Empirical Near Ground Path Loss Modeling in a Forest at VHF and UHF Bands

Yu Song Meng, *Student Member, IEEE*, Yee Hui Lee, *Member, IEEE*, and Boon Chong Ng, *Senior Member, IEEE*

***Abstract*—Near ground radio wave propagation is examined in a tropical plantation experimentally at VHF and UHF bands. The propagation loss with forest depth is empirically analyzed using an integrated model combining both the foliage induced effect and the ground effect. Several well-known empirical foliage models are compared and analyzed. It is observed that the fitted ITU-R model taking into account the ground reflection, can provide a close approximation to the path loss in a tropical palm plantation. However, the accuracy of this model becomes poor when lateral wave dominates in the VHF band. A modification to the ITU-R model is then proposed taking into consideration the lateral wave effect. The modified model is verified using measured and published data, and found to have higher accuracy for large foliage depth in the VHF band as compared to the existing empirical foliage models.**

***Index Terms*—Forest, lateral wave, near ground, path loss, VHF and UHF.**

I. INTRODUCTION

THE topic of radio wave propagation in forested environment has been the focus of much theoretical [1]–[6] and experimental [7]–[12] research over the years. As a result, there is a large body of literature that addresses the characterization of the behavior of radio waves in the forest environment. In 1967, Tamir [1] proposed a half-space model to deal with radio wave (1–100 MHz) propagation in the forest and explained the associated phenomenon dominated by a lateral wave mode of propagation. Subsequently, he [2] extended his study on the propagation in forested environment to the dissipative dielectric slab model to account for the ground effect on radio wave (2–200 MHz) propagation. After that, Li *et al.* [3], [4] performed an extensive study of the four-layered model with the lateral wave mode of propagation in anisotropic forests using dyadic Green's functions. Besides these VHF and UHF radio wave propagation studies, higher frequency (up to 60 GHz) channel characterization with foliage effect taken into account has been studied with the radiative energy transfer (RET) theory [5]. A statistical wave propagation model (SWAP) has also been developed to provide an accurate and time-efficient simulation tool for wave propagation over long distances within forested environments by Wang and Sarabandi [6]. Besides these theoretical studies, experimental foliage loss modeling [7], [9]–[12] has also been carried out at different operational context and physical situations.

In recent years, there has been a growing interest in the near ground (0.5 $\sim$ 3 m above ground) communications in forest areas at VHF and UHF bands. Its application is of scientific and military importance, for example, battlefield communication networks (Fig. 1). These applications require a detailed understanding of the forested propagation channel in order to establish a good communication link. However, from the addressed literatures [1]–[12], the implementation of theoretical models [1]–[6] is quite complicated and may not appeal to ordinary users, although they can predict the forested signal attenuation accurately. The empirical foliage loss models [7], [9]–[12] that are based on specific measured data are not universally applicable due to the variety of operational contexts and physical situations. Therefore, the empirical near ground path loss modeling in a forest environment is very important and significant for the implementation of a reliable modern communication system.

The objective of this paper is to perform experimental path loss modeling for the near ground radio wave propagation in a tropical plantation at 240 and 700 MHz over a large forest depth. The measured path loss is compared to the predicted path loss estimated from empirical models [9]–[12] taking into consideration the ground reflection for near ground communication systems. Based on these comparisons, a new model that takes into account the lateral wave effect is recommended and verified using measured and published data.

This paper consists of four major sections. The theoretical background of the near ground forested radio wave propagation is given in Section II. In Section III, the forest environment and the measurement setup are described. Empirical path loss modeling for the near ground forested radio wave propagation is presented and compared to the integrated models such as the plane earth path loss model and several well-known foliage models in Section IV. Based on the comparisons and observations, a modified ITU-R model taking into account the lateral wave effect is proposed, and verified in Section V. This is followed by the conclusions of the findings in Section VI.

II. THEORETICAL BACKGROUND

For the radio wave propagation, the free space path loss model [13] shown in (1) acts as a lower bound for the estimation of path loss

$$L_{\text{free}}(\text{dB}) = -27.56 + 20\log_{10}(f) + 20\log_{10}(d) \qquad (1)$$

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Y. S. Meng and Y. H. Lee are with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore (e-mail: meng0006@ntu.edu.sg; eyhlee@ntu.edu.sg).

B. C. Ng is with the Advanced Communications Laboratories, Defence Science Organization (DSO) National Laboratories, Singapore and also with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore (e-mail: ebcng@ntu.edu.sg).

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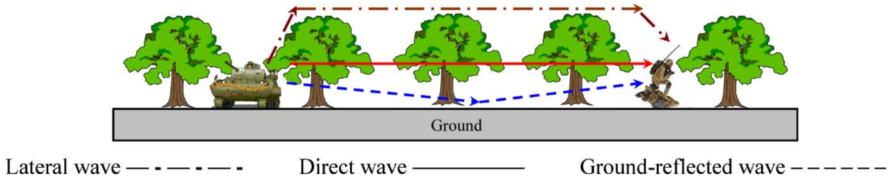


Fig. 1. Geometry of radio wave propagation in a forest with bare ground region over a large foliage depth.

where f is the frequency in MHz, d is the distance between the isotropic transmit and receive antennas in meters.

When the radio wave propagates near the ground with a line of sight (LoS) condition, the path loss can be better described by the plane earth (PE) path loss model [13] rather than the free space model. The plane earth path loss model includes the effect of ground reflection and is given as

$$L_{\mathrm{PE}}(\mathrm{dB}) = 40\log_{10}(d) - 20\log_{10}(h_T) - 20\log_{10}(h_R) \quad (2)$$

where d is the distance between the isotropic transmit and receive antenna in meters, h_T and h_R are the transmit and receive antenna heights, respectively, also in meters. In this model, there is an assumption that d is much larger the h_T and h_R.

A. Radio Wave Propagation in Forest

As compared to the well studied terrestrial radio wave link, the appearance of the forest medium induces an additional effect on the propagating waves. Since the forest is a random medium with many discrete scatterers such as the randomly distributed leaves, branches and tree trunks, radio waves propagating in the forest naturally experiences multiple scattering, diffraction, and absorption of radiation. These different propagation mechanisms, when combined, can result in severe fades in the received signal, and produce an excess vegetation induced loss as compared to terrestrial propagation. These fade effects have to be considered in order to establish a highly reliable near ground communication link.

As a supplement to the well-established theoretical studies [1]–[6] of radio wave behavior in the forest environment, some significant experimental works [7]–[12] have been carried out to gain a practical insight into the forested radio wave propagation. These practical works are summarized below.

In 1966, Burrows [7] proposed an algorithm which can be used to predict the path loss in a jungle with antenna height included, and its formulation in dB is expressed as

$$\begin{aligned} L_{\mathrm{forest}}(\mathrm{dB}) &= 40\log_{10}(d) - 20\log_{10}(h_T) - 20\log_{10}(h_R) \\ &\quad -20\log_{10}\left(\frac{3R_0}{2R}F_sF_j\right) \quad (3) \end{aligned}$$

where R_0 is the radiation resistance of the dipole antenna in free space and R is the total antenna resistance in the vicinity of the ground and foliage. F_s is the shadow factor that accounts for the effect of the curvature of the earth, F_j is the factor that accounts for the effect of the jungle, and h_T and h_R are the transmit and receive antenna heights, respectively. The relationship between the antenna height and the path loss in (3) is verified in [7] through measurements performed within a tropical jungle with foliage depth of up to 6.4 km in Thailand. In the experiment, horizontally polarized antennas were used at a frequency of 100 MHz, with the transmit antenna height, h_T kept at a constant of 24.2 m, and the receive antenna height, h_R varied from 5–30 m.

Later, in 1984, Tewari *et al.* [8] performed an in-depth empirical modeling of antenna height gain on the path loss in the forest, based on the measurements conducted in various tropical rainforest, with foliage depths of up to 4 km in India. Both vertically and horizontally polarized antennas at frequencies from 50 to 800 MHz were used with the transmit antenna height, h_T varying from 3.95–16.45 m, and the receive antenna height, h_R varying from 1.5–3.5 m above the ground, while maintaining the condition of $h_T \cdot h_R > 10$. They then derived the antenna height gain on the path loss in the forest as shown in (4)

$$G_{AH}(\mathrm{dB}) = -12 - 4\log_{10} f + 20\log_{10} h_T + 20\log_{10} h_R \quad (4)$$

Comparative study of (3) and (4) with the plane earth path loss model in (2) shows that, the ground reflected wave has a predominant effect on VHF and UHF radio wave propagation over large foliage depths. This ground reflected wave tends to cancel the direct wave and results in the received field strength (path loss) being proportional (inverse proportional) to the product of the antenna heights for a fixed foliage depth. This reflection effect will be more apparent when the antenna height is low, i.e., near ground.

As reported by Tamir [1], [2] and Li *et al.* [3], [4], the lateral wave appears dominant at the treetops over a large forest depth at VHF and UHF bands. Therefore, for the VHF and UHF near ground radio wave propagation through a large foliage depth, the main contribution to the received signal strength is not only due to the through-foliage-components such as direct wave and ground reflected wave, but also the lateral wave, as shown in Fig. 1. The through-foliage-components such as the direct and reflected waves suffer high attenuation due to the physical properties of the vegetation such as tree trunks, leaves and branches. In the next subsection, some well-known empirical foliage loss models that take into consideration these physical properties of the vegetation channel are reviewed and studied.

B. Summary of the Empirical Foliage Loss Models

Much effort has been put into the empirical modeling of the foliage induced excess loss at different frequencies and geometries [9]–[12]. The following summarizes these well-known empirical foliage loss models, which will be discussed and evaluated in this study of the near ground forested radio wave propagation.

Weissberger's modified exponential decay model [9] as in (5) is applicable where a ray path is blocked by dense, dry, in-leaf trees found in temperate climates. It is applicable in situations where propagation is likely to occur through a grove of trees rather than by diffraction over the treetop

$$L_W(\mathrm{dB}) = \begin{cases} 1.33 \times f^{0.284} d^{0.588} & 14\ \mathrm{m} < d \leq 400\ \mathrm{m} \\ 0.45 \times f^{0.284} d & 0\ \mathrm{m} \leq d < 14\ \mathrm{m} \end{cases} \quad (5)$$

where f is the frequency in GHz, and d is the depth of the trees in meters. The frequency range over which this model is valid is from 230 MHz to 95 GHz.

ITU Recommendation (ITU-R) [10] was developed from measurements carried out mainly at UHF, and was proposed for cases where either the transmit or the receive antenna is near to a small $(d < 400\ \mathrm{m})$ grove of trees so that the majority of the signal propagates through the trees. This model (6) is commonly used for frequencies between 200 MHz to 95 GHz

$$L_{\mathrm{ITU-R}}(\mathrm{dB}) = 0.2 \times f^{0.3} d^{0.6}. \quad (6)$$

The COST 235 model [11] which was proposed based on measurements made in millimeter wave frequencies (9.6–57.6 GHz) through a small $(d < 200\ \mathrm{m})$ grove of trees is

$$L_{\mathrm{COST}}(\mathrm{dB}) = \begin{cases} 26.6 \times f^{-0.2} d^{0.5} & \text{out-of-leaf} \\ 15.6 \times f^{-0.009} d^{0.26} & \text{in-leaf.} \end{cases} \quad (7)$$

In the COST 235 model (7), measurements were performed over two seasons, when the trees are in-leaf and when they are out-of-leaf. Similarly, this model is applicable for frequencies between 200 MHz to 95 GHz. For both ITU-R and COST 235 models, f is the frequency in MHz, and d is the depth of trees in meters.

From the study of existing established model, it is found that the foliage induced excess loss in general, can be well represented by the following expression:

$$L_{\mathrm{foliage}}(\mathrm{dB}) = A \times f^B d^C. \quad (8)$$

The three parameters, A, B and C in (8) can be empirically determined, depending on the type of foliage, where B and C are the two parameters which indicate the frequency dependence and the distance dependence of the foliage induced excess loss in the proposed model. In [12], Al-Nuaimi and Stephens performed an optimization for these three numerical parameters (A, B, C) using the least squared error fit for several sets of measurement data. These data sets were collected during two foliation states, in-leaf and out-of-leaf, at 11.2 and 20 GHz. They then derived the fitted ITU-R (FITU-R) model [12]

$$L_{\mathrm{FITU-R}}(\mathrm{dB}) = \begin{cases} 0.37 \times f^{0.18} d^{0.59} & \text{out-of-leaf} \\ 0.39 \times f^{0.39} d^{0.25} & \text{in-leaf.} \end{cases} \quad (9)$$

From the review of these empirically established models, it can be found that the optimization of these models is based on the measured data at VHF to millimeter waves and covers a relatively short foliage depth (maximum of 400 m). Moreover, the research findings from Tamir [1], [2] and Li *et al.* [3], [4] state that the lateral wave becomes dominant at relatively large forest depth, especially when both the transmitter and the receiver are placed inside the forest in the VHF and UHF bands. These observations motivate us to perform a further investigation to check whether these empirical models [9]–[12] are applicable for the near ground long range (up to few km) communication at VHF and UHF bands. In the following part, comparative analysis of the various integrated models which takes into consideration both the foliage induced effects and the ground effect is performed. From the comparison, a simplified empirical model suitable for use in near ground radio wave propagation over a large forest depth at VHF and UHF bands is identified.

Fig. 2. Photograph of the plantations under measurements.

III. MEASUREMENT CAMPAIGN

A. Experimental Site

The measurements were performed on the island of Singapore during the northeast monsoon season, when the average monthly rainfall is 280 mm. The foliage chosen for this study is a palm plantation over a nearly flat terrain as shown in Fig. 2. The terrain consists mainly of soil and sand, with some parts covered with grass. The palm trees have an average height of approximately 5.6 m and are nearly equally spaced with a distance of 7 m. The average tree trunk diameter at antenna height is around 0.4 m. The foliage depth is more than 1000 m. This foliage depth is calculated based on GPS readings. During the measurement, the forest is dry with slight or no wind.

B. Measurement Setup

The measurement was carried out using continuous wave (CW) soundings at VHF (240 MHz) and UHF (700 MHz). Details of the measurement methodology are shown in the Fig. 3. Omnidirectional antennas with a typical gain of 2.4 dBi were placed inside the forest and at a constant height of 2.15 m with a vertical polarization. Amplifiers were used at both the transmitter (high power amplifier) and the receiver (low noise amplifier) to ensure the quality of measured signal. The experimental data was captured by the spectrum analyzer and stored into a control computer via GPIB interface for post-processing. Readings were taken at 9 predefined grids at the receiver side as shown in Fig. 3. The purpose of taking measurements at 9 grid points with half wavelength (i.e., 0.5λ) separation is to minimize the spatial effect on the received signal, for example,

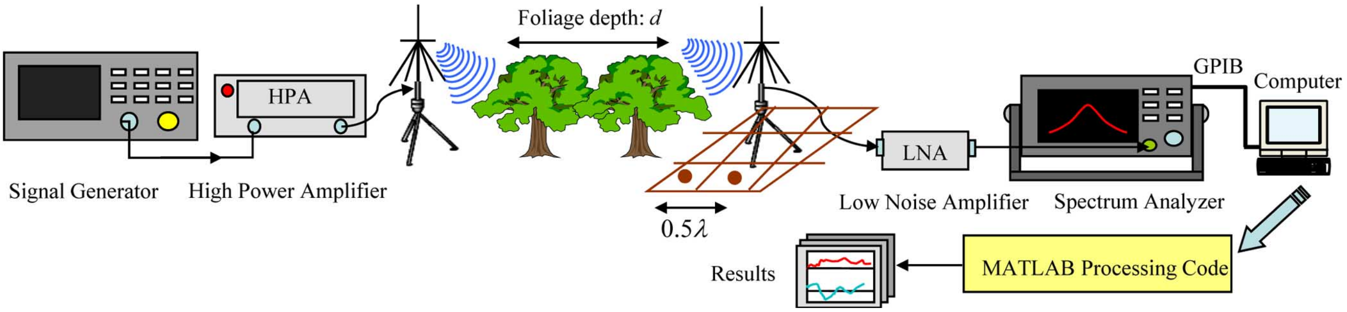


Fig. 3. The schematic diagram of measurement setup.

the distance of the antenna from the tree trunks. This is because forest is a rich scattering environment and any slight change in antenna location will influence the propagation paths, hence, cause significant variations to the measured results. Moreover, in order to minimize the temporal effect due to the possible slight wind on the propagating wave, 5001 peak marker readings of the spectrum analyzer at 0.01 s intervals were recorded at each grid. During the measurements, there is a restriction on human activities so as to minimize human induced effects. Calibration of the system effect from the experimental data is performed through the removal of the antenna gain and the measurement of a back to back connection between the transmitter and the receiver.

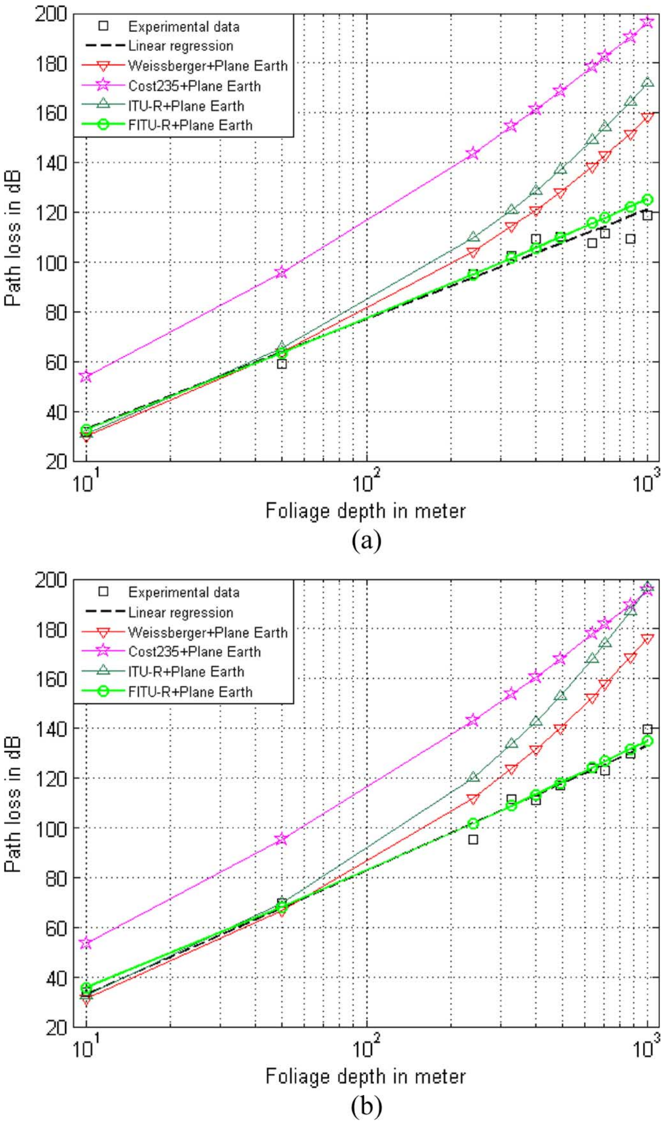
IV. PATH LOSS MODELING IN FOREST

A. *Comparisons Between the Measured and Predicted Loss*

In this section, in order to provide a true representation of the channel parameter, the local mean path loss was estimated after the removal of the temporal and spatial fluctuations. The measured path loss versus foliage depth at 240 and 700 MHz in the palm plantation shown in Fig. 2 are plotted with the best fit line (Fig. 4). Comparison is performed among the predicted path loss using the various integrated models taking into considerations both the foliage induced effects and the ground effect. The different foliage loss models given in (5)–(7) and (9) in the previous section, together with the perfect plane earth path loss model in (2) are used. For both the COST 235 model and the FITU-R model, only the in-leaf foliage models are used since the tropical plantation under consideration is an evergreen one.

From Fig. 4, it is found that at a short forest depth, the predicted values by the Weissberger, ITU-R and FITU-R models with ground reflection considered are in good agreement with measured data, except the predicted values by the COST 235 model with ground reflection considered. This is because the COST 235 model is optimized from the measured data at millimeter waves (up to 57.6 GHz), which results in a higher predicted path loss at VHF and UHF bands.

As the forest depth increases, the ability to predict the path loss by the Weissberger model and the ITU-R model with ground reflection considered becomes poor. The Weissberger model and the ITU-R model with ground reflection considered at large foliage depth overestimates the path loss significantly by up to 40 dB at 1000 m above the measured data. The overestimation of the path loss increases gradually as the foliage depth increases. This is because the optimization of both the models is based on experimental data for small foliage depths (<400 m) at VHF and UHF bands. Therefore, these two models have poor prediction accuracy at large foliage depth where there may be other propagation mechanisms that are not accounted for. An example of such propagation mechanisms is the lateral



(a)

(b)

Fig. 4. Measured and predicted path loss with foliage depth. (a) Path loss at 240 MHz; (b) path loss at 700 MHz.

wave over the treetops, which appears dominant at large foliage depth as stated by Tamir [1], [2] and Li *et al.* [3], [4] for VHF and UHF radio wave propagation in forests.

Furthermore, it can be observed that the predicted path loss from the FITU-R model with the plane earth model closely matches the measured data for both 240 and 700 MHz wave propagation as compared to other models at larger forest depth. This is because the FITU-R model is derived from a set of data measured at 11.2 and 20 GHz in uniformly distributed plantations where the trees are equally spaced and with very little or no undergrowth, and the terrain of the plantation is quite similar to the one used in our measurements. Since the optimization of the FITU-R model is based on the measured data from a number of sites with different path geometries and tree types (horse chestnut, lime and sycamore, etc.), its ability to accurately predict the foliage loss is significantly better. The most significant point is that, the good prediction ability from the FITU-R model with ground reflection considered is due to the "dual-slope" foliage loss phenomenon at millimeter frequency as reported by Al-Nuaimi and Stephens [12], and further examined by Rogers *et al.* [5] and Wang and Sarabandi [6]. This phenomenon can be summarized as such; there is an initial high attenuation rate at millimeter frequency which is caused by the significant diminution of the coherent component of the propagating wave; as the forest depth increases, the incoherent (diffuse) components due to the forward scattering caused by the leaves and the branches become dominant, and thus counteracts the loss due to absorption by the foliage media and yields a much lower attenuation rate. This is the main reason for the FITU-R model with ground reflection considered to have better prediction accuracy as compared to the Weissberger model and the ITU-R model. These two models are derived from the database for a small foliage depth (<400 m) at VHF and UHF bands where the coherent component of the propagating waves is dominant, and almost no forward scattering mechanism is taken into account since large forest depth are not covered.

However, it can also be observed that the FITU-R model shows a similar slope at 700 MHz, whereas at 240 MHz, the distance attenuation rate for the measured data is less than that of the predicted distance-attenuation rate based on the FITU-R model (the smaller slope from the best fit line as compared to the slope from the FITU-R model). The difference between the predicted loss and the measured loss at 240 MHz is from 6.4–12.9 dB as foliage depth is more than 500 m. The difference is mainly due to the appearance of the lateral wave effect at 240 MHz as discussed in our previous work [14] but may not appear at 700 MHz at the forest depths considered. The lateral wave can enhance the radio wave propagation over a very large foliage depth and reduce the path loss relatively. As known, the FITU-R model is derived from measured data taken at frequencies between 11.2–20 GHz (foliage depth $d < 120$ m), where no lateral wave effect exists. This accounts for the ability for the FITU-R model to predict the path loss at 700 MHz to a higher accuracy as compared to that at 240 MHz in this plantation.

B. Model Optimizations

Although the FITU-R model shows a good ability to predict the foliage loss, there is still significant error between the predicted and the measured path loss for both frequencies as in Fig. 4. This could be due to the assumption of the perfect plane earth model in (2). In order to reduce the effect induced by the perfect plane earth model, a fitted ground reflection (FGR) model will be introduced. The FITU-R model together with the fitted ground reflection model given in (10) is then applied to fit our measured data

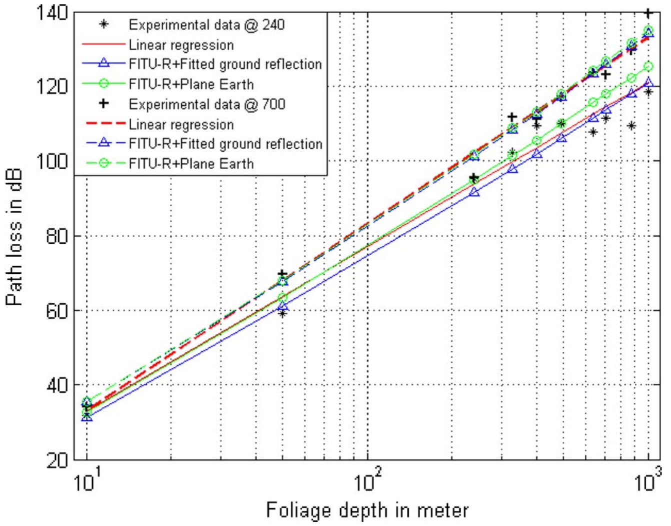


Fig. 5. Results with optimization of ground reflection.

$$L_{\mathrm{FGR}}(\mathrm{dB}) = 10n\log_{10}(d) - 20\log_{10}(h_T) - 20\log_{10}(h_R) \quad (10)$$

$$L_{\mathrm{forest}}(\mathrm{dB}) = L_{\mathrm{FGR}}(dB) + 0.39f^{0.39}d^{0.25} \quad (11)$$

where n will be determined empirically. Fig. 5 shows the least squared error fit of (11) with the measured data. The n values determined at 240 and 700 MHz are 3.85 and 3.97, respectively. Compared to the ideal plane earth model in (2) where an n value of 4 is assumed, it can be observed that, at 700 MHz, the n value of 3.97 is almost the same as the assumed n value of 4. This shows that there is an approximate ideal ground in this palm plantation. Moreover, it is found that the larger difference in n value (3.85 compared to 4) at 240 MHz is mainly due to the appearance of the lateral wave, since the forest environment was similar for the measurements done at both 240 and 700 MHz. As stated before, the FITU-R model does not take into account the lateral wave effect, therefore, the optimization process of (11) transfers the lateral wave effect into the fitted ground reflection model, which reduces its n value significantly.

In order to study the performance of the fitted model, the root mean square (RMS) error, E_{rms} as in [12], between the measured loss and the predicted loss by the fitted model is calculated. Here, $E_{\mathrm{rms}} = \sqrt{(\sum_{i=1}^{N} E_i^2)/N}$, where N is the number of sample points, and E_i is the difference between measured and predicted values at the ith measurement point.

It is found that the corresponding improvement in RMS error decreases from 5.89–4.61 dB (1.28 dB improvement), and 3.07–3.00 dB (0.07 dB improvement), for the FITU-R model with perfect plane earth model to the FITU-R model with fitted ground reflection model for the two frequencies respectively.

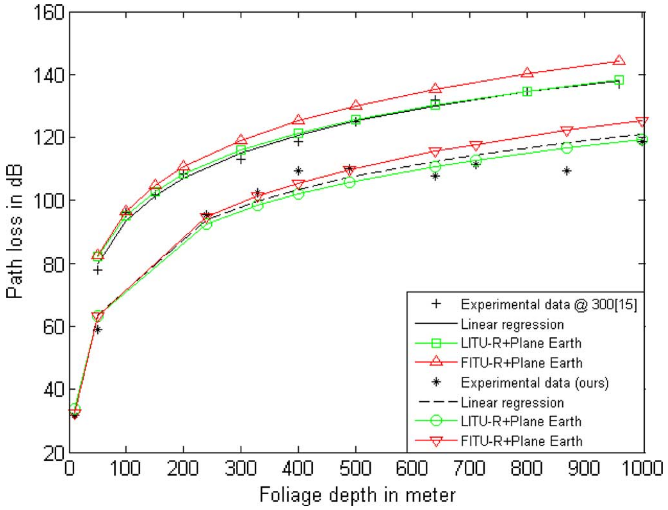


Fig. 6. Comparisons of the predicting ability with LITU-R and FITU-R model. Also shown are the experimental data by Joshi *et al.* [15] at 300 MHz.

The smaller n value of 3.85 and the larger improvement in RMS error of 1.28 dB at 240 MHz is due to the existence of the lateral wave that does not exist at 700 MHz. This analysis agrees with the gradual decrease of the distance attenuation slope due to the existence of lateral wave at 240 MHz as discussed before.

Since the FITU-R model is not applicable for the prediction of foliage loss when the lateral wave effect is to be taken into consideration, the following expression in (12) is used to fit the measured data. This proposed expression attempts to model the forest radio wave propagation taking into account the lateral wave effect under the assumption of a perfect plane earth reflection. The three numerical values A, B, and C are estimated using least squared error fit on the measured data and are found to be 0.48, 0.43, and 0.13, respectively. The positive A, B, and C values are consistent with both the anticipated radio wave behaviors and that observed in the measured data. That is, as the frequency and forest depth increase, the path loss increases. The corresponding RMS fitted error is 4.29 dB, which is an improvement of 1.60 dB as compared to the previous improvement of 1.28 dB with fitted ground reflection model.

$$L_{\text{forest}}(\text{dB}) = Af^{B}d^{C} + 40\log_{10}(d) - 20\log_{10}(h_T) - 20\log_{10}(h_R). \quad (12)$$

Therefore, in this paper, the expression in (13) is proposed for the modeling of excess foliage loss with lateral wave effect taken into account, lateral ITU-R (LITU-R) model, which can be used for long range propagation in foliage areas in the VHF band

$$L_{\text{LITU-R}}(\text{dB}) \cong 0.48 \times f^{0.43}d^{0.13}. \quad (13)$$

V. VERIFICATION OF THE PROPOSED MODEL

A. *Verification With the Experimental Data*

The prediction accuracy of (13) is verified through the experimental data reported by Joshi *et al.* [15] where the forest terrain is fairly flat, consisting of soil, limestone and sandstone (similar terrain effect to ours), and the vegetation mainly consists of deciduous plants with some evergreen plants which is located in Jefferson National Forest, Montgomery County, VA. The measured result at 300 MHz is used because there is quite a high probability for the existence of lateral wave at the foliage depth covered. This result from [15] is plotted against the predicted loss from the proposed integrated model of the LITU-R model with perfect plane earth model in Fig. 6. The foliage depth covered at 300 MHz is from 50–960 m and the antenna is at a height of 0.75 m.

From Fig. 6, it is found that, the proposed LITU-R model with perfect plane earth model shows good prediction accuracy as compared to the comparisons and analysis made in [15]. Even when compared to the predicted results by FITU-R model with perfect plane earth model, the accuracy of the proposed LITU-R model with perfect plane earth model is significantly better and increasingly at large foliage depths. For example, the improvement for the LITU-R model as compared to FITU-R model with perfect plane earth model at 960 m is 5.7 dB. This is because the proposed LITU-R model is based on the measured data up to a foliage depth of 1000 m, which has taken into consideration the lateral wave induced effect as compared to other integrated models. Moreover, the similar terrain effect enhances the predication ability of the proposed LITU-R model with perfect plane earth model for these plantations.

B. *Verification With the Simulated Data*

Due to the lack of the experimental data over the deep forest (>1000 m) in a similar scenario (near ground communication, i.e., at the tree trunk layer, with both transmitter and receiver located in the forest), the proposed LITU-R model is compared to the analytical results reported by Li *et al.* [3] using the numerical simulation. The forest is assumed to be with a height of 25 m, and canopy and trunk layers to be 10 and 15 m high, respectively. The transmit and receive antenna heights, h_T and h_R, used in his simulation are 5 m and 10 m respectively. The reported results at 200 MHz which is close to the frequency of 240 MHz where the LITU-R model is proposed are selected for comparisons with the predicted values from the empirical models and shown in Fig. 7.

From Fig. 7, it can be observed that the predicted values by LITU-R model with perfect plane earth model are quite close to the numerically simulated results by Li *et al.* [3]. This is not surprising, since the simulation process in [3] has taken into consideration the lateral wave contributions, especially at larger foliage depth when both the transmitter and the receiver were placed inside the forest. It is because the lateral wave travels mostly in the lossless air region and becomes dominant at relatively large foliage depth. This is also the main reason for the poor prediction accuracy with FITU-R model since its optimization process did not consider the lateral wave contribution.

There is still an obvious difference between the analytical results [3] and predicted results using the LITU-R model with perfect ground plane. This is mainly due to the assumptions of the structures for the tree canopy and trunks which is different with the realistic cases. The difference may also be due to the forest dielectric parameters used in the simulation. Besides these

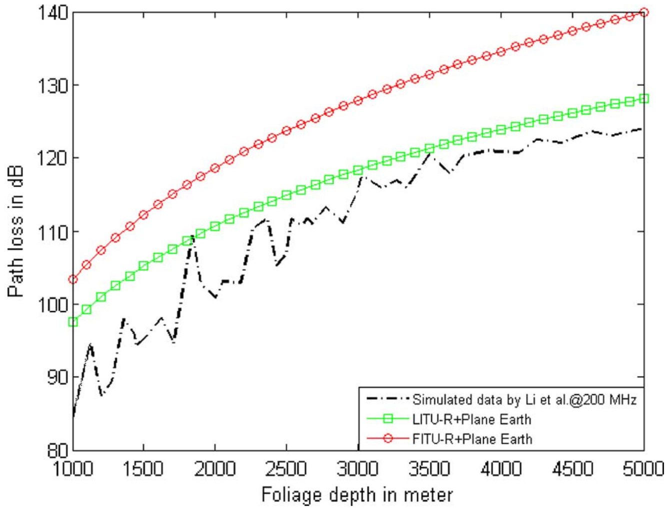


Fig. 7. Predicted path loss in forest at 200 MHz covering a long foliage depth of 1000–5000 m. Also shown are the simulated data by Li *et al*. [3].

influences, the optimization progress for LITU-R model in (13) also produces a significant effect on its prediction ability since the optimization is only based on the data at a single frequency (240 MHz) and needs to be improved with more experimental data.

The above-mentioned comparative study of the predicted values by the LITU-R model and the plane earth path loss model with the measured/simulated data validates the prediction ability of the proposed LITU-R model. The LITU-R model is found to be a good model for the prediction of foliage loss over a large foliage depth (up to 5 km) at VHF band for near ground (mainly at the tree trunk level) forested radio wave propagation. This is verified for the frequencies, 200, 240, and 300 MHz, with high accuracy. Due to the lack of experimental data with lateral wave contributions at higher frequencies, the prediction ability of the present LITU-R model is limited to these lower frequencies. For example, as compared to the UHF (e.g., 500 MHz) simulation results presented by Li *et al.* in [3], the present LITU-R model can only provide high accuracy prediction for distances less than 1200 m. When the distance is above 1200 m, the LITU-R model tends to underestimate the propagation loss. Furthermore, it can be assumed that as the communication point approaches the treetop level, the accuracy will decline. This is because there will be more contribution by the lateral wave as reported in [2], and there is the possibility of the existence of the Norton wave as reported by Liao and Sarabandi in [16].

However, the most important point here is the way to empirically model the near ground radio wave propagation loss in a forest environment. The empirical modeling with (12) has shown good potential, and can be used easily by ordinary users with excellent prediction ability.

VI. CONCLUSION

This paper performs a detailed study of the near ground path loss modeling at VHF and UHF bands in forested environments. An integrated model with ground and foliage effect is proposed which takes into consideration the frequency, antenna height, and foliage depth. Comparative study of the integrated model with several well-known foliage loss models and plane earth path loss model has been performed with the measured path loss. It is found that the FITU-R model derived by Al-Nuaimi and Stephens with the perfect plane earth model matches our results best. This is because, the FITU-R model is an optimized model with different path geometries and tree types, and takes into consideration the forward scattering mechanism at large foliage depths.

However, the lateral wave as proposed by Tamir becomes dominant in the VHF band when the foliage depth is increased. Therefore, the FITU-R model does not predict well the foliage loss over large forest depth since it does not take into account the lateral wave effect. The LITU-R model is proposed in this paper to account for the lateral wave effect in such situations. The proposed model is tested and found to be a better model for the prediction of foliage loss over a large foliage depth (up to 5 km) at VHF band (verified for 200, 240, and 300 MHz). However, the prediction accuracy of the proposed LITU-R model can be improved, based on the path geometry, tree type and frequency, and is an interesting topic for future research work.

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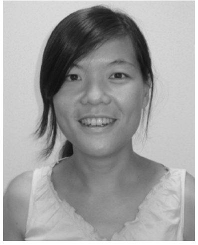
Yu Song Meng (S'09) received the B.Eng. (Hons) degree in electrical and electronics engineering from Nanyang Technological University, Singapore, in 2005, where he is currently working toward the Ph.D. degree.

He has been with the School of Electrical and Electronic Engineering, Nanyang Technological University since May 2008, as a Research Engineer. His research interest includes wireless channel characterizations and modeling, and channel sounder design.



Yee Hui Lee (S'96–M'02) received the B. Eng. (Hons) and M.Eng. degrees in electrical and electronics engineering from the Nanyang Technological University, Singapore, in 1996 and 1998, respectively, and the Ph.D. degree from the University of York, York, U.K., in 2002.

Since July 2002, she has been an Assistant Professor at the School of Electrical and Electronic Engineering, Nanyang Technological University. Her research interests are in antenna design, evolutionary techniques, computational electromagnetic, channel characterization and rain propagation.

Boon Chong Ng (M'88–SM'06) received the B.Eng degree (Hons) in electrical engineering from the National University of Singapore, in 1988, and the M.Sc. degree in electrical engineering, the M.Sc. in statistics, and the Ph.D. degree in electrical engineering, from Stanford University, Stanford, CA, in 1990, 1996, and 1998 respectively.

From 1988 to 1989 and 1990 to 1993, he was a Research Engineer with the Defence Science Organization (DSO), Singapore. In 1998 was a Research Assistant in the Information Systems Laboratory at Stanford University. Currently, he holds the appointment of Head of the Advanced Communications Laboratories and is a Principal Member of the Technical Staff at DSO National Laboratories, and is also an adjunct Associate Professor at the School of Electrical and Electronic Engineering, Nanyang Technological University. He leads research and development groups in MIMO communications, software and cognitive radios.

Dr. Ng was the recipient of the Singapore Government DTTA postgraduate fellowship from 1993 to 1997.