FOLIAGE ATTENUATION IN URBAN TROPICAL VEGETATION AT MILLIMETER WAVE FREQUENCY BANDS

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This thesis is dedicated to my family especially my beloved husband, sons, parents, siblings and friends for their unconditional support, inspiration and motivation.

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ABSTRACT

Millimeter wave (mmWave) bands offer greater bandwidth for the 5th Generation (5G) communication system in order to achieve higher data rates. Understanding the mmWave channel is a fundamental requirement to develop the future 5G systems. Therefore, extensive field measurements with respect to the behavior in realistic channels must be carried out to characterize these bands. To date, little knowledge is established on the foliage attenuation of mmWave bands in tropical environment. Existing measurements have been carried out mostly in the temperate region where the vegetation has different physical characteristics compared to those in tropical region. Thus, this research aims to measure and characterise the foliage attenuation in urban tropical environment. The site for real time data collection is located within Universiti Teknologi Malaysia Kuala Lumpur campus where vegetation geometries are observed as a single tree or a row of trees within small cell radius up to 200 m. Both the deployed direct Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) links operate at millimeter frequencies particularly at 6, 10, 18, 20, 28 and 38 GHz. The measurement system is arranged based on typical narrowband setup under full foliage environment. The received signal strength (RSS) is collected throughout the experiment in foliated environment and compared to the free space measurement. A signal generator is configured to transmit pure continuous wave through a steerable directional horn antenna. The RSS values are captured on a portable spectrum analyzer. In general, the measurement results show that the most significant foliage attenuation is caused by the NLOS link through the trunk followed by the branches and tree-top. Average foliage attenuation observed to be highest at 38 GHz between 18.1 dB to 30.6 dB and lowest at 6 GHz between 11.3 dB to 22.9 dB for NLOS slant paths obstructed by a single tree. Meanwhile a single tree obstruction at horizontal path induces foliage attenuation of 44.28 dB at 20 GHz by Eugenia tree, whereas the lowest attenuation of 22.35 dB at 6 GHz is attributed by weeping bottlebrush tree. On the other hand, the highest foliage attenuation induced by a line of trees occurs to be 49.86 dB at 28 GHz. Other important factors such as measurement geometry and vegetation density are observed. For instance, the foliage attenuation is higher at denser foliage and larger foliage depth. In general, the existing empirical models underestimate the tropical foliage measurements. The inaccuracies of these models could be due to the fact that the size, types and density of trees in tropical region is different from temperate region. It is found that the overall trend shows that foliage attenuation is more severe at higher mmWave frequencies at least by 21 dB as compared to the lower ones.

ABSTRAK

Gelombang milimeter frekuensi (mmWave) menawarkan jalur lebar yang lebih besar untuk sistem komunikasi Generasi ke-5 (5G) untuk mencapai kadar data yang lebih tinggi. Memahami saluran mmWave merupakan keperluan asas untuk membangunkan sistem-sistem 5G masa depan. Oleh itu, ukuran lapangan yang menyeluruh berkenaan dengan tingkah laku dalam saluran persekitaran realistik perlu dilakukan untuk mencirikan jalur gelombang ini. Setakat ini, sedikit pengetahuan pada rosotan perambatan mmWave oleh dedaunan di rantau tropika telah diketahui. Kebanyakkan ukuran sedia ada telah dijalankan di rantau sederhana. Tapak pengumpulan data terletak di dalam kampus Universiti Teknologi Malaysia Kuala Lumpur di mana geometri tumbuh-tumbuhan dikenal pasti sebagai pokok tunggal atau deretan pokok dalam radius sel kecil sehingga 200 m. Kedua-dua garis nampak (LOS) dan bukan garis nampak (NLOS) beroperasi pada frekuensi milimeter terutamanya pada 6, 10, 18, 20, 28 dan 38 GHz. Sistem pengukuran adalah berdasarkan persediaan jalur sempit lazim di dalam persekitaran dedaun penuh. Kekuatan isyarat yang diterima (RSS) dikumpul sepanjang eksperimen dalam persekitaran dedaun penuh dan ruang bebas. Penjana isyarat dikonfigurasikan untuk menghantar gelombang tulen berterusan melalui antena corong berarah boleh-kendali. Nilai RSS dirakam pada penganalisa spektrum mudah alih. Secara umum, keputusan pengukuran menunjukkan rosotan perambatan oleh dedaunan yang ketara disebabkan oleh pautan NLOS melalui batang pokok diikuti oleh dahan-dahan dan puncak pokok. Rosotan purata disebabkan oleh semua 3 pautan diperhatikan adalah tertinggi pada 38 GHz antara 18.1 dB kepada 30.6 dB dan terendah pada 6 GHz antara 11.3 dB kepada 22.9 dB untuk pautan NLOS yang serong yang dihalang oleh sebatang pokok. Sementara pautan secara mendatar yang dihalang oleh sebatang pokok menyebabkan rosotan dedaun 44.28 dB pada 20 GHz oleh pokok Eugenia. Manakala, rosotan purata terendah iaitu 22.35 dB pada 6 GHz disebabkan oleh pokok Weeping bottlebrush. Sebaliknya, rosotan tertinggi disebabkan oleh barisan pokok ialah 49.86 dB pada 28 GHz. Faktor penting yang lain seperti geometri pengukuran dan kepadatan tumbuh-tumbuhan dikenalpasti. Sebagai contoh, rosotan dedaun adalah lebih tinggi disebabkan oleh dedaun yang lebih padat pada kedalaman dedaunan yang lebih besar. Secara umum, model empirik sedia ada adalah di bawah anggaran pengukuran dedaunan tropikal. Ketidaktepatan model ini mungkin disebabkan oleh saiz, jenis dan kepadatan pokok di rantau tropika yang berbeza dari rantau sederhana. Didapati bahawa rosotan perambatan oleh dedaunan pada frekuensi gelombang milimeter lebih tinggi adalah ketara sekurang-kurangnya sebanyak 21 dB berbanding dengan gelombang milimeter yang lebih rendah.

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LIST OF ABBREVIATIONS

5G	-	5th Generation
5GIC	-	5G Innovation Centre
5GNOW	-	5th Generation Non-Orthogonal Waveforms for Asynchronous Signalling
BS	-	Base Station
CA	-	Carrier Aggregation
CoMP	-	Coordinated Multipoint
CW	-	Continuous Wave
dB	-	Decibel
DBA	-	Distorted Born approximation
dBm	-	Power ratio in dB referenced to one milliwatt
dRET	-	Discrete RET
EHF	-	Extremely High Frequency
eMBB	-	Enhanced Mobile Broadband
ETSI	-	European Telecommunications Standards Institute
FCC	-	Federal Communications Commission
Gbps	-	Giga-bit-per-second
GHz	-	Gigahertz
IQR	-	Interquartile Range
ISI	-	Inter Symbol Interference
ITS	-	Intelligent Transportation Systems
LMDS	-	Local Multipoint Distribution Service
LTE	-	Long Term Evolution
LTE-A	-	Long Term Evolution-Advanced
LOS	-	Line-of-Sight
M2M	-	Machine-to-Machine
MA	-	Maximum Attenuation
MED	-	Modified Exponential Decay
MHz	-	Megahertz
MIMO	-	Multiple-Input Multiple-Output
mmWave	-	Millimeter Wave

MMSE	-	Minimum Mean Square Error
mMTC	-	Massive Machine Type Communication
MNOs	-	Mobile Network Operators
METIS	-	Mobile and Wireless Communications Enablers for the Twenty-twenty Information Society
MoM	-	Method of Moments
NLOS	-	Non-Line-of-Sight
NZG	-	Nonzero Gradient
NGMN	-	Next Generation Mobile Networks
PLE	-	Path Loss Exponent
QoS	-	Quality of Service
RSS	-	Received Signal Strength
SHF	-	Super High Frequency
UHF	-	Ultra High Frequency
U-NII	-	Unlicensed National Information Infrastructure
UTM	-	Universiti Teknologi Malaysia
UWB	-	Ultra Wide Band
URLLC	-	Ultra-Reliable Low Latency Communications
VHF	-	Very High Frequency
VNA	-	Vector Network Analyzer
VNI	-	Visual Networking Index
WiFi	-	Wireless Fidelity
WLAN	-	Wireless Local Area Network
WPAN	-	Wireless Personal Area Network
WRC	-	World Radiocommunication Conference

LIST OF SYMBOLS

λ - Wavelength
P_r - Received Signal Power
P_t - Transmitted Signal Power
G_t - Transmitter Antenna Gain
G_r - Receiver Antenna Gain
m - Meter
cm - Centimeter
π - Pi
θ - Angle
C - Constant
c - Speed of light
f_c - Carrier Frequency
f - Frequency
d - The transmitter and receiver separation distance in meters
L_{fs} - Free Space Path Loss
L_{fol} - Foliage Path Loss
A - Foliage Attenuation
α - Attenuation Rate in dB/m
n - Path Loss Exponent
X_S - Gaussian distributed random variable
σ - Variance of random component
L - Loss in dB
A_m - Maximum Attenuation
R_0 - Initial Attenuation value in dB/m
R_{infty} - Final Specific Attenuation value in dB/m
d_1 - RX Antenna to Foliage distant
h_1 - Height of RX Antenna
d_2 - TX Antenna to Foliage distant
h_2 - Height of TX Antenna
d_{TR} - Separation Distance of RX and TX Antennas

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CHAPTER 1

INTRODUCTION

1.1 Brief Introduction

Smart phone usage has been growing exponentially ever since it was introduced. By 2020, mobile and wireless traffic volume is expected to increase thousand-fold over 2010 figures [1]. There would be billions of devices when the network is ready for 5G deployment due to many new applications beyond personal communications [2]. The rise in the number of users and devices and the demand for higher data rates suggest a serious challenge to the current mobile communication systems.

Today's cellular system and wireless devices operating frequency spectrum is typically from 700MHz to 6GHz with channel bandwidth of 5 to 100 MHz. The current allocated frequency bands below 6 GHz are almost fully utilized [3]. To overcome the bandwidth congestion, great amount of underutilized spectrum between 3GHz to 300GHz with wavelength of 1-100 mm better known as millimeter wave (mmWave) spectrum has the capability to be exploited for future 5G mobile communication system [4, 5]. The massive amount of channel bandwidth and potential multi-Gigabit per-second (Gbps) data rates in the mmWave band present a new opportunity for future broadband mobile communication systems [6]. These bands were previously ruled out due to the propagation impairments such high path loss, rain attenuation, penetration loss, atmospheric absorption, foliage attenuation etc.

The channel bandwidth of mmWave channel is much larger than the microwave frequency i.e. 500MHz per channel or more as compared to today's microwave bandwidth of 5-20MHz [7]. The small wavelength enables large amount of antennas to be placed in the transceiver, encouraging the use of multi-input and multi-output (MIMO) technique to improve the spectral efficiency and simultaneously provide coverage enhancement [8]. Interest in mmWave research is driven by the desire to accommodate the 5G system with solid foundation: to support massive capacity and connectivity, to accommodate the Quality of Service (QoS) requirement and efficiently make use of available spectrum [1].

One of the critical impairments in outdoor non-line-of-sight (NLOS) mmWave propagation is foliage attenuation. Foliage attenuation is the excess loss cause by foliage and vegetation obstruction along the propagation paths. The involved physical process in the propagation of the radio wave through vegetation is complex due to foliage structure which is composed of randomly oriented trunks, branches, twigs and leaves [9]. Absorption, scattering, diffraction and depolarization can cause the propagating signal to deviate from its path [10]. The foliage attenuation in tropical region could differ from the ones in temperate region. Tropical vegetation has broad leaves whereas leaves of vegetation in temperate region are generally needle-like and the vegetation is evergreen all year round in tropical environment unlike in the temperate region. Moreover, foliage effect is more pronounced with contribution of environmental factors such as wind, rain precipitation and humidity. In order to understand the nature of trees in which the radio wave is travelling into, it is critical to study the impact of foliage effect in mmWave propagation.

1.2 Problem Statement

Despite the potential of mmWave, there are a number of challenges in realizing the vision of mobile networks in these bands. MmWave signals exhibit reduced diffraction and a more specular propagation than their microwave counterparts, and hence they are much more exposed to blockages [7, 11]. An outdoor urban environment objects such as foliage [12, 13], high-rise buildings[4, 14, 15], vehicular traffic and pedestrian [16, 17] are large relative to the wavelength and this causes pronounced propagation effect when a given link is obstructed.

Large scale path loss prediction has been the fundamental technique used in cellular planning and design since the advent of cellular industry. The existing prediction models may not be sufficiently accurate to characterize the path loss on cellular systems in tropical region. Early propagation measurements and models have only recently become available when underutilized mmWave frequency spectrum is being explored [6, 18]. It is necessary to have empirical results that reflect the true behavior of the radio channel (i.e., the propagation channel characteristic due to foliage). Recent studies suggest that mmWave propagation has wider coverage when highly directional steerable antennas are used at the base station and mobile device compared to omnidirectional antennas used in present-day microwave counterparts[7, 19]. One of the critical impairments in mmWave communication is the propagation loss through foliage. Due to the small wavelength, the mmWave signal tends to be prone to the blockage due to foliage, which requires a larger margin in the link budget for the system design [4, 6, 7].

To date, there is insufficient knowledge of foliage attenuation for mmWave propagation in outdoor urban tropical environments [3, 6, 9]. Previous, measurements have been carried out mostly in the temperate region. Existing literature has focused primarily on the 28 and 38 GHz Local Multipoint Distribution Service (LMDS). Field measurements on tropical foliage attenuation have been carried out in the emerging of WiFi technology, wireless sensor network (WSN) and broadband fixed wireless access but the frequency investigated is limited to the range 2.4 and 5.8 GHz [20, 21, 22]. Therefore, measurements and analyses to characterize the foliage attenuation are essential to allow realistic modeling of mmWave channel characteristic before an efficient 5G mobile communication system can be realized.

1.3 Objectives of Research

The objectives of the research are as follows:

1) To conduct received signal strength (RSS) measurement in free space and tropical foliated channels at mmWave frequencies in three different measurement scenarios; single tree at slant path, single tree at horizontal path and a line of trees.

2) To analyze the foliage attenuation over various mmWave frequencies and foliage depths at different type of trees.

3) To formulate the Path loss exponent of measured attenuation as a function of vegetation depth.

1.4 Scope of Research

Feasibility study is conducted on both the fundamental theory of radiowave propagation and the foliage effect on the narrowband link performance. The site for data collection is located within UTM Kuala Lumpur campus and vicinity areas since it represents an urban outdoor tropical environment where vegetation geometries can be observed as: (1) single tree and (2) a row of trees within small cell radius up to 200 m. Both the deployed Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) links operate at mmWave frequencies particularly at 6, 10, 18, 20, 28 and 38 GHz. 28 and 38 GHz are chosen as they are considered as potential frequencies for future 5G mobile systems. While the rest of frequencies are chosen as reference based on other foliage studies found in the literature [19, 23, 24, 25, 26]. Investigation of foliage attenuation is performed on 7 species of common tropical trees in urban area. There are Angsana, Golden Penda, Ficus, Eugenia Brush Cherry, Red Palm, Weeping bottlebrush and Eugenia Oleina.

The measurement system is arranged based on typical narrowband setup on full leaf vegetation. The narrowband measurement enables thorough study of foliage effects on radio propagation through, around and underneath the vegetation medium. The NLOS links comprise of 3 different scenarios namely a single tree obstruction at slant path, a single tree obstruction at horizontal path and a line of trees obstruction. All scenarios are observed at the aforementioned 6 mmWave operating frequencies.

The received signal strength (RSS) is collected throughout the experiment in dry foliated environment only. Neither wind effect nor precipitation is observed in this research. The narrowband channel model development is beyond the scope of this thesis. Also, wideband parameter such as RMS delay spread will not be covered in this study due to equipment constrain. The empirical results are validated by comparison with existing empirical models and simulated using MATLAB.

1.5 Contributions of the Thesis

This study has collected RSS measurements results from the 6, 10, 18, 20, 28 and 38 GHz narrowband channel in free space and foliated environment. Directional horn antennas have been used for both slant and horizontal paths on 7 species of common tropical trees.

Empricial results show that for slant path geometry measurement, the trunk of the trees attenuates the signal more than the branches and treetop links due to scattering from the lower region of the canopy and the diffraction loss caused by major fresnel zone blockage. The relationship between attenuation and foliage depth appears to be nonlinear where the attenuation rate is initially higher at small foliage depth and become smaller at larger foliage depths. The empirical foliage attenuation rates can be used to estimate the total path loss through foliage in a common urban area in future mmWave ray-tracing algorithms and upper-layer system design.

1.6 Organization of Thesis

The thesis consists of five chapters, each describing particular area of the research.

Chapter 1 briefly introduces the millimeter wave cellular system followed by the problem statement, objectives and scope of the research as well as the contributions of the thesis.

Literature Review is detailed in Chapter 2. The essential theory of propagation in wireless communication is reviewed in order to understand the inevitable path loss due to foliage. Previous studies and developed models are also presented.

Chapter 3 describes the research methodology including the outdoor setups used for the RSS measurement. Tree species are identified physically. The simulation software MATLAB is utilized in order to analyze and clearly visualize the overall data.

Chapter 4 explains the results and analyses of the measured data. Evaluation and foliage attenuation relationship to the mmWave frequencies, tree types and foliage depth are presented in this chapter. Path loss exponent or average path loss over the separation distance is discussed as well.

Finally, this thesis is concluded in Chapter 5. Key findings and recommendations for future research works are described.

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