Investigation of Rainfall Effect on Forested Radio Wave Propagation

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

***Abstract*—In this paper, the rainfall is found to have distinct effect on various parts of the propagating components for the VHF radio wave propagation in a tropical forest. By the studies of the measured power delay profiles under different weather conditions, it is observed that the lateral wave is the dominant mode of the VHF propagation and is not affected by the presence of rain as it is similar to free space propagation over the tree tops, while the significant multipath components which propagate through the forest medium is heavily influenced. This is again verified through the estimated delay spread statistics.**

***Index Terms*—Delay spread, forest, propagation, rainfall effect, VHF.**

I. Introduction

VEGETATION plays a significant role on the fading phenomena in wireless communication [1]–[4]. Since Tamir [1] raised the concept of lateral wave (1–100 MHz) propagation in forested environment, much effort has been put in by researchers to study the foliage medium as a propagation channel. Recently, narrowband (900–1800 MHz) investigations have been performed on the effects of foliage on cellular base-to-mobile propagation [2], [3]. The temporal variation of the received signal due to the effects of wind has been examined and found to be Rician distributed. In the near-ground wideband channel measurements [4], different antenna heights and radiation patterns were found to have different effects on the radio wave (300, 1900 MHz) propagation in both dry and wet foliage conditions. From open literature, wind has been well studied and found to play an important role on the forested radio wave propagation. However, the effects of rainfall on the forested channel remains unexplored, especially at VHF since it is well known that rainfall affects propagation only at high frequencies of above 5 GHz [5]. 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.

As a continued work from the previous one [6], where the narrowband study of the combined effects of wind and rain is presented, the main objective of this paper is to study the rainfall effect on a tropical forested propagation channel of wideband signals in the VHF (240 MHz) band. The rain intensity and its influence on various parts of the propagating components are investigated in detail.

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The authors 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; ebcng@ntu.edu.sg).

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II. Measurement Campaign

A measurement campaign that lasted for two weeks was performed in Singapore during the northeast monsoon season in December 2006. This is generally the wettest month of the year with an average monthly rainfall of 280 mm. The foliage chosen for this study is a palm plantation which spreads over a nearly flat terrain with an area of more than 0.7 km^2. The palm trees are approximately 5.6 m in height and 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 covered in this experiment is 710 m. The transmit and receive antennas are both kept stationary inside the palm plantation and at a constant height of 2.15 m.

The transmitter consists of a vector signal generator, used to produce a carrier wave at 240 MHz modulated using Binary Phase Shift keying (BPSK). Due to the power constraint of the signal generator and the high attenuation resulting from the foliage depth (especially since the foliage is damp due to the rainfall during this monsoon season), a 10 W high power amplifier is required to amplify the transmitted signal. With experiences from previous experiment campaigns, a 63-bit maximal length pseudo-random noise (PN) code at 5 Mchips/s is used. This results in a time resolution of 200 ns for the received signal. This BPSK modulated PN signal after amplification is fed into a vertical polarized omni-directional antenna with 2.4 dBi of gain.

At the receiver, the signal is intercepted using an identical omni-directional antenna. The received signal then passes through a low noise amplifier with 20 dB of gain and 2.9 dB of noise figure before being down-converted to an intermediate frequency (IF) of 20.4 MHz. The IF signal is then sampled at a rate of 100 MSamples/s and stored into a data logger for offline data processing.

In order to study the rainfall effect on the propagating wideband signal, the weather information is derived from the S-band weather radar located at Changi which is set up by the National Environment Agency (NEA) [7], Singapore. The weather radar covers an elevation angle range from 1° to 40°, with a reflectivity scan every 1° up to a maximum range of 240 km. A full set of reflectivity information is obtained every 4 minutes. Fig. 1 shows a sample of the radar image for the rain intensity in units of mm/hour derived from the reflectivity data using the ITU-R recommendations [8] for the region.

III. Results and Discussions

The measured signal is down-converted to its baseband signal via a software program. The baseband signal then undergoes

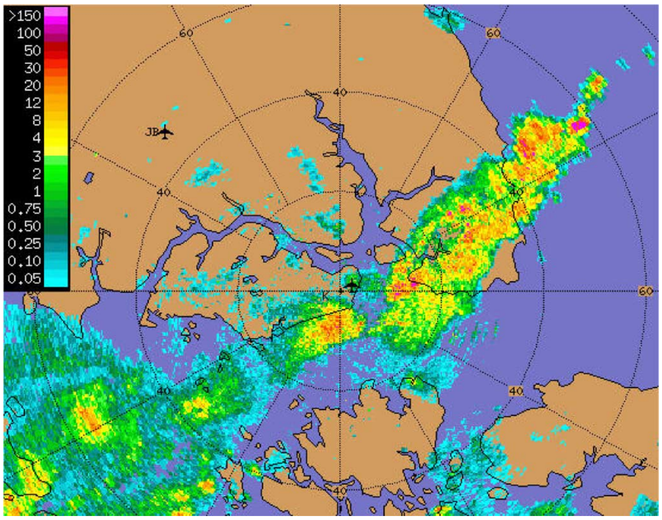

Fig. 1. Radar image for the rain intensity display from the NEA weather radar.

cross-correlation with a copy of the known original 63-bit PN sequence. This will produce the complex channel impulse response $h(n, \tau)$, which can be expressed as

$$h(n, \tau) = \sum_{k=0}^{N} a_k \exp(j\varphi_k)\delta(\tau - \tau_k) \quad (1)$$

where n is the consecutive impulse index, a_k, τ_k, and φ_k are the signal strength, propagation delay and phase shift of the kth multipath component. N is the number of multipath components.

The power delay profile (PDP) is the envelope of the received power and is proportional to $|h(n, \tau)|^2$. Fig. 2 shows the measured normalized back-to-back power delay profile for the channel sounder (used to remove the system effects from the measured signal) and the typical result of propagation through the forested channel when there is no rainfall effect (dry foliage, used for comparison purposes). Fig. 3 shows samples of the PDP for three typical (representative of more than 85% of all the estimated PDPs) results obtained in the palm plantation under different rain intensities (RI): slight rain ($\mathrm{RI} <$ 2 mm/hour), moderate rain (2 mm/hour $< \mathrm{RI} <$ 10 mm/hour) and heavy rain ($\mathrm{RI} >$ 10 mm/hour), according to the classification system given by the NEA of Singapore. During this measurement, the slight rainfall experienced ranges from 0.8 to 1.2 mm/hour, the moderate rainfall experienced ranges from 4.8 to 9.6 mm/hour, and the heavy rainfall experienced ranges from 13.4 to 28.8 mm/hour. These rainfall data derived from the S-band RADAR is classified based on the average rainfall experienced in the tropical region around Singapore. The plots in Fig. 3 are the mean PDP obtained from an average of 1024 consecutive channel impulses acquired in order to smooth out the noise floor and minimize the temporal variations due to any slight wind conditions. From Fig. 2, compared to the back to back system calibration measurement, it can be seen that, besides the first arrival (at the time index of 0 μs), there are several multipath clusters within a 25 dB (threshold) of the dominant component (first arrival) for the dry forested radio propagation channel. This indicates that at 240 MHz, there is a significant amount of multipath components propagating through the forested channel. These multipaths might be due to reflection, diffraction, scattering, or a combination from the broad leaves, branches and tree trunks. Comparing the forested propagation results shown in Figs. 2 and 3, it is found that there is negligible change in the received signal strength of the first arrival even when the rain intensity increases from no rain to heavy. This can be explained by the presence of lateral waves as introduced by Tamir [1]. In Tamir's model, the lateral wave is the dominant wave for the propagation over large separation between transmitter and receiver in the VHF band. The lateral wave propagates immediately above the tree tops and a large portion of its path is in free space (air region). Since rainfall only causes a significant amount of attenuation at frequencies above 5 GHz [5] in free space, the dominant component resulting from lateral waves is not affected by the rainy weather conditions. Therefore, resulting in an almost constant power for the first arrival regardless of weather conditions.

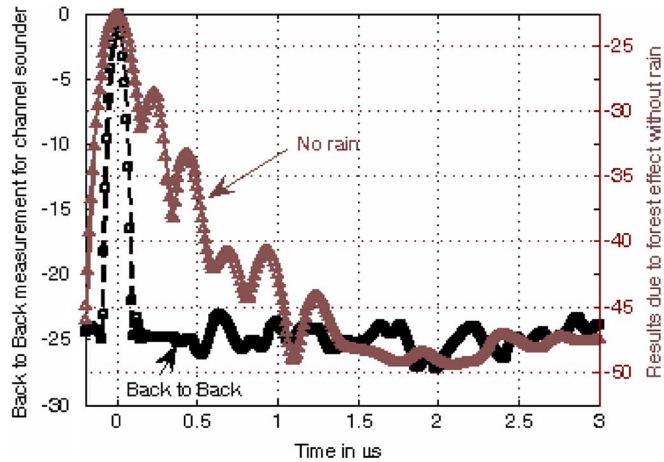

Fig. 2. Power delay profile for back-to-back measurement and forested propagation without rain effect.

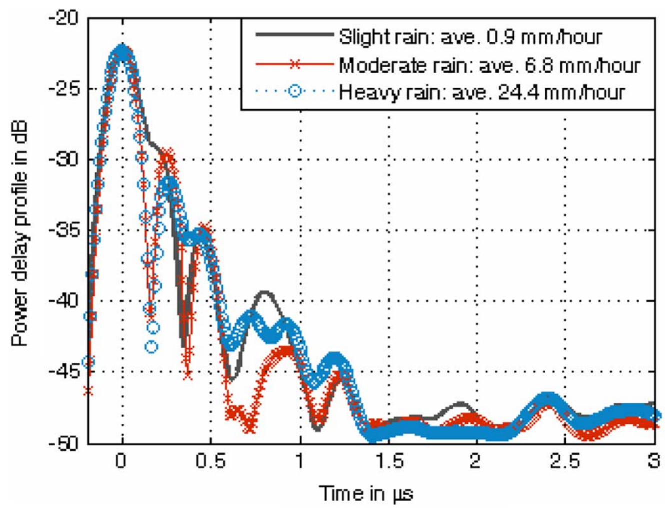

Fig. 3. Typical results in the tropical forest under different rainfall intensities.

However, it can be observed from Fig. 3 that, in general, there is an additional loss induced by the rainfall on the multipath components as compared to no rainfall condition shown in Fig. 2. This is because, as compared to the almost-free-space propagating lateral wave (main composite of the dominate component), the multipath components propagate directly through the forested environment via the foliage medium. The accumulation of the rain water on the discrete scatterers such as the randomly distributed leaves, branches and tree trunks in the forest, produces a significant amount of attenuation and absorption of the propagating multipath components. Therefore, it can be observed that the multipath components are attenuated to different extents under different rain intensity conditions. For example, in Fig. 3, the first multipath cluster under moderate rain is about -29.5 dB and the corresponding first multipath cluster under heavy rain is about -32.5 dB. There is around 3 dB difference between the received signal strength of the first recorded multipath cluster under the two different rainfall conditions. This 3 dB difference is purely due to the different in rain intensity. The same is observed for the comparison of results under no rain, slight rain and moderate rain weather conditions. This is indicates that, the attenuation and absorption increases when there is an increased accumulation of rain water on the discrete scatterers as rain intensity increases. That is, as the signal propagates through the foliage medium, the damp foliage together with the different rainfall conditions causes the multipath components to be attenuated to a different extent.

It is also observed from Fig. 3 that there are possibly more variations in the multipath components when there is a heavy rainfall, as compared to when there is no, slight or moderate rainfall. This may be because the unsteady heavy rainfall (most of time in the form of thunderstorm in Singapore) causes motion of the foliage medium such as the broad palm leaves, and hence results in a variation of the position of the scatterers and thus the variation in the multipath components as compared to the no rainfall, the steady slight rainfall and the moderate rainfall conditions. However, this conclusion is not conclusive from the PDPs in Figs. 2 and 3.

Next, the root mean square (RMS) delay spread $(\tau_{\rm rms})$, and number of multipath clusters $(N_{\rm mp})$ in excess of -25 dB from the dominant component which may contain multiple physical paths combined into a single energy component, are used to characterize the PDPs. The RMS delay spread, which measures the standard deviation of the delay spread of the mean PDP about its mean delay spread $\bar{\tau}$, is defined as the square root of the second central moment of the mean PDP and is given by

$$\tau_{\rm rms} = \sqrt{\frac{\sum_{k=1}^{N} (\tau_k - \bar{\tau})^2 a_k^2}{\sum_{k=1}^{N} a_k^2}} \tag{2}$$

where the mean delay spread $\bar{\tau}$ is given by

$$\bar{\tau} = \frac{\sum_{k=1}^{N} \tau_k a_k^2}{\sum_{k=1}^{N} a_k^2}. \tag{3}$$

The estimated mean RMS delay spread $\tau_{\rm rms}$, and number of multipath clusters $N_{\rm mp}$, is summarized in Table I. From Table I, it is observed that, rainfall plays a significant role on the forested radio wave propagation. The RMS delay spread $\tau_{\rm rms}$, decreases monotonously as weather changes from no rain to slight and moderate rain (both are steady rain rate cases). Similar observations for the RMS delay spread at 1900 MHz in wet foliage (foliage depth: 50, 100, and 150 m) and dry foliage has been reported in [4], where there is around 5–10 ns decrease in the RMS delay spread for wet foliage propagation. This is due to the relative decrease in the strength of the multipath components compared to the dominant component in the PDPs for the wet foliage due to the rainfall influences that de-weights the corresponding delays to reduce its delay spread statistics as compared to the PDPs for the dry foliage.

TABLE I
SUMMARY OF MEAN RMS DELAY SPREAD AND NUMBER OF MULTIPATH CLUSTERS IN A TROPICAL FOREST

Weather	*RMS* τ_{rms}	*Number of clusters*
No rain (dry)	0.2137 μs	5
Slight rain	0.1639 μs	4
Moderate Rain	0.1316 μs	4
Heavy rain	0.2206 μs	5

Moreover, from Table I, it is observed that the decrease in the RMS delay spread is more than 50 ns as the foliage becomes wet during our measurements. This is much larger than those (around 5 ns to 10 ns decrease in the RMS delay spread) obtained in [4]. The main reason is due to the existence of the lateral wave at 240 MHz but not at 1900 MHz. The larger foliage depth of 710 m (while 50–150 m in [4]) and the extremely wet tropical foliage in the rainy reason during our measurements, that enhances the relative contribution of the lateral wave in the first arrival signal. This results in the dominant wave consisting of mainly lateral waves as compared to the attenuated direct wave and ground reflected wave at 240 MHz. As explained, the lateral wave is not affected by the rainfall as compared to the wave components that propagate through the foliage medium and are highly attenuated due to the accumulation of the rain water on the foliage medium. This phenomenon increases the difference in the relative strength of the dominant component to the multipath components in the PDPs at 240 MHz, and also decreases the RMS delay spread much more as compared to the results presented in [4]. This is also verified through the number of multipath clusters $N_{\rm mp}$ in the estimated PDPs as shown in Table I. It is found that for threshold level of 25 dB below the maximum component of the PDP, the number of multipath clusters $N_{\rm mp}$ decreases under the slight and moderate rain intensity as compared to the no rain weather.

Furthermore, it is found that both the RMS delay spread and number of multipath clusters increase when the rainfall becomes heavy. The estimated RMS delay spread is even higher than that of no rain weather condition. As explained before, this may be due to the variations in multipath components generated by the unsteady heavy downpour that induces motion to the wet foliage medium.

IV. CONCLUSION

Rain influence on the various aspects of the propagating components in a tropical forest has been investigated. It is found that the lateral wave at VHF band is the dominant mode of propagation and is not affected by the presence of rain as it is similar to free space propagation over the tree tops. The multipath components induced by the discrete scatterers such as leaves, branches and tree trunks due to the wet foliage channel are significantly affected by the variation in rain intensity. This is due to the accumulation of rain water on the foliage medium that produces higher attenuation and absorption of the propagating multipath components. These effect results in a variation of the RMS delay spread and the number of effective multipath clusters. Under steady rainfall, the RMS delay spread and the number of multipath clusters decrease as the intensity of the rain increases. However, unsteady heavy downpour can induce motion of the damp foliage medium, and thus generate a variation in the multipath components.

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