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PATH LOSS MODELING FOR NEAR-GROUND VHF RADIO-WAVE PROPAGATION THROUGH FORESTS WITH TREE-CANOPY REFLECTION EFFECT

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Abstract—This paper presents a new methodology to model the near-ground short-range propagation loss in forested areas at the VHF and the UHF band. The path loss modeling is performed by an integration of the foliage induced effect and the effect from the radio-wave reflection/reflections. The analysis shows that the reflection from the dense tree canopy is important for short-range propagation at the VHF band and therefore, cannot be ignored. When taking into consideration the contribution from the possible tree-canopy reflection, the modeled path loss is reduced by more than 15 dB in the VHF band. A good agreement of the modeled path loss with the measured loss in tropical forested areas is achieved.

1. INTRODUCTION

Great interests arise in the deployment of attended/unattended wireless sensor networks for military applications, such as battlefield sensor networks for communication between dismounted soldiers/military vehicles, and unattended ground sensor networks for military surveillance, mainly at the VHF and the UHF bands recently. To achieve a successful implementation of these military sensor networks, characterization and modeling of wireless communication channel is important. In tropical areas, forested channel is often encountered. Therefore, a proper way to model the propagation loss in forested environment is necessary for establishing a reliable wireless network. For an implementation of military sensor networks in forested areas, the heights of the transmitter (Tx) and receiver (Rx) are low and therefore, not

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only the foliage effect needs to be considered, but also the effect of the ground reflection for near-ground propagation. Radio-wave propagation in a forest with near-ground antenna heights then becomes an attractive topic [1–6]. Analytical [1–3] and empirical [4–6] path loss modeling has been performed in such environments at the VHF and the UHF bands.

The analytical methods proposed by Li et al. [1], Liao et al. [2], and Li et al. [3], show high prediction accuracy. However, they are complicated and require great computational resource, then may not appeal to ordinary users. The empirical methodology by Goldman et al. [4] provides an easier way of modeling the path loss in forests, but this method is very site-specific. Following a similar method to [4] but with the introduction of tree shadowing effect, we performed an empirical path loss modeling with linear regression at a different plantation in [5]. It is concluded in [5] that the extracted path loss exponent n only follows the same trend by frequency as in [4]. That is, as frequency increases, the path loss exponent n decreases generally at the VHF and the UHF bands. Therefore, a proper empirical way to model the near-ground path loss in forest with good accuracy becomes attractive. Joshi et al. [6] attempts to predict the path loss in forests at the VHF and the UHF bands with several well-known foliage loss models. A detailed study of the empirical VHF and UHF path loss modeling in forests has been recently conducted in [7] with ground reflection and lateral wave [8] considered for long-range forested propagation.

In this paper, we conduct a theoretical analysis and study of radio-wave propagation in forests with short forested depths. With the geometrical ray tracing within the forested areas in Section 2, it is found that the possible reflection from the tree canopy is also important for short-range forested propagation as the radio-wave is coherent, and can decrease the propagation loss significantly. This is followed by the empirical verifications in a highly structured palm plantation which is often found in many Southeast Asian agricultural countries, and a natural rainforest in Section 3. The conclusion of this paper is presented in Section 4.

2. RAY TRACING AND PROBLEM FORMULATION

For the radio-wave propagation in free space, the path loss can be predicted by the free space loss (FSL) equation [9],

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

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

As a plane terrain appears, ground reflection may occur. The boundary can be determined with the help of the 1st Fresnel zone, since the energy transmitting from transmitter to receiver concentrates mainly on this region. The size of the 1st Fresnel zone surrounding the geometrical ray paths is shown in Fig. 1. The semi-minor axis h_0 of the ellipse can be computed from the expression [10]

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

where λ is the wavelength. The outer bound of the 1st Fresnel zone varies with the propagating frequency. The large ellipse (dash line) in Fig. 1 represents the 1st Fresnel zone at low frequency, and the small ellipse (solid line) represents the 1st Fresnel zone at high frequency. This is because the low frequency signal has a large propagating wavelength.

When there is a single ground-reflected ray, the path loss can be described by [9, Chap. 3],

$$L_{1-reflected}(\text{dB}) \cong L_{FSL}(\text{dB}) - 20\log_{10}(\Delta\Phi) \tag{3}$$

where $\Delta\Phi$ is the phase difference between the direct and reflected rays given by,

$$\Delta\Phi = \frac{4\pi h_T h_R}{\lambda d} \tag{4}$$

Here, h_T and h_R are the transmitting and receiving antenna heights over the ground in meters, respectively. It is assumed that d is much larger than h_T and h_R.

In this paper, a second reflected wave caused by the tree canopy for short-range forested propagation is introduced since the radio-wave is coherent. Therefore, when this second reflected wave is present, the path loss can be described by [9, Chap. 4],

$$L_{2-reflected}(\text{dB}) \cong L_{FSL}(\text{dB}) - 10\log_{10}(1 + 2\Delta\Phi_1\Delta\Phi_2) \tag{5}$$

where $\Delta\Phi_1$ and $\Delta\Phi_2$ are the phase differences between the direct and the ground-reflected rays, and the direct and possible tree-canopy-reflected rays, respectively. The phase difference $\Delta\Phi_1$ and $\Delta\Phi_2$ can be computed by (4) where $h_T = h_R = h_2$ for the ground-reflected ray and $h_T = h_R = h_1$ for the tree-canopy-reflected ray as shown in Fig. 1 in our study.

For the radio-wave propagation through the foliage medium, there is an additional (excess) loss on the propagating components such as direct wave and reflected waves. Much effort has been put in the empirical modeling of the foliage-induced excess loss at different frequencies and geometries [11–13], and has been summarized in [14]. The well-known empirical models are listed below.

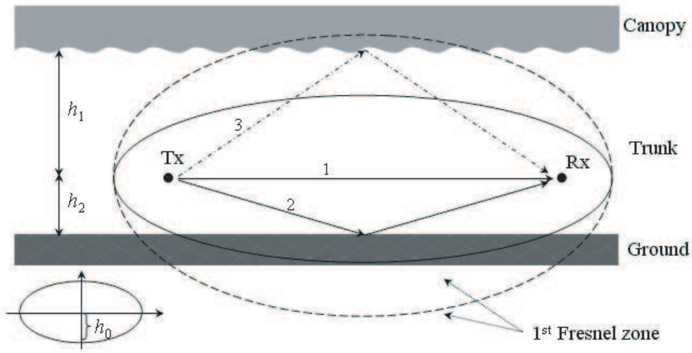


Figure 1. Ray tracing geometry of the direct — 1, ground-reflected — 2, and tree-canopy-reflected — 3 waves.

(i) Weissberger's modified exponential decay model [11] in (6) is applicable where a ray path is blocked by dense, dry, in-leaf trees found in temperate climates. It is applicable in the situations where the propagation is likely to occur through a grove of trees rather than by diffraction over the canopy top, and is given by

$$L_W(\text{dB}) = \begin{cases} 1.33 \times f^{0.284} d_f^{0.588} & 14\,\text{m} < d_f \leq 400\,\text{m} \\ 0.45 \times f^{0.284} d_f & 0\,\text{m} \leq d_f < 14\,\text{m} \end{cases} \tag{6}$$

where f is the frequency in GHz, and d_f is the foliage depth in meters.

(ii) ITU Recommendation (ITU-R) [12] was developed from measurements carried out mainly at UHF, and was proposed for the cases where either the transmitting or receiving antenna is near to a small ($d_f < 400\,\text{m}$) grove of trees so that the majority of the signal propagates through the trees. It is described as

$$L_{ITU-R}(\text{dB}) = 0.2 \times f^{0.3} d_f^{0.6}. \tag{7}$$

(iii) COST235 model [13] which was proposed based on measurements made in millimeter wave frequencies (9.6 GHz to 57.6 GHz) through a small ($d_f < 200\,\text{m}$) grove of trees is

$$L_{COST}(\text{dB}) = \begin{cases} 26.6 \times f^{-0.2} d_f^{0.5} & \text{out-of-leaf;} \\ 15.6 \times f^{-0.009} d_f^{0.26} & \text{in-leaf.} \end{cases} \tag{8}$$

In COST235 model (8), measurements were performed over two seasons, when the trees are in-leaf and when they are out-of-leaf. For both ITU-R and COST235 models, f is the frequency in MHz, and d_f is the foliage depth in meters.

In this paper, the foliage-imposed effect on the propagating waves is examined with the above-mentioned models (6)–(8). For the short-range near-ground forested radio-wave propagation, the propagation loss is modeled by an integration of the foliage-imposed effect and the effect from the radio-wave reflections such as the ground reflection and the possible tree-canopy reflection. This proposed integration model is discussed and evaluated experimentally in the following part.

3. MEASUREMENTS AND VERIFICATIONS

3.1. Measurement Campaigns

The measurements have been conducted in two tropical foliage areas; a highly structured palm plantation shown in Fig. 2(a); and a natural rainforest shown in Fig. 2(b). Details of the forests are described below.

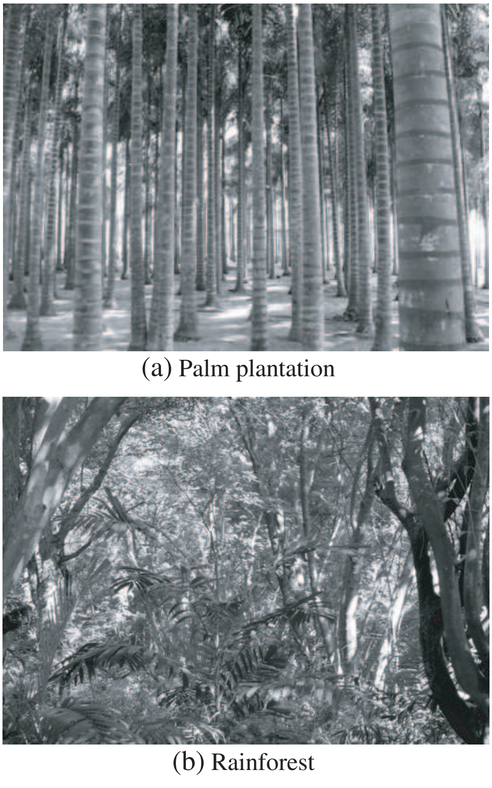


Figure 2. Photograph of the tropical forested areas under considerations.

3.1.1. Palm Plantation:

This is a rectangular shaped site planted with palm trees (analogous to coconut tree), 10 m in height. The forested terrain is fairly flat, consisting of soil and sand. The trees are nearly equally spaced with a separation of 1.2 m and their trunks have an average diameter of 20 cm. The leaves of these trees form a dense canopy. Since the site is close to the sea, the environment is very humid.

3.1.2. Tropical Rainforest:

The natural rainforest consists of trees with an average height of 10 m to 11 m and main trunk diameter of 30 cm to 45 cm. These trees are irregularly spaced with separations ranging from 4 m to 7 m. The ground of the rainforest is crowded with dense undergrowth of scrubs and saplings with heights of 1.5 m to 4 m. A dense canopy is also formed by the leaves.

Narrowband measurements of signal strength at 13 frequencies within the bands of 40 ∼ 80 MHz, 250 ∼ 300 MHz, and 500 ∼ 630 MHz were carried out. The details of the measurement setup can be obtained from our previous works [5, 7]. During the measurements, the covered forested depth is from 31 m to 62 m in the palm plantation and 92 m to 114 m in the rainforest. The antenna heights are kept at a constant of 2.15 m. Before the measurements are taken, the noise floor at the receiver is observed and found to be around −75 dBm to −76 dBm. All the data is collected under sunny and no-wind weather conditions with limited human activities.

3.2. Analysis and Verifications

The computed minor axis h of the 1st Fresnel zone is shown in Table 1. As shown in Fig. 1, $h_1 = 6.85\,\text{m}$ and $h_2 = 2.15\,\text{m}$ for the palm plantation, and $h_1 = 4.65\,\text{m}$ and $h_2 = 2.15\,\text{m}$ for the rainforest. From

Table 1. Fresnel radius at different frequencies and forested depth.

f (MHz)	40	80	250	300	500	630
h_0(m) @ 31 m	7.6	5.4	3.0	2.8	2.2	1.9
h_0(m) @ 62 m	10.8	7.6	4.3	3.9	3.0	2.7
h_0(m) @ 92 m	13.1	9.3	5.3	4.8	3.7	3.3
h_0(m) @ 114 m	14.6	10.3	5.8	5.3	4.1	3.7

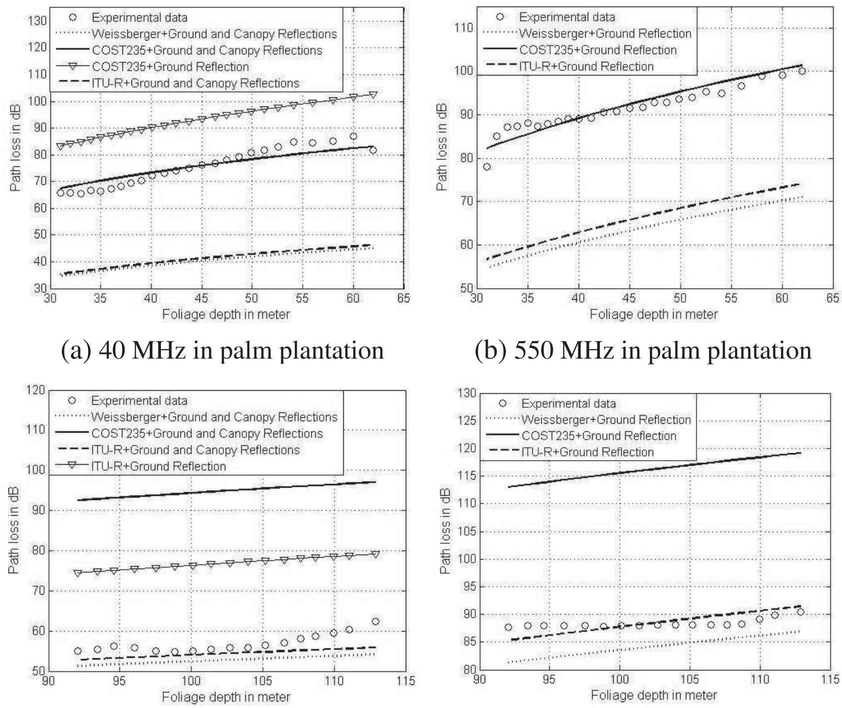
Table 1, it can be concluded that the ground reflection exists for all the frequencies of interest in both forested areas. However, the possible tree-canopy reflection only exists when the signal is within the VHF band of 40 $\sim$ 80 MHz for the palm plantation, and within the VHF band of 40 $\sim$ 80 MHz and 250 $\sim$ 300 MHz for the rainforest in this study. In the following part, when ground and possible tree-canopy reflections exist, the path loss is predicted by

$$PL_{forest}(\mathrm{dB}) \cong L_{foliage}(\mathrm{dB}) + L_{2-reflected}(\mathrm{dB}) \tag{9}$$

whereas when there is only ground reflection, the path loss is

$$PL_{forest}(\mathrm{dB}) \cong L_{foliage}(\mathrm{dB}) + L_{1-reflected}(\mathrm{dB}) \tag{10}$$

where $L_{foliage}$ can be L_W, L_{ITU-R}, or L_{COST}, and the perfect reflection is assumed.



(a) 40 MHz in palm plantation

(b) 550 MHz in palm plantation

(c) 40 MHz in rainforest

(d) 550 MHz in rainforest

Figure 3. Measured and predicted path loss at VHF and low UHF bands with $h_1 = 6.85$ m and $h_2 = 2.15$ m in the palm plantation, and $h_1 = 4.65$ m and $h_2 = 2.15$ m in the rainforest.

The predicted loss from (9) and (10) is plotted in Fig. 3 compared to the measured local mean path loss, which is a moving average of the path loss along a 10 m linear track [9]. The moving average is employed to minimize the tree-trunk-induced shadowing effect as reported in [5]. For the COST235 model, the in-leaf model is used.

It is observed that the COST235 model gives the best fit for the measured path loss in the palm plantation with the ground and possible tree-canopy reflections considered at 40 MHz (VHF) in Fig. 3(a) and with only the ground-reflection considered at 550 MHz (UHF) in Fig. 3(b), while the ITU-R model shows a best prediction ability for the path loss in the rainforest with ground and possible tree-canopy reflections considered at 40 MHz (VHF) in Fig. 3(c) and with only ground-reflection considered at 550 MHz (UHF) in Fig. 3(d). The excellent prediction ability of the COST235 model in the palm plantation and the ITU-R model in the rainforest with the considered reflection/reflections is also verified for all other used frequencies. The difference between the best foliage-induced loss models (the COST235 model in the palm plantation and the ITU-R model in the rainforest respectively) we observed is mainly due to the different type of the forests found in the propagation path for the two measurement campaigns. It is noted that, the three foliage loss models, Weissberger, ITU-R, and COST235, are derived and optimized on the experimental data collected in the different foliage plantations.

It is known that both the Weissberger model and the ITU-R model are derived from databases where the measurements are performed at the VHF and the UHF bands through a small grove of trees, while the COST235 model is derived from the measured data at the millimeter waves. For the palm plantation, the dominant dense tree trunks and highly humid environment results in a measured path loss that is higher than other forested environments. Therefore, the COST235 model with the considered reflection/reflections is an ideal model for modeling the short-range path loss at the VHF and the UHF bands for this palm plantation. For the rainforest, sparsely spaced tree trunks with dense undergrowth have a leafy, undergrowth-dominant propagation path that is more similar to the scenarios where the Weissberger and the ITU-R models are derived. The humid tropical climate results in an underestimation of the foliage loss by the Weissberger model since it is based on dense, dry, in-leaf trees in temperate climates. Therefore, the ITU-R model with the considered reflection/reflections is found to be the best prediction model for this rainforest.

The most significant point in this study is that, for short-range near-ground propagation at the VHF band, the tree-canopy-induced reflection cannot be ignored when the empirical path loss modeling is performed. Both measurement campaigns in the palm plantation and the rainforest have justified this conclusion. It is shown in Fig. 3(a) that, at 40 MHz, the COST235 model taking into consideration both the ground and possible tree-canopy reflections gives excellent modeling capability for the measured data. The COST235 model taking into considerations only the ground reflection tends to overestimate the measured path loss by more than 15 dB. Similar observation is found in Fig. 3(c), where the ITU-R model with the ground and possible tree-canopy reflections considered reduces the predicted path loss by more than 20 dB in a slight longer forested depth. The ITU-R model also gives a good fit to the measured data. This is because, when both the ground and possible tree-canopy reflections are taken into account, the convergence of the possible tree-canopy-reflected wave with the ground-reflected wave at the receiver reduces the overall propagation loss. Both measurement campaigns show that the reflection from the tree canopy in the VHF band is important and has to be taken into account while the short-range near-ground empirical modeling in forested environments is performed

Moreover, it is found that the standard deviation of the differences between the measured and predicted values as shown in Fig. 3 is 2.7 dB at 40 MHz and 1.8 dB at 550 MHz for the palm plantation, and 3.3 dB at 40 MHz and 1.4 dB at 550 MHz for the rainforest respectively. The deviation (difference) is mainly due to the assumed perfect reflection in the modeling process. Practically, the roughness [15] of the canopy/trunk interface and trunk/ground interface is known to result in imperfect reflections. As compared to the deviation at 550 MHz, there is a larger deviation at 40 MHz for both plantations. This is due to the rough canopy/trunk interface by the naturally grown canopy and branches as shown in Fig. 1 since other conditions are kept the same for both frequencies. Furthermore, there is a higher variation of the standard deviation for the rainforest (1.9 dB) as possible tree-canopy reflection appears, compared to the palm plantation (0.9 dB). This is due to the difference in vegetation within the forested environments under measurements. The canopy/trunk interface is rougher in the rainforest as compared to the palm plantation as in Fig. 2. Therefore, when applying (9) with possible tree-canopy reflection considered in other plantations, one needs to take into consideration the roughness of the canopy/trunk interface relative to the frequency of operation.

4. CONCLUSIONS

This paper reports path loss modeling in the tropical forested areas using the existing empirical foliage loss models. Theoretical study shows that the dense tree-canopy-induced reflection is of high importance at the VHF band for the short-range near-ground propagation in the forested areas. This is because, for a short propagation range, the tree-canopy is within the 1st Fresnel zone and the propagating radio-wave is much coherent.

Experimental verifications of the contribution from the possible tree-canopy reflection are conducted within two different tropical forested areas. It is found that due to the different foliage type, the COST235 model and the ITU-R model have the best fit for the two considered forested propagation channels respectively. The COST235 model gives a good fit to the dense trunk-dominant palm plantation and the ITU-R model gives a good fit to the leafy undergrowth-dominant rainforest.

Most importantly, both measurement campaigns verify the importance of taking into consideration the possible tree-canopy reflection for short-range near-ground propagation at the VHF band. The modeled and the measured results are in good agreement with each other when the possible tree-canopy reflection is taken into consideration. Therefore, when the empirical modeling for short-range near-ground forested channel at the VHF band is performed, the possible tree-canopy reflection has to be taken into account. Moreover, the tree-canopy reflection effect on the short-range forested propagation can be further studied with the antenna-height effect, and will be an interesting future research work.

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