figure 4 shows samples of the results of measurements in the oil palm plantation. The results from measurements along a row of palm trees show that due to shadowing by tree trunks, the initial gradient of the attenuation curve is very steep. However, the results from measurements between two rows of palm trees show smaller initial attenuation gradients because attenuation is due mainly to free space loss, ground reflection and/or canopy reflection. Figure 4 also shows that as the frequency increases, the differences in attenuation between the measurements along a row of palm trees and between two rows of trees increases, especially at short vegetation depths. This is important for the selection of frequency for use in different plantations and wireless sensor node positioning.

Figure 5 shows the fitting of the various models, both in their generic form and using the parameter values recommended for some of the models, to the measured data in the palm plantation at 2.5 GHz. Conceptually, the RET model should be able to fit the measured data better as it accounts for the coherent, forward scatter and diffuse

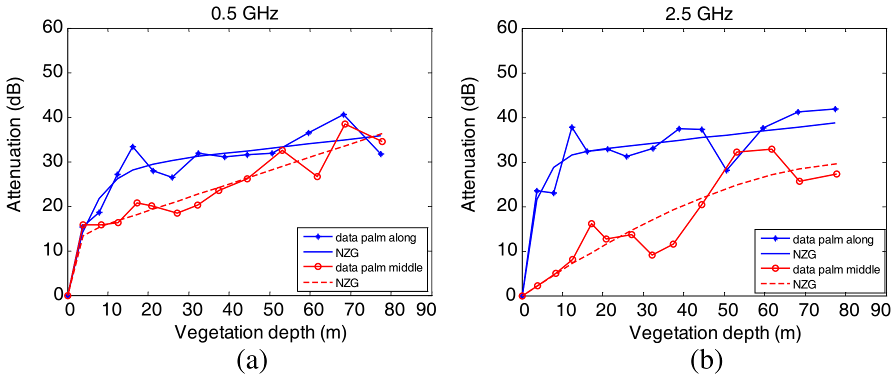


Figure 4. Signal attenuation along a row of palm trees and in-between two rows of palm trees for transmissions at (a) 500 MHz and, (b) 2.5 GHz.

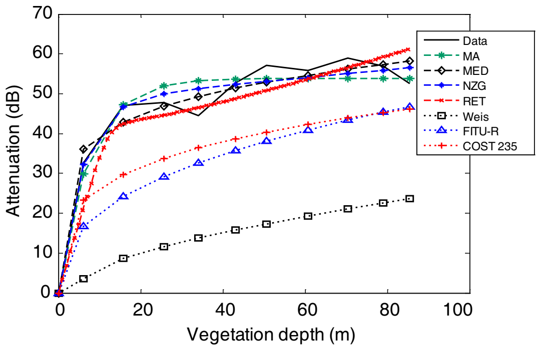


Figure 5. Comparison of attenuation models based on best-fit analysis for measurements at 2.5 GHz in oil palm plantation.

components separately, a tri-gradient framework model. The figure shows that the performances of MED, NZG, MA and RET models are very close (differences in their RMSE values are within 1.7 dB) and can be used to model vegetation attenuation. However the RET model is more computationally intensive and has therefore been assessed only at a limited number of discrete frequencies. Another limitation of the RET model is the lack of an explicit frequency scaling parameter, thereby requiring the model values to be assessed at individual frequencies. The Weissberger, COST235 and FITU-R models have also been fitted to the measured data.

All the average values of the model parameters obtained by fitting the generic MA, MED and NZG models to the data from the mango plantation (45 frequencies) and oil palm plantation (69 frequencies) measurements, and the associated average RMSE values are given in Table 4. Since most wireless sensor devices operate in the ISM bands, the average values of the parameters are also provided for frequencies close to these bands. For each antenna height, the minimum RMSE value has been highlighted. The table shows that the NZG model gives consistently low RMSE values. Vegetation density is not homogeneous which leads to significant variation in signal strength from one position to the next. In [8], spatial averaging was implemented to smooth these variations. This technique has not been used in this paper because one of the main objectives was to identify critical issues in WSN planning and node deployment. These variations would therefore account for the large RMSE values computed for certain measurements. It can be observed from the table that the average model parameter values also vary significant between different sets of measurements. This poses a significant challenge to the optimization of the models for application in different scenarios with the same model parameter values. Therefore, in the following section, the performances of the models will be evaluated using recommended model parameter values.

5. EVALUATION OF VEGETATION ATTENUATION MODELS

Most wireless sensor systems operate in the 433.050–434.790 MHz, 902.000–928.000 MHz, 2.4–2.5 GHz and 5.725–5.875 GHz ISM bands. A majority of the wireless sensors on the market operate in the 2.4–2.5 GHz band [18]. Many researchers planning WSNs use the two-ray (consisting of the direct and ground reflected paths) model to predict network coverage [19]. For ground reflection path to exist the boundary of the first Fresnel Zone, defined by (11) must be greater than, the antenna height.

$$h_0 = \frac{1}{2}\sqrt{\lambda d} \tag{11}$$

where d is the distance from the transmitter and λ is the wavelength. For the various measurements, the minimum distances at which ground reflected components were expected are given in Table 5 for frequencies close to the ISM bands. The table shows that ground reflection only started to be present for distances beyond 9 m. For higher frequencies, longer distances were required. It can be concluded that for the antenna heights used and the path lengths considered, the impact

Table 4. Average model parameter value estimates from fitting generic models to data and the average fitted RMS errors for frequencies from 400 MHz to 7.2 GHz (AVG) and frequencies close to the ISM bands (ISM).

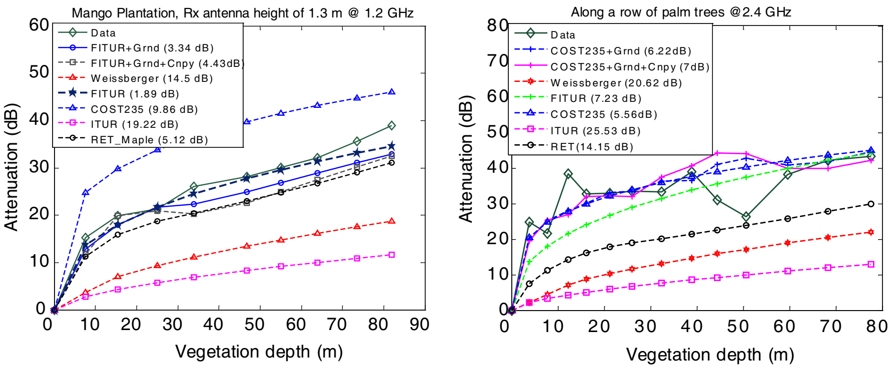
Receiver Ant. Height ->		Mango Plantation								Oil Palm Plantation			
		1.3 m		2.2 m		1.72m		2.6 m		2.6 m along		2.6 m between	
Model	Par	AVG	ISM	AVG	ISM	AVG	ISM	AVG	ISM	AVG	ISM	AVG	ISM
MA	α	0.38	0.43	0.34	0.45	0.38	0.44	0.37	0.45	0.35	0.37	0.37	0.51
	A1	2.46	2.50	2.79	2.40	2.32	2.33	2.73	2.65	2.87	3.15	2.52	2.30
	R	2.72	1.40	2.59	1.75	2.55	3.60	5.27	4.35	8.05	6.54	1.01	0.76
	RMSE	4.56	3.35	9.79	4.01	2.96	3.38	2.66	3.40	5.25	4.92	3.54	4.03
MED	X	0.57	0.42	0.53	0.58	0.53	0.38	0.57	0.73	0.50	0.57	0.55	0.36
	Y	0.38	0.37	0.40	0.32	0.36	0.55	0.42	0.43	0.47	0.53	0.21	0.23
	Z	0.29	0.45	0.25	0.44	0.38	0.33	0.28	0.30	0.17	0.19	0.59	0.70
	RMSE	4.90	3.41	10.61	4.70	2.98	3.29	2.57	3.66	4.17	4.51	3.52	3.73
NZG	R_∞	0.18	1.03	1.13	0.37	0.15	0.17	0.25	0.17	0.18	0.12	0.29	0.52
	R_0	3.13	3.90	2.21	1.80	4.31	6.43	6.63	5.73	9.65	8.08	1.90	2.58
	K	42.91	31.33	28.91	22.67	32.93	34.33	36.02	39.33	27.03	29.33	23.87	18.00
	RMSE	**3.61**	**2.54**	**5.58**	**3.63**	**2.56**	**2.50**	**2.20**	**2.73**	**4.24**	**4.48**	**3.34**	**3.62**

Table 5. Boundary distance for the first fresnel zone for different frequencies and antenna heights.

Frequency (MHz)	**Antenna Heights**				**Canopy Height**
	1.3	**1.76**	**2.2**	**2.6**	**1.8**
400	9.01	16.52	25.81	36.05	17.28
900	20.28	37.17	58.08	81.12	38.88
2400	54.08	99.12	154.88	216.32	103.68

of ground reflection was more significant at low frequencies and low antenna heights.

The models, using their recommended parameter values in open literature, have been assessed for accuracy using the measured data. Examples of the performances of the models, considering ground and canopy reflections are shown in Figure 6 together with RMSE values from the fittings. Some of the models with high RMSE values have been removed from the figures for clarity. Detailed analyses have also been conducted on the variation of the models' performances within the different frequency bands. For frequencies up to 2 GHz at the



(a) (b)

Figure 6. Comparison of vegetation attenuation models at; (a) 1.2 GHz in mango plantation, (b) 2.4 GHz along a row of oil palm trees.

receiver antenna height of 1.3 m, the FITU-R model gave the smallest RMSE values. For example the RMSE value for the FITU-R model in Figure 6(a) is 1.8 dB. However at frequencies above 2 GHz, the COST 235 model provided the highest accuracy of all the models assessed. For measurements between two rows of palm trees the smallest RMSE is given by the RET model using parameter values specified for maple tree at 2.5 GHz.

The RSME values for the various models for different measurements and antenna heights are summarized in Table 6. For the MA model, the two sets of values of the parameters as specified by the ITU, [6], have been used to evaluate the model. The average values of NZG models for vegetation in-leaf were reported in [1] (NZG-SNJ), and values published in [2] (NZG-SV) have also been used to assess its performance. The results show that the COST235 model performs, overall, better than the other models. The RET model yields the best results in three instances for parameter values provided for maple tree. However, the model generates high RMS errors in other cases making it unreliable. The MA and Weissberger models perform poorly at all the frequencies and measurement heights. In [8], the authors have evaluated the COST235 and ITU-R models for measurements in a palm plantation and in rainforest. Their study at 40 MHz show that COST 235 model with ground and canopy reflections provided the best fit to the data from the palm plantation and the ITU-R model, Equation (4), with both components in the rainforest. In that study, at 550 MHz, taking only the ground reflection component into account, COST 235 model provided good results in the palm plantation and

Table 6. Average RMSE values of various models based on all measurements in the frequency range 400 MHz to 7.2 GHz (AVG) and frequencies around the ISM band (ISM).

	Mango Plantation								**Palm Plantation**			
	1.3 m		2.2 m		1.72 m		2.6 m		Along @ 2.6 m		Between 2 rows@ 2.6m	
	AVG	ISM	AVG	ISM	AVG	ISM	AVG	ISM	AVG	ISM	AVG	ISM
FSL	15.5	11.5	16.4	13.1	19.1	24.0	14.7	18.3	16.4	16.8	6.6	5.8
FSL_Ground	15.7	11.5	16.3	13.3	19.2	23.6	14.7	18.8	16.4	17.3	6.5	5.8
FSL_Canopy	15.4	11.2	16.4	13.0	19.2	23.9	14.7	18.2	16.3	16.7	6.6	5.9
FSL_Ground_Canopy	15.8	11.2	16.4	13.1	19.3	23.5	14.7	18.7	16.3	17.1	6.5	5.8
COST235	**9.2**	11.0	**12.1**	11.7	**7.7**	7.1	**7.5**	6.7	**5.4**	6.5	14.6	17.7
COST235_Ground	9.5	11.0	12.2	11.6	7.9	**6.9**	7.6	6.9	5.6	**6.4**	14.7	17.3
COST235_Ground_Canopy	10.1	11.7	12.6	11.9	8.0	6.9	7.8	6.9	5.9	7.0	14.9	17.5
COST235_Canopy	9.7	11.6	12.4	12.1	7.9	7.1	7.7	**6.6**	5.7	7.1	14.8	17.9
FITUR	12.7	9.6	15.3	10.0	9.1	14.6	10.5	12.2	9.8	11.7	14.6	11.6
FITU-R_Ground	13.1	9.7	15.7	10.5	9.4	14.7	10.6	12.4	10.1	12.6	14.8	11.7
FITU-R_Canopy	13.2	9.5	15.8	9.8	9.3	14.3	10.8	11.7	10.1	11.7	14.8	11.3
FITU-R_Ground_Canopy	13.7	9.7	16.1	10.2	9.5	14.3	11.0	11.9	10.3	12.6	15.0	11.3
ITUR	11.5	10.0	13.6	12.0	17.4	24.2	12.3	18.4	14.4	17.6	4.9	5.3
ITUR_Ground	11.9	9.9	13.6	12.2	17.6	23.9	12.2	18.9	14.4	18.1	5.0	5.9
ITUR_Canopy	11.6	9.8	13.8	11.9	17.5	24.0	12.3	18.2	14.3	17.5	5.1	**5.1**
ITUR_Ground_Canopy	12.2	9.8	13.8	12.0	17.6	23.7	12.2	18.7	14.3	18.0	5.2	5.7
Weissberger	15.0	13.3	16.2	14.8	20.0	27.2	15.3	21.4	17.4	20.0	6.7	7.2
MA1	15.8	12.9	17.1	14.6	20.8	26.7	16.1	21.1	18.0	20.0	7.4	7.1
MA2	17.4	14.5	18.3	15.9	21.7	28.0	17.3	22.3	19.1	20.8	8.6	8.2
NZG-SNJ	11.4	7.6	12.6	9.7	16.1	20.1	11.4	14.3	13.2	13.3	5.3	6.1
NZG-SV	20.6	23.1	22.2	22.6	8.4	7.8	14.6	12.7	13.4	15.0	23.7	27.6
RET_Gingko	16.2	16.5	18.2	16.8	11.0	10.3	9.6	9.2	10.4	11.5	14.7	17.5
RET_Plain_American Tree	25.5	26.0	26.7	25.2	15.2	15.7	15.8	15.8	17.3	18.6	20.9	23.9
RET_Maple	10.8	**6.6**	12.6	**9.6**	15.7	19.2	11.0	13.7	12.4	12.6	**4.9**	5.6

the ITUR model in the rainforest. This study has shown that at 1.3 m antenna height at 500 MHz, the FITU-R model with ground reflection gives the smallest RMSE of 5.0 dB. At higher antenna heights, the performance of the COST 235 model is superior. Overall, and for most frequencies, the COST 235 provides more reliable prediction of signal attenuation in the presence of vegetation in the direct path between the antennas from amongst all the models, using their recommended parameter values. Although the RET model, using parameter values obtained for maple trees, offer the smallest RMSE, a combination of ITUR and ground reflection also offers a consistent prediction over the wide range of frequencies for signal propagation between rows of palm trees. The differences between the RMSE values of the RET, ITUR, and free space loss models combined with ground reflection are less than 1.7 dB. The values of relative permittivity of the ground and the canopy that have been used in the modeling are 10 (for average ground) and 1.12 [10], respectively.

6. CONCLUSION

This paper has presented vegetation attenuation measurements in mango and oil palm plantations. The objective of the study was to ascertain the best model for application in wireless sensor network planning and deployment in agricultural environment, especially in plantations. The measurements conducted were predominantly in managed plantations which are representative of the locations for possible wireless sensor network deployment. The results show that wireless sensor node deployment should take advantage of the grid-like tree planted pattern in plantations and should preferable be positioned at trunk height or above the canopy to maximize range and improve the signal to noise ratio.

The individual generic models have been fitted to the data. The Non-Zero Gradient model consistently provides very good results. Although the RET model also provides good estimates, it requires more input parameters, is computationally intensive and insufficient optimized parameter values are available which presents a challenge to the wider application of the model. All models performed better when they were fitted to the data in their generic form. However, the values of the parameters of the models obtained from these fittings vary significantly with frequency, antenna height, measurement location and tree type. This makes it difficult to optimize the parameters for a wider application unless using a large database of measurement that includes data from most scenarios and vegetation types.

To assess the wider application of the models, root means square errors (RMSEs) between the models and the measured data for frequencies from 400 MHz to 7.2 GHz, in steps of 100 MHz, have been calculated. The RMSEs for frequency components around the Industrial, Scientific and Medical (ISM) bands have also been computed separately as most of WSN devices operate in these bands. Results show that the COST235 model provides consistently low RMSEs where there are trees in the line-of-sight path. For measurements between two rows of palm trees, the path loss can be predicted using RET and ITU-R models. However using the free space loss model combined with ground reflections provides a consistent prediction with an average RMS error within 1.7 dB of that of the RET and ITUR models.

Overall, it can be concluded from this study that when there are trees in the line of sight path, the COST 235 model should be used for WSN planning. However, for networks where the sensors are positioned between two rows of trees, the model which combines either the RET, ITUR or free space loss model with ground reflection should be used. Although with a worst RMSE from amongst the three, the free space loss model provides consistent results. The inhomogeneous density of the vegetation medium introduces significant variations in signal strength from one position to the next that results in inflated RMS errors when fitted to models. However understanding these variations is also important for WSN nodes positioning. The characteristics of commercial plantations, which are often mono-cropped and planted in a defined pattern, as oppose to the random spatial distribution of trees in the natural forest, can be used to enhance WSN coverage, minimize cost and provide reliable communication for sensor fusion applications.

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