INFLUENCES OF WIND AND RAIN ON RADIO WAVE PROPAGATION IN FOLIATED FIXED WIRELESS ACCESS AT 5.8 GHz

NOR AISHAH BINTI MUHAMMAD

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

AUGUST 2012

This thesis is specially dedicated to
my family for their endless support, encouragement, inspiration and motivation
throughout my academic career

ACKNOWLEDGEMENT

First and foremost, I would like to express my utmost gratitude to my project supervisor, Prof. Dr. Tharek Abd Rahman for being a dedicated mentor in guiding me towards the completion of this research. Special thanks to my co-supervisor, P.M. Ir. Dr. Sharul Kamal Abdul Rahim for allocating his time on giving advice and support throughout this project. I would also like to give my most sincere thanks to Dr. Ian Wassell from Digital Technology Group, University of Cambridge for his valuable advice and assistance to improve this project.

My warmest thanks are extended to my family especially to my husband, for his unconditional understanding and advices when I seem to lose my focus in studies. Besides that, I would like to thank all former and current staffs and students of Wireless Communication Centre (WCC) for being so accommodating and affable for their cooperation and assistance especially to Mr. Mohamad, Mr. Chua Tien Han, Mr. Khomeini and Mr. Hafizul who helped a lot in measurement process. Finally, my deepest appreciation goes to my dearest friends for their endless love, support and motivation. Needless to say, this dissertation could have not been completed without the aforementioned people as well others who might have contributed indirectly.

ABSTRACT

Movement of objects due to wind and rain in the vicinity of fixed wireless access introduces an adverse environment for high frequency radio wave propagation. In recent years, fixed wireless access deployed in suburban and rural areas are surrounded by large number of trees and hills. Although the transmitter and receiver of fixed wireless access remain in stationary positions, movement of trees in this foliated fixed wireless access would scatter, diffract and absorb the wireless signal causing signal fading. In this study, the focus was on the measurement temporal scale of the received signal strength in foliated fixed wireless access operating at the 5.8 GHz frequency of the Unlicensed National Information Infrastructure band. Based on the temporal scale of the measured received signal strength profiles of three different links comprising one line-of-sight and two non line-of-sight links, it was observed that line-of-sight link worked well even when it rained. The existence of trees in the vicinity of the transmission path caused signal deterioration where the received signal strength faded from 3 dB to 16 dB as the rain intensity increased. The wetness in the trees caused by rain had affected the received signal strength. To characterize the measured received signal strength, statistical characterization of the combined effects of several typical weather phenomena often experienced in a tropical region was also presented. The Rician distribution was used to characterize the fast fading effect due to both wind and rain. A smaller K-factor of the distribution represented more intense wind and rain conditions. Meanwhile, Log-normal distribution was found to be suitable in describing the slow fading characteristics in a foliated channel. The work reported in this thesis has determined the effects of wind and rain in the deployment of fixed wireless access in foliated channel to ensure optimized links be provided for end users.

ABSTRAK

Pergerakan objek-objek yang disebabkan oleh angin dan hujan di sekitar capaian wayarles tetap mengujudkan keadaan buruk kepada perambatan gelombang radio berfrekuensi tinggi. Kebelakangan ini, capaian wayarles tetap yang dipasang di kawasan pinggir dan luar bandar adalah dikelilingi oleh pokok-pokok dan bukit-bukit. Walaupun, penghantar dan penerima capaian wayarles tetap ini berada pada kedudukan pegun, pergerakan pokok-pokok di kawasan capaian wayarles tetap yang berdedaun akan memecah, membelau dan menyerap isyarat wayarles menyebabkan berlakunya pemudaran isyarat. Dalam kajian ini, tumpuan dibuat kepada kekuatan isyarat penerima berskala masa yang diterima dalam capaian wayarles tetap di kawasan berdedaun yang beroperasi pada frekuensi 5.8 GHz Prasarana Maklumat Kebangsaaan Tanpa Lesen. Berdasarkan isyarat penerima berskala masa yang di ukur pada tiga sambungan yang berbeza terdiri daripada satu sambungan garis nampak dan dua sambungan garis tidak nampak, diperhatikan bahawa sambungan garis nampak berada dalam keadaan baik meskipun pada ketika hujan. Kewujudan pokok-pokok di sekitar laluan rangkaian menyebabkan kemerosotan isyarat di mana kekuatan isyarat penerima berubah daripada 3 dB kepada 16 dB apabila kekuatan hujan bertambah. Kebasahan dalam pokok-pokok yang disebabkan oleh hujan telah menjejaskan kekuatan isyarat yang diterima. Untuk mencirikan kekuatan isyarat yang diterima, pencirian statistik daripada kesan gabungan beberapa fenomena cuaca yang kebiasaannya dialami oleh rantau tropika juga dibentangkan. Taburan Rician telah digunakan untuk mencirikan kesan cepat pudar yang disebabkan oleh angin dan hujan. Faktor-K yang kecil daripada taburan mewakili keadaan yang lebih berangin dan hujan. Sementara itu, taburan Log-normal didapati sesuai untuk menggambarkan ciri-ciri pemudaran perlahan yang berlaku di dalam kawasan berdedaun. Hasil kajian dalam tesis ini telah menentukan kesan angin dan hujan dalam pemasangan capaian wayarles tetap di dalam kawasan berdedaun untuk memastikan rangkaian yang optimum dapat di berikan kepada pengguna.

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LIST OF ABBREVIATIONS

BFWA	-	Broadband Fixed Wireless Access
BWA	-	Broadband Wireless Access
CAT5e	-	Category 5e
dB	-	Decibel
dBm	-	Power ratio in dB referenced to one milliwatt
dBW	-	Power in dB relative to one Watt
DG	-	Dual Gradient
dRET	-	Discrete RET
DTM	-	Digital Terrain Model
FCC	-	Federal Communications Commission
FWA	-	Fixed Wireless Access
IEEE	-	Institute of Electrical and Electronics Engineers
IP	-	Internet Protocol
ISS	-	Integrated Sensor Suite
ITU	-	International Telecommunication Union
ITU-R	-	ITU-Recommendation Sector
LOS	-	Line of Sight
MAC	-	Media Access Control
MED	-	Modified Exponential Decay Model
MLE	-	Maximum Likelihood Estimation
MMD	-	Malaysia Meteorological Department
MWA	-	Mobile Wireless Access
NaN	-	not a number
nLOS	-	near line of sight
NLOS	-	Non Line of Sight
NZG	-	Non-Zero Gradient
OFDM	-	Orthogonal Frequency Division Multiplexing

PC	-	Personal Computer
PDF	-	Probability Density Function
PTP	-	Point-to-Point
RET	-	Radiative Energy Transfer
RMS	-	Root mean square
ROF	-	Rate of Fall
RSS	-	Received Signal Strength
SNR	-	Signal-to-Noise Ratio
UNII	-	Unlicensed National Information Infrastructure
UPS	-	Uninterruptible Power Supply
UTM	-	Universiti Teknologi Malaysia
UTP	-	Unshielded twisted pair
VHF	-	Very High Frequency
WCC	-	Wireless Communication Centre
WLANs	-	Wireless Local Area Networks

LIST OF SYMBOLS

P_t	-	Transmitted signal power
G_t	-	Transmitter antenna gain
G_r	-	Receiver antenna gain
d	-	The transmitter and receiver separation distance in meters
L_s	-	System loss factor
L_f	-	Free space path loss
Le	-	Excess loss
L	-	Total path loss
f	-	Frequency
h_t	-	Height of the transmitter
h_r	-	Height of the receiver
r	-	Fresnel zone radius
n	-	Integer
λ	-	Wavelength
d_1	-	Distance from one end terminal to point where Fresnel zone is being determined in meters
d_2	-	Distance from the other end terminal to point where Fresnel zone is being determined in meters
r_1	-	First Fresnel zone
E_o	-	Free space field strength
$F(v)$	-	Complex Fresnel integral
α	-	Diffraction angle
L_d	-	Diffraction Loss

γ	-	Specific attenuation
E_{rms}	-	RMS Error
N	-	Number of the sample points
E_i	-	Difference between the experimental and theoretical values
s	-	Amplitude of constant component
σ	-	Variance of random component

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CHAPTER 1

INTRODUCTION

1.1 Background of Research

Nowadays, wireless technology is as an important alternative to its wired counterpart for delivering information to the end users. Deployment of wireless network has attracted great interest in recent years especially in suburban and rural areas whereby these technologies allow less investment in deployment costs, particularly for last-mile connectivity in densely populated areas. As a result, there is an increasing demand for wireless communication to deliver both higher bandwidth and better quality of service. Variants of wireless access services include Fixed Wireless Access (FWA), Mobile Wireless Access (MWA) and Broadband Wireless Access (BWA) [1]. In an FWA setup, both the transmitter and receiver are either fixed on top of a building's rooftop or mounted on a wall. The transmitter and receiver are usually separated by a significant distance, requiring therefore an in-depth understanding of the transmission path used by the radio waves.

Broadband Fixed Wireless Access (BFWA) is currently one of the most popular wireless solutions due to the advantages provided by the technology to the subscriber access area. The solution is able to offer competitive investment and maintenance costs, high speed data transfer rate, high scalability as well as high capacity [2]. Technical specifications for broadband wireless access system for different coverage ranges and frequency bands, known as 802.11a, 802.11b, and 802.11g [1], are provided by Institute of Electrical and Electronics Engineers (IEEE) as part of their activities on the Wireless Local Area Networks (WLAN) The wide deployment of WLAN in densely populated areas such as private residential area, airports and university campuses however leads to cases of heavy utilization and congestion in the frequency spectrum used by the 802.11b/g band. In addition, the frequency spectrum suffers from interference due to the usage of devices that operate in the same 2.4 GHz range such as blue-tooth, cordless phone and microwave ovens. Therefore, 802.11a can be used as a bridging system to create a wireless link in these congested areas. 802.11a band uses a licensed-exempted frequency band which is also known as the Unlicensed National Information Infrastructure (UNII) band that was developed by the Federal Communications Commission (FCC) in 1997. The designated spectrum for the band covers both the 5150- 5350 MHz and 5725-5825 MHz bands with a total of twelve non-overlapping channels, giving 802.11a significant aggregate bandwidth and reliability advantages over 802.11b/g. Moreover, 802.11a can provide higher data rates up to 54 Mbps compared to 802.11b by using Orthogonal Frequency Division Multiplexing (OFDM) modulation format.

1.1 Problem Statement

Since the performance of wireless communication systems depends greatly on the characteristics of the transmission medium, a thorough knowledge of the surrounding environment is crucial in ensuring excellent wireless link performance. In FWA, both transmitter and receiver are remained in stationary position, thus the movement of objects in the vicinity could deteriorate the received power level. The presence of trees in the vicinity of a fixed wireless link for example induces a significant fading impact on the radio wave propagation [3-7]. It is however common for trees to be present between the transmitting and receiving antennas especially in suburban and rural regions which surrounded by a large number of trees and hills. Furthermore, the changes experienced by the trees such as growth over time will affect the condition of the link performance. However, removing all these natural obstructions is considered unrealistic. This scenario occurs in the wireless network deployed within Universiti Teknologi Malaysia (UTM). UTM has an area of 1777 hectares that consists of a large number of trees and hills while the transmitter and receiver antennas are usually positioned below rooftop level or near to the ground. Since the accommodation for students in UTM is scattered, internet access via a wired network is less cost-effective compared to the BFWA. The wireless technology is less expensive than its wired counterpart as the wireless technology requires significantly less investment in the cabling infrastructure. However, the presence of trees in the vicinity of the transmission path can cause fading of the transmitted signal which subsequently affects the overall wireless link performance.

Weather is another important factor that needs to be considered in foliated wireless link. Previous studies have focused on weather-induced effects such as wind-flow and rainfall in temperate region [8-11] but little consideration has been given to date to the weather-induced effects in tropical region, particularly in the UNII band. Although it is well known that the rain significantly affects radio wave propagation in transmission frequencies above 10 GHz for line of sight (LOS) link**,** the rain effect is most likely results in temporary failure of the wireless link at 5.8 GHz, yet it is still remained less addressed. The existing prediction models may not be sufficiently accurate to characterize the fading on fixed wireless access in tropical region. Thus, a thorough analysis on how both wind and rain affect wireless links in a tropical or an equatorial region is required since this region is surrounded by trees which retain most of their leaves throughout the year. Moreover, this region has an extensive amount of water in the atmosphere due to the heavy rainfall that occurs frequently throughout the year. The accumulations of rain water on the tree components possibly become a dominant source of absorption hence contribute to attenuation in the propagating wave.

1.3 Objectives of the Research

Based on the research problem statement above, the research objectives are therefore:

1) To investigate the additional loss caused by vegetation blockage that exists in the vicinity of installed fixed wireless links.
2) To identify additional losses introduced by different wind and rain condition in foliated channel.
3) To analyze the temporal variation of received signal strength (RSS) due to wind and rain in foliated channel.

1.4 Scope of Research

The research first studies extensively both the concept of outdoor wireless propagation and the fading phenomena that affect the link performance. The site used for real time data acquisition is located in the UTM campus area where fixed point-to-point links serve as bridges deployed in the wireless network used to provide internet connection in the student's accommodation. Both the deployed LOS and NLOS links operate at 5.8 GHz.

In order to obtain the received signal strength (RSS), a signal that provides an indication of the quality of the link, and its temporal variation, scripting commands are executed using a router board and radio unit. The scripting commands are remotely logged by a server located in Wireless Communication Centre (WCC), UTM. Weather information such as rain, wind and humidity meanwhile are recorded using a Davis Vantage Pro 2 wireless weather station that is installed near the experimental sites. MATLAB coding is subsequently used to match the RSS logged at any given time to the relevant weather data. Later, ICS-Telecomm is used to predict the additional attenuation for obstructed LOS links.

1.5 Organization of Thesis

The thesis is divided into five chapters, each focusing on a particular area of the research. The thesis is organized as follows:

Chapter 1 briefly introduces fixed wireless access technology and states the problem to be investigated, the objectives of this research and the scope of the project.

In Chapter 2, the essential theory and propagation model relevant to the research field are reviewed in order to better understand the fading phenomena. Previous studies and developed models are also presented. Furthermore, the chapter introduces the theoretical principles of propagation study used in the analysis carried out in Chapter 4. This chapter also explains the Malaysian weather, in particular both the local wind flow and rainfall distribution.

Chapter 3 describes the research methodology including the outdoor setups used for both the RSS measurement and the weather station. The simulation software Kiwi Syslog Daemon, Kiwi Log Viewer, and MATLAB are utilized in order to analyze and clearly visualize the overall data. This chapter also presents the simulation steps to predict the RSS and clutter losses using ICS-Telecomm.

Chapter 4 explains the results and conducts a statistical analysis of the measured data. The data obtained from each link is analyzed and further discussed. This chapter also presents the validation of the measurement by comparing the simulation results and the measured data. Discrepancies and agreement between the simulation and measurement results are also explained in detail.

Finally, this thesis is concluded in Chapter 5. Moreover, important project findings, key contributions and recommendations for future research works are described.

REFERENCES

1. Pandya, R., *Introduction to WLLs: Application and Deployment for Fixed and Broadband Services*. 2003, Piscataway, N.J.: Prentice Hall.
2. Morais, D.H., *Fixed Broadband Wireless Communications: Principles and Practical Applications*. 2004, New Jersey: Pearson Education.
3. Al-Nuaimi, M.O. and A.M. Hammoudeh, *Measurements and predictions of attenuation and scatter of microwave signals by trees.* Microwaves, Antennas and Propagation, IEE Proceedings -, 1994. 141(2): p. 70-76.
4. Dal Bello, J.C.R., G.L. Siqueira, and H.L. Bertoni, *Theoretical analysis and measurement results of vegetation effects on path loss for mobile cellular communication systems.* Vehicular Technology, IEEE Transactions on, 2000. 49(4): p. 1285-1293.
5. Gans, M.J., et al., *Propagation measurements for fixed wireless loops (FWL) in a suburban region with foliage and terrain blockages.* Wireless Communications, IEEE Transactions on, 2002. 1(2): p. 302-310.
6. Pelet, E.R., J.E. Salt, and G. Wells, *Effect of wind on foliage obstructed line-of-sight channel at 2.5 GHz.* Broadcasting, IEEE Transactions on, 2004. 50(3): p. 224-232.
7. Yu Song, M., et al. *Wind and rain influences on forested radiowave propagation*. in *Antennas and Propagation Society International Symposium, 2007 IEEE*. 2007.
8. Hashim, M.H. and S. Stavrou, *Wind influence on radio waves propagating through vegetation at 1.8 GHz.* IEEE Antennas and Wireless Propagation Letters, 2005. 4: p. 143-146.
9. Joshi, G.G., et al., *Near-ground channel measurements over line-of-sight and forested paths.* IEEE Proceedings - Microwaves, Antennas and Propagation, 2005: p. 589-596.
10. Lewenz, R. *Path loss variation due to vegetation movement*. in *IEE National Conference on Antennas and Propagation*. 1999.
11. Pelet, E.R., J.E. Salt, and G. Wells, *Effect of wind on foliage obstructed line-of-sight channel at 2.5 GHz.* IEEE Transactions on Broadcasting, 2004. 50(3): p. 224-232.

12. Pahlavan, K. and P. Krishnamurthy, *Principles of Wireless Networks: A Unified Approach*. 2002, USA: Prentice Hall.
13. Rappaport, T.S., *Wireless Communication Principles and Practices*. 2nd ed. 2002, USA: Prenctice Hall Inc.
14. Lecours, M., et al., *Statistical modeling of the received signal envelope in a mobile radio channel.* IEEE Transactions on Vehicular Technology, 1988. 37(4): p. 204-212.
15. Barclay, L.W., *Propagation of Radiowaves*. 2003, UK: The Instituition of Electrical Engineers.
16. Anderson, H.R., *Fixed Broadband Wireless System Design*. 2003, UK: John Wiley & Sons Ltd.
17. Feuerstein, M.J., et al., *Path loss, delay spread, and outage models as functions of antenna height for microcellular system design.* IEEE Transactions on Vehicular Technology, 1994. 43(3): p. 487-498.
18. Saunders, S.R. and A.A. Zavala, *Antennas and Propagation for Wireless Communication Systems*. 2007, UK: John Wiley & Sons Ltd.
19. S. Helhel, Ş. Özen, and a.H. Göksu, *Investigation of GSM signal variation depending weather conditions.* Progress In Electromagnetics Research B, 2008. 1: p. 147-157.
20. Howard H. Xia, et al., *Radio Propagation Characteristics for Line-of -Sight Microcellular and Personal Communications.* IEEE Transactions on Antennas and Propagation, 1993. 41(10): p. 1439-1447.
21. Parsons, J.D., *The Mobile Radio Propagation Channel*. 2000, UK: John Wiley & Sons Ltd.
22. Pearce, J. and D. Mittleman, *Defining the Fresnel zone for broadband radiation.* Physical Review E, 2002. 66(5): p. 056602.
23. Deygout, J., *Multiple Knife-Edge diffraction of microwaves.* IEEE Transactions on Antennas and Propagation, 1966. AP-14(4): p. 480-489.
24. Epstein, J. and D.W. Peterson, *An Experimental Study of Wave Propagation at 850 MC.* Proceedings of the IRE, 1953. 41(5): p. 595-611.
25. ITU-R, *Attenuation in vegetation*, in *P.833-6*, I.T. Union, Editor. 2007: Geneva.
26. Head, H.T., *The Influence of Trees on Television Field Strengths at Ultra-High Frequencies.* Proceedings of the IRE, 1960. 48(6): p. 1016-1020.

27. LaGrone, A. and C. Chapman, *Some propagation characteristics of high UHF signals in the immediate vicinity of trees.* IRE Transactions on Antennas and Propagation, 1961. 9(5): p. 487-491.

28. Lagrone, A.H., P.E. Martin, and C.W. Chapman, *Height gain measurements at VHF and UHF behind a grove of trees.* IEEE Transactions on Broadcasting, 1963. BC-9(1): p. 37-54.

29. Weissberger, M.A., *An initial critical summary models for predicting the attenuation of radio waves by foliage*, in *Electromagnetic Compatibility Analysis Center*. 1981, MD: Annapolis.

30. Yu Song, M., L. Yee Hui, and N. Boon Chong, *The Effects of Tropical Weather on Radio-Wave Propagation Over Foliage Channel.* IEEE Transactions on Vehicular Technology, 2009. 58(8): p. 4023-4030.

31. Crosby, D., et al. *Time variability of the foliated fixed wireless access channel at 3.5 GHz*. in *Vehicular Technology Conference* 2005.

32. Baum, D.S., et al. *Measurement and characterization of broadband MIMO fixed wireless channels at 2.5 GHz*. in *IEEE International Conference on Personal Wireless Communications*. 2000.

33. Gans, M.J., et al., *Propagation measurements for fixed wireless loops (FWL) in a suburban region with foliage and terrain blockages.* IEEE Transactions on Wireless Communications, 2002. 1(2): p. 302-310.

34. Greenstein, L.J., et al., *Ricean K-Factors in narrow-band fixed wireless channels: Theory, experiments, and statistical models.* IEEE Transactions on Vehicular Technology, 2009. 58(8): p. 4000-4012.

35. Hashim, M.H. and S. Stavrou, *Measurements and modelling of wind influence on radiowave propagation through vegetation.* IEEE Transactions on Wireless Communications, 2006. 5(5): p. 1055-1064.

36. Perras, S. and L. Bouchard. *Fading characteristics of RF signals due to foliage in frequency bands from 2 to 60 GHz*. in *The 5th International Symposium on Wireless Personal Multimedia Communications*. 2002.

37. Benzair, B., H. Smith, and J.R. Norbury. *Tree attenuation measurements at 1-4 GHz for mobile radio systems*. in *Sixth International Conference on Mobile Radio and Personal Communications*. 1991.

38. Hansen, F. and F.I. Meno, *Mobile fading: Rayleigh and lognormal superimposed.* IEEE Transactions on Vehicular Technology, 1977. 26(4): p. 332-335.

39. N. C. Rogers, et al., *A generic model of 1-60 GHz radio propagation through vegetation - Final Report*. 2002.

40. Yu Song, M., L. Yee Hui, and N. Boon Chong, *Study of propagation loss prediction in forest environment.* Progress In Electromagnetics Research B, 2009. 17: p. 117-133.

41. International Telecommunication Union, *Recommendation and Reports of CCIR, 1986 (also questions, study, programmes, resolutions, opinions and decisions)*, in *Propagation in Non-Ionized Media*. 1986, ITU: Geneva.

42. International Telecommunication Union, *Attenuation in vegetation*, in *Recommendation ITU-R P.833-7*. 2012, Radio Communication Sector of ITU: Geneva.

43. Seville, A. and K. Craig, *Semi-empirical model for milimetrewave vegetation attenuation rates.* Electronic Letter, 1995. 31(17): p. 1507-1508.

44. Al-Nuaimi, M.O. and R.B.L. Stephens, *Measurements and prediction model optimisation for signal attenuation in vegetation media at centimetre wave frequencies.* IEEE Proceedings -Microwaves, Antennas and Propagation, 1998. 145(3): p. 201-206.

45. Seville, A., *Vegetation attenuation: Modelling and measurements at milimetric frequencies*, in *IEE 10th International Conference on Antennas and Propagation*. 1997: Edinburgh, Scotland. p. 2.5-2.8.

46. Meng, Y.S. and Y.H. Lee, *Investigations of foliage effect on modern wireless communication systems : A review.* Progress In Electromagnetics Research M, 2010. 105.

47. Johnson, R.A. and F. Schwering, *A transport theory of milimeter wave propagation in woods and forest*, in *Technical Report CECOM-TR-85-1*. 1985: Forth Monmouth.

48. Al-Nuaimi, M.O. and A.M. Hammoudeh, *Measurements and predictions of attenuation and scatter of microwave signals by trees.* IEE Proceedings - Microwaves, Antennas and Propagation, 1994. 141(2): p. 70-76.

49. Schwering, F., E.J. Violette, and R.H. Espeland, *Millimeter-wave propagation in vegetation: Experiments and theory.* IEEE Transactions on Geoscience and Remote Sensing, 1988. 26(3): p. 355-367.

50. Didascalou, D., M. Yuunis, and W. Wisbeck, *Milimeter-wave scattering and penetration in isolated vegetation structures.* IEEE Transactions on Geoscience and Remote Sensing, 2000. 38(5): p. 2106-2113.

51. Fernandes, T.R., et al., *A discrete RET model for millimetre-wave propagation in isolated tree formations.* IEICE Transaction Communication, 2005. E88-B(6): p. 2411-2418.

52. Fernandes, T.R., et al. *Modeling radiowave propagation through vegetation media: A comparison between RET and dRET models*. in *Second European Conference Antennas Propagation*. 2007. Edinburgh, UK.

53. Tewari, R.K., S. Swarup, and M.N. Roy, *Radio wave propagation through rain forests of India.* IEEE Transactions on Antennas and Propagation, 1990. 38(4): p. 433-449.

54. Cavdar, I.H., *UHF and L band propagation measurements to obtain log-normal shadowing parameters for mobile satellite link design.* IEEE Transactions on Antennas and Propagation, 2003. 51(1): p. 126-130.

55. Cavdar, I.H., H. Dincer, and K. Erdogdu. *Propagation measurements at L-band for land mobile satellite link design*. in *Proceedings 7th Mediterranean Electrotechnical Conference*. 1994.

56. Durgin, G., T.S. Rappaport, and X. Hao, *Measurements and models for radio path loss and penetration loss in and around homes and trees at 5.85 GHz.* IEEE Transactions on Communications, 1998. 46(11): p. 1484-1496.

57. St Michael, H. and I. Otung. *Characterization and prediction of excess attenuation of microwave radio signals by vegetation forms*. in *Twelfth International Conference on Antennas and Propagation (ICAP 2003)*. 2003.

58. Naz, N. and D.D. Falconer. *Temporal variations characterization for fixed wireless at 29.5 GHz*. in *IEEE 51st Vehicular Technology Conference Proceedings*. 2000.

59. Al-Nuaimi, M.O. and R.B.L. Stephens, *Estimation of the effects of hilltop, singly distributed, trees on the path loss of microwave signals.* Electronics Letters, 1997. 33(10): p. 873-874.

60. Iskander, M.F. and Y. Zhengqing, *Propagation prediction models for wireless communication systems.* IEEE Transactions on Microwave Theory and Techniques, 2002. 50(3): p. 662-673.
61. Torrico, S.A., H.L. Bertoni, and R.H. Lang, *Modeling tree effects on path loss in a residential environment.* IEEE Transactions on Antennas and Propagation, 1998. 46(6): p. 872-880.
62. Dilworth, I.J. and B. L'Ebraly. *Propagation effects due to foliage and building scatter at millimetre wavelengths*. in *Ninth International Conference on Antennas and Propagation*. 1995.
63. Kajiwara, A., *Foliage attenuation characteristics for LMDS radio channel.* IEICE Transaction Communication, 2000. E83-B(9): p. 2130-2134.
64. Hashim, M.H. and S. Stavrou, *Dynamic impact characterization of vegetation movements on radiowave propagation in controlled environment.* IEEE Antennas and Wireless Propagation Letters, 2003. 2: p. 316-318.
65. Hashim, M.H., D. Mavrakis, and S.R. Saunders. *Measurement and analysis of temporal fading due to moving vegetation*. in *Twelfth International Conference on Antennas and Propagation*. 2003.
66. Liou, A., et al., *Characterization of fading on fixed wireless channels between 200 MHz and 2 GHz in suburban macrocell environments.* IEEE Transactions on Wireless Communications, 2009. 8(10): p. 5356-5365.
67. Robert, K.C., *Propagation Handbook for Wireless Communication System Design*. 2003, USA: CRC Press LLC.
68. Ramachandran, V. and V. Kumar, *Invariance of accumulation time factor of Ku-band signal in the tropics.* Journal of Electromagnetic Waves and Applications, 2005. 19(11): p. 1501-1509.
69. Recommendation and Reports of the CCIR, *Report 563-2 ITU/CCIR*. 1982.
70. Mandeep, J.S. and K. Tanaka, *Effect of Atmospheric Parameters on Satellite Link.* International Journal of Infrared and Millimeter Waves, 2007. 28(10): p. 789-795.
71. *Malaysian Meteorological Department*. 2012, Ministry of Science Technology and Innovations (MOSTI) Jalan Sultan, Petaling Jaya, Selangor.
72. Jamaludin Suhaila, et al., *Trends in Peninsular Malaysia Rainfall Data During the Southwest Monsoon and Northeast Monsoon Seasons: 1975–2004.* Sains Malaysiana, 2010. 39(4): p. 533-542.

73. Darus, Z.M., et al., *The Development of Hybrid Integrated Renewable Energy System (Wind and Solar) for Sustainable Living at Perhentian Island, Malaysia.* European Journal of Social Sciences, 2009. 9(4): p. 557-563.

74. Farriz, M.B., et al. *A study on the wind as a potential of renewable energy sources in Malaysia*. in *2010 International Conference on Electrical Engineering/Electronics Computer Telecommunications and Information Technology (ECTI-CON)*. 2010.

75. Malaysian Meteorological Department. 2010; Available from: http://www.met.gov.my.

76. Hanna, S.R. and J.C. Chang, *Representativeness of wind measurements on a mesoscale grid with station separations of 312 m to 10 km.* Boundary-Layer Meteorology, 1992. 60(4): p. 309-324.

77. Mikrotik, *MikroTik RouterOS™ v. 2.9 Reference Manual*. 2007.

78. International Telecommunication Union, *Calculation of Free-Space Attenuation*, in *Recommendation ITU-R P.525-2*. 1994, ITU: Geneva.

79. Ly, P.L., T.A. Rahman, and M.K. Abu, *Investigation of foliage effects via remote data logging at 5.8GHz.* WSEAS Transactions on Communications, 2010. 9(4): p. 237-247.

80. Acuña, E. and C. Rodriguez, *The treatment of missing values and its effect on classifier accuracy classification, clustering, and data mining applications*, D. Banks, et al., Editors. 2004, Springer Berlin Heidelberg. p. 639-647.

81. Dalley, J.E.J., M.S. Smith, and D.N. Adams. *Propagation losses due to foliage at various frequencies*. in *IEE National Conference on Antennas and Propagation*. 1999.

82. Chua, T.H., I.J. Wassell, and T.A. Rahman. *Combined effects of wind speed and wind direction on received signal strength in foliated broadband fixed wireless links*. in *2010 Proceedings of the Fourth European Conference on Antennas and Propagation (EuCAP)*. 2010.

83. Dyrbye, C. and S.O. Hansen, *Wind loads on structures*. 1997, West Sussex: John Wiley & Sons. 19-20.

84. Cullen, S., *Trees and wind: Wind scales and speeds.* Journal of Arboriculture, 2002. 28(5): p. 237-242.

85. Trexler, J.C. and J. Travis, *Nontraditional regression analyses.* Ecology, 1993. 74: p. 1629-1637.

86. Murata, F., et al., *Relationship between Wind and Precipitation Observed with a UHF Radar, GPS Rawinsondes and Surface Meteorological Instruments at Kototabang, West Sumatera during September—October 1998.* Journal of the Meteorological Society of Japan, 2002. 80(3): p. 347-360.

87. Cotton, S.L. and W.G. Scanlon, *Higher Order Statistics for Lognormal Small-Scale Fading in Mobile Radio Channels.* IEEE Antennas and Wireless Propagation Letters, 2007. 6: p. 540-543.

88. Fort, A., et al., *An ultra-wideband body area propagation channel Model-from statistics to implementation.* IEEE Transactions on Microwave Theory and Techniques, 2006. 54(4): p. 1820-1826.