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FURTHER STUDY OF RAINFALL EFFECT ON VHF FORESTED RADIO-WAVE PROPAGATION WITH FOUR-LAYERED MODEL

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Abstract—In this paper, rainfall effect on the VHF radio-wave propagation in a tropical forest is further studied in details. Theoretical study and experimental investigations are performed with the help of a four-layered model for forested environment. It is found that the lateral wave traveling along the air-canopy interface, the direct waves, and the ground reflected waves are the main modes for VHF radio-wave propagation in forest. The rainfall can affect these propagating waves to different extents. Especially, due to the increase in the dielectric permittivity of the wet canopy layer by rain water, the time of arrival of the direct wave traveling through the canopy layer can be delayed significantly. Finally, the dielectric permittivity for the wet canopy layer under different rain events is evaluated empirically.

1. INTRODUCTION

Wireless communication in forested environments at VHF and UHF bands has been an interesting research topic for many years [1–7]. Analytical study by Tamir [1] in 1967 shows that the lateral wave propagating along the treetops plays a major role in the received field over large foliage depth at VHF band (1–100 MHz). He described the forest configuration as a "dissipative slab". Subsequently, Dence and Tamir [2] extended their theoretical study on the lateral wave propagation by taking into consideration the ground reflection effects for the frequency range of 2–200 MHz. It is noted that, as the frequency

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increases to above 200 MHz, the representation of the forest as a dissipative dielectric slab becomes poor. This is because the forest can no longer be regarded as a homogeneous medium with reference to the wavelength of the propagating signal [3]. The forest configuration is therefore represented as two dielectric slabs by Cavalcante et al. [4], Seker et al. [5], and Li et al. [6, 7]; the canopy layer; and the trunk layer. Dyadic Green's function based method [4, 6, 7], and Hertz Potential based method [5] have been successfully used to study and analyze the behavior of VHF and UHF radio-wave propagation over a large foliage depth. The propagation of the radio-wave is typically expressed in terms of direct waves, multiple reflected waves, and lateral waves.

Recently, a review of VHF and UHF radio-wave propagation in forests has been conducted in [8]. The open literature shows that, the effects of rainfall on the forested channel is still not thoroughly investigated, especially at VHF band since it is well-known that rainfall affects radio-wave propagation only at high frequencies of above 5 GHz [9]. Little consideration is given to the accumulation of rain water on the foliage medium that can potentially become an important source of absorption and attenuation of the propagating wave even at VHF band. Our previous works have attempted to characterize and model the forested channel with the effects of rain [10] and wind and rain [11] experimentally. Both studies indicate that, rainfall is an important factor needed to be considered even for VHF forested radio-wave propagation.

As a continuation of the channel characterization and modeling work in [10] and [11], the objective of this paper is to investigate the rainfall effects on a forested channel at VHF band, with the help of a four-layered model for forested environment. In the remaining of this paper, Section 2 gives a description of the theoretical background for this research work. In Section 3, experimental work for investigation of rainfall effects is reported first. The rainfall effects on each layer of the four-layered model are then studied and discussed. The dielectric permittivity for the wet canopy layer under different rain events is evaluated empirically. This is followed by conclusions in Section 4.

2. THEORETICAL BACKGROUND

2.1. Four-layered Model

With the introduction of the two dielectric slabs to represent the canopy and trunk layers, wireless communication through forests at frequencies of above 200 MHz can be studied with a four-layered model [4–7], where the dielectric canopy and trunk slabs are positioned between the electrically isotropic air layer and the ground layer, as

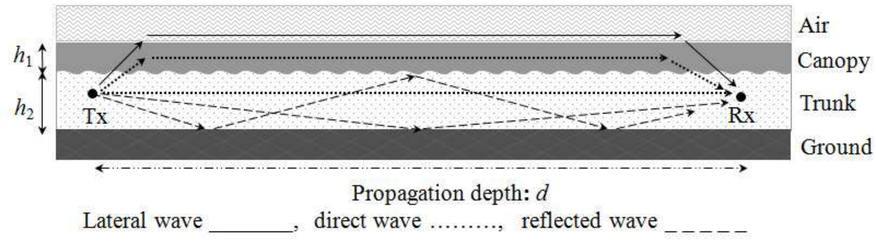

Figure 1. Ray tracing geometry in a four-layered model.

shown in Fig. 1. The vertical heights of the canopy and trunk layers are h_1 and h_2 respectively, while the heights of the air and ground layers are infinite. For simplicity, in this study, the canopy layer and the trunk layer are assumed to be homogeneous and their corresponding effective permittivity is denoted by $\epsilon_1\epsilon_0$ and $\epsilon_2\epsilon_0$. The scalar permittivity for the air layer and the ground layer is denoted by ϵ_0 and $\epsilon_3\epsilon_0$, respectively. Similar to those indicated in [4–7], all four layers are assumed to be magnetically isotropic and characterized by the free-space permeability μ_0.

2.2. Propagation Modes and Waves

The radio-wave propagation in the aforementioned four-layered model can be expressed in terms of the lateral waves propagating along the interfaces between two adjacent layers, the direct waves propagating through the different layers, and the single/multiple-reflected waves reflected off the interface of the different layers as shown in Fig. 1. The analytical work by Li et al. [6, 7] reported that the lateral wave along the air-canopy interface (over the treetops) plays a major role in the near-ground communication over a large foliage depth at VHF and UHF bands. Other propagation modes such as direct waves, and reflected waves as shown in Fig. 1 also play important roles in the forested radio-wave propagation. For realistic wireless communication in forested areas however, their contributions to the received field are strongly dependent on the roughness of the interface [12], weather conditions [10, 11] etc.

In this following, the rainfall effects on the main propagating waves as indicated in the four-layered model are investigated experimentally, and the direct derivation of dielectric permittivity of foliage layers is proposed.

3. MEASUREMENT RESULTS AND ANALYSIS

The experimental investigation of rainfall effects on VHF radio-wave propagation in a tropical forest is conducted through the study and analysis of the measured channel impulse responses. With the help of the channel impulse responses and the four-layered model, the distinct rainfall effects on each main propagating wave is observed and analyzed.

3.1. Measurement Techniques and Forest Environment

Spread spectrum based wideband measurements have been carried out with a matched filter detector at the receiver. Maximal-length pseudo-noise (PN) sequence is implemented at the transmitter and modulated using Binary Phase Shift Keying (BPSK). In this study, 63-bit PN sequence with a data rate of 5 Mchips/s is used. This translates into a multipath dynamic range of 36 dB, and a time resolution of 0.2 µs for the measurements.

The forested environment under measurements is shown in Fig. 2, and is the same palm plantation as reported in [10, 11]. It spreads over a nearly flat terrain, and the trees are approximately 5.6 m in height and nearly equally spaced with a distance of 7 m. The average tree trunk diameter at the antenna height of 2.15 m is around 0.4 m. This antenna height is close to the canopy layer. In this paper, the experimental results at the foliage depth of 710 m with static antennas and at a frequency of 240 MHz are reported and analyzed.

Figure 2. Plantation under measurement.

3.2. Results and Analysis

The forested channel of interest is investigated with its channel impulse response $h(n,\tau)$ in this study. $h(n,\tau)$ is obtained by correlating the known transmitted signal with the received one, and is expressed as,

$$h(n,\tau) = \sum_{k=0}^{M} \alpha_k \exp(j\varphi_k)\delta(\tau - \tau_k) \tag{1}$$

where n is the consecutive impulse index, α_k, τ_k, and φ_k are the signal strength, the propagation delay and the phase shift of the kth multipath component. M is the number of multipath clusters. In the following part, the analysis will be performed on the instantaneous power delay profile (PDP), which is the envelope of the received power and is proportional to $|h(n,\tau)|^2$. An example of 1024 consecutive measured PDPs with rainfall effect is shown in Fig. 3. The measured PDPs under the influence of different rain events as in [10] will be discussed with the help of four-layered model in this paper.

3.2.1. Propagation Delay

The plot in Fig. 4(a) is a typical mean PDP obtained from an average of 1024 consecutive instantaneous PDPs acquired to smooth

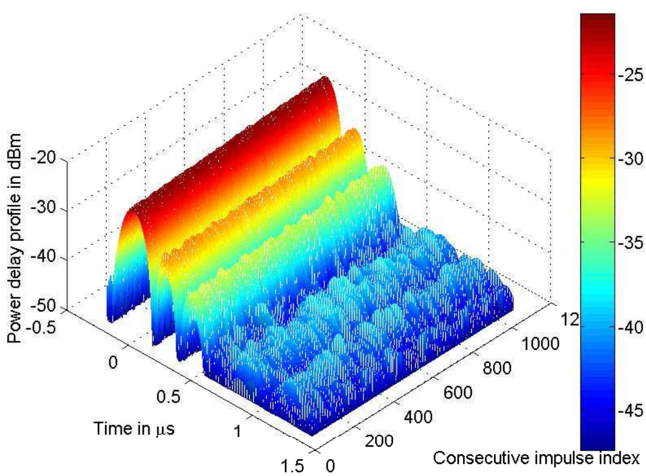

Figure 3. An example of the consecutive measured PDPs with rainfall effect.

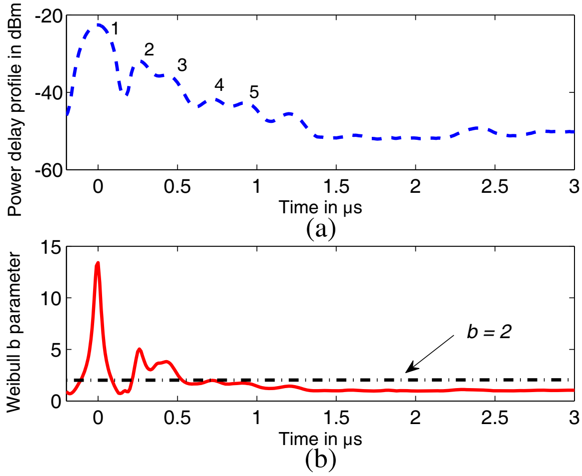

Figure 4. (a) Power delay profile in dBm, (b) variation of the Weibull b parameter with the time delay. Both are results under heavy rain (24.4 mm/h).

out the noise floor and minimize the temporal variations by the raindrops. It is observed from Fig. 4(a) that, besides the first arrival (cluster at the time index of 0 μs), there are several delayed arrivals within 25 dB (threshold) of the dominant arrival (first cluster). This indicates that at 240 MHz, the physical paths/propagation modes in the forested channel are not unique. In this part, the potential physical paths/modes for each arrival/cluster shown in Fig. 4(a) are discussed with the concept of propagation delay.

The propagation delay can be estimated as in [5],

$$t_d = \frac{d\sqrt{\varepsilon_r}}{c} \tag{2}$$

where d is the propagation depth in meter, c is the speed (3e8 m/s) of radio-wave in free space, and ϵ_r is the effective relative permittivity of the assumed homogenous layer. As introduced before, ϵ_r is; ϵ_1 for the canopy layer; ϵ_2 for the trunk layer; and ϵ_3 for the ground layer. The effective relative permittivity for typical tropical forests [2] is shown in Table 1. Generally, for the study of four-layered model, ϵ_2 for the trunk layer is suggested to be of 'thin' tropical forests given in Table 1, and ϵ_1 for the canopy layer is initially taken to be of 'average' tropical forests. In [4], ϵ_1 is varied until a best fit is obtained between their analytical results and the experimental results used by Dence and Tamir in [2]. The estimated ϵ_1 in [4] is 1.12. This value, together with a value of ϵ_2 of

1.03 is later used in the analytical studies done by Li et al. [6, 7] with success. From our previous study [13], the proposed empirical path loss model derived from the measured data under dry weather in this tropical forest is in good agreement with the analytical results reported in [7] at VHF band. It can be concluded that, these parameters ($\epsilon_1 = 1.12$, $\epsilon_2 = 1.03$) agrees well with the practical dielectric values of this tropical forest under dry weather. However, as a rain event appears, due to the accumulation of rain water on the foliage medium within the canopy layer, the relative permittivity of the canopy layer increases significantly. Hence, in this study, the relative permittivity ϵ_1 for the wet canopy layer under different rain events is assumed to be in the range between 'average' to 'dense' forest type (1.1 to 1.3).

Table 1. Characteristic parameter of typical forests [2].

Forest type	ε_r
Thin	1.03
Average	1.1
Dense	1.3

Due to the rough interface [12] between the canopy layer and the trunk layer in this tropical forest, the main propagating modes are; the lateral wave which propagates along the air-canopy interface; the direct wave which propagates through the trunk layer; the direct wave which propagates through the canopy layer; and the reflected waves which is reflected off the ground layer. With the four-layered model (Fig. 1), it can be found that, the physical propagation path lengths of the lateral wave, the direct waves, and the single ground-reflected wave are almost the same when the foliage depth is large ($h_1, h_2 \ll d$). Therefore, the delay in the arrival time of each wave is mainly due to the difference in the relative permittivity ϵ_r of the layer in which they propagate through. Only the multiple-reflected (at least twice) waves will arrive at the receiver after a long time delay due to their relatively longer propagation paths. These multiple-reflected waves will also arrive with smaller amplitude after the multiple-reflections.

The arrival time of the multipaths is normalized to the first arrival, the lateral wave. The lateral wave is assumed to be the first arrival since it travels along the air-canopy interface and therefore, most of its path is in the air region where $\epsilon_r = 1$, which is the smallest permittivity amongst the different layers. The relative propagation delays for the other paths are estimated using Equation (2) and given in Table 2. Due to the limitation of the sounding technique allowed, the time resolution of the measurement is 0.2 μs. Therefore, the lateral wave propagating along the air-canopy interface, the direct wave propagating in the trunk layer, and the ground reflected wave all appears within the first arrival/cluster in the measurement results. This results in an increase in the 3-dB width of the first cluster as shown in Fig. 4(a) to 0.17 μs, as compared to the 3-dB width (0.07 μs) of the back-to-back measurement in [10].

Moreover, the second arrival/cluster in the measured PDP as shown Fig. 4(a) is found to center at 0.26 μs. This second cluster is probably due to the direct waves propagating in the canopy layer since its theoretically estimated arrival time in Table 2 is from 0.12 to 0.33 μs, by varying the relative permittivity ϵ_1 in Equation (2). The third (0.43 μs), fourth (0.72 μs) and fifth (0.94 μs) arrivals/clusters are due to the multiple-reflections of the waves and therefore, have a longer propagation time delay and relatively smaller amplitudes. These observations agree well with theoretical estimations, and can be further verified through the study of temporal variations of the multipath clusters during the different rain events.

Table 2. Relative delay for the main components in the tropical forest.

Mode	Δt_d
Lateral wave along air-canopy	0 μs
Direct wave in trunk layer	0.04 μs
Direct wave in canopy layer	0.12 to 0.33 μs
Reflected wave from ground	0.04 μs

3.2.2. Temporal Variations

The temporal variations of the propagating components at different rainfall rates can be studied through the use of the Akaike's Information Criterion [14]. It is found that [15], the falling raindrops induced temporal variation can be accurately and conveniently modeled using the Weibull function,

$$P_{a,b}(x) = abx^{b-1} \exp(-ax^b), \ x \geq 0 \tag{3}$$

where parameter a is derived from the mean square value of the distribution and the parameter b. The parameter b controls the spread of the distribution, and gives an indication of the variation of the interested channel; a small value of b corresponds to a large dispersion. Moreover, a value of $b = 2$ yields the Rayleigh distribution, and $b < 2$ indicates severe temporal fading. The corresponding variation of the Weibull b parameter with the time delay for the measured PDP in

Fig. 4(a) under a heavy rainfall is plotted in Fig. 4(b). It can be seen that, the empirical Weibull b parameter is very high (~ 14) for the first arrival. It then decreases significantly for the second (~ 5) and third (~ 3.8) arrivals. Finally, it falls below 2 for the subsequent arrivals. That is, the first arrival is the most coherent contribution in the received filed. This is because its main compositions are; the lateral wave propagating along the air-canopy interface, the direct wave traveling in the trunk layer, and the ground reflected wave. The coherency for the latter arrivals gradually decreases since these components are from multiple-reflections.

The variation of the Weibull b parameter under different rain events is shown in Fig. 5 for comparisons. From Fig. 5, it can be seen that, the b parameter for the first arrival is almost always constant regardless of the rain rate, since its composite is highly coherent. For the second main cluster, it can be observed that, as the rain rate increases, the estimated Weibull b parameter decreases correspondingly. That is, the composite for the second cluster is from the components which are affected by the rainfall effects or by the varying medium through which they propagate. The variation of the medium is due to the falling raindrops. Since the rainfall affects radio wave propagation only at high frequencies of above 5 GHz in free space as stated in [9], it can be concluded that the temporal variation of the second cluster is from the variation of the propagation medium induced

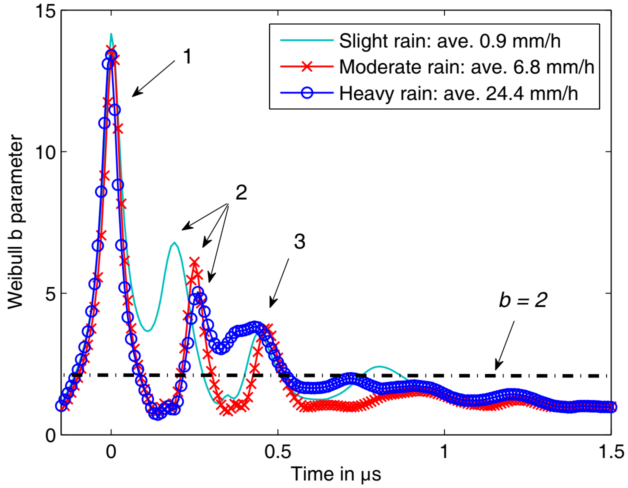

Figure 5. Variation of the Weibull b parameter with the time delay under different rain rate as in [10].

by the falling raindrops. With the four-layered model shown in Fig. 1, only the canopy layer can be affected by the rain events. The falling raindrops cause movements to the broad palm leaves in the canopy layer. From the analysis given in the previous section, it is concluded that the second arrival cluster is from direct wave propagating through the canopy layer.

The high b ($\sim$ 14) value for the first arrivals thus indicates no components of the direct wave through the canopy layer within the first arrivals/cluster. It is also observed that, the multiple-reflected waves as shown in the third and latter arrivals are much more incoherent, and is significantly affected by the movement induced in the canopy layer due to the falling raindrops.

Moreover, from Fig. 5, it can be seen that, the increase in rain rate results in not only a lower Weibull b value, but also a longer delay in the arrival time of the second cluster. The arrival time for the second cluster increases significantly as the rain rate increases. This is because of the increased accumulation of rain water in the canopy layer which increases the effective dielectric permittivity of the layer. The increase in dielectric permittivity thus reduces the propagation speed of radio-wave within the canopy layer. The actual time of arrival of 0.19 to 0.26 µs of the direct wave through the canopy layer as the rain rate increases from 0.9 mm/h to 24.4 mm/h can be extracted from Fig. 5. The actual measured time of arrival (0.19 to 0.26 µs) is within the range of the theoretically estimated time of arrival of 0.12 to 0.33 µs as tabulated in Table 2. The measured time of arrival is in good agreement with the estimated time of arrival.

3.2.3. Empirical Dielectric Permittivity

From the analysis given above, an empirical method for directly deriving the dielectric permittivity of the foliage layers (canopy/trunk layers) can be proposed in this study. This is a simple alternative to the ones used in [4] and [16], where inverse method is performed to estimate the parameters by fitting their respective analytical models containing dielectric parameters with the experimental data. In our proposed method, the dielectric permittivity for the different foliage layers can be reversely derived from the measured time delay through Equation (4),

$$\varepsilon_r = \left[\Delta t_d \frac{c}{d} + 1\right]^2 \tag{4}$$

where Δt_d is the delay time for the radio-wave propagation in the layer of interest relative to the free space propagation, d is the propagation depth in meter, and c is the speed (3e8 m/s) of radio-wave in the free space. As compared to the inverse method [4, 16], the main advantage of the proposed method is that, it can directly estimate the dielectric parameters from the measurements data, and easier to apply.

However, in this proposed method, the accuracy of the derived dielectric permittivity of the different layers is dependent on the time resolution of the sounding technique. For example, in this study, only the effective relative permittivity ϵ_1 for the canopy layer in this tropical forest can be derived. This is due to the limitation in allowable time resolution of 0.2 μs. With this resolution, only the wave propagating through the canopy layer can be isolated by examining the measured PDPs. The estimated effective relative permittivity ϵ_1 for the canopy layer under different rain rates by Equation (4) is found to be within the range of 1.17 to 1.23, and it increases as the rainfall rate increases.

4. CONCLUSIONS

This paper presents a further study of the rainfall effects on wireless communication within the forest at VHF band. The theoretical estimation and experimental investigation show that the lateral wave along air-canopy interface, the direct waves through the trunk layer and the canopy layer, and the ground-reflected waves are the main modes for propagation over large foliage depths at VHF band. The direct wave traveling through the canopy layer is the only wave that can be affected by the falling raindrops during a rain event. This is verified by two methods; through the estimation of the time of arrival of the direct wave traveling through the canopy layer relative to other propagation modes such as lateral wave and reflected waves; and through the study of the temporal variations using the Weibull b parameter.

Finally, a method to empirically derive the dielectric parameters for the different layers in a forested environment is proposed. The effective relative permittivity ϵ_1 for the canopy layer under different rain rates is found to be within the range of 1.17 to 1.23 in this study.

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