VHF and UHF wireless channel measurement and modeling for foliage environment

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**VHF AND UHF WIRELESS CHANNEL
MEASUREMENT AND MODELING FOR FOLIAGE
ENVIRONMENT**

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A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Doctor of Philosophy

2009

Statement of Originality

I hereby certify that the work embodied in the thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

Date

MENG YUSONG

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Summary

In this thesis, a detailed study on channel characterization and modeling of the forested environment for military applications such as surveillance and battlefield communication networks is undertaken. The scenarios of military applications such as communication systems mounted on vehicles or carried by soldiers, require knowledge of near-ground radio wave propagation in forests at VHF and UHF bands. In this research study, a series of experimental work was carried out in different types of foliage plantations, forested depth, and weather conditions, to examine the effects of radio wave propagation through forested paths. The path loss in the forests, for near-ground communication systems, can be empirically modeled using well-known through-vegetation loss models with the ground reflection taken into consideration. Depending on the type of forests or plantations, the through-vegetation loss models such as Weissberger, ITU-R, COST235 and FITU-R models can be used to model the forested propagation loss.

However, our experimental study shows that, the prediction accuracy using these through-vegetation loss models decreases gradually as the forested depth increases. This is due to the appearance of the lateral wave, which is dominant over a large forested depth at VHF band. Therefore, a new model, the Lateral ITU-R (LITU-R) model is proposed. This model is verified using both measured data

and some existing published data. At short forested range, the accuracy of these models is not ideal. Therefore, for short-range propagation through forest, the author suggests considering the possible canopy reflection into the path loss model since the tree canopy reflection becomes critical at short-range and seems to decrease the path loss significantly. In this research, for short-range forested propagation loss modeling at VHF and UHF bands, well-known through-vegetation loss models taking into consideration both the ground reflection and the tree canopy reflection is ideal for path loss prediction.

The research work continues by studying the weather effect on the forested path loss. It was found that there are deep power variations under atrocious weather conditions. A popular fade-mitigation technique: Multiple-Input-Multiple-Output (MIMO) technique is therefore studied preliminarily. It is observed that highly dependent multi-propagation paths are produced due to the presence of lateral waves over larger forested depth. Through the study of the mutual impedance and angular pattern of the receiving antenna array, it is found that, in the forested environment where there is a large angular spread of multipaths, the mutual coupling induced change in the antenna angular pattern becomes a dominant factor. This lowers the correlation property between the multiple receptors.

This thesis studies the forested propagation path using measurement results. The different dominant propagation components at varying forested depths are considered and path loss models are proposed based on the dominant propagation components. The weather induced temporal variation on the propagation signal is also examined. Finally, mitigation technique using MIMO technique is studied.

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List of Abbreviations and Symbols

Abbreviations

ADC	Analog to Digital Convertor
BER	Binary Error Rate
BPSK	Binary Phase Shift Keying
CDF	Cumulative Distribution Function
cm	centimeter
CW	Continuous Wave
DG	Dual gradient
DSP	Digital Signal Processing
dB	Decibel
dBi	Decibel referenced to an isotropic antenna
dBm	Decibel referenced to a milliWatt
FFT	Fast Fourier Transform
FGR	Fitted Ground Reflection
FSL	Free Space Loss
GHz	GigaHertz
GPIO	General Purpose Interface Bus

GPS	Global Positioning System
HPA	High Power Amplifier
Hz	Hertz
IF	Intermediate Frequency
ITU	International Telecommunication Union
kHz	kilohertz
km	kilometer
LNA	Low Noise Amplifier
LO	Local Oscillator
LoS	Light of Sight
LSE	Least Square Error
MF	Matched Filter
MHz	MegaHertz
MIMO	Multiple Input Multiple Output
MLS	Microwave Landing System
MoM	Method of Moment
NEA	National Environment Agency
NEC	Numerical Electromagnetic Code
NZG	Nonzero gradient
ns	nanosecond
PC	Personal Computer
PDF	Probability Density Function
PDP	Power Delay Profile
PE	Plane Earth
PG	Processing Gain

PN	Pseudo-random Noise
RET	Radiative Energy Transfer
RF	Radio Frequency
RI	Rain Intensity
RMS	Root Mean Square
Rx	Receiver
SIMO	Single Input Multiple Output
SNR	Signal-to-Noise Ratio
Tx	Transmitter
UHF	Ultra High Frequency
VHF	Very High Frequency
VI	Virtual Instrument
VNA	Vector Network Analyzer
VSG	Vector Signal Generator
WS	Wind Speed

Symbols

a_k	signal strength of the k^{th} multipath component
b	Weibull b parameter
d	forest depth
d_0	close-in reference distance
E_i	the difference between measured and predicted values at the i^{th} point
E_{rms}	the RMS error
f	frequency
h_0	the semi minor axis of the Fresnel ellipse
h_T	the transmit antenna height
h_R	the receive antenna height
$h(j, \tau)$	j^{th} complex channel impulse response
$h_{l,j}(\tau)$	j^{th} complex channel impulse response at the l^{th} receiving antenna
$I_0(\cdot)$	the modified Bessel function of the first kind and zeroth order
j	consecutive impulse index
K	Rician K factor
L	code length
m	the shape parameters for Nakagami distribution
n	path loss exponent
N	number of multipath components
N_{mp}	number of multipath clusters
P_T	transmitted power
R_c	PN code bit rate
S	antenna spacing

ω_j	Akaike weight
X	Gaussian random variable
μ	mean value
σ	standard derivation
σ^2	variance
τ_k	propagation delay of the k^{th} multipath component
τ_{rms}	RMS delay spread
$\bar{\tau}$	mean delay spread
φ_k	phase shift of the k^{th} multipath component
λ	wavelength of the propagating radio wave
Ω	the scale parameters for Nakagami distribution
$\Gamma(\cdot)$	the gamma function

Chapter 1

Introduction

The characteristics of a wireless communication channel can severely affect the overall performance of any wireless system [1]-[4]. The transmitted signal will be attenuated when it propagates through the channel from the transmitter to the receiver. Moreover, the transmitted signal could arrive at the receiver through multiple paths which can mainly be classified into reflection, diffraction, or scattering from obstacles and scatterers as shown in Figure 1.1. These multipath components experience different attenuations and arrive with different time delays and phases. This process results in the constructive or destructive summation of the signals arriving at the receiver. This received signal poses severe limitations on the reliability of the signal transmission process, and is an interesting research topic. For military applications in the Asia-Pacific region, communication systems are designed and to be used within the forested environment mainly at the VHF and UHF bands. Therefore, the understanding of the VHF and UHF propagation channels through a forested environment is of high research importance. This is the focus of this PhD thesis.

Figure 1.1 The wireless propagation landscape.

1.1 Motivation

Great interests arise in the deployment of attended/unattended sensor networks for military applications, such as battlefield sensor networks for wireless communication between dismounted soldiers/military vehicles, and unattended ground sensor networks for military surveillance, recently. To achieve a successful implementation of these military sensor networks, the need for a complete understanding of wireless communication channel is important. In such scenarios, the heights of the transmitters and receivers in the network are low, and therefore, in order to understand the propagation of electromagnetic waves through the foliage channel, not only the effects of the dielectric medium of the forest needs to be considered, but also the effect of the ground reflection for near-ground propagation. The understanding of the propagation characteristics within the channel is necessary for establishing a reliable communication link. This is very important for the implementation of wireless sensor networks for military

applications in the tropical region where the thick evergreen forests are often encountered.

Figure 1.2 Conceptual diagram of the military wireless sensor network in a forest.

The conceptual diagram of a military wireless sensor network in a forest is shown in Figure 1.2. From Figure 1.2, it is shown that the transmitted signal interacts with a realistic terrain over long distances including the effect of the ground (due to near-ground applications) and the effect of the dielectric medium of forests (undergrowth layer, tree trunk layer, tree canopy layer and above tree canopy layer). It is known that, a forest is a random medium with many discrete scatterers such as the randomly distributed leaves, branches and tree trunks. Hence, radio wave propagation in a forested environment experiences multiple scattering, diffraction, and absorption of radiation. These will affect wireless communication significantly and impose stringent constraints on system design [1]-[4]. Therefore, accurate modeling of wave propagation behaviors through forested environment has attracted significant attention in recent years. A large body of literature addressing the topic of VHF and UHF radio wave propagation in forested environments both theoretically [5]-[20] and experimentally [21]-[41] can be found.

The theoretical studies [5]-[19] show that, at VHF and UHF bands, the forested environments can be conveniently analyzed using a multi-layered model (three layered model [5]-[8], [15]-[16], [18]-[19] or four layered model [9]-[14], depending on the frequency of operation). Dyadic Green's function based method [8]-[9], [11]-[14], Hertz Potential based method [10], full-wave Parabolic Equation (PE) algorithm [15] and semi-exact solution for the received field by surface-field integration technique through an application of the equivalence or Huygen's principle [19] *etc.* have been successfully used to study and analyze the behaviors of the VHF and UHF radio wave propagation over a large forested depth with the multi-layered model. The propagation of the electric field in forests at VHF and UHF bands is expressed in terms of direct waves, multiple reflected/scattered waves, and lateral waves as shown in Figure 1.2. Through these studies, it is found that, although these physics-based models provide us with invaluable knowledge of the radio wave propagation in the forests at different frequencies, they invariably require the use of numerical analysis methods to provide solutions to the intractable mathematical formulations and requires heavy computational resources.

Direct measurements provide us with the exact characteristic of site-specific communication scenarios. Based on an ensemble of measurements, empirical models can usually be developed through regression techniques. As compared to the analytical models as in [5]-[20], the advantage of empirical models is the simplicity of the final mathematical expressions that describe the scenarios and, hence, their straightforward application, although these empirical models might fail to give any indication of the physical processes involved in the propagation of radio waves within the forested channel. To deploy the military

wireless sensor networks in a realistic forest successfully, empirical propagation models that can enable the accurate prediction of radio wave interactions with a realistic forested terrain over long distances, taking into account the ground effect for near-ground applications, will be the emphasis of this PhD degree study.

A lot of efforts have been put in the empirical characterization and modeling of VHF and UHF radio wave propagation in forested environments [21]-[41]. They have been carried out under different operational contexts and in different physical situations concurrently with theoretical studies [5]-[20]. Ground reflection [21], depolarization [24], antenna height gain [25], seasonal variation [27] *etc.* on the propagating radio wave in the forested environment have been discussed respectively. Based on the large measurement databases, three well-known empirical through-vegetation propagation loss models were developed. Weissberger's modified exponential decay model [35] and ITU-R model [36] for through-vegetation radio wave propagation were summarized for the VHF and UHF measurement at a forested depth less than 400 m, and COST235 model [37] was proposed based on measurements made in millimeter wave frequencies (9.6 GHz to 57.6 GHz) at a forested depth of less than 200 m.

However, these empirical models [35]-[37] do not take into consideration the ground reflection effect [20]-[21] and other propagation effects such as lateral wave along the treetops [5] *etc.* Therefore, these models can not be directly used for the radio wave interactions with a realistic forested terrain over a long distance taking into consideration the ground effect. The researchers in [40]-[41] therefore attempts to model the propagation loss within the forest with the integration of the

empirical through-vegetation loss model [35]-[37] and the plane earth (PE) path loss model [2]. However, these integrated models in [40]-[41] are inconclusive, especially for the modeling of the propagation loss at larger forested depth, where the overestimation of the propagation loss with the integrated model is observed [41]. This is due to the limitation of the database from which the empirical through-vegetation loss models [35]-[37] were derived and optimized from (the forested depth used for measurements is less than 400 m), and also the lateral wave effect which is dominant at large forested depth [5], [11]-[14] that is not accounted for. Therefore, properly empirical path loss modeling for large forested depth becomes attractive and significant for the implementation of the military wireless sensor networks in forests.

With the empirical path loss modeling of forest effect at VHF and UHF bands, there is also a requirement to take into consideration weather effects such as wind or/and rain induced temporal variations/attenuations on the radio wave propagation within the model. From the addressed literature, although the wind effect on the slant foliage path is studied [42]-[43], there is minimal research work done on the rain effect and the combined effect of wind and rain in a forested path. It is well known that rainfall affects the propagation links only at high frequencies of above 5 GHz [44]. Therefore, the effect of rainfall on the forested channel remains unexplored at VHF and UHF bands, and 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. This is especially true in a tropical country like Singapore where heavy rain and strong wind are often experienced.

Moreover, due to the rich scattering property of the forested medium, the popular mitigation technique: Multiple-Input-Multiple-Output (MIMO) technique [45]-[46] can be used. This technique has the potential to improve coverage, reliability, capacity, and data rate. It provides a probable solution for the improvement of the quality of the received signal in the forest. This can complement the spatial diversity technique used in the foliage channel [47]-[48], and is also an interesting topic to explore.

1.2 Objective

In response to the aforementioned problems, the objective of this PhD thesis is to empirically study the near-ground radio wave propagation in forests at VHF and UHF bands. In order to improve the reliability and capability of this propagation link, the potential for the application of MIMO technique is investigated. To fulfill the objective, the focus of this thesis is as follows:

1. A comprehensive literature review of the channel characterization and path loss modeling, especially in forested environments, is performed. The exercise creates a strong foundation and background for further exploration.

2. Proper wideband and narrowband channel sounding systems [2], [4] are developed to perform the measurements in forests. The performance of the proposed systems is evaluated theoretically and experimentally.

3. Near-ground path loss modeling in the short-range and long-range forested depths is conducted, and comparative study between the measured data and the well-known through-vegetation loss models [35]-[37] with ground reflection considered is performed.

4. Wideband and narrowband characterization of weather induced effect such as wind and rain is investigated. The statistical modeling of these weather effect induced temporal variation in forested channel is described.

5. Measurement with multiple receiving antennas is carried out to study the potential for the application of the MIMO technique through the investigation of the spatial correlation coefficient, and some recommendations are given.

The outcome of the PhD degree study has produced some fundamental contributions and developments over the existing research works, and is outlined in the next section.

1.3 Major Contribution of the Thesis

In this PhD study on the near-ground channel modeling and characterizations in the forests at VHF and UHF bands, four major measurement campaigns (lasting from 2 to 4 weeks each) have been carried out in different forested areas located around Singapore. With the analysis and modeling of the processed data, the contributions and developments over the existing research works have been made. The following is the list of major contributions in this PhD study:

1. Wideband channel sounding system has been developed to perform the vector signal measurements up to a bandwidth of 50 MHz, which is currently limited by the Analog to Digital Convertor (ADC) card. The developed sounding system can support the measurement of up to four synchronized receiving branches.

2. An integrated model with ground and foliage effect taken into consideration is developed. This integrated model considers the operational frequency, antenna height, forested depth, and ground reflection effect for the near-ground communication over a large forested depth. In particular, empirical foliage excess loss model: Lateral ITU-R (LITU-R) model is proposed in this thesis to account for the lateral wave effect over a large forested depth. The proposed model is tested and found to be a better model for the prediction of foliage loss over a large forested depth at VHF band.

3. For short-range propagation in forests, both the theoretical and experimental results show that the dense canopy induced reflection cannot be ignored when performing empirical modeling with well-known through-vegetation loss models. When the possible tree canopy reflection appears, the propagation loss can decrease significantly.

4. Rain influence on the various aspects of propagating components in a tropical forest is investigated. Its effect on the lateral wave, the through-forest-components such as the direct and reflected waves, and multi-scattered components induced by the discrete scatterers such as leaves, branches and tree trunks at VHF band is discussed in detail. It is found that the lateral wave at VHF

band is not affected by the presence of rain as it is similar to free space propagation over the treetops, and the through-forest-components and multi-scattered components in the wet forested channel are significantly affected by the variations in rain intensity. The dielectric permittivity for the wet canopy layer of the multi-layered model under different rain events is evaluated empirically.

5. Narrowband study of the combined effect due to the wind and rain on the propagating waves is conducted. The fast fading components due to the weather induced temporal variation is studied and modeled statistically. It is found that the distribution of fast fading components resembles a Weibull/Rician distribution function. Its Weibull b parameter/Rician K factor decreases gradually as the strength of wind and rain increases. Moreover, it is observed that the power variations and deep fades in the received signal are clearly noticeable as the strength of wind and rain increases.

6. The Single-Input-Multiple-Output (SIMO) technique is used to mitigate the weather and foliage induced fading in order to improve the radio link in the forest. The correlation properties between two spatial receptors are studied empirically. When there is lateral wave effect, the two spatial receptors are highly-correlated. The coupling effect between the diverse receptors is also investigated through the study of the receiving mutual impedance and the resultant antenna angular pattern.

1.4 Organization of the Thesis

The remaining part of the thesis is organized as follows. The literature review on the channel characterization and modeling is presented in Chapter 2. It gives some basic concepts about radio wave propagation and summarizes the empirical characterization of the propagation channel within the forested environments. In Chapter 3, three different sounding systems have been developed and tested in the laboratory. The accuracy and resolution of the measurement systems have been studied. The theoretical and experimental performance for the proposed systems are compared and reported in this chapter.

Chapter 4 describes the narrowband path loss modeling in tropical forests at short-range and long-range. The modeling of the path loss in forests is performed with an integrated model. The optimization process for the forested channel is detailed and a new model is then proposed. The new empirical foliage excess loss model (LITU-R model) is verified through the use of simulation results [13] and experimental data [41] reported by other researchers.

In Chapter 5, both the narrowband and wideband investigations of the weather induced effect on the radio wave propagation in forested environment have been discussed in detail. The narrowband modeling of the wind and rain induced temporal variation on the forested channel is performed.

Next, the SIMO technique (can be extended to MIMO technique) is used as a mitigation technique to improve the performance of long-range propagation links in the forest. This technique is studied in Chapter 6. The correlation properties

between the two spatial receptors are investigated through the study of the receiving mutual impedance and the antenna angular pattern.

Finally, Chapter 7 concludes the thesis and gives recommendations for future work.

Chapter 2

Literature Review

In this chapter, an introduction to concepts behind channel characterization and modeling are presented. This will be useful for the further exploration of the radio wave propagation in the forests and other environments. A comprehensive review on the modeling and characterization of the forested environments is then detailed. The theoretical and experimental methodologies in the latest research are described and summarized.

2.1 Basic of Radio Wave Propagation

As the radio wave propagates between the transmitter and receiver, the propagation mechanisms includes: attenuation, reflection, diffraction, and scattering *etc.* A summation of all the signals arriving at the receiver due to these propagation mechanisms can cause severe fading on the propagating waves and therefore limits the performance of wireless systems [1]-[4]. Normally, these fading processes are classified as path loss, shadowing (or slow fading) and multipath fading (or fast fading). An example of the three fading processes is illustrated in Figure 2.1.

Figure 2.1 The three scales of the signal variation [1] in a wireless channel.

2.1.1 Path Loss

The path loss is an overall decrease in the field strength as the separation between the transmitter and receiver increases [1]-[4]. When the radio wave propagates through free space, the path loss [2], [4] can be predicted by the free space loss (FSL) model,

$$L_{FSL}(dB) = -27.56 + 20\log_{10}(f) + 20\log_{10}(d) \quad (2.1)$$

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

When the radio wave propagates near the ground with a light of sight (LoS) condition, the path loss can be better described by the plane earth (PE) path loss model [1]-[4] rather than the free space model, since it includes the effect of ground reflection and is given as,

$$L_{PE}(dB) = 40\log_{10}(d) - 20\log_{10}(h_T) - 20\log_{10}(h_R) \quad (2.2)$$

where d is the distance between the isotropic transmitting and receiving antennas in meter, and h_T and h_R are the transmitting and receiving antenna heights, respectively, also in meter. In this model, there is an assumption that d is much larger than h_T and h_R .

However, due to the presence of the reflection, diffraction, and scattering *etc.* in a realistic environment, the path loss cannot be predicted by Equation (2.1) and (2.2) accurately. A popular empirical path loss modeling method [4] is then introduced as,

$$L(dB) = L_0 + 10n \log_{10}\left(\frac{d}{d_0}\right) \quad (2.3)$$

where n is the path loss exponent, d is the distance between transmitter and receiver, and d_0 is the reference distance. The parameter L_0 is the path loss in dB at the reference point d_0 . The path loss exponent n depends on the environments and on the availability of a LoS connection between the transmitter and receiver, and can be extracted from the measured data using the least squares curve fitting technique (linear regression technique).

2.1.2 Shadowing

Shadowing is defined as the variation of the local mean value (averaged over a distance of 10λ [4], where λ is the signal wavelength) around the path loss. It is due to the relatively varying nature of the particular obstructions between the transmitter and receiver, such as trees, mountainous, or high buildings in the outdoor environments as shown in Figure 1.1; and furnitures, walls or people in the indoor environments. The shadowing causes significant variations in the signal strength over large distances of hundreds of meters in the rural/suburban environments, whereas in urban environments, shadowing causes significant variations in signal strength over small distances of a couple of meters. The

significance of the shadowing effect is of course highly frequency dependent. In general, this variation can be up to around 20 dB as introduced in [1] for typical urban areas. When this shadowing effect is considered, the path loss equation in (2.3) can be rewritten as,

$$L(dB) = L_0 + 10n \log_{10}\left(\frac{d}{d_0}\right) + X \quad (2.4)$$

where the new parameter X , is a Gaussian-distributed random variable with zero mean and standard deviation σ_x .

2.1.3 Multipath Fading

Multipath fading can be classified into two categories: the small-scale (scale of a wavelength [4]) spatial variation of the received power in a mobile channel, and the temporal variation of the received power in a fixed channel. In essence, both the small-scale spatial variation and the temporal variation are due to the relative movement of the reflectors/scatterers to the transmitter and receiver. In the following, both the narrowband and wideband characterizations and modeling of the multipath fading are introduced briefly, and details can be found in [1]-[4].

A) Narrowband Characterization

The narrowband characterization of the multipath fading is usually performed through the statistical modeling of the signal envelope (amplitude) using the commonly known distributions associated with radio propagation channel [1]-[2],

[4], namely Gaussian, Rician, Rayleigh, Nakagami and Weibull. The mathematical expressions for each distribution are shown in the following equations,

Gaussian distribution is as:

$$P_r(r) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(r-\mu)^2}{2\sigma^2}} \quad (2.5)$$

where μ and σ are the mean and standard deviation of the random variable r .

Rician distribution is as:

$$P_r(r) = \frac{r}{\sigma^2} e^{-\left(\frac{r^2+s^2}{2\sigma^2}\right)} I_0\left(\frac{sr}{\sigma^2}\right) \quad (2.6)$$

where $I_0(\cdot)$ is the modified Bessel function of the first kind and zero order, s is the amplitude of the steady component, and σ^2 is the variance of the random component.

In literature, the Rician distribution function is often described in term of a fading parameter K , commonly known as the Rician K factor, and shown below,

$$K(dB) = 10 \log_{10}\left(\frac{s^2}{2\sigma^2}\right). \quad (2.7)$$

The physical interpretation of the Rician K factor depends on the type of multipath channel. For the mobile channel where the transmitter and receiver are moving, the Rician K factor is the ratio of the power of the dominant component to the power of the random scattered components. For a fixed channel where both the transmitter and the receiver are stationary, the Rician K factor is the ratio of the mean power to the variance of the received component. This is used to characterize the temporal variability of the propagation channel which is particularly sensitive to any movement of the scattering objects, such as human, vehicle or foliage medium. In this thesis, the transmitter and receiver are kept stationary during the measurements. Therefore, the Rician K factor has the latter definition.

Rayleigh distribution is as:

$$P_r(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} \quad (2.8)$$

where σ is the standard deviation of random scattered components.

Nakagami distribution is as:

$$P_r(r) = \frac{2m^m}{\Gamma(m)\Omega^m} r^{(2m-1)} e^{-\left(\frac{mr^2}{\Omega}\right)} \quad (2.9)$$

where m and Ω are the shape and scale parameters respectively, and $\Gamma(\cdot)$ is the gamma function. This is a more general fade function which tries to model a combination of distributions. For $m = 1$, this fade distribution reduces to a

Rayleigh fade channel, and for $m = (K+1)^2/(2K+1)$, it approximates a Rician fade channel with parameter K , and for $m = +\infty$, there is no fade in the channel.

Lastly, Weibull distribution given below is used:

$$P_r(r) = a \cdot b \cdot r^{b-1} \cdot \exp(-a \cdot r^b) \quad (2.10)$$

where $r \geq 0$, and parameter a can be derived from the mean square value of the distribution and parameter b . The parameter b controls the spread of the distribution; a small value of b corresponds to a large dispersion. Moreover, it is noted that, a value of $b = 2$ yields the Rayleigh distribution, and $b < 2$ implies more severe fading.

B) Wideband Characterization

It is known that, the multipath components induced by the reflection, diffraction, or scattering from the obstrucers and scatterers in the channel experience different attenuations and arrive at the receiver with different time delay and phase. The wideband characterization of the multipath fading [1]-[2], [4] is usually performed through its time-variant channel impulse response $h(t, \tau)$, as shown in Figure 2.2. Each bin represents the multipath components from a cluster of scatters as shown in Figure 1.1 after a similar delay. The complex channel impulse response $h(t, \tau)$ can be expressed as:

$$h(t, \tau) = \sum_{k=0}^N a_k(t) \exp\{j\varphi_k(t)\} \delta\{\tau - \tau_k(t)\} \quad (2.11)$$

where t and τ are observation and application times of the impulse, respectively, $a_k(t)$, $\tau_k(t)$, and $\varphi_k(t)$ are the time-varying amplitude, propagation delay and phase shift of the k^{th} multipath component, and N is the number of multipath clusters.

Figure 2.2 Tapped delay line model of a multipath channel.

The instantaneous power delay profile (PDP) is the envelope of the received power and is proportional to $|h(t, \tau)|^2$. The Root Mean Square (RMS) delay spread which is an indicator of the system performance can be estimated from the PDP, and is defined as the square root of the second central moment of the PDP and given by

$$\tau_{rms} = \sqrt{\frac{\sum_{k=1}^N (\tau_k - \bar{\tau})^2 a_k^2}{\sum_{k=1}^N a_k^2}} \quad (2.12)$$

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

$$\bar{\tau} = \frac{\sum_{k=1}^N \tau_k a_k^2}{\sum_{k=1}^N a_k^2} . \quad (2.13)$$

2.2 Propagation in Foliage Environments

In this section, theoretical and experimental methodologies on the modeling and characterization of the forested channel are described in detail. Some observations and findings based on the study of the effects from a single tree or a line of trees are introduced to assist the understanding of a forested propagation channel for our future research study.

2.2.1 Propagation in Forests

From the literature, it is found that most of the reported work focuses on the study of path loss in the forests at different frequencies theoretically and experimentally. However, limited work is done on the multipath characterizations (such as delay dispersion) except for those done by Seker and Schneider [30], Joshi *et al.* [41], Palud *et al.* [55], Sarabandi *et al.* [59], and Oestges *et al.* [63] *etc.*, where some site-specific multipath information is given. However, these works are not conclusive. Therefore, the reviews in this section are concentrated on the path loss modeling in forests.

A) Theoretical Study

1) Modeling at VHF and UHF bands

Since 1967, Tamir [5] proposed a half-space model to deal with radio wave (1-100 MHz) propagation in forest and explained the associated phenomenon dominated by a lateral wave mode of propagation. Subsequently, Dence and Tamir [6] and Tamir [7] extended the theoretical study on the propagation in forested environment to the “dissipative dielectric slab” model to account for the ground effects on radio wave propagation in the frequency range of 2-200 MHz, where a three-layered model with air layer, forest layer and ground layer is proposed. In the case studies by Tamir [5], and Dence and Tamir [6], both the transmitter and receiver are located in the forested medium. In Tamir’s later research [7], he dealt with the case where either of the terminals is outside of the forested medium and this study was performed through a ray-tracing approach. Recently, with the above three-layered model, full-wave Parabolic Equation (PE) algorithm [15] and semi-exact solution for the received field by surface-field integration technique through an application of the equivalence or Huygen’s principle [19] are implemented at VHF band to study the radio wave propagation in a truncated forest. However, unlike Tamir [7], noticeable asymmetry in the treatment of upward and downward links is experienced when one of the terminals is located outside of the forest [15]. In [19], Liao and Sarabandi report that ray-tracing in [7], provides accurate results at distant points from the vegetation truncation plane when the receiver height is large in terms of the wavelength. However, this method tends to underestimate the path loss for the case when the receiver is close to the ground. Moreover, the exact Sommerfeld integral solution was successfully implemented with the three-layered anisotropic slab model at 25-100 MHz by Li and Ling [16], where the effective

permittivity and conductivity of the whole forest layer is extracted and show considerable anisotropy and frequency dependence.

The representation of the forest as a “dissipative dielectric slab” [5]-[7] becomes poor for frequencies above 200 MHz where the vegetation cannot be regarded as a homogeneous medium, since the dimensions of the vegetation is at a magnitude of an order of the wavelength [7]. After successfully examining the above-mentioned three-layered model using the dyadic Green’s function in [8], Cavalcante *et al.* then proposed a four-layered (air layer, canopy layer, trunk layer and ground layer) model in [9] to take into account the vertical non-homogeneities of the forests with the lateral wave mode for propagation when the frequency is above 200 MHz (mainly in UHF). In their work, two isotropic and homogeneous dielectric layers placed over a semi-infinite ground plane are used to represent the tree canopy and the tree trunk layers of a forest as shown in Figure 2.3. The anisotropies are later introduced into the dielectric medium of the four-layered model by Seker and Schneider in [10] using the Hertz potential to analyze wave propagation in forests at the frequency range of 200-2000 MHz.

In the more recent years, as a continued work of the analysis and study of the forested environments as a four-layered model at VHF and UHF bands, Li *et al.* [11]-[14] performed a extensive study of the radio wave propagation in a four-layered forest through the full-wave analysis using the dyadic Green’s functions. All the layers in the four-layered geometry was initially assumed to be isotropic and homogeneous in [11] and [12] where the closed form of the electric fields was obtained by using the quasi-static approximation, saddle-point technique, and

branchcut integrations in the complex plane, and hence, expressed in terms of direct waves, multiple reflected waves, and lateral waves. Research has also been conducted for the case where the receiver is located within the trunk layer [11] and for case where the receiver is located within the canopy layer [12]. For both the cases, the transmitter is located within the trunk layer. They [13]-[14] extended these studies to a more general case with two electrically anisotropic canopy and trunk layers in the frequency range of 200-2000 MHz. Unfortunately, as reported by Li *et al.* [12], the integral representation of the solution is sufficiently complicated such that considerable effort is required before numerical computations can be obtained.

Figure 2.3 Dissipative dielectric slab model (a case with air layer, canopy layer, trunk layer and ground layer), also shown is the dominant mechanisms for radio wave propagation in a forest at VHF and UHF bands.

In all the above publications, the lateral wave along the upper-side air-canopy interface is found to play a major role in the communication over a large forested depth at the VHF and the UHF bands. Lateral wave along other interfaces; the canopy-trunk and the trunk-ground *etc.*, and multiple reflected waves from the interfaces between adjacent layers in the multi-layered models also play an

important role for the radio wave propagation in forests. Moreover, Sarabandi and Koh [17] performed a study on the effect of air-canopy interface roughness on HF and VHF wave propagation in forests. The analytical formulation is based on the volumetric integral equation in conjunction with the distorted Born approximation. It was shown that the interface roughness attenuates the lateral wave slightly, and the attenuation rate increases when the RMS height of the interface roughness is increased. Later, Liao and Sarabandi [18] extended the research work from [17] to the scenario where either the transmitter or the receiver or both, are located above the dielectric layer. In such a scenario, the Norton wave is observed. Although the Norton wave is highly localized near the air/dielectric interface, it contributes significantly as a form of radio wave propagation over forested medium.

Furthermore, these theoretical studies ([5]-[19]) show that, for the radio wave propagation with both communication terminals located in the forest at VHF and UHF, the dominant propagating wave will be the coherent component at small forested depth. As the forested depth increases, the incoherent (diffuse) components due to the forward scattering caused by leaves and branches become dominant, which tends to counteract the loss due to absorption and attenuation. Moreover, as the forested depth increases even further, the lateral wave [5] along the treetops provides the main contribution to the received field. The schematic diagram of the dominant propagation mechanisms is shown in Figure 2.3.

2) Modeling at microwave and millimeter-wave

As the frequency increases to high ends of microwave and millimeter-wave, the lateral wave [5] over a large forested depth will no longer exist. This is because the

RMS height of the air-canopy interface roughness [17] is increased significantly relative to the wavelength of the propagating signal and therefore, attenuates the wave propagating along the treetops (*i.e.* the lateral wave) significantly. In this case, the multiple scattering due to the dielectric object such as branches, twigs, and leaves in the forest become a significant contribution over a large forested depth, since the object size becomes more comparable to the signal wavelength. Koh, Wang, and Sarabandi [49] applied a full-wave numerical technique, method of moments (MoM) to calculate the scattering from a cluster of leaves or needles at 35 GHz. They pointed out that the widely used Foldy's approximation in conjunction with single scattering theory overestimates the attenuation rate at millimeter-wave frequencies. Later, Wang and Sarabandi [50] used distorted Born approximation to macro-model the scattering pattern from dielectric objects in forest. By including multiple scattering effects in the simulation model, a much better agreement is obtained for both mean and standard deviation of the path loss. The effect on the reduction of the computational resources for the simulation was performed in the subsequent work by Wang and Sarabandi [51].

Corresponding to the coherent approach based on wave theory, incoherent approach with radiative transfer theory has also been used to predict and analysis the wave propagation in forests at high microwave and millimeter-wave frequency [26], [38]. However, the radiative transfer approach is generally applied to a homogeneous medium. In order to overcome this limitation and to apply it on the inhomogeneous foliage medium, an improved version of the discrete radiative transfer is proposed by Diadascalou *et al.* for isolated vegetation specimens [52], and further enhanced by Fernandes *et al.* [53]. However this algorithm requires

discretization of the foliage into small cells, and therefore is numerically intractable for large propagation distances as pointed out by Wang and Sarabandi [51], although it is attempted by Lang *etc.* [54] for the cellular propagation in a tree trunk dominated park environment.

In summary, it is found that these models invariably require the use of numerical analysis methods to provide solutions to the intractable mathematical formulations and heavy computational resources are required. However, these theoretical analyses provide us invaluable knowledge about the details of the radio wave propagation in the forests at different frequencies and at different distances. These literature reviews are very useful for our further experimental study.

B) Experimental Study

Direct measurement of the forested channel provides us with an exact characterization of the site specific measurement scenarios [21]-[41]. Based on an ensemble of measurements, empirical statistical models can be developed. Although applicability of such models may be limited to the specific forested environments, they enable us to get useful information for future exploration.

A number of experimental work has been reported on topics such as range dependent effects [21], [28], [31]-[41], antenna height gain effects [21], [25], depolarization effects [24], [56], seasonal variations [27], [35], and [37], tree density [57], [58], temporal fluctuations [55], and multi-scattering effect [26], [31] *etc.* on the propagating radio waves. In the following, the useful information is refined.

1) Path loss modeling

Path loss in forest is the most important topic which needs to be discussed in this thesis. It determines the range of coverage and the quality of signal provided by the wireless systems. At present, most of the experimental studies are on the path loss range dependence from various aspects [21], [28], and [31]-[41].

Three well-known through-vegetation path loss models are discussed first. The main advantage of these models lies in the simplicity of the mathematical expressions to describe them, leading to their straightforward applications.

i) Weissberger's modified exponential decay model [35] as in (2.14) 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 group of trees rather than by diffraction over the treetops.

$$L_w(dB) = \begin{cases} 1.33 \times f^{0.284} d^{0.588} & 14m < d \leq 400m \\ 0.45 \times f^{0.284} d & 0m \leq d < 14m \end{cases} \quad (2.14)$$

where f is the frequency in GHz, and d is the depth of the trees in meter. The difference in path loss for trees in-leaf and out-of-leaf has been found to be about 3 to 5 dB.

ii) ITU Recommendation (ITU-R) [36] was developed from measurements carried out mainly at UHF, and was proposed for cases where either the

transmitting or receiving antenna is near to a small ($d < 400$ m) group of trees so that the majority of the signal propagates through the trees

$$L_{ITU-R}(dB) = 0.2 \times f^{0.3} d^{0.6}. \quad (2.15)$$

iii) The COST235 model [37] which was proposed based on measurements made in millimeter wave frequencies (9.6 GHz to 57.6 GHz) through a small ($d < 200$ m) group of trees is

$$L_{COST}(dB) = \begin{cases} 26.6 \times f^{-0.2} d^{0.5} & \text{out-of-leaf;} \\ 15.6 \times f^{-0.009} d^{0.26} & \text{in-leaf.} \end{cases} \quad (2.16)$$

In the COST235 model (2.16), 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 is the depth of the trees in meter.

From the study of existing established model [35]-[37], it is found that the through-vegetation path loss in general, can be well represented by the following expression:

$$L_{foliage}(dB) = A \times f^B d^C \quad (2.17)$$

The three parameters, A , B and C in (2.17) can be empirically determined, depending on the type of vegetation. In [60], 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 foliage states, in-leaf and out-of-leaf, at 11.2 GHz and 20 GHz. They then derived the fitted ITU-R (FITU-R) model [60]:

$$L_{FITU-R}(dB) = \begin{cases} 0.37 \times f^{0.18} d^{0.59} & \text{out-of-leaf;} \\ 0.39 \times f^{0.39} d^{0.25} & \text{in-leaf.} \end{cases} \quad (2.18)$$

The practical application of the wireless systems very often is over a large forested depth. Therefore, many terrain effects need to be considered, for example, the diffraction due to a forested hill [23], the reflection from a flat terrain [20], [41]. For the forested hill induced diffraction effect, Meeks [23] pointed out that two knife edge models is sufficient to characterize the terrain diffraction, while for the path loss modeling in forest over a flat terrain, a lot of work has been done as detailed below in order to characterize and model the path loss accurately.

In 1966, Burrows [21] proposed an algorithm which can be used to predict the radio gain (inverse to the path loss) in a jungle as

$$\frac{P_r}{P_t} = \left(\frac{3h_T h_R}{2d^2} \right)^2 \left(\frac{R_0}{R} \right)^2 F_s^2 F_j^2 \quad (2.19)$$

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 shadowing 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 transmitting

and receiving antenna heights, respectively. Transforming (2.19) into decibels and expressing it in the path loss form yields

$$PL_{forest}(dB) = 40 \log_{10}(d) - 20 \log_{10}(h_T) - 20 \log_{10}(h_R) - 20 \log_{10}\left(\frac{3R_0}{2R} F_s F_j\right). \quad (2.20)$$

The relationship between antenna height and the received power in (2.19) and (2.20) is verified in [21] through measurements performed within a tropical jungle with forested 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 transmitting antenna height, h_T kept at a constant of 24.2 m, and the receiving antenna height, h_R varied from 5 m to 30 m.

Later, in 1984, Tewari *et al.* [25] 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 rainforests, with forested 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 transmitting antenna height, h_T varying from 3.95 to 16.45 m, and the receiving antenna height, h_R varying from 1.5 to 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 (2.21),

$$G_h(dB) = -12 - 4 \log_{10} f + 20 \log_{10} h_T + 20 \log_{10} h_R. \quad (2.21)$$

Subsequently, Tewari *et al.* [28], Seker and Schneider [30], and Kovacs *et al.* [34] *etc.* conducted a series of VHF and UHF empirical path loss modeling in forest with terrain effect considered. All the aforementioned modeling scenarios are carried out with regression techniques and good accuracies have been achieved in their measurement environments.

Recently, the growing interest on the near-ground communications in forested areas at VHF and UHF bands due to the military and scientific applications [18]-[19], and [39]-[41] *etc.* requires a thorough understanding of the propagation channel. Goldman and Swenson [39] and Joshi *et al.* [41] started the work by performing an experimental characterization of the near-ground forested path loss with a simplified version of Equation (2.3) as shown (2.22),

$$PL_{forest}(dB) = a + b \log_{10} d \quad (2.22)$$

where a and b are the two constants based on measured data, and the physical interpretation of b is the attenuation per decade of distance which is equal to $10n$ as in Equation (2.3). The channel parameters estimated through Equation (2.22) in [39], [41] are of high accuracy but too site specific. For example, the estimated b is 42.4 at 302 MHz for the forested environment described in [39] and 45.4 at 300 MHz for the forested environment described in [41]. Unfortunately, these values are not applicable to other forested environments. Moreover, similar path loss measurements and modeling for near-ground communications for cellular [57] and UWB application [58] have also been conducted in tropical and temperate forests

with different tree densities, respectively. Obviously, there is no evidence that the estimated model parameters can be universally applicable.

However, motivated by the work in [40]-[41], the physically based empirical statistical models which derive the channel behaviors from basic principles of radio propagation can be chosen for performing channel modeling in forested environments. Such models are attractive since they are applicable to many different forest types and geometries, and can produce models with a good accuracy.

From the study of antenna height gain effect in forests [21], [25], it is found that the obtained antenna height gain functions in Equations (2.20) and (2.21) are very similar to the plane earth propagation where there is a ground reflected component in Equations (2.2). That is, there is a ground reflection effect in the forests which contributes significantly at VHF and UHF bands (this is also consistent with the theoretical study in [20], that is, the roughness of the ground is small compared to the incident wavelength at VHF, so the reflection from the ground is, in its major part, in the specular direction [61]). The effect of the ground reflection cannot be ignored for the derivation of the proper physical based empirical statistical model. In order to fully utilize the through-vegetation path loss models [35]-[37], and [60] within different tree densities, at different operating frequencies, and under different humidity conditions, the path loss over a large forested depth can be modeled with the following expression,

$$PL_{forest}(dB) = L_{PE}(dB) + L_{foliage}(dB) \quad (2.23)$$

where $L_{foliage}$ can be L_W , L_{ITU-R} , L_{COST} , and others, and L_{PE} accounts for the perfect ground reflection. This experimental verification and the study of Equations (2.23) will be the focus of this PhD thesis.

In addition, the theoretical work by Tamir [7] and Liao and Sarabandi [19], and the experimental work by Lagrone *et al.* [62] showed that the diffraction loss L_{diff} by the edge of the forested medium is significant when one or both terminals are outside of the forest. Therefore, its effect, L_{diff} , should be added to Equations (2.23) while performing modeling of the path loss with either the transmitter or the receiver outside of the forests.

2) Variation due to other effects

Amplitude of the received signal in forest at a fixed depth can be varied due to various factors: depolarization effect [24], [56], seasonal variations [27], [35], [37], [60], and [64], humidity effect [27], [41], and [64], and temporal fluctuations [55] due to the movement of the vegetation. They will be discussed in details in the following parts individually.

i) Depolarization effect: While the radio waves propagate through a forest, they can get substantially depolarized due to their interactions with the foliage medium. This is because; the conductivity of the foliage medium makes the foliage support induced currents that tend to be randomly oriented and, therefore, it produces a depolarization of the overall propagating field. Results of depolarization measurements in tropical moist deciduous and wet evergreen forests at 50-800 MHz are reported in [24]. They concluded that vertically polarized

waves suffer 5 dB to 15 dB higher depolarization than horizontally polarized waves. The cross polarization discrimination (XPD), which is defined as the ratio of the amplitude of the orthogonally polarized component of the radio waves, produced by some propagation mechanism, to the amplitude of the original plane polarized waves, is found to be dependent on frequency as well as the separation between the transmitter and the receiver. Similar observation is also found in temperate forests by Kovacs *et al.* [56] at higher frequencies of 400 MHz and 1900 MHz.

ii) Seasonal variations: For the seasonal variation of the forests, the in-leaf and out-of-leaf status of forests will be the predominant effect on radio wave propagation. The general expressions for the vegetation loss under in-leaf and out-of-leaf conditions can be obtained in [35], [37], and [60]. Moreover, long term measurements (over a one year period) have also been conducted in [27] and [64]. Low [27] found that, the seasonal field-strength variation is almost independent of the frequency in the UHF band, and it is also approximately the same magnitude for both the deciduous and coniferous forests. Evans [64] reported that the maximum difference between the winter (out-of-leaf) and the late summer (full in-leaf) conditions is 8 dB at 462 MHz.

iii) Humidity effect: The change in the humidity of forests correspondingly results in a variation in the electrical constants (conductivity and permittivity) of the forests, and thereby can influence the radio wave propagation. Low [27] reported that the humidity in the tree trunks became small when there is a drastic drop in temperature to below 0°C in early February. When the humidity in the tree

trunk is low, the received power at 457 MHz and 914 MHz increases by an average value of 2 dB to 3 dB, as compared to the power received when the temperature is above 0°C in January of the same year. Following this study, Evans [64] conducted measurements over a one-year period at 462 MHz. He concluded that diurnal variations from wet to dry conditions (including mist) can result in a signal strength fluctuation of about 1~1.5 dB. Changes occurs throughout the year, however, the most significant changes occurs in late summer when the foliage volume (a grove of naturally seeded, mature beech and oak trees with 150 m of diameter) is at its maximum.

Recently, a comparative study [41] of the propagation over dry and wet (due to rain) foliage conditions was conducted by Joshi *et al.* They reported that at 1900 MHz under wet foliage conditions, the propagation loss are approximately 29~32 dB greater than the propagation loss measured under dry foliage conditions. The foliage depth considered is between 50 m to 150 m. However, the effects of rainfall on the forested channel remain unexplored, especially at VHF since it is well known that rainfall affects propagation only at high frequencies of above 5 GHz [44]. 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 in VHF band.

iv) Temporal fluctuations: The temporal effect is believed to be more apparent for the radio links within the forest, since the scatterers within the foliage path such as leaves, twigs, and branches can easily be varied by wind [65] and others factors. In the literature, little work is published on the topic of the forested

radio wave propagation taking into consideration various weather effects. Work related to this topic includes the investigation of the wind effect on an isolated tree [42]-[43], [66]. This will be reviewed in the next section. However, more work can be done in this area.

Therefore, the characterizations of radio wave propagation in forests with weather effects such as wind and/or rain become important for the assignment of the proper fade margin in the radio link design, and will be studied in Chapter 5.

2.2.2 Propagation through Tree/ a Line of Trees

As compared to the channel characterization and modeling in forests, a large number of theoretical and experimental works have been done on the study of a single tree or a line of trees on the radio wave propagation due to commercial applications such as cellular base-to-mobile link [43], [66], [74], [78], and [83]-[86], mobile-satellite link [67]-[73], [80]-[81], and high speed point-to-point fixed link at microwave and millimeter wave frequencies [38], [42], [75]-[77], and [79]. The aforementioned channel information such as path loss, shadowing, and multipath fading due to the tree/trees has been discussed, and an important mitigation technique: spatial diversity is attempted to improve the degraded radio link due to the tree induced shadowing and multipath fading in [47]-[48]. In this section, some useful information which can be used to help the characterization of the forested channel is summarized.

A) Path Loss and Shadowing

1) Isolated tree/trees

The research on isolated trees induced shadowing effect was firstly initialized by Vogel and Goldhirsh [68] experimentally due to the implementation of the land mobile satellite system. Their subsequent work contributed to this research area significantly [69]-[72], where the tree induced slant shadowing effect at UHF, L band, and K band have been investigated respectively. A frequency scaling formulation relating the median attenuations of tree canopies was proposed in [71]-[72]. Furthermore, the dependence of shadowing on the slant path elevation angle for a single tree is also reported in [71]. Subsequently, a comparative study of tree induced shadowing was performed in [80] by Sofos and Constantinou. Measurements of slant path propagation through trees for different scenarios have also been conducted by other researchers [73], [81]. Their reported observations are in good agreement with those reported by Vogel and Goldhirsh.

Different from the abovementioned slant path measurements for mobile satellite application, horizontal path measurements with an isolated tree is carried out at microwave and millimeter wave frequencies for a high speed point-to-point propagation link [60], [79], and [82]. Al-Nuaimi and Stephens [60] pointed out that the through-vegetation path loss models in general can better be represented empirically by the expression in Equation (2.18), as compared to models such as the nonzero gradient (NZG) model [32] and the ITU-R model *etc.*

Theoretical studies with radiative transfer theory [52]-[53] have been used to evaluate the through-vegetation attenuation on an isolated tree. These are later

adopted by International Telecommunication Union (ITU) [65]. However, this method requires four input parameters extracted from path loss measurement data, which makes this method in essence a semi-empirical model. Typical values of the input parameters for different tree specimen can be found in [65].

2) Trees with terrain effect

Since the cellular link serves both the urban and the rural areas, the typical terrain effect such as tall buildings and high hills in addition to the trees needs to be considered. The foliage loss with hill effect is discussed in [70], [74]-[75] and [83]. Both the studies in [74] and [83] shows that knife edge diffraction can be used to predict the effect of the foliage loss with a hill. Reasonable agreement is found between modeled results and measured results. Furthermore, Al-Nuaimi and Stephens [75] indicated that the presence of one or more single trees on the peak of a hill can lead to a relative enhancement of the signal by at least 10 dB at 20 GHz as compared to the diffraction loss for a path obstructed by a hill.

Correspondingly, the influence of a tree or lines of trees planted along the streets has recently been studied both experimentally [76]-[77], [84] and theoretically [85]-[86]. Actual path information is found experimentally in [76]-[77], and [84] at different frequencies for different scenarios. Analytical methods such as Physical Optics [85] method and Ray Optical method [86] is also successfully used to evaluate the path loss with a line or multiple lines of trees placed on an avenue and a street in parallel to a row of buildings. Good agreement between the available experimental data and the analytical results are achieved.

B) Multipath Fading

From the addressed literature, it is found that a large amount of work has been done on the narrowband modeling of the foliage induced multipath fading [43], [78], [83] and [87]-[91]. Multipath fading makes itself evident in spatial variations of the signal over distances over an order of a wavelength [4], and in the time variation of a CW signal due to the relative motion of individual scatters such as wind induced movement of the foliage medium [42]-[43], [66], [78], [87]-[88], and [90]-[91]. Lewenz [90] started the study of the effect of the movement of the foliage at 2 GHz with large transmission paths (approximately 4.5 km), partially blocked by trees. In his study, the path loss and the wind speed were monitored over several weeks. Later, Perras and Bouchard [66] extended this study to three foliated channels featuring two to four trees and with relatively small transmission distances (up to 110 m) and the received signal power was monitored at their frequency of interest (2.45, 5.25, 29, and 60 GHz) for a period of 45 days. In both studies, four categories of wind velocity ranging from low to high were analyzed. The variation in received power was found to be strongly dependent on the wind velocity.

Statistical analysis of the wind induced foliage movement effect is examined with Equation (2.5)-(2.6), (2.8)-(2.10) in [43] and [78], and the wind induced temporal variation (at a short period of less than 1 min) is found to be Rician distributed. Hashim and Stavrou [43] reported that the Rician K factor was found to vary exponentially with wind speed at frequencies of 0.9, 2, 12 and 17 GHz in a controlled environment of the anechoic chamber and the outdoor environment. Similar work [87]-[89] has also been conducted in controlled

conditions. Ledl *et al.* [87] shows that the analytical results based on a *3D-lattice* model at 38 GHz band is in a good agreement with the experimental data. However, different from the study by Hashim and Stavrou [43], the median Rician K factor in [91] is found to be approximately inversely proportional to average wind speed empirically based on the outdoor experimental data for a link distance of up to 17 km in a period of 1 year.

Comparing to the above-mentioned narrowband multipath fading studies, some effort has been placed in the wideband multipath characterizations of tree induced effects by Bultitude [67], Palud *et al.* [55], and Savage *et al.* [92] *etc.* Typical wideband parameters such as delay spread are found for different tree specimens. Some of these parameters are summarized by ITU in [65], and shown in Table 2.1 below.

Table 2.1 Characteristics of delay through vegetation[#]

Parameters	Ginkgo	Cherry, Japanese	Trident maple	Korean pine	Himalayan cedar	Plane tree, American	Dawn redwood
Vegetation depth (m)	5.4	6.2	4.3	5.2	4.7	6.5	4.7
Delay spread (ns)	7.27	8.23	5.89	6.62	6.39	2.56	6.56

[#] The data in Table 2.1 was obtained for a 3.5 GHz carrier signal modulated with a 1.5 ns pulse. The 3 dB bandwidth of the resulting pulse-modulated signal is 0.78 GHz.

In summary, it is found that although these path loss modeling and multipath fading characterizations are restricted to the single/a lines of trees, the proposed methodologies contributes significantly to the characterizations of the

forested channel, especially for the statistical modeling of the weather induced temporal effect.

2.3 Conclusions

This chapter has been designed to be a general introduction to the concepts and techniques of channel modeling and characterization in foliage environments. Starting with a brief introduction to the interested channel information, the characterization of the foliage environments has been classified into two categories: forest based and a tree/a line of trees based. Both the theoretical and experimental characterizations and modeling of the forested channel have been reviewed in detail. The information for a tree/a line of trees based channel has also been reviewed. It is understood that a proper empirical path loss model in the forest is needed, and the multipath characterization of the forest is lacking, especially for the temporal variations induced by weather effects. Therefore, in the following chapters, we will focus our investigations in these areas.

Chapter 3

Channel Sounder and Pretrial Study

In the previous chapter, a literature review was given on the channel characterization and modeling of the foliage environments. It is found that certain parameters derived from the experimental data can provide an adequate description of the foliage channel empirically. In this chapter, the channel sounders used in the measurement campaigns to obtain both the narrowband and the wideband experimental data for this research study are described, and the pretrial study for the measurement campaigns is reported.

3.1 Channel Sounder

3.1.1 Narrowband System

The most common technique for obtaining channel characteristics with narrowband signal transmission is to excite the channel using an un-modulated RF carrier (Continuous Wave: CW signal) [2]. The channel of interest varies relatively to the transmitter/receiver. These variations are observed in terms of an amplitude

change and/or a phase shift of the received signal. This variation in the amplitude and/or phase of the received signal is a result of the addition of signals arriving at the receiver with random amplitude and phase through different propagation paths. The path loss and shadowing effect can then be easily estimated using Equation (2.4) by regression techniques. The behavior of multipath fading can be described using Equations (2.5)-(2.6), and (2.8)-(2.10) where reasonable agreement is achieved with CW measurements of the fading envelope as summarized in [1]-[2], and [4].

(a) Transmitter

(b) Receiver and data logger

Figure 3.1 Block diagram of a transmitter, receiver and data logging system for narrowband measurement.

Figure 3.1 shows the block diagram of the narrowband sounder used in the experiment campaigns. Omni-directional antennas with vertical polarization are placed in the forest. Appropriate amplifiers are used at both the transmitter (high

power amplifier) and the receiver (low noise amplifier) to ensure the quality of the measured signal. The experimental data is captured by the spectrum analyzer and stored into a control computer via General Purpose Interface Bus (GPIB) for post-processing.

This narrowband sounding technique is easy to implement and allows for a longer sounding range as compared to the wideband sounding techniques. Channel parameters such as path loss, shadowing, and some narrowband multipath characteristics can be obtained through a series of CW measurements. However, it can not provide any information related to the wideband multipath characteristics such as delay dispersions, *etc.* Hence, the wideband channel sounder is required and discussed below.

3.1.2 Wideband System

Two different wideband sounding systems have been used in our measurement campaigns; Vector Network Analyzer (VNA) based system; and spread spectrum based system. Details of these two sounding methods and comparative studies of these two methods can be found in [2]. In this report, an introduction to the two wideband channel sounders is presented.

A) VNA Based System

VNA based channel measurement systems are extremely popular in the short-range wideband channel characteristic measurements [1]-[2], [4], and [93], and are reported thoroughly in these literatures. It presents an attractive measurement

solution since it is a system that is simple to implement. Figure 3.2 shows a basic block diagram of a VNA based measurement system. The data acquisition/logging system is normally built into the VNA which can be controlled by a computer through the GPIB bus. In addition to the VNA, other components that are required includes, appropriate amplifiers, cables and antennas.

Figure 3.2 Block diagram of the VNA based wideband measurement system.

The VNA based measurement technique is a wideband coherent frequency response measurement technique that performs coherent amplitude/phase measurements. Being a frequency domain technique, the measured complex samples of the S_{21} parameter is directly correlated to the channel transfer function $H(f)$. The sampled frequency response $H(f)$ of the multipath radio channel is converted into the impulse response $h(\tau)$ in the time domain by taking the inverse Fast Fourier Transform (FFT) process. The important measurement parameters for the VNA based system are as follows.

i) The measurement bandwidth over which the samples are taken, $BW_m = f_{max} - f_{min}$. BW_m determines the time resolution T_{res} that can be achieved in the time domain. The relationship between the BW_m and T_{res} is given as

$$T_{res} \approx \frac{1}{BW_m}. \quad (3.1)$$

ii) The frequency difference between successive sample points Δf_m determines the unambiguity in range and delay in time as reported in [94]. The unambiguous range of the measurements is the range or delay over which the received energy can be unambiguously related to a certain transmitted pulse. For larger distances, aliasing due to under-sampling in the frequency domain will occur. The unambiguous range d_{unamb} is given by

$$d_{unamb}(m) = \frac{3e8}{\Delta f_m}. \quad (3.2)$$

iii) Influence of the processing window. Before transforming the measured frequency response to the impulse response in the time domain, the samples are weighted in order to suppress undesired sidelobes at the cost of a slightly decreased resolution (a widening of the peak width). For this weighting, the Hanning window function was chosen in our study. The Hanning window function is used since it gives a good compromise between the widening of the main peak width and the suppression of the sidelobes. An example of the Hanning window effect is shown in Figure 3.3, where the sidelobes due to the default rectangular window is suppressed, but at a cost of the slight widening of the main peak width.

Figure 3.3 An example for influence of the processing window.

In summary, the generic VNA based system is relatively flexible since the frequency of operation, multipath resolution and maximum measurable delay can be configured by adjusting the operating parameters of the VNA. However, this technique can only support a relatively short measurement distance if a single VNA system is used [2], [4], and [93]. Some effort is made to extend the sounding distance. For example, Sarabandi *et al.* [59] has extended the sounding distance to 1000 m using two VNAs. These VNAs have to be synchronized through two rubidium atomic clocks. Therefore, the whole sounding system becomes very costly. Moreover, the VNA based system is susceptible to interference from impulsive noise occurring within the frequency band of interest. This interference from impulsive noise is difficult to remove from the measured S_{21} parameter during post processing. Furthermore, VNA systems suffer from relatively long measurement time and slow update rate [93], which restrict their use to the characterization of a relatively stationary channel. Therefore, the VNA based system was only used in our initial studies [95], [96] *etc.* As the forested depth and environment complexity increases, the spread spectrum based system is used. This

is because the spread spectrum based system is less costly for long-range measurement and is less susceptible to interference from the complex environments. Most of our measurement campaigns are conducted using this system, especially for the investigation of the dynamic property of the foliage medium which can be easily influenced by wind and rain. The spread spectrum based system will be elaborated next.

B) Spread Spectrum Based System

The spread spectrum based measurement is a time domain technique. It is pioneered by Cox [97] and found to be a better choice for measurement since it can cover a long sounding range, require a low transmitted power, and has a low probability of suffering from interference. Recently, Kivinen *et al.* [98] performed a comparative study between the sliding correlator [97] and the matched filter (MF) detector [99] at the receiver for the determination of the channel impulse response $h(\tau)$ with a popular spread spectrum technique: maximal-length pseudo-noise (PN) sequences (“*m*-sequences”) implemented.

Figure 3.4 shows the basic block diagram of the spread spectrum based system used in our measurements. The transmitter in Figure 3.4(a) consists of a vector signal generator, a high power amplifier and an Omni-directional antenna. These equipments are all general-purpose laboratory instruments, and easy to handle. The receiver system, however, as in Figure 3.4(b) is comparatively complex. The received signal passes through another Omni-directional antenna, a low noise amplifier, and is then down-converted to an intermediate frequency (IF).

This captured IF signal is then processed onboard/stored into a harddisk for post-processing by a Virtual Instrument (VI) controlled data logger.

(a) Transmitter

(b) Receiver

Figure 3.4 Block diagram of the spread spectrum based wideband measurement system.

The data logger is designed and constructed in this research study using VI concept, where a VI is a computer-based software-driven instrument that interacts with external systems, for example, a 14-bit dual-channel PXI digitizer [100].

In the following part, the performance of the designed data logger is studied using a Binary Phase Shift keying (BPSK) modulated 10-Mchip/s 511-bit

and 1023-bit PN code and a matched filter detector with digital signal processing (DSP) method as in [98]. The theoretical and practical system performance is then compared and discussed.

1) Processing gain

The processing gain (PG) is the difference between the output and input signal-to-noise ratios (SNR) of a system. For a BPSK modulated m -sequence coded sounding system, PG can be obtained [98] as

$$PG \cong 10 \log_{10}(L) \quad (3.3)$$

where L is the m -sequence code length. For the code length L of 511, the theoretical PG is found to be 27.1 dB by (3.3), which means that when the RF input power into the receiver is equal to the system noise of the receiver, the output from the matched filter detector will be 27.1 dB above the mean noise level.

The practical PG of our system is tested in the laboratory with the help of the instantaneous power delay profile (PDP) which is proportional to $|h(\tau)|^2$. An example of PDP from the matched filter detector with a transmitted power (P_T) of 0 dBm and an input SNR of 0 dB is shown in Figure 3.5. From Figure 3.5, a PG of 24.2 dB is obtained. This is about 3 dB less than the theoretical value of 27.1dB. The difference between the theoretical and practical values is due to the attenuation of the transmitted power through the RF components used and the additional internal system noise.

Figure 3.5 Power delay profile at $L = 511$, $P_T = 0$ dBm, and input $SNR = 0$ dB.

Figure 3.6 A measured relationship between input SNR and output SNR at $L = 511$ and 1023, $P_T = -70$ dBm.

Regression technique is then used to obtain a more accurate and practical PG since the relationship between the input SNR and output SNR is expected to be linear. Figure 3.6 shows the measured input SNR vs output SNR when $L = 511$ and 1023 , and a transmitted power, $P_T = -70$ dBm. Using linear regression, the PG is found to be 23.8 dB and 26.9 dB for the 511-bit and the 1023-bit m -sequences respectively within the linear region. These values obtained are close to the theoretical values of 27.1 dB and 30.1 dB respectively.

Figure 3.6 also shows another important system property. As the input SNR increases beyond a certain limit of 25 dB and 26.7 dB (1 dB compression point) for 511-bit and 1023-bit respectively, the system is over-driven and reaches saturation. Meaning to say, the system dynamic range is reached.

2) *Dynamic range*

The required dynamic range of the measurement system depends on how large a difference needs to be observed between the largest and the smallest received path components in the output PDP from the matched filter detector. The theoretical dynamic range for any m -sequence coded waveform (code length L) is $20\log_{10}(L)$ in dB [2], [98], which is mathematically given as twice of the PG . That is, the theoretical difference of the dynamic ranges between a 511-bit and a 1023-bit m -sequences that is used for Figure 3.6 is

$$20\log_{10}(1023) - 20\log_{10}(511) = 6 \text{ dB}$$

which is close to the obtained practical difference of 5.6 dB in Figure 3.6 within the saturation region.

3) *Multipath resolution*

Multipath resolution capability of the sounder is the minimum time between two discernable impulse delays and is limited by the modulated signal bandwidth in our system. The studies in [2], [98] show that the resolution in time-domain is equivalent to the reciprocal of the PN code bit rate R_c .

In order to investigate the accuracy of our system, a simulation for a 2-ray channel as shown in Figure 3.7 is used. A 1-m cable is used for simulating the path of the first arrival, and a longer cable of 50 m, 100 m, and 150 m for scenario *a*, *b*, *c* respectively, is used for simulating the path of the second arrival ray. Figure 3.8 shows an example of the PDP for scenario *a* where $P_T = -70$ dBm and input $SNR = -10$ dB.

Figure 3.7 Simulated 2-ray channel.

Figure 3.8 Power delay profile at $L = 511$, $P_T = -70$ dBm, and input $SNR = -10$ dB for scenario a .

The measured path difference in Figure 3.8 can be calculated by,

$$(0.19e-6 \text{ s}) * 0.85 * (3e8 \text{ m/s}) = 48.5 \text{ m}$$

Here, $0.19e-6$ s is the time difference between the two discernable impulse delays, $3e8$ m/s is the radio wave speed in free space, and 0.85 is the relative propagation velocity of radio wave in the RF cables used. The theoretical and measured path differences for all the scenarios are summarized in Table 3.1. The measured values and the theoretical values are in good agreement, which verifies the high accuracy of this measurement system. The slight error is mainly due to the splitters, connectors, actual measured length of cable and actual value of the relative propagation velocity.

Table 3.1 Theoretical and measured difference of the simulated path.

Scenarios	Theoretical	Measured
<i>a</i>	49 m	48.5 m
<i>b</i>	99 m	98.6 m
<i>c</i>	149 m	149.45 m

4) Power accuracy and sensitivity

To ensure accurate measurements with the PXI digitizer based system, power calibrations have been conducted in laboratory with the direct connection between a vector signal generator and the PXI digitizer. The results for the calibration are shown in Figure 3.9. It can be found that, good accuracy has been achieved with the proposed system even when the input power to the PXI digitizer based system is as low as -90 dBm.

Figure 3.9 The relationship between the transmitted power and the estimated power with PXI digitizer based system.

3.2 Pretrial Study

3.2.1 Comparisons of System Performance in Campus Trial

Measurements with VNA (HP 8753E) and spread spectrum based systems were carried out in the Campus of Nanyang Technological University (NTU), Singapore, to evaluate their performance before practical trials. Table 3.2 lists the bandwidth and resolution for each system used in the Campus measurements respectively.

Table 3.2 Bandwidth and resolution for VNA and spread spectrum based systems[#]

Technique	Bandwidth/data rate	Resolution
VNA	300 MHz	3.3 ns
Spread spectrum	20 Mchip/s	50 ns

[#]For VNA based system, the number of swept point is 1601; for spread spectrum based system, 1023 bit *m*-sequence is used [126].

Typical results for channel power delay profiles with the VNA and spread spectrum based systems at the same environment in NTU Campus are shown in Figure 3.10. It can be found that, both the measurement systems produce similar results, except that the result from the VNA is finer due to its better time resolution. That is, both the system can measure the reflected/scattered components from the main clusters as shown in Figure 3.11. However, there is a good ability for the VNA with better resolution to isolate the components from each main cluster as compared to spread spectrum based system.

Figure 3.10 Comparative study of the performance for VNA and spread spectrum based systems [126].

Figure 3.11 Cluster model for the radio wave propagation.

However, the bandwidth allowed for transmission (5 Mchip/s is the maximum rate allowed in the interested forests to avoid the interference on the other communication systems in the use) and the long propagation distance limits the usage of the VNA based system in our later study. Moreover, with the experience from [30], [41], and also from our pretrial measurements in forests, 63 bit *m*-sequence is found to be a good choice. This is because 63 bit *m*-sequence with a data rate of 5 Mchip/s can cover a maximum delay (path difference) of 12.6 μ s (3780 m), which is enough for the measurements in the coming trials.

3.2.2 Link Budget

The link budget has been calculated in the pretrial study to estimate the range of the proposed sounder. The link budget is listed below, and all the parameters are the values given in the datasheet. It is noted that, the actual performace of the hardware is much better than these given values from our observations with laboratory tests.

The link budget is as,

	19 dBm	(Power from signal generator)
+	>19 dB	(Gain for high power amplifier)
+	> 2.4 dBi	(Typical antenna gain at transmitter)
+	> 2.4 dBi	(Typical antenna gain at receiver)
+	> 20 dB	(Gain for low noise amplifier)
–	6.5 ~ 14 dB	(Cable loss used within 200 to 700 MHz)

> 56.3 ~ 48.8 dB = Total gain within 200 to 700 MHz

For the PXI digitizer based system (it has a lower sensitivity as compared to narrowband system with spectrum analyzer, and is discussed here as an example), the results in Figure 3.9 shows that, the system can measure the power as low as -90 dBm accurately. Therefore, with the total gain calculated above for the frequency within 200 to 700 MHz, it can be found that, the sounding system can allow a total loss of 146.3 to 138.8 dB. This is good enough for our later measurements as referred to those simulated and measured results by other researchers [13], [41].

3.2.3 System Calibration

In order to extract the exact channel information, the whole system is carefully calibrated on-site twice, once before and once after the measurement campaigns. Before the measurement campaign, the non-linear components such as the amplifiers are calibrated for temperature and gain stability through laboratory tests. The amplifiers are made to operate under different temperature (from 25°C to 55°C) for a period of 1 hour. The fluctuation in temperature and gain is recorded and used for calibration. The system effect is minimized through the removal of the antenna gain and the measurement of a back-to-back connection between the transmitter and the receiver.

For accurate data measurements, the transmitter and receiver uses an external source (10 MHz signal from the GPS receiver) as a reference signal. The time synchronization is also achieved through the GPS time-stamping [101] during the wideband measurements. On the other hand, the transmitted frequency is

carefully selected to ensure that there is no interference signal within the band of transmission. This is done by monitoring the environmental noise floor within the frequency band of interest in the forested environments for more than half an hour. If interference is likely to occur, an alternative frequency band is chosen.

3.2.4 Proposed Scheme in Measurement Campaigns

Due to the practical requirements for the implementation of the military wireless sensor networks in the forests, the objective of this PhD study is to investigate the near-ground channel information and characteristics. This restricts the antenna height used in the measurement, which is unlike those used in the cellular/satellite application where the antenna height is higher. The effect of the antenna height in a forest has been explored by other researchers such as Burrows [21], Tewari *et al.* [25] and Joshi *et al.* [41] experimentally. Therefore, the height of the antennas is chosen to be of a value of 2.15 m, which is close to the height when a sensor is placed on a military vehicle during most of our major measurement campaigns in the forests, although some measurements are also conducted at other heights.

Since the communication links in the military wireless sensor networks is expected to be hundreds of meters to kilometers, and the database for those empirical through-vegetation loss models in Equation (2.14)-(2.16) and (2.18) is limited to a forested depth less than 400 m, the focus of this study will be on the investigations of the long-range radio wave propagation in forests. The study of the short-range communication in the forests with VNA based measurements [95]-[96] is used to help us achieve a better understanding of the realistic radio wave propagation in forest, and will not be the focus in this PhD study.

3.3 Conclusions

This chapter presents an introduction to the sounding systems and techniques used in wireless channel measurements and characterizations, and the pretrial study before the main measurement campaigns.

For the sounding systems, both the narrowband and wideband sounders are presented. It is found that the narrowband sounder is simple to be implemented, and provides adequate narrowband channel information, such as path loss, shadowing, and narrowband multipath characteristics. For the required wideband channel information, such as delay dispersion, *etc.*, VNA based wideband system and spread spectrum based wideband system are used and therefore, presented in this chapter.

As compared to the mature VNA based system, special attention is given to the design and construction of the VI controlled PXI digitizer based system for spread spectrum based measurements in this chapter. With the implementations of the spread spectrum technique and the method of matched filter detection, the performance of the designed sounding system is studied and verified through extensive laboratory tests. It is found that measured results are in good agreements with theoretical ones.

Comparisons between the performances of the spread spectrum based system and VNA based system have been conducted in NTU Campus. It is found that, similar measurement results for the main clusters can be achieved, although VNA provides a better resolution to isolate the components from each cluster.

Due to the practical implementation of the military wireless sensor networks in the forests, channel information from long-range near-ground measurements is required. However, for the actual measurements in a realistic environment (where there is high probability of interference from impulsive noise, and the interested forested channel is dynamic) and also the limitation of the sounding bandwidth, the spread spectrum based system is preferred. This system has the advantage of being low in cost and being less susceptible to interference.

Therefore, in our measurement campaigns in forested environments with long forested depth, both the narrowband system and spread spectrum based system are used. The extracted narrowband and wideband channel characteristics are analyzed and discussed in the following chapters.

Chapter 4

Path Loss Modeling in Forests

Near-ground radio wave propagation is examined within tropical forests experimentally at VHF and UHF bands. The propagation loss at different forested depth is analyzed using a proposed integrated model which combines both the forest induced effect and the ground reflection effect. Several well-known empirical through-vegetation loss models are compared and analyzed in this chapter. It is observed that, for long-range forested communications at VHF band, the lateral wave has to be taken into consideration in order to achieve better prediction ability. Therefore, in this chapter, a new model, the Lateral ITU-R model, is proposed. This proposed model is evaluated and found to be a better model for long-range path loss prediction in the VHF band. For short-range propagation, the theoretical analysis and empirical results show that the reflection from the dense tree canopy is of significant importance for short-range radio wave propagation at VHF band and therefore, cannot be ignored. When taking into consideration the possible contribution from the tree canopy reflection, the modeled path loss is found to be reduced by more than 15 dB in the VHF band.

This modeled path loss is in a good agreement with the measured propagation loss in the forest.

4.1 Long-Range Forested Propagation

Previous theoretical studies [6]-[14], [20] and empirical investigations [21], [25], and [41] show that the ground reflection is an important factor when it comes to VHF and UHF forested propagation. Therefore, in this research work, the path loss of a forested channel is modeled using Equation (2.23). The well-established empirical through-vegetation loss models given in Equation (2.14)-(2.16), (2.18) will be integrated into Equation (2.23) to take into account the forest induced effect.

Through the study of the models given in Equation (2.14)-(2.16), (2.18), it is concluded that these models are optimized based on the measured data over a relatively short forested depth (maximum of 400 m) in the frequency range of VHF to millimeter waves. For long-range forested path loss modeling, the research findings from Tamir [5], [7] and Li *et al.* [11]-[14] contribute significantly. Their works state that the lateral wave becomes dominant at relatively large forested depth, especially when both the transmitter and the receiver are placed within the forest and when the frequency of operation is in the VHF and UHF bands. These observations motivate us to perform further investigation to study the validity of these empirical models [35]-[37], [60] when applied to near-ground, long-range (hundreds of meters to few kilometers) communication links at VHF and UHF bands. For all these models, the effect of the ground reflection is added as given in

Equations (2.23) since the measurement campaigns are performed near to a flat ground.

In the following part, comparative analysis of the various integrated models which take into consideration both the forest induced effects and the ground reflection effect is performed. From the comparison, a simplified empirical model suitable for use in near-ground radio wave propagation over a large forested depth at VHF and UHF band is identified.

4.1.1 Measurement Campaign

The measurements were performed on the island of Singapore during the northeast monsoon season, when the average monthly rainfall is 280 mm. The forest chosen for this study is a palm plantation over a nearly flat terrain as shown in Figure 4.1. 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. In order to make the measurement results more representative, the measurement points and path were selected arbitrarily as shown in Figure 4.2, where the forested depth can be more than 1000 m. This forested depth is calculated based on GPS readings. During the measurements, the forest is dry and with slight or no wind, and both the antenna heights are kept at 2.15 m as indicated before.

Figure 4.1 Photograph of the plantations under measurements.

Figure 4.2 Description of main measurement locations and paths in the tropical palm plantation. The picture is downloaded from Google Earth[®].

The measurement was carried out using narrowband CW sounder at VHF (240 MHz) and UHF (700 MHz) band. Readings were taken at 9 predefined square grids at the receiver side as shown in Figure 4.3. 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. 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. The reason to use the 9 grid as in Figure 4.3 but not the linear track in [102] is because it is difficult to align the measurements points along a line in a very large forested depth. 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 0.01s 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.

Figure 4.3 The schematic diagram for the predefined 9-grid square.

4.1.2 Path Loss Modeling

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 the forested depth at 240 MHz and 700 MHz in the palm plantation shown in Figure 4.1 are plotted with the best fitted line (Figure 4.4). The best fit lines are estimated through the linear regression method. The two empirical expressions at 240 MHz and 700 MHz are,

At 240 MHz:

$$PL(dB) = 4.4 \times 10 \log_{10}(d) - 11 \quad (4.1)$$

At 700 MHz:

$$PL(dB) = 5 \times 10 \log_{10}(d) - 17 \quad (4.2)$$

where PL is the path loss in dB, and d is the forested depth in meter. The shadowing value is then obtained to be 4.46 dB at 240 MHz, and 3.45 dB at 700 MHz. This indicates that there is a higher shadowing effect (4.46 dB) at lower frequency (240 MHz) as compared to the higher frequency (700MHz). From the estimated results in Figure 4.4, it is found that the measured data at larger forested depth contributes more to the higher estimated shadowing value at 240 MHz. The empirical expression in Equation (4.1) overestimates the propagation loss a lot as compared to the measured data. This could be due to the lateral wave effect [5], and will be examined later.

(a) Path loss at 240MHz

(b) Path loss at 700MHz

Figure 4.4 Measured and predicted path loss with forested depth.

Comparison is then performed among the predicted path loss using the various integrated models taking into considerations both the forest induced effects and the ground reflection effect. The different through-vegetation loss models given by Equation (2.14)-(2.16), and (2.18) in Chapter 2, together with the perfect plane earth path loss model in Equation (2.2) are used. For both the COST235 model and the FITU-R model, only the in-leaf loss models are used since the tropical plantation under consideration is an evergreen one.

From Figure 4.4, it is found that at a short forested depth, the predicted values by the Weissberger, ITU-R and FITU-R models with ground reflection considered are in good agreements with measured data, except the predicted values by the COST235 model with ground reflection considered. This is because the COST235 model is optimized from the measured data at very high millimeter waves (up to 57.6 GHz), which results in a higher predicted path loss at VHF and UHF band.

As the forested 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 forested depth overestimates the path loss significantly up to 40 dB at 1000 m above the measured data. The overestimation of the path loss increases gradually as the forested depth increases. This is because the optimization of both the models is based on experimental data for small forested depths (< 400 m) at VHF and UHF band and therefore, these two models have poor prediction accuracy at large forested depth where there may be other

propagation mechanisms that are not accounted for. An example of such propagation mechanisms is the lateral wave over the treetops, which appears dominant at large forested depth as stated by Tamir [5], [7] and Li *et al.* [11]-[14] 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 MHz and 700 MHz wave propagation as compared to other models at larger forested depth. This is because the FITU-R model is derived from a set of data measured at 11.2 GHz and 20 GHz in uniformly planted 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 path loss in forests 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 [60], and further examined by Rogers *et al.* [38] and Wang and Sarabandi [51]. 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 forested 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 medium 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 with a small forested depth (< 400 m) at VHF and UHF band where the coherent component of the propagating waves is dominant, and less forward scattering mechanism is taken into account since large forested depth are not considered.

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 fitted 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 dB to 12.9 dB as the forested depth is more than 500 m. The difference is mainly due to the appearance of the lateral wave effect at 240 MHz [28], [103]. The lateral wave can enhance the radio wave propagation over a very large forested depth and reduce the path loss relatively. As known, the FITU-R model is derived from measured data taken at frequencies between 11.2 GHz to 20 GHz (forested depth $d < 120$ m). The lateral wave does not exist at these millimeter wave frequencies. This is because the RMS height of the interface roughness [17] for the adjacent layers in the multi-layered model is increased significantly relative to the wavelength of the propagating signal (11.2 GHz to 20 GHz). Therefore, the wave propagating along the interface (*i.e.* the lateral wave) is attenuated significantly. The FITU-R model predicts the path loss at 240 MHz to a poor accuracy as compared to that at 700 MHz in the forested environment. This is due to a higher contribution from the lateral wave at the lower frequency of 240 MHz.

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 found from Figure 4.4. This could be due to the assumption of the perfect plane earth model in (2.2). In order to investigate the effect induced by the perfect plane earth model, a fitted ground reflection (FGR) model is introduced in (4.3). The FITU-R model together with the FGR model in (4.4) is then applied to fit our measured data.

$$L_{FGR}(dB) = 10n \log_{10}(d) - 20 \log_{10}(h_T) - 20 \log_{10}(h_R) \quad (4.3)$$

$$L_{forest}(dB) = L_{FGR}(dB) + 0.39 f^{0.39} d^{0.25} \quad (4.4)$$

where n will be determined empirically. Figure 4.5 shows the least squared error fit of Equation (4.4) with the measured data. The n values determined at 240 MHz and 700 MHz are 3.85 and 3.97, respectively. Comparing to the ideal plane earth model in (2.2) 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 at VHF and UHF band. This is also consistent with the findings reported by Burrows [21] and Tewari *et al.* [25], where they concluded that the ground reflection in the forest is approximately perfect for frequencies from 50 to 800 MHz. That is, for the VHF and UHF radio wave propagation in forested environment, a perfect ground reflection can be assumed [20].

Figure 4.5 Results with optimization of ground reflection.

Moreover, it is known that, for the same ground surface, the scattering from a rough surface is more apparent at 700 MHz as compared to 240 MHz. This can be verified with the “Rayleigh criterion” [102], [104]: $v > \lambda / (8 \cos \theta_i)$, where v is surface roughness, and θ_i is the incident angle of the incoming wave. This indicates that a perfect ground reflection can be assumed at 240 MHz. Hence, the larger difference in n value (3.85 as compared to 4) at 240 MHz is mainly due to the appearance of the lateral wave. As stated before, the FITU-R model does not take into account the lateral wave effect, therefore, the optimization process of (4.4) transfers the lateral wave effect into the fitted ground reflection model, which reduces its n value significantly.

From the literature study reviewed in Chapter 2, it is found that the foliage effect can be modeled empirically by Equation (2.17). Moreover, the above-

mentioned study shows that a perfect ground reflection can be assumed in this palm plantation. Therefore, a better empirical path loss model can be achieved by using the expression in (4.5). This proposed expression attempts to model the radio wave propagation in the forest by taking into account the lateral wave effect in the excess foliage loss model under the assumption of a perfect plane earth reflection.

$$L_{forest}(dB) = Af^B d^C + 40 \log_{10}(d) - 20 \log_{10}(h_T) - 20 \log_{10}(h_R) \quad (4.5)$$

where the three numerical values A , B , and C are estimated using least squared error fit on the measured data. It is found to be 0.48, 0.43 and 0.13 at 240 MHz, 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 forested depth increase, the path loss increases.

In order to study the performance of the fitted model, the RMS error, E_{rms} as in [60], between the measured loss and the predicted loss by the fitted model is calculated as follows,

$$E_{rms} = \sqrt{\frac{\sum_{i=1}^N (E_i^2)}{N}} \quad (4.6)$$

where N is the number of sample points and E_i is the difference between measured and predicted values at the i^{th} measurement point.

It is found that, the corresponding improvement in RMS error decreases from 5.89 dB to 4.61 dB (1.28 dB improvement) at 240 MHz, and 3.07 dB to 3.00 dB (0.07 dB improvement) at 700 MHz, for the FITU-R model with perfect plane earth model as compared to the FITU-R model with fitted ground reflection model. 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 which is not apparent at 700 MHz for the forested depth under measurements. 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. When the lateral wave effect is considered in the excess foliage loss model, and a perfect ground reflection is assumed, 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.

Therefore, in this study, the expression in (4.7) 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 forested areas in the VHF band.

$$L_{LITU-R}(dB) \cong 0.48 \times f^{0.43} d^{0.13}. \quad (4.7)$$

4.1.3 Verification of the Proposed Model

A) Verification with the Experimental Data

The prediction accuracy of (4.7) is verified through the experimental data reported by Joshi *et al.* [41] where the forested 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, Virginia, USA. The measured result at 300 MHz is used because there is quite a high probability for the existence of lateral wave at the forested depth covered. This result from [41] is plotted against the predicted loss from the proposed integrated model of the LITU-R model with perfect plane earth model in Figure 4.6. The forested depth covered at 300 MHz is from 50 m to 960 m and the antenna is at a height of 0.75 m.

From Figure 4.6, 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 [41]. 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 forested 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 forested depth of 1000 m, which has taken into consideration the lateral wave induced effect as compared to other through-vegetation loss models. Moreover, the similar terrain effect enhances the predication ability of the proposed LITU-R model with perfect plane earth model for these plantations.

Figure 4.6 Comparisons of the predicting ability with LITU-R and FITU-R model.

Also shown are the experimental data by Joshi *et al.* [41] at 300 MHz.

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.* [13] 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 transmitting and receiving 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 Figure 4.7.

Figure 4.7 Predicted path loss in forest at 200 MHz covering a long forested depth of 1000 m to 5000 m. Also shown are the simulated data by Li *et al.* [13].

From Figure 4.7, 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.* [13]. This is not surprising, since the simulation process in [13] has taken into consideration the lateral wave contributions, especially at larger forested 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 forested 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 [13] 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 forested dielectric parameters used in the simulation. Besides these influences, the optimization progress for LITU-R model in (4.7) 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 model is found to be accurate for near-ground (mainly at the tree trunk layer) radio wave propagation at VHF band over large forested depths. It is assumed that as the communication point is close to the treetops, the accuracy will decline. This is because the lateral wave will contribute more as reported in [7], and there is the possibility of the existence of the Norton wave as reported by Liao and Sarabandi [18].

However, the most important point here is the way to empirically model the near-ground radio wave propagation loss in a forested environment. The empirically modeling with (4.5) has shown a good potential, and can be used easily by the ordinary users with excellent prediction ability.

4.1.4 Summary

A detailed study of the near-ground path loss modeling at VHF and UHF band over a large forested depth is performed in this section. An integrated model with ground reflection and foliage effect is proposed, which takes into consideration the frequency, antenna height, and forested depth. Comparative study of the integrated model with several well-known through-vegetation 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 forested depths.

However, the lateral wave as proposed by Tamir becomes dominant in the VHF band when the forested depth is further increased. Therefore, the FITU-R model parameters do not fit well the foliage loss over larger forested depth since it does not take into account the lateral wave effect. The LITU-R model is then proposed in this study 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 larger forested depth (up to 5 km) at VHF band (verified for 200 MHz, 240 MHz 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.

4.2 Short-Range Forested Propagation

As discussed in Chapter 2, a lot of empirical path loss modeling has been conducted within a short-range in the forested environment using Equation (2.22). This empirical methodology provides an easy way to model the forested path loss. However, this method tends to be very site-specific and can vary significantly depending on the type of foliage, operating frequency, and the nature of the forest components (wet trunk, dry leaves, *etc.*) within the forests. Following a similar method by Goldman and Swenson [39] but with the tree shadowing effect introduced, we performed an empirical path loss modeling at a different plantation in [96]. It is concluded in [96] that the extracted path loss exponent n only follows the same trend by frequency. That is, as frequency increases, the path loss exponent n decreases in general at VHF and UHF band. Therefore, a proper empirical way to model the short-range near-ground path loss in forests with good accuracy becomes attractive.

From open literature, it is found that the reflections from the upper boundary of the forest for a long-range forested path can be neglected, since the canopy-trunk interface is rough and gradual [33] and the propagating components are incoherent [3], [38], and [51]. However, for a short-range forested path, the reflections from the upper boundary of the forest formed by the tree canopy may no longer be neglected [11], since the propagating component is coherent and therefore, the reflected components contribute significantly. A geometrical ray tracing of the propagation in a short-range forest can be found in Figure 4.8.

Figure 4.8 Ray tracing geometry of the direct¹, ground reflected², and canopy reflected³ waves.

The boundary for the reflection to occur can be determined with the help of the 1st Fresnel zone, since the energy transmitting from transmitter (Tx) to receiver (Rx) concentrates mainly within this region. The size of the 1st Fresnel zone surrounding the geometrical ray paths is shown in Figure 4.8. The semi-minor axis h_0 of the ellipse can be computed from the expression [2], [4]:

$$h_0 = \frac{1}{2} \sqrt{\lambda d} \quad (4.8)$$

where λ is the wavelength and d is the distance between the transmitter and the receiver in meter. The outer bound of the 1st Fresnel zone varies with the operating frequency. The large ellipse (dash line) in Figure 4.8 represents the 1st Fresnel zone at low frequency, and the small ellipse (solid line) represents the 1st Fresnel zone at high frequency.

When there is a single reflected ray (e.g. ground reflection), the path loss can be described by [102] in (4.9), which is another expression for Equation (2.2),

$$L_{1\text{-reflected}}(dB) \cong L_{FSL}(dB) - 20 \log_{10}(\Delta\Phi) \quad (4.9)$$

where $\Delta\Phi$ is the phase difference between the direct and reflected rays given in (4.10),

$$\Delta\Phi = \frac{4\pi h_T h_R}{\lambda d} \quad (4.10)$$

Here, h_T and h_R are the transmitting and receiving antenna heights over the reflected plane in meter, respectively. The assumption that d is much larger than h_T and h_R must hold.

For the short-range forested propagation, a second reflected wave due to the tree canopy may exist and is introduced here. When the second reflected ray is present, the path loss can be described by [102] as in (4.11),

$$L_{2\text{-reflected}}(dB) \cong L_{FSL}(dB) - 10 \log_{10}(1 + 2\Delta\Phi_1\Delta\Phi_2) \quad (4.11)$$

where $\Delta\Phi_1$ and $\Delta\Phi_2$ are the phase differences between the direct and the ground reflected rays, and the direct and canopy reflected rays, respectively for radio wave propagation in short-range forests. The phase difference $\Delta\Phi_1$ and $\Delta\Phi_2$ can be estimated by (4.10) where $h_T = h_R = h_2$ for the ground reflected ray and $h_T = h_R = h_1$ for the canopy reflected ray as shown in Figure 4.8.

(a) Palm plantation

(b) Rainforest

Figure 4.9 Photograph of the tropical foliage areas under considerations for short-range propagation.

4.2.1 Measurement Campaign

The measurements have been conducted in two tropical foliage areas; a highly structured palm plantation shown in Figure 4.9(a); and a natural rainforest shown in Figure 4.9(b). It is noted that, the palm plantation in Figure 4.1 is not used in

this study. This is because, the antenna height under measurements is close to the rough canopy-trunk interface in the palm plantation shown in Figure 4.1, and the reflection from this interface is not easy to exist. The forests under measurements for the study of the possible canopy reflection are with a dense canopy, and the canopy-trunk interface is not rough. Details of the forests are described below.

A) Palm Plantation

This is a rectangular shaped site planted with palm trees as shown in Figure 4.9(a) (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 0.2 m. The leaves of these trees form a dense canopy. The site is close to the sea therefore, the environment is very humid.

B) Tropical Rainforest

The natural rainforest as in Figure 4.9(b) consists of trees with an average height of 10 m to 11 m and main trunk diameter of 0.3 m to 0.45 m. 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 narrowband measurements in Figure 3.1. During the measurements, the forested depth covered 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 a sunny and no wind weather condition with limited human activities.

4.2.2 Analysis and Verifications

The estimated minor axis h_0 of the 1st Fresnel zone is shown in Table 4.1. As shown in Figure 4.8, $h_1 = 6.85$ m and $h_2 = 2.15$ m for the palm plantation, and $h_1 = 4.65$ m and $h_2 = 2.15$ m for the rainforest. From Table 4.1, 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 40~80 MHz for the palm plantation, and within the VHF band of 40~80 MHz and 250~300 MHz for the rainforest within the forested depths covered. In the following part, when ground reflection and possible tree canopy reflection exist, the path loss is predicted as

$$PL_{forest}(dB) \cong L_{foliage}(dB) + L_{2-reflected}(dB) \quad (4.12)$$

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

$$PL_{forest}(dB) \cong L_{foliage}(dB) + L_{1-reflected}(dB) \quad (4.13)$$

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

Table 4.1 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

The predicted loss from Equation (4.12) and (4.13) is plotted in Figure 4.11 and Figure 4.12 against the measured local mean path loss, which is a moving average of the path loss along a 10 m linear track [102] as in Figure 4.10. The moving average is employed to minimize the spatial variation (due to the tree shadowing effect) on the received power. For COST235 model and FITU-R model, the in-leaf model is used.

Figure 4.10 The schematic diagram for the linear track.

(a) 40 MHz

(b) 550 MHz

Figure 4.11 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.

Figure 4.12 Measured and predicted path loss at VHF and low UHF bands $h_1=4.65$ m and $h_2=2.15$ m in the rainforest.

It is observed that COST235 model gives the best fit for the measured path loss in the palm plantation with ground and possible canopy reflections considered at 40 MHz (VHF) in Figure 4.11(a) and with only ground reflection considered at 550 MHz (UHF) in Figure 4.11(b), while the ITU-R model shows a best prediction ability for the path loss in the rainforest with ground and possible canopy reflections considered at 40 MHz (VHF) in Figure 4.12(a) and with only ground reflection considered at 550 MHz (UHF) as in Figure 4.12(b). The difference between the measured and predicted values is mainly due to the assumed perfect reflection in the modeling process. The ground roughness [2], [4], and [102], and canopy-trunk interface roughness [17] are known to result in imperfect reflections.

The excellent prediction ability of COST235 model in the palm plantation and ITU-R model in the rainforest with reflection/reflections considered is also verified for all other frequencies used. The difference between the observed best forest induced excess loss models (COST235 model in the palm plantation and ITU-R model in the rainforest respectively) is mainly due to the different type of foliage found in the propagation path for the two measurement campaigns. The databases from which the four models, Weissberger, ITU-R, FITU-R, and COST235, are derived and optimized are based on different foliage types.

It is known that both the Weissberger model and ITU-R model are derived from databases where measurements are performed at VHF and UHF bands through a small group of trees, while the COST235 and FITU-R model is derived from the measured data at millimeter wave frequencies. Especially, the COST235 model is optimized from the measured data at a much higher frequency (up to 57.6

GHz) as compared to the database at 11.2 GHz and 20 GHz for the FITU-R model. For the palm plantation, the dominant dense tree trunks and highly humid environment results in a measured path loss that is higher than other foliage environments. Therefore, the COST235 model with reflection/reflections considered is an ideal model for modeling the short-range path loss at the VHF and 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 reflection/reflections considered is found to be the best prediction model for this rainforest environment.

However, the most significant point is, for short-range, near-ground propagation at VHF band, the tree canopy induced reflection may not be ignored when performing empirical path loss modeling. Both the measured results in the palm plantation and the rainforest show the possible contribution from canopy reflection. It is shown in Figure 4.11(a) that, the COST235 model taking into consideration both the ground and possible 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 Figure 4.12(a), where the ITU-R model with ground and possible canopy reflection considered reduces the predicted path loss by more than 20 dB in a slight longer foliage depth. The ITU-R model also gives a good fit to the measured data. This is because, when both the

ground and canopy reflections are taken into account, the convergence of the reflected rays (the possible canopy reflected wave, and the ground reflected wave) at the receiver reduces the overall propagation loss. Both measurement campaigns show that the reflection from tree canopy in the VHF band is important and needs to be taken into account while performing short-range, near-ground empirical path loss modeling in forested environments.

Moreover, it is found that the standard deviation of the differences between the measured and predicted values as shown in Figure 4.11 and Figure 4.12 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 [102], [104] 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 Figure 4.8 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 the possible 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 Figure 4.9. Therefore, when applying Equation (4.12) with 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.

4.2.3 Summary

The theoretical analysis with the help of the geometrical ray tracing shows that the dense tree canopy induced reflection is of high importance at VHF band for short-range, near-ground path loss modeling in forests. This is followed by the experimental verifications of the possible tree canopy reflection contribution within two different tropical forested areas by taking into consideration the foliage induced additional loss on the propagating waves. It is found that due to the different foliage type, the COST235 and the ITU-R models have the best fit for the two forested propagation channels considered 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 significantly, both measurement campaigns verify the importance of taking into consideration the possible tree canopy reflection for short-range, near-ground propagation at VHF band. The modeled and measured results are in good agreement with each other when the canopy reflection is taken into consideration. The analysis of the results from experimental data shows that, when the boundary condition in Equation (4.8) for the consideration of tree canopy reflection effect is met, the roughness of the canopy-trunk interface relative to the operating frequency also has to be considered. The tree canopy reflection effect can be reduced when the roughness of the canopy-trunk interface increases. This is observed from the experimental results.

4.3 Conclusions

In this chapter, path loss modeling taking into consideration the ground reflection is studied for both long-range and short-range forested paths. Good accuracy is obtained between the measured data and the modeled values. Most importantly, experimental results show that the lateral wave plays an important role in long forested range, while the canopy reflection may contribute significantly for the short-range forested propagation.

However, it is found that, due to the variety of operational context and physical situations, there is no a unique empirical through-vegetation loss model which can be used universally. A number of experimental works [35]-[37], [60] in different measurement scenarios have produced several empirical models: Weissberger, ITU-R, FITU-R, and COST235 models, and also LITU-R model proposed in our study. The research shows that, in general, there is a high probability that, Weissberger, ITU-R, FITU-R, and LITU-R models are applicable for VHF and UHF radio wave propagation, and COST235 is applicable for millimeter wave frequencies. However, the best empirical model can vary depending on the density and the type of the forests. In our study, it is found that for a very dense tree-trunk dominant palm plantation, the COST235 model can provide good prediction ability even for the VHF and UHF radio wave propagation.

Chapter 5

Weather Effects on the Forested Radio Wave Propagation

The dynamic properties of the tropical forested channel due to weather effects on VHF and UHF radio wave propagation are investigated. In this study, the rainfall effect and the combined effects of wind and rain are discussed. The rainfall effect is studied through the wideband sounding investigations. It is found to have distinct effects on various parts of the propagating components for the VHF radio wave propagation in a tropical forest, where the direct wave propagating through the canopy layer is heavily affected. This is verified through the estimated delay spread statistics, and also the empirical dielectric constant of the canopy layer. The combined effects of wind and rain are also studied through a statistical modeling of the received amplitudes from the narrowband measurements. The induced temporal effects are discussed and compared to the theoretical models. It is found that the distribution of the temporal fading components resembles a Weibull/Rician distribution function. Its Weibull b parameter/Rician K factor

decreases gradually as the strength of either wind or rain increases due to the movement of the foliage components.

5.1 Rainfall Effect on the Forested Propagation

5.1.1 Measurement Campaign

The distinct rainfall effect is investigated through the spread spectrum measurements as discussed in Figure 3.4. The transmitter consists of a vector signal generator, used to produce a BPSK modulated carrier wave at 240 MHz. Due to the power constraint of the signal generator and the high attenuation resulting from the forests (especially since the foliage is damp due to the rainfall during the monsoon season), a 10 W high power amplifier is required to amplify the transmitted signal. With experiences from pretrial measurement campaigns and also the constraint of the signal bandwidth which is allowed to transmit, a 63 bit m -sequence with a data rate of 5 Mchip/s is used in our study. This results in a time resolution of 0.2 μ s for the received signal. This BPSK modulated m -sequence 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 IF signal of 20.4 MHz. The IF signal is then sampled at a rate of 100 MSample/s and stored into a data logger for offline data processing. It is noted that the tropical forest, where these measurements are conducted, is the same as the one presented in

Chapter 4, Section 4.1. The forested depth covered in this experiment is 710 m. The transmitting and receiving antennas are both kept stationary inside the palm plantation and at a constant height of 2.15 m.

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) [105], Singapore. The weather radar covers an elevation angle range from 1° to 40° , and is 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. Figure 5.1 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 [106] for the region.

Figure 5.1 Radar image for the rain intensity display from the NEA weather radar.

5.1.2 Rainfall Effect on Delay Statistics

The measured signal is down-converted to its baseband signal via a software program. The baseband signal then undergoes cross-correlation with a copy of the known original 63 bit m -sequence. This will produce the complex channel impulse response $h(t, \tau)$ as in Equation (2.11).

The instantaneous power delay profile (PDP) is the envelope of the received power and is proportional to $|h(t, \tau)|^2$. In order to smooth out the noise floor and minimize the temporal variations due to any slight wind conditions during the measurements, the mean PDP is considered and obtained from an average of 1024 consecutive channel impulses acquired, for the fixed communication channel in our study. Figure 5.2 shows the measured normalized back-to-back mean PDP 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 purpose). Figure 5.3 shows samples of the mean PDP for three typical (representative of more than 85% of all the estimated mean PDPs) results obtained in the palm plantation under different rain intensities (RI): slight rain ($RI < 2$ mm/hour), moderate rain ($2 \text{ mm/hour} < RI < 10 \text{ mm/hour}$) and heavy rain ($RI > 10$ 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. From Figure 5.2, compared to

the back-to-back system calibration measurement, it can be seen that, besides the first arrival (at the time index of 0 μ s), there are several multipath clusters within a 25 dB (threshold) of the dominant arrival (first arrival) for the dry forested radio propagation channel. This indicates that at 240 MHz, the physical paths/propagation modes in the forested channel are not unique. These multipath clusters might be due to single/multiple reflection, diffraction, scattering, or a combination from the broad leaves, branches and tree trunks. Moreover, it is found that there is a wider main lobe for the dry forested channel (realistic channel), as compared to the back-to-back measurement. This is mainly due to the low time (spatial) resolution of 0.2 μ s (60m) used in the measurements, which makes the multipath components less distinguishable.

Comparing the forested propagation results shown in Figure 5.2 and Figure 5.3, 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 is mainly due to the contribution from the lateral waves as introduced by Tamir [5]. 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 [44] in free space, the dominant component resulting from lateral waves is not affected by the rainy weather condition. Therefore, resulting in an almost constant power for the first arrival regardless of weather conditions.

Figure 5.2 Power delay profile for back-to-back measurement and forested propagation without rain effect.

Figure 5.3 Typical results in the tropical forest under different rainfall intensities.

However, it can be observed from Figure 5.3 that, in general, there is an additional loss induced by the rainfall on the multipath clusters as compared to no rain condition shown in Figure 5.2. This is because, as compared to the almost free-space propagating lateral wave (main composite in the first arrival), the multipath clusters 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 clusters. Therefore, it can be observed that the multipath clusters are attenuated to different extents under different rain intensity conditions. For example, in Figure 5.3, 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 rain rate 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 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 clusters to be attenuated to a different extent.

It is also observed from Figure 5.3 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 distinguishable multipath components as compared to no rainfall, slight rainfall and moderate rainfall conditions. However, this conclusion is not conclusive from the mean PDPs in Figure 5.2 and Figure 5.3.

Table 5.1 Summary of mean RMS delay spread and number of distinguishable multipath clusters in a tropical forest.

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

Next, the RMS delay spread (τ_{rms}), and number of distinguishable multipath clusters (N_{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 mean PDPs. The RMS delay spread is estimated with Equations (2.12) and (2.13), and is summarized in Table 5.1. From Table 5.1, it is observed that, rainfall plays a significant role on the forested radio wave propagation. The RMS delay spread, τ_{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 (forested depth: 50 m, 100 m, and 150 m) and dry foliage has been reported in [41], where there is around 5 ns to 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 mean 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 mean PDPs for the dry foliage.

Moreover, from Table 5.1, 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 [41]. 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 [41]) and the extremely wet tropical foliage in the rainy reason during our measurements, enhance 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 mean PDPs at 240 MHz, and also decreases the RMS delay spread much more as compared to the results presented in [41]. This is also verified through the number of multipath clusters N_{mp} in the estimated mean PDPs as shown in Table 5.1. It is found that for threshold level of 25 dB below the maximum component of the mean PDP, the number of multipath clusters N_{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 distinguishable 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 spatial variations in multipath components generated by the unsteady heavy downpour that induces motion to the wet foliage medium.

In a summary, rainfall effects on the various propagating components in a tropical forest have been investigated in this section. It is found that, the lateral wave at VHF band which is the main contribution in the first arrival, is not affected by the presence of rain as it is similar to free space propagation over the tree tops. The multipath clusters due to the single/multiple reflections, scattering *etc.* are significantly affected by the variation in the rain intensity since they mainly propagate through the foliage medium. 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 spatial variation in the multipath components.

5.1.3 Rainfall Effect on Different Propagation Mechanisms

In the previous subsection, the rainfall effects on the delay statistics have been discussed. It is found that, the distinct rainfall effects on “the wave in air region”

and “the waves through foliage” can result in a variation in the delay statistics as the rain intensity varies. However, the rainfall effect on the each propagation mechanism such as direct wave, single/multiple reflected waves is not fully explored, and will be the focus of this subsection.

This study is conducted with the help of a stratified model (four-layered model [9]-[14]) as shown in Figure 5.4, with the introduction of the two dielectric slabs to represent the canopy and trunk layers. The dielectric canopy and trunk slabs are positioned between the electrically isotropic air layer and the ground layer. The vertical heights of the canopy and trunk layers are h_c and h_t 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 [9]-[14], all four layers are assumed to be magnetically isotropic and characterized by the free space permeability μ_0 .

Figure 5.4 Ray tracing geometry of the direct wave (.....), reflected wave (_ _ _), and lateral wave (____) in a four-layered model.

The radio wave propagation in the abovementioned 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 indicated in Figure 5.4. The analytical work by Li *et al.* [11]-[14] reported that the lateral wave along the air-canopy interface (treetops) plays a major role in the near-ground communication over a large forested depth at VHF and UHF bands. Other propagation modes such as direct waves, and reflected waves as shown in Figure 5.4 also plays an important role in the radio wave propagation over a forested environment. For realistic wireless communications in forested areas however, their contributions to the received field are strongly dependent on the roughness of the interface [17], foliage density and type, and antenna heights *etc.*

A) Propagation Delay

The measured power delay profile for the forested environment under the influence of different rain events as in Figure 5.3 will be used to study the rainfall effects on different propagation mechanisms at VHF band (240 MHz in this study), which is carried out with the propagation delay. The propagation delay can be estimated as [10],

$$t_d = d\sqrt{\varepsilon_r}/c \quad (5.1)$$

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 layers. As shown in Figure 5.4, 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 [6] is shown in Table 5.2. 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 5.2, and ε_1 for the canopy layer is initially taken to be of ‘average’ tropical forests. In [9], ε_1 is varied until a best fit is obtained between their analytical results and the experimental results used by Dence and Tamir in [6]. The estimated ε_1 in [9] is 1.12. This value, together with a value of ε_2 of 1.03 is later used in the analytical study done by Li *et al.* [13] with success. From our previous study in Chapter 4, the proposed empirical path loss model derived from the measured data under dry weather in this tropical forest are in good agreement with the analytical results reported in [13] at VHF band. It can be concluded that, these parameters ($\varepsilon_1 = 1.12$, $\varepsilon_2 = 1.03$) agrees well with the practical dielectric values of this tropical forest under dry weather conditions. 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 5.2 Characteristic parameter of typical forest [6].

Forest type	ε_r
‘Thin’	1.03
‘Average’	1.1
‘Dense’	1.3

Due to the rough interface between the canopy and the trunk layer in this tropical forest as shown in Figure 4.1, the main propagating modes/clusters as

referring in Figure 3.11 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 (Figure 5.4), it can be seen that, the physical propagation path lengths of the lateral wave, the direct wave, and the single ground reflected wave are almost the same when the forested depth is large ($h_c, h_t \ll d$). Therefore, the delay in arrival time of the 3 paths is 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 coming component, 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. Here, the typical mean PDP under heavy rain (24.4 mm/h) as shown in Figure 5.3 is highlighted for discussions, and similar results and analysis can be applied to the PDP under other rain events. The relative propagation delays for the other paths are estimated using Equation (5.1) and given in Table 5.3. Due to the limitation of the sounding technique, the time resolution of the measurement is 0.2 μ s. 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 Figure 5.3 to $\sim 0.17 \mu\text{s}$, as compared to the 3-dB width ($\sim 0.07 \mu\text{s}$) of the back-to-back measurement in Figure 5.2.

Table 5.3 Relative delay for main components in the tropical forest.

Mode	Δt_d
Lateral wave along air-canopy	$0 \mu\text{s}$
Direct wave in trunk layer	$0.04 \mu\text{s}$
Direct wave in canopy layer	$0.12 \text{ to } 0.33 \mu\text{s}$
Reflected wave from ground	$0.04 \mu\text{s}$

Moreover, the second arrival/cluster in the measured PDP for the heavy rain event as shown Figure 5.3 is found to center at $0.26 \mu\text{s}$. This second cluster is probably due to the direct waves propagating in the canopy layer since the theoretically estimated arrival time in Table 5.3 is from 0.12 to $0.33 \mu\text{s}$, by varying the relative permittivity ε_1 in Equation (5.1). The third ($0.43 \mu\text{s}$), fourth ($0.72 \mu\text{s}$) and fifth ($0.94 \mu\text{s}$) 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.

B) Temporal Variations

Typical channel models, such as Gaussian, Rician, Rayleigh, Nakagami, and Weibull distribution functions, are discussed for the rainfall induced temporal variations of the amplitude $a_k(t)$ in the tapped delay line model $h(t, \tau)$ as shown in Equation (2.11). The Akaike's Information Criterion (AIC) based method

proposed by Schuster *et al.* [107] is used in this study to obtain a channel model suitable for the analysis and design of communication systems. The reason for using AIC based method but not the goodness-of-fit (GOF) tests is because, the AIC based method is not only for identifying the good distribution in the candidate set, but also for providing information on the relative approximation quality of each distribution. The theoretical model selection is based on the Akaike weight ω_j , defined as,

$$\omega_j = \frac{e^{-\frac{1}{2}\varphi_j}}{\sum_{i=1}^J e^{-\frac{1}{2}\varphi_i}} \quad (5.2)$$

where $\varphi_j = aic_j - \min_i(aic_i)$, and aic_j is determined by

$$aic_j = -2 \sum_{n=1}^N \log g_{\hat{s}_j}(x_n) + 2U \quad (5.3)$$

where $\min_i(aic_i)$ denotes the minimum aic value over all J candidate families (Gaussian, Rician, Rayleigh, Nakagami, and Weibull distributions in this study), g is the probability density function of the theoretical channel model of interest, $\hat{s}_j$ are the estimated quantities for the distributions by the maximum likelihood estimator (MLE), and U is the dimension of the vector $\hat{s}_j$. N is the number of samples $x = [x_1 \ x_2 \ \dots \ x_N]$ for the tap amplitude $a_k(t)$. As a rule of thumb, $N/U \geq 40$ is required in order to obtain useful aic values [107]. The model with the highest Akaike weight ω_j , is the best distribution in the candidate set. In this study, $N = 1024$, and AIC based method is applied on the measured channel impulse response $h(t, \tau)$ for different rain rates.

The typical mean PDP during a heavy rain (24.4 mm/hour) event and the associated Akaike weight for each candidate family are plotted in Figure 5.5. From Figure 5.5, it is found that, the Weibull function is a better model to describe the tap amplitude distributions for the first three main path clusters (main contribution in the received signal), and the Rayleigh function becomes a better fit for the latter multipath clusters (incoherent components due to multiple scattering mainly). The Weibull and Rayleigh functions are found to give better fit for all the different rain rates considered.

Figure 5.5 Mean PDP and Akaike weights under heavy rain (24.4 mm/hour).

For simplicity, the Weibull function is used as a general channel model to analyze the measured channel since it is analytically tractable. The characteristics of parameter b in the Weibull function, gives an indication of the variation of the

channel as discussed in Chapter 2. The parameter b controls the spread of the distribution; a small value of b corresponds to a large dispersion. Moreover, it is noted that, a value of $b = 2$ yields the Rayleigh distribution, and $b < 2$ implies more severe fading. Therefore, in the following, the Weibull b parameter is used as an indicator to study the rainfall induced temporal variations.

Figure 5.6 (a) Power delay profile in dB, (b) Variation of the Weibull b parameter with the time delay. Both are results under heavy rain (24.4 mm/h).

The corresponding variation of the Weibull b parameter with the time delay for the measured PDP under heavy rainfall is plotted in Figure 5.6. It can be seen that, the empirical Weibull b parameter is very high (~ 14) for the first cluster. It then decreases significantly for the second (~ 5) and third (~ 3.8) clusters. Finally, it falls below 2 for the subsequent arrivals. That is, the first cluster is the most coherent contribution in the received field. 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 where multiple scattering becomes dominant.

Figure 5.7 Variation of the Weibull b parameter with the time delay under different rain rate as in Figure 5.3.

The variation of the Weibull b parameter under different rain events is shown in Figure 5.7 for analysis. From Figure 5.7, it can be seen that, the b parameter for the first cluster 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 [44], it can be concluded that the temporal variation of the second cluster is from the variation of the propagation medium induced by the falling raindrops. With the four-layered model shown in Figure 5.4, only the canopy layer can be significantly 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 subsection, it is concluded that the second arrival cluster is from direct waves propagating through the canopy layer.

The high b (~ 14) value for the first cluster thus indicates no components of the direct waves 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 Figure 5.7, 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 speed of the radio wave propagation 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 Figure 5.7. 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 5.3. The measured time of arrival is in good agreement with the estimated time of arrival.

C) Empirical Dielectric Permittivity

From the analysis given above, an empirical method for deriving the dielectric permittivity of the foliage layers (canopy/trunk layers) is proposed. This is a simple alternative to the one proposed in [16], [108]. From Equation (5.4), the dielectric permittivity for the different foliage layers can be reversely derived from the measured time delay by

$$\varepsilon_r = [\Delta t_d c/d + 1]^2 \quad (5.4)$$

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 free space. In [108], the inverse method is performed by fitting the experimental propagation data into the respective theoretical model containing dielectric parameters. The main advantage of our proposed method is that, it can estimate the dielectric parameters for the individual layers in the four-layer model; the canopy layer; and the trunk layer, whereas the inverse method in [108] and also the method in [16] evaluates the overall dielectric parameter for the entire forest slab.

However, in this proposed method, the accuracy of the derived dielectric permittivity of the different layers depends on the time resolution of the sounding technique. For example, in our study, due to the limitation of the time resolution

(0.2 μ s), only the effective relative permittivity ϵ_1 for the canopy layer (the wave propagating through this layer can be isolated) in this tropical forest can be derived. The estimated effective relative permittivity ϵ_1 for the canopy layer under different rain rates by Equation (5.4) is found to be within the range of 1.17 to 1.23, and it increases as the rainfall rate increases.

In a summary, a study of the different propagation modes/clusters for wireless communications within the forest at VHF band is conducted. Through theoretical estimation and experimental investigation, it is found 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 radio wave propagation over large forested depths at VHF band. Of the different modes /clusters of propagation, the direct waves traveling through the canopy layer is the only waves 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 waves traveling through the canopy layer relative to other propagation modes such as lateral waves and reflected wave; 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 the 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.

5.2 The Combined Effect of Wind and Rain

5.2.1 Measurement Campaign

The combined effect of wind and rain which is often encountered in the tropical forest is studied through the narrowband measurements in this study. The measurements are carried out using CW transmission at 240 MHz and 700 MHz. Omni-directional antennas with a typical gain of 2.4 dBi were used for transmission and reception. Both antennas were kept stationary inside the forested channel and at a fixed height of 2.15 m with vertical polarization throughout the measurements. The radio wave from a signal generator passes through a 10 W high power amplifier before being fed into the transmitting antenna.

Figure 5.8 The schematic diagram of measurement setup and a generic view of the 1st Fresnel zone (@ 240 MHz _ _ _ _ _; @ 700 MHz _____).

At the receiver, the Omni-directional antenna is connected to a low noise amplifier with 2.9 dB noise figure and 20 dB gain before passing into a spectrum analyzer. The span of the spectrum analyzer is set to be 2 kHz around its center frequency to minimize the noise bandwidth. Details of the measurement setup can be found in Figure 5.8. A total of 5001 peak marker readings at 0.01 s intervals

were recorded by a Labview program through a GPIB connection, so as to study the temporal variations due to the effects of wind and rain. It is noted that the tropical forest, where these measurements are conducted, is the same as the one presented in Chapter 4, Section 4.1. The forested depth in this study is 400 m.

The weather information is derived from the same weather RADAR as discussed before. According to the NEA classification system, rain is classified by its rain intensities (RI) as: slight rain ($RI < 2$ mm/hour), moderate rain ($2 \text{ mm/hour} < RI < 10$ mm/hour) and heavy rain ($RI > 10$ mm/hour), whereas wind is classified by the wind speed (WS) as light wind ($WS < 20$ km/hour), windy ($20 \text{ km/hour} < WS < 40$ km/hour) and strong wind ($WS > 40$ km/hour). During this measurement, the slight rainfall experienced ranges from 0.2 to 1.8 mm/hour, the moderate rainfall experienced ranges from 2.6 to 8.6 mm/hour, and the heavy rainfall experienced ranges from 12 to 24.2 mm/hour, while the light wind experienced ranges from 0.7 to 17.6 km/hour, the windy experienced ranges from 24.1 to 30.7 km/hour, and the strong wind experienced ranges from 40.6 to 54.1 km/hour.

(a) Results at 240MHz

(b) Results at 700MHz

Figure 5.9 Typical temporal variations of received signals under different weather phenomena.

5.2.2 Results and Discussions

The typical (representative of more than 78 % of all the estimated results) envelope fading waveforms corresponding to different weather phenomena at 240 MHz and 700 MHz are shown in Figure 5.9. It is found that for both frequencies, the power variations and deep fades are more noticeable as the strength of wind and rain increases. Meaning, fade variations are largely dependent on the wind and rain effects on this tropical forested channel. In general, there is lower received power as wind and rain become stronger. This implies that, strong wind and rain causes higher signal attenuation. The average signal attenuation varies from -65 dBm to -80 dBm, and -90 dBm to -108 dBm respectively for 240 MHz and 700 MHz as the strength of wind and rain increases. This 15 dB and 18 dB variation for 240 MHz and 700 MHz respectively, in signal strength is purely due to weather effects. This shows the significance of wind and rain effects on the temporal variation of the propagating signal even at VHF and UHF band, and has to be taken into account when determining the fade margin for communication systems used in the tropical forested environments.

Empirical cumulative distribution function (CDF) is used to analysis the wind and rain induced effects on the forested radio wave propagation. The empirical CDF results at 240 MHz and 700 MHz, corresponding to the experimental results shown in Figure 5.9, are plotted in Figure 5.10. In Figure 5.10, it is observed that, the received power decreases significantly due to the wind and rain influences. The flatter CDF curve under heavier wind and rain indicates an increase in temporal variations of the received signal. This increase in temporal variation is due to the weather induced motion of the foliage medium since the

transmitting antenna and the receiving antenna are kept stationary during measurements.

(a) CDF at 240MHz

(b) CDF at 700MHz

Figure 5.10 Typical CDF for the weather induced variations.

(a) PDF at 240MHz

(b) PDF at 700MHz

Figure 5.11 Examples of PDF derived from measured data fitted with different distribution under heavy rain and strong windy effects.

In order to model the weather induced temporal effects on the envelope of the received CW signal, the received signal is normalized to its mean [43], [78] to extract the temporal variations. The temporal variation is characterized statistically through the commonly known distributions associated with radio propagation channel [1], [2], and [4], namely Gaussian, Rician, Rayleigh, Nakagami and Weibull as before.

The distribution of the measured data is compared to the five theoretical distributions. Examples of the experimental probability density function (PDF) are plotted in Figure 5.11 (under the effect of heavy rain and strong windy). Using the Maximum Likelihood Estimation (MLE) method [109] in Matlab, the theoretical parameters for the five abovementioned distributions are estimated. The set of parameters that maximizes the likelihood function to fit the measured data is determined.

To find a suitable envelope fade distribution from the Gaussian, Rician, Rayleigh, Nakagami, and Weibull distributions for temporal variation in the fixed communication links, the AIC based method is used in our study. The reason for using AIC based method but not the goodness-of-fit (GOF) tests as in [43], [78] is due to the additional information on the relative approximation quality of each distribution it can provide.

The Akaike weights ω_j as in Equation (5.2), for each distribution under different weather phenomena is calculated and tabulated in Table 5.4, corresponding to the data shown in Figure 5.9. The theoretical model with the

largest ω_j is considered to be the best distribution function of the five for describing the weather induced temporal variations in the forested channel. From Table 5.4, the Weibull distribution functions is found to be a more general model with good fit for the description of wind and rain induced temporal variations for both frequencies (240 MHz and 700 MHz). It is also obvious that the Rician and Rayleigh distribution will become an appropriate model to describe the temporal variations as the strength of the wind and rain increases. This is also similar to the observations reported in [43], [91] for the modeling of temporal variations in the fixed communication link due to the effect from wind.

Table 5.4 Akaike weights ω_j for each distribution at different weather phenomena.

Frequency in MHz	Weather phenomena	Gaussian ω_j	Rician ω_j	Rayleigh ω_j	Nakagami ω_j	Weibull ω_j
240 MHz	No rain; Light wind	1.0000	0.0000	0.0000	0.0000	0.0000
	Slight rain; Windy	0.0000	0.0000	0.0000	0.0000	1.0000
	Moderate rain; Windy	0.0000	0.0000	0.0000	0.0000	1.0000
	Heavy rain; Strong wind	0.0000	0.9947	0.0053	0.0000	0.0000
700 MHz	No rain; Light wind	0.0000	0.0000	0.0000	0.0000	1.0000
	Slight rain; Wind	0.0000	0.0000	0.0000	0.0000	1.0000
	Moderate rain; Wind	0.0000	0.0679	0.0000	0.0000	0.9321
	Heavy rain; Strong wind	0.0000	0.2971	0.3845	0.0000	0.3184

In our later analysis, both the Weibull b factor and the Rician K factor as defined before for Weibull distribution and Rician distribution respectively, will be discussed. This is used to assist a more comprehensive understanding of the forested radio wave propagation with the combined effect from wind and rain. The moment-method [110] is used in our study to estimate the Rician K factor of the received signals under different weather conditions. The empirical Weibull b parameter and Rician K factor are tabulated in Table 5.5 and Table 5.6.

Table 5.5 Weibull b paramter under different weather phenomena.

Frequency in MHz	No rain; Light wind	Slight rain; Windy	Moderate rain; Windy	Heavy rain; Strong wind
240 MHz	10.49	5.17	4.22	1.94
700 MHz	6.01	3.57	2.76	2.31

Table 5.6 Rician K factor under different weather phenomena.

Frequency in MHz	No rain; Light wind	Slight rain; Windy	Moderate rain; Windy	Heavy rain; Strong wind
240 MHz	17.07dB	10.19dB	7.48dB	-3.19dB
700 MHz	11.23dB	6.52dB	3.43dB	-1.99dB

From Table 5.5 and Table 5.6, it can be observed that the Weibull b parameter and the Rician K factor are highly correlated. They decrease as the strength of wind and rain increases for both frequencies. That is, the temporal variation of the received signal increases as the strength of the wind and rain increases. This is because the wind and rain induced movements of the physical elements (such as leaves and branches) within the forested channel increases with the increase in strength of wind and rain. This will therefore increase the signal variance relative to the mean component of the signal strength. It is also observed that under similar weather conditions, in general, at higher frequency (700 MHz), there is a lower Weibull b parameter and Rician K factor. This is because the wavelength is smaller and thus more comparable to the size of the physical elements in the forested channel. Therefore, the higher frequency (700 MHz) gets influenced by the weather effect more readily as compared to the lower frequency (240MHz). An exception can be seen at 700 MHz under heavy rain and strong wind weather condition, where both the Weibull b parameter and Rician K factor are smaller at 240 MHz as compared to that at 700 MHz. This can be explained

with the help of the 1st Fresnel zone as shown in Figure 5.8. The estimated h_0 with Equation (4.8) are 11.2 m and 6.5 m for 240 MHz and 700 MHz respectively.

Comparing this estimated h_0 of the 1st Fresnel zone with the antenna height of 2.15 m, and the palm tree canopy height of 5.6 m, it is found that there are relatively much less randomly distributed broad leaves of the palm tree that falls within the 1st Fresnel zone for 700 MHz as compared to 240 MHz (Figure 5.8). Meaning, most of the 1st Fresnel zone for 700 MHz is occupied by tree trunks where movements due to heavy rain and strong wind is limited as compared to the movement of broad leaves and branches which have significant contributions within the 1st Fresnel zones at 240 MHz. This may be the main reason for the lower Weibull b parameter and Rician K factor at 240 MHz as compared to 700 MHz under the heavy rain and strong wind weather condition.

Furthermore, due to the increase in amount of leaves and branches included in the 1st Fresnel zone at lower frequencies, there is a larger Weibull b parameter (Rician K factor) variation of 8~9 (19~20 dB) due to weather variations at 240 MHz as compared to the Weibull b parameter (Rician K factor) variation of 3~4 (12~13 dB) at 700 MHz. This indicates that, at higher frequencies, the relative increase in the temporal variation is significantly less than those at lower frequencies when the weather conditions changes from no rain with slight wind to heavy rain with strong wind.

5.2.3 Summary

Experimental results with the narrowband measurements indicate that the power variations and deep fades in the received signal are clearly noticeable as the strength of wind and rain increases. Moreover, it is found that the fast fading components due to the weather induced temporal variation can better be modeled using a Weibull/Rician distribution, in general. The decrement of Weibull b parameter (also Rician K factor) as atrocious weather appears indicates an increase of the temporal variation in the received signal at all frequencies. This process is a result of the wind and rain induced movement of the foliage medium. Fewer amounts of temporal variations are observed at higher frequencies as compared to lower frequencies under strong wind and rain conditions since the 1st Fresnel zone decreases in volume as frequency increases thus excluding most of the more moveable scatterers such as the leaves and branches. This study is useful for the design of fade margin for VHF and UHF communication systems in a tropical forest.

5.3 Conclusions

The characterization and modeling of the tropical weather effects on the forested radio wave propagation channel is performed in this chapter. Both the wideband study of rainfall effect and the narrowband investigation of the combined wind and rain effects on a tropical forested channel have been conducted.

It is found that weather effects such as wind, rain *etc.* can vary the property of the forested medium significantly. These weather effects result in an additional

attenuation and temporal variation of the propagating signals. The amount of additional attenuation caused is frequency dependent and can easily affect the reliability of the communication link within the forested environment. The temporal variation induced by the weather effect for forested radio wave propagation can be approximately modeled with Weibull/Rician function.

In order to improve the reliability of the communication link within the forested environments, fade mitigation techniques can be important and might be required. In the next chapter, the feasibility of using one of the popular mitigation techniques: the MIMO technique [45], [46] is discussed and investigated for application within the forested environments.

Chapter 6

Fading Mitigation

The feasibility of using MIMO technique within a forested environment is examined in this chapter. The preliminary experimental investigation is carried out through the wideband channel characterization with SIMO system in a tropical forest. Complex spatial correlation between the SIMO sub-channels has been studied. It is found that the presence of lateral waves in the forested environment is the main reason for the highly dependent multiple propagation paths. These highly dependent multipaths produce a high spatial correlation between diverse receptors when used in a forested environment. The mutual coupling effects between the receptors are analyzed through the study of the antennas' mutual impedance and angular pattern of the receiving array. It is found that, in the forested environment where there is a large angular spread of multipaths, when spatial diversity is used, the coupling induced change in the antenna pattern becomes a dominant factor. This lowers the correlation property between the multiple receptors.

6.1 Introduction

Wireless systems that use multiple antennas at both the transmitter and the receiver to create a MIMO system have drawn considerable attention in recent years [45], [46]. MIMO systems are shown to greatly improve coverage reliability, data rate, capacity, or a combination, thereby enhancing the overall system performance. Achieving these goals, however, requires careful design of the modulation and coding scheme to fully exploit all the degrees of freedom offered by the MIMO system.

Before embarking on the MIMO system (such as modulation and coding scheme) design, the propagation channel of interest needs to be fully explored. This is because the radio propagation channel plays an important role on the system performance [111]-[112], [115]. For example, the correlation between the MIMO sub-channels is a critical factor that affects the channel capacity [111]-[114]. Jensen *et al.* [115] pointed out that the low correlation between the sub-channels is a necessary but not sufficient condition for a good MIMO performance. The propagation channel must also possess some appropriate characteristics (low correlation channel with keyhole effect [116] can degrade the system performance).

With the help of an accurate MIMO radio channel model, high performance MIMO communication systems can be designed and system performance can be accurately predicted. Even for a spatial correlated propagation channel, good system performance can also be achieved if the correlated channel is known beforehand. An example of the application of a MIMO system in a spatially

correlated channel is through the FFT-based hybrid antenna selection scheme as proposed by Molisch *et al.* [117].

Therefore, for the implementation of the MIMO system in a forested environment, the characterization and modeling of the radio wave propagation with multiple antennas within a forest becomes an important topic and is the focus of this chapter. The separation of the antennas is limited to a maximum of 2 m in this study. This is because, for wireless sensor networks implemented on military vehicles such as tanks, the maximum antenna separation is approximately 2 m. Therefore, multiple antennas with a space up to 2 m are examined in this work.

6.2 Measurement Campaign and Data Processing

6.2.1 Measurement Campaign

The forest under consideration in this study is the same as that shown in Chapter 4, Section 4.1, and Chapter 5. The measurements were conducted at 240 MHz with forested depths of 330 m, 400 m, and 710 m. It is noted that, during the measurements, the forest was wet and there was very little or no wind.

A wideband SIMO channel sounding system, which is an upgraded version (two synchronized receiving branches used to form an *antenna array*, and the cables/components in the respective branch are kept identical) of the previous one in Figure 3.4 is used. The measurement methodology in this study is shown in Figure 6.1, and the details of the setup are listed in Table 6.1. For a comparative study of the mutual coupling effect between the two adjacent antennas shown in

Figure 6.1, measurements with a single receptor (antenna) were performed at the corresponding locations where the *antenna array* for the SIMO measurement was placed. The measurements with the single antenna at each location were conducted consecutively within a very short period, and the captured data will be used to build a *virtual array* without the mutual coupling effect as reported in [118]. Note that the direction of arrival of the transmitted wave is fixed at an angle of 90° as shown in Figure 6.1(b) throughout all the experiment campaigns. The investigation of other angles of arrival is also important and is included as one of the future work. During the measurements, there is a restriction on human activities so as to minimize the human induced effects on the measured raw data.

(a) The basic instruments and setup

(b) The layout of the diverse reception. The measurement path of the diverse reception is with a 90° angle respect to the signal arrival direction

Figure 6.1 The schematic diagram of measurement setup.

Table 6.1 Description of the setup.

Transmitter	
Antenna	1
Antenna Height	2.15 m
Frequency	240 MHz
Power	+24 dBm
Modulation Type	BPSK
Data rate	5 Mchips/s
Length of m -sequence	63 bit
Time resolution	0.2 μ s
Receiver	
Antenna	2
Antenna Height	2.15 m
Low Noise Amplifier	20 dB gain & 2.9 dB noise figure
Splitter for Local Oscillator	Max 1° phase unbalance
Intermediate Frequency	20.4 MHz
Digitizer	2 channel (synchronized)
Sampling rate	100 Msample/s
Depth of Forest	330 m, 400 m, 710 m

6.2.2 Data Processing

In order to evaluate the potential implementation of the MIMO technique in the forested environment, the spatial correlation coefficient between the two adjacent antennas with an antenna spacing of d (The methodology is shown in Figure 6.1) is obtained by using (6.1) as in [114], where $h_{1,n}(\tau)$ and $h_{2,n}(\tau)$ are the two corresponding n^{th} complex channel impulse responses estimated from the two individual antennas respectively, and $*$ denotes complex conjugate,

$$\rho(d) = \frac{E \{h_{1,n}(\tau)h_{2,n}^*(\tau)\}}{\sqrt{E \{|h_{1,n}(\tau)|^2\} E \{|h_{2,n}(\tau)|^2\}}} . \quad (6.1)$$

Figure 6.2 Illustration of the sequential correlation.

For the reliable study, the sequential correlation within 1024 time frame for the *antenna array* and the *virtual array* is performed as illustrated in Figure 6.2 respectively, and the average quantities are estimated statistically. This is important, especially for the *virtual array* where the environments at the separate recording period for the respective receiving branch are not exactly the same. Note that unlike the *antenna array*, the *virtual array* with two separate single receptor has no time correlation between the two receiving branch. An example of the distribution for the empirically estimated correlation coefficients for both the *antenna array* and the *virtual array* with an antenna spacing of 1.2λ (λ is the wavelength of the propagating signal) is shown in Figure 6.3. The estimated mean

correlation coefficient is 0.508, with a standard deviation of 0.026 for the *antenna array*, and a mean correlation coefficient of 0.606, with a standard deviation of 0.031 for the *virtual array* at this specific antenna space as shown in Figure 6.3. The variation may be due to the slight variations in the channel due to its complexity and the slight wind induced movement of the channel components during the measurements. Moreover, it is found that there is a slight higher variation of 0.031 for the measurements with the unsynchronized *virtual array* as compared to that of 0.026 for the *antenna array* under the same environments. The estimated mean correlation coefficients with different antenna spaces d for the two reception scenarios (*antenna array* and *virtual array*) are plotted in Figure 6.4.

From Figure 6.4, the estimated correlation coefficient is high for both the *antenna array* reception and the *virtual array* reception (larger than 0.5 even as the antenna spacing is more than 1.5λ , where 1.5λ is close to the maximum space to form a diversity on a military vehicle). High correlation coefficients are also observed at the other two forested depths (330 m and 400 m) with both measurement scenarios: *antenna array* and *virtual array*. In general, the coefficients change from 0.55 to 0.83 at 330 m, 0.63 to 0.87 at 400 m for the antenna spacing d as shown in Figure 6.4. The high correlation coefficient at large forested depth is mainly due to the appearance of lateral wave in the forest, which was first introduced by Tamir [5] and later empirically verified by Tewari *et al.* [28]. This has also been investigated in our previous chapters. The lateral wave travels mostly in the lossless air region and is dominant at large forested depth, especially when both the transmitter and the receiver are placed inside the forest. In this case, there will be a strong dependence of the signals at the respective

receiving branches due to the dominant lateral wave, which is highly coherent, therefore, resulting in high correlation coefficients.

Figure 6.3 Probability density function of spatial correlation coefficient at antenna space of 1.2λ for the *antenna array* and *virtual array*.

Figure 6.4 Spatial correlation coefficients with different dual-receptor separation d at a forested depth of 710 m.

Furthermore, it can be observed that the correlation coefficients are smaller when the *antenna array* is used as compared to the *virtual array*. Since other influences and variations are kept to a minimum during the measurements, the difference in correlation coefficient is attributed mainly to the coupling effect in the *antenna array*. This means that the appearance of the mutual coupling between elements of the *antenna array* decreases the correlation of the signals captured by each element. As known, the mutual coupling can induce current/voltage on each receiving terminal (which can be characterized by the mutual impedance) and result in a variation of the antenna pattern. In the following part, both the mutual coupling induced effects; mutual impedance; and antenna angular pattern variation, on the correlation properties will be discussed in detail.

6.3 Results and Discussions

Mutual coupling effects on the antenna array have been of great interest to many researchers [119], [120], and [121]-[123]. Recently, two frameworks for the analysis of MIMO wireless systems have been introduced to account for mutual coupling effects of the antenna arrays by Wiesbeck *et al.* [121] and Jensen *et al.* [122]. The mutual coupling effect on the performance of wireless systems have been evaluated successfully with the analysis of the mutual impedance [120], [122] and the antenna pattern [123] between the antenna arrays. Hence, these two parameters: mutual impedance and antenna pattern are discussed below for our study of the mutual coupling effect on the spatial correlation properties between the antenna arrays.

6.3.1 Receiving Mutual Impedance

From the experimental results, it is found that the mutual coupling can influence the correlation property between the received signals when the *antenna array* is used. In an *antenna array*, the spacing between the antenna elements is very important. When the antenna space is small (less than 1λ), as shown in Figure 6.4, the spatial correlation coefficient for the *antenna array* is much smaller than that of the *virtual array*. However, when the antenna spacing is increased to more than 1λ , the spatial correlation coefficient between the *antenna array* and the *virtual array* approaches the same value. Also noted is the fact that, the larger the antenna separation, the smaller the correlation coefficient, in general. These findings also hold for measurements at 330 m and 400 m.

Figure 6.5 The theoretical receiving mutual impedance with $50\ \Omega$ load.

For a detailed understanding of the coupling effect, the mutual impedance is used to evaluate the mutual coupling effect between the two receiving branches. For the estimation of the mutual impedance at the receiving terminals, Hui *et al.* [119] proposed a new method where the antennas are excited by a plane wave, instead of exciting one antenna with a voltage source and calculating the excited current at the second antenna. His results showed a high consistency between the measured and theoretically calculated receiving mutual impedance. In this study, the method described in [119] is used. The theoretical receiving mutual impedance is calculated using a simulation tool, *4nec2* [124], which is the Numerical Electromagnetic Code (NEC) [125], a method of moment (MoM) based antenna modeler and optimizer. The simulated mutual impedance is shown in Figure 6.5.

From Figure 6.5, it is observed that the mutual impedance between the two receiving terminals decreases gradually as the antenna spacing increases. Of particular interest is when the antenna spacing is 1.2λ , the mutual impedance is found to be zero. This shows a negligible antenna coupling induced current/voltage at one another's receiving terminal. Therefore, the correlation coefficient for both the *antenna array* and the *virtual array* at an antenna spacing of 1.2λ is expected to be the same. However, the empirically estimated correlation coefficient shows a difference of around 0.1 at this antenna spacing as shown in Figure 6.4.

Theoretically, examining the correlation coefficient from the point of the receiving mutual impedance, the correlation coefficient should increase when there is a mutual coupling between the diverse receptor. This is because the coupling effect can induce an additional current/voltage on the other branch, and causes the

received signals at the two separate branches to be dependent on each other. However, an opposite trend is observed in this experiment. The correlation coefficient is smaller when the *antenna array* is used as compared to the case when the *virtual array* is used.

These indicate that the mutual coupling induced current/voltage on each terminal is not the dominant effect which influences the correlation property between the diverse receptors. In the next subsection, another coupling induced effect: the variation of the antenna angular pattern is studied.

6.3.2 Angular Pattern Effect

In an *antenna array*, the coupling between the diverse terminals affects not only the induced current/voltage on each receiving element, but also the antenna angular radiation pattern of the *antenna array*. Through the numerical simulation, antenna pattern in the receiving mode has been calculated using a vertically linear polarized plane wave propagating in the +Y direction towards a two-element *antenna array*. Both antennas are terminated with $50\ \Omega$ load as in real measurements. The estimated 3-D angular patterns with axial ratio and 2-D antenna patterns in E and H planes under different scenarios are shown in Figure 6.6 to Figure 6.9 for discussion, respectively.

From previous discussions, the receiving mutual impedance for the antenna spacing of 1.2λ is zero, however, there is a difference of around 0.1 between the correlation coefficients for the *antenna array* and the *virtual array*. The antenna patterns shown in Figure 6.6 and Figure 6.8 provide a good explanation. It is

observed that when the *antenna array* with a spacing of 1.2λ is used, the mutual coupling induces a change in the antenna angular pattern resulting in the array being more directive in the direction of the incoming wave (towards +Y direction) in the H-plane in Figure 6.8 as compared to the isolated antenna pattern in Figure 6.6. A large angular spread of the scattered components in the forest is indicated by a comparative study in [41]. In [26], the angular spread of the multipath (scattered components) is reported to be at least 30° in azimuth and 20° in elevation when a scan was performed using a narrow beam-width (1.2° and 4.8°) receiving antenna by performing an azimuth scan over an angular range of $\pm 15^\circ$ and an elevation scan over an angular range of $\pm 10^\circ$. Therefore, it can be concluded that the mutual coupling induced directivity makes the received signal less dependent since the captured components are from radiation sources at different spatial directions (propagating paths). This results in a smaller correlation between the two receptors of the *antenna array*.

As the antenna spacing d increases, the coupling effect will decrease in theory. This is consistent with the fact that as the antenna spacing d increases to 1.52λ in the measurements, the correlation coefficients for both the *antenna array* and *virtual array* converges (Figure 6.4). This is because the coverage of the antenna pattern for the *antenna array* (Figure 6.9) in the direction of the incoming wave becomes broader as compared to those with a smaller antenna space as shown in Figure 6.7 and Figure 6.8. This makes the antennas in the *antenna array* at a space 1.52λ capture the incoming signals from the similar excited sources compared to those for the antennas in the *virtual array*, and result in the processed correlation coefficients close to each other.

(a) 3-D pattern with axial ratio

(b) 2-D antenna pattern in E-plane

(c) 2-D antenna pattern in H-plane

Figure 6.6 Antenna pattern of single antenna for the *virtual array* in receiving mode and with a termination of $50\ \Omega$ load.

(a) 3-D pattern with axial ratio

(b) 2-D antenna pattern in E-plane

(c) 2-D antenna pattern in H-plane

Figure 6.7 Antenna pattern of the *Antenna array* with 0.8λ space in receiving mode and with terminations of $50\ \Omega$ load.

(a) 3-D pattern with axial ratio

(b) 2-D antenna pattern in E-plane

(c) 2-D antenna pattern in H-plane

Figure 6.8 Antenna pattern of the *Antenna array* with 1.2λ space in receiving mode and with terminations of $50\ \Omega$ load.

(a) 3-D pattern with axial ratio

(b) 2-D antenna pattern in E-plane

(c) 2-D antenna pattern in H-plane

Figure 6.9 Antenna pattern of the *Antenna array* with 1.52λ space in receiving mode and with terminations of $50\ \Omega$ load.

Furthermore, results in Figure 6.5 show that, the mutual impedance for the *antenna array* with an antenna spacing of 0.8λ and 1.52λ are very similar, in terms of both amplitude and phase. This implies that theoretically, their difference in correlation coefficient between the *antenna array* and the *virtual array* at these spacing should be similar. However, from Figure 6.4, the difference in the correlation coefficient between the *antenna array* and the *virtual array* at 0.8λ is 0.2, whereas the difference in the correlation coefficient at 1.52λ is only 0.03. With similar mutual impedance at 0.8λ and 1.52λ , the difference in the correlation coefficient is definitely due to the mutual coupling induced antenna angular pattern variations shown in Figure 6.7 and Figure 6.9. The mutual coupling at the small spacing of 0.8λ in the *antenna array* strongly affects the antenna angular pattern and makes it more directive (less coverage) as shown in Figure 6.7 and therefore, decreases the correlation coefficient quite a lot (0.2). Whereas at the antenna spacing of 1.52λ in Figure 6.9, although the antenna pattern is also affected, the capture coverage of incoming signal is much broader, therefore, produces a small difference in the correlation coefficient. This further validates the previous conclusion that the mutual coupling induced directivity of the receiving terminal makes the received signal less dependent since the captured components are from radiation sources at different spatial directions, and results in a smaller correlation coefficient.

Comparisons of the antenna patterns for two scenerios are performed in this study; two antennas with load terminations of $50\ \Omega$ in the receiving mode, where the vertically polarized plane wave in the +Y direction incidents on the two receiving antennas; and two antennas both excited with voltage sources (active

mode). Example of the antenna patterns in the H-plane under both scenerios with 1.52λ space is shown in Figure 6.10. It can be found that, the patterns are similar. The main difference is that, the pattern under active mode is symmetrical, while the pattern under receiving mode is stronger in the antenna foreside in the direction of the incident plane wave. The observation holds for all the scenarios with different antenna spacings. This shows that, both antennas in the receiving mode actually act as active element due to the induced voltage/current on the antenna array when the plane wave incidents on the antennas. Therefore, the induced voltage/current on the antenna elements causes coupling between the antenna elements and thus have a similar performance as the two active antenna elements (excited with voltage sources). As the seperation between the two-antenna elements increases, the coupling between the two antennas decreases correspondingly.

(a) Receiving mode

(b) Active mode

Figure 6.10. 2-D antenna pattern of the *Antenna array* with 1.52λ space in H-plane.

6.4 Conclusions

This chapter investigates experimentally the spatial correlation property between the SIMO sub-channels in a tropical forest for the potential implementation of MIMO technology at military frequency band. The main focus of the chapter is on the antenna coupling induced effect on the correlation property.

It is observed that for the radio wave propagation in the forested environment at VHF band, the appearance of lateral waves at large forested depth results in a strongly dependent physical propagation channel. This produces an overall high correlation coefficient regardless of the antenna spacing, and indicates a poor potential for MIMO applications even in the rich scattering forested environments at VHF band.

Moreover, the theoretical and experimental results show that the antenna coupling effect on the correlation property between the diverse receptors depends on the interplay between the receiving mutual impedance and the antenna angular pattern [120]. In our measurements, the mutual coupling induced variation of the antenna angular pattern is found to be the dominant factor, since it reduces the correlation properties between the SIMO sub-channels significantly. Therefore, when designing a system with multiple antennas for the applications in forested environments, one has to look at both the mutual coupling impedance and the antenna angular pattern of the *antenna array*.

Chapter 7

Conclusions and Recommendations

7.1 Conclusions

In this thesis, the empirical channel characterization and modeling of the forested environments have been conducted and reported. Special attention is given to the near-ground propagation in forested environments at VHF and UHF bands. This is due to the recent interest in military applications such as military surveillance, and battlefield communication networks. In order to perform a reliable research study, four major measurement campaigns (lasting for 2 to 4 weeks each) have been carried out in different forests located in Singapore. Based on the investigation and analysis, the results and contributions of this thesis have been made over the existing research works, and can be summarized into three major categories below.

1. The VHF and UHF radio wave propagation at the tree trunk layer of the forested environments is emphasized in this research work due to practical military applications. The propagating waves are found to experience multiple scattering, diffraction, and absorption of radiation *etc.* The dominant propagation mechanism

is dependent on the forested depth. At a short forested depth, the coherent component is dominant which makes the reflection from the tree canopy an important potential source of contribution. However, the significance of this tree canopy reflection will vary depending on the operating frequency and the type of forest. As the forested depth increases, the incoherent (diffuse) components due to the forward scattering caused by leaves and branches become dominant. This tends to counteract the loss due to absorption and attenuation. When the forested depth is increased further, the lateral wave along the treetops becomes the main contribution to the received field.

Based on these investigations, a new empirical methodology of path loss modeling in the forested environments is proposed by superimposing the foliage effect on the dominant propagating waves. The empirical studies within several forests show that the lateral wave needs to be considered for high accuracy path loss modeling at long-range. Whereas the tree canopy reflections needs to be considered for high accuracy path loss modeling at short-range. Thereby, a new LITU-R model which accounts for the lateral wave effect over a large forested depth is proposed and verified with both measured data and published data where different type of plantations and antenna heights have been experienced. It was found to model the long-range path loss with higher accuracy as compared to other models. For short-range path loss modeling, it is proposed that the contribution from the tree canopy reflections has to be considered. The contribution is highly dependent on the relative roughness (relative to the operating frequency) of the lower boundary formed by the tree canopy. When the possible contribution from canopy reflection exists, it can reduce the forest induced attenuation significantly.

2. Heavy rainfall and strong wind are very often experienced in the tropical and equatorial regions like Singapore. These weather effects will naturally vary the properties of the foliage medium. For example, after a heavy downpour, the tree trunks are often wet and therefore, more conductive. It results in a variation in path attenuation of the radio wave propagation. This variation in path attenuation depends on the frequency of operation. Similarly, wind causes movement of a foliage channel. Therefore, the understanding of the effects from both the wind and the rain on a foliage channel is important. The focus of this thesis is on the understanding of the weather effects on a forested channel so as to improve the reliability of communication links for military applications. These weather conditions are examined in two parts:

i) The rainfall is found to have distinct effects on various parts of the propagating components for the VHF radio wave propagation in the tropical forest. Through the study 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 treetops. However, the multipath components which propagate through the forested medium are significantly affected by the presence of rain. This is verified through the estimated delay spread statistics and also the empirical dielectric constant of the canopy layer.

ii) Narrowband study of the combined effect due to the wind and rain on the propagating waves is conducted. The fast fading components due to the

weather induced temporal variation is studied and modeled statistically. It is found that the distribution of fast fading components resembles a Weibull/Rician distribution function. Its Weibull b parameter/Rician K factor decreases gradually as the strength of wind and rain increases. Moreover, it is observed that the power variations and deep fades in the received signal are clearly noticeable as the strength of wind and rain increases.

3. The feasibility of using the MIMO technique within a forested environment to improve the reliability of communication link is examined in this thesis. It is found that the presence of lateral wave in the forested environment is the main reason for the highly dependent multiple propagation paths. These highly dependent multipaths produce a high spatial correlation between diverse receptors when used in a forested environment. The mutual coupling effects between the receptors are analyzed through the study of the antennas' mutual impedance and angular pattern of the receptor array. It is found that, in the forested environment where there is a large angular spread of multipaths, when MIMO technique is used, the coupling induced change in the antenna pattern becomes a dominant factor. This lowers the correlation property between the multiple receptors.

This research work allows for the understanding of VHF and UHF radio wave propagation in the forested environment when both terminals are embedded in the tree trunk layer (near-ground). In this study, the path loss modeling is performed with the considerations of lateral wave contribution at long-range forested path, and the possible contribution of the tree canopy reflection at short-range forested path. The additional weather effects on the path loss in the forested

environment are also discussed. Weather effect is found to be an important factor which can result in deep fades in the received field. In order to compensate the fading effect, a popular mitigation technique: the MIMO technique is studied preliminarily. The coupling effect between the diverse receptor is discussed.

7.2 Recommendations for Future Work

Based on the empirical studies developed in this thesis, there is great potential in extending the scope of the present work. Some recommendations are given below.

1. The present time-domain sounding system in Section 3.1.2B can be improved. An oscilloscope based receiver, which is a general-purpose laboratory instrument, is recommended. The oscilloscope based receiver can be developed with more receiving branches, and high sampling rate (the sampling rate can go up to 4 Gsample/s normally).

2. The accuracy of the proposed LITU-R model needs to be further improved with more experimental data covering larger forested depth. The present model only considers three types of plantations. The data from different operational contexts and physical situations can make the LITU-R model semi-universally applicable.

3. The existence and possible contribution of the tree canopy reflection for short-range radio wave propagation in forests need to be further investigated and verified. The present study of the tree canopy reflection is based on the

investigation of the forested depth dependence. The contribution of the tree canopy reflection can be further studied with the antenna height dependence for short-range forested propagation.

4. An empirical model for the variations of Weibull b parameter/Rician K factor with wind speed/rain intensity can be derived based on long-term measurements. This is useful for the design of link budget of any communication system. The excess loss of the wet foliage medium with forested depth can also be an interesting research topic. This work can be extended to seasonal and diurnal variations to develop a more general empirical model for forested propagation.

5. The most interesting work that needs to be carried out is the application of the mitigation technique: MIMO techniques in the forested environment. Our present work is just a preliminary investigation of one aspect for the implementation of MIMO techniques; the spatial correlation at the receiver where the measurement path is 90 degrees with respect to the direction of the signal arrival. The Binary Error Rate (BER), diversity gain, and the spatial correlation at the receiver where the measurement path is with other angles with respect to the direction of the signal arrival *etc.* in the forests also needs to be explored. Other mitigation techniques should also be considered. Moreover, more efforts are needed to make towards wideband channel characterization with a better sounding resolution (presently at 5 Mchips/s). A more thorough wideband model of the propagation mechanism suitable for MIMO system evaluation should be pursued.

Some recommendations for future work are given in this section. The present sounding system can be improved to allow for better resolution and dynamic range. More measurements and experimental data are suggested to improve the accuracy of the proposed LITU-R model, to further verify the possible contribution from the tree canopy reflection for short-range forested propagation, and to further investigate the weather induced effect on a forested channel. Most importantly, further studies on the use of a MIMO system within a forested environment for the improvement in the reliability of the communication link should be performed. The research topic covered is very interesting and there are numerous research works that need to be done in this area.

Author's Publications

Portions of the work reported in this thesis have been published previously in the following papers.

Journal Papers Published

1. Y. S. Meng, Y. H. Lee, and B. C. Ng, "Further study of rainfall effect on VHF forested radio-wave propagation with four-layered model," *Progress In Electromagnetics Research*, vol. PIER 99, pp. 149-161, 2009.
2. Y. S. Meng, Y. H. Lee, and B. C. Ng, "The effects of tropical weather on radio-wave propagation over foliage channel," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 8, pp. 4023-4030, Oct. 2009.
3. Y. S. Meng, Y. H. Lee, and B. C. Ng, "Study of propagation loss prediction in forest environment," *Progress In Electromagnetics Research B*, vol. 17, pp. 117-133, 2009.
4. Y. S. Meng, Y. H. Lee, and B. C. Ng, "Study of the diversity reception in a forested environment," *IEEE Transactions on Wireless Communications*, vol. 8, no. 5, pp. 2302-2305, May, 2009.

5. Y. S. Meng, Y. H. Lee, and B. C. Ng, "Empirical near ground path loss modeling in a forest at VHF and UHF bands," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 5, pp. 1461-1468, May, 2009.
6. Y. S. Meng, Y. H. Lee, and B. C. Ng, "Investigation of rainfall effect on forested radio wave propagation," *IEEE Antennas and Wireless Propagation Letters*, vol. 7, pp. 159-162, 2008.
7. Y. S. Meng, Y. H. Lee, and B. C. Ng, "VHF and UHF channel characterization in a tropical rainforest," *Journal on Information Technologies and Communications, English Series on "Research, Development and Application on Electronics, Telecommunications and Information Technology"*, no. 2, pp. 3-10, Dec. 2007, Vietnam. ISSN 0866-7039. **[Invited]**

Journal Papers under Review

8. Y. S. Meng, Y. H. Lee, and B. C. Ng, "Path loss modelling for near-ground VHF radio-wave propagation through forest with tree-canopy effect," submitted to *IET Microwaves, Antennas & Propagation*, in Nov. 2009, under review.
9. Y. S. Meng, and Y. H. Lee, "Investigations of foliage effect on modern wireless communication systems: a review," submitted to *IET Communications*, in Nov. 2009, under review.

Conference Papers Published

1. Y. H. Lee, and Y. S. Meng, "Investigation of low altitude air-to-ground channel over a tropical sea surface at C band," in *Proc. 26th Progress In Electromagnetics Research Symposium*, Moscow, Russia, Aug. 2009, pp. 414-417. Selected to publish in *PIERS Online*, vol. 5, no. 4, pp. 385-388, 2009.

2. Y. S. Meng, Y. H. Lee, and B. C. Ng, "Statistical modeling of rainfall effect on a foliage propagation path," in *Proc. 2009 IEEE AP-S International Symposium on Antennas and Propagation and 2009 USNC/URSI National Radio Science Meeting*, Charleston, South Carolina, USA, Jun. 2009.
3. Y. S. Meng, and Y. H. Lee, "Practical wideband channel sounding system for air-to-ground measurements at C band," in *Proc. IEEE International Instrumentation and Measurement Technology Conference*, Singapore, May, 2009, pp. 771-775.
4. Y. S. Meng, Y. H. Lee, and B. C. Ng, "Near ground channel characterization and modeling for a tropical forested path," in *Proc. XXIXth URSI General Assembly*, Chicago, USA, Aug. 2008.
5. Y. H. Lee, Y. S. Meng, and Y. H. Heng, "Experimental characterizations of an air to land channel over sea surface in C band," in *Proc. XXIXth URSI General Assembly*, Chicago, USA, Aug. 2008.
6. Y. H. Lee, Y. S. Meng, and O. N. Tay, "Characterization of Wi-Fi antenna system on a remote controlled helicopter," in *Proc. 2008 Asia-Pacific Symposium on Electromagnetic Compatibility & 19th International Zurich Symposium on Electromagnetic Compatibility*, Singapore, May, 2008, pp. 319-322.
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