Dynamic Impact of Vegetation on Wireless Communication Systems

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Abstract

The crucial areas for future improvements by network operators are the Quality of Service (QoS) and network capacity. In order to meet the capacity demands, there is a tendency to shift the operating frequency towards higher frequency bands. There is also a drive to move from a macrocell type network to a microcell type network. As most neighbourhoods have some sort of vegetation that can expand over the years, the previously insignificant shadowing effects will become more pronounced. In addition to that, the movement of vegetation structure will introduce an additional adversity for high frequency radiowave propagation. Two series of measurement campaigns, controlled environment: for signal operating at 0.9, 2, 12 and 17GHz, and outdoor environment: for signal operating at 1.8GHz had been carried out as the main components of this research work to investigate this impact.

In the controlled environment measurement campaign, the radiowaves propagation experiments were conducted in a laboratory environment of an anechoic chamber, where a controllable wind generator was implemented to simulate the wind influence. Two vegetation samples of different sizes and shapes were used and placed in between the transmitter and receiver antennas inside the chamber. On the other hand, the outdoor measurements were conducted in real environments with the influence of natural wind conditions. The transmitted signals from existing base stations were measured using a scanning receiver to capture signal variations and deep fades. Three experimental sites were identified which included single-tree, line-of-trees and group-of-trees configurations. The impact of vegetation movement under different wind influences was analysed in terms of the first- and second-order statistics of the received signals. The results indicated similar wind dependency behaviour of the signal for both measurement campaigns and the fading amplitude can be represented by a Rician distribution. It was also observed that the received signal variations tend to increase as wind speed increases from calm to windy conditions. Once in the windy state, it has been found that any further increment of the wind speed has less of an effect on the received signal.
Apart from analysing the signal over different wind speeds, the work also compared the impact at different frequencies, sizes of vegetation and vegetation structures. Based on the k-factor values derived from the results of controlled environments, it was noted that higher frequency signals and larger vegetation size would result in lower k-factor, thus indicated higher random multipath contributions. This is particularly obvious during the transition period from calm to windy condition. In addition, the comparison over different vegetation structures of outdoor experiments indicated that the changing rate of fast-fading distribution was related to the flexibility and density of the vegetation.

Using the results of the outdoor measurement campaign, an empirical model of this dynamic behaviour has been proposed for use in future planning of more robust wireless systems providing services in vegetated areas. The model was developed to predict k-factor values lognormally distributed around an estimated exponential curve. The constants incorporated in the model were determined from outdoor measurements data of Site1 and 2. Finally, the predicted k-factor values generated from the newly developed model were assessed against the measured data of Site 3, which showed a good agreement between them, thus confirms its validity and accuracy.
Acknowledgement

I wish to express my sincere and highest gratitude to my supervisor Dr. Stavros Stavrou for his continuous support and encouragement throughout the course of this research work. His valuable guidance has helped a great deal towards all of the achievements that may be attributed to this study. My thanks are also due to Dr. Simon Saunders for initially introduced me to the project, Dr. Timothy Brown and Dr. Dimitris Mavrakis for their co-operation in conducting some of the related experiments. I am also grateful to all my friends, staff and colleagues at the Centre for Communication Systems Research, University of Surrey, United Kingdom for creating it a pleasant working environment.

This work is a special dedication to my parents, Hashim Abdullah & Munirah Salleh, and my brothers and sisters for their support, prayers, well wishes, and most of all, for believing in me when no one else does.
## Glossary of Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
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<tbody>
<tr>
<td>AFD</td>
<td>Average Fade Duration</td>
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<tr>
<td>AMSS</td>
<td>Aeronautical Mobile Satellite System</td>
</tr>
<tr>
<td>BFWA</td>
<td>Broadband Fixed Wireless Access</td>
</tr>
<tr>
<td>BWA</td>
<td>Broadband Wireless Access</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
</tr>
<tr>
<td>CDS</td>
<td>Cellular Design Services</td>
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<tr>
<td>CW</td>
<td>Continuous Wave</td>
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<tr>
<td>DCS</td>
<td>Digital Cellular System</td>
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<tr>
<td>DFM</td>
<td>Dynamic Foliage Modulation</td>
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<tr>
<td>DG</td>
<td>Dual Gradient</td>
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<tr>
<td>EERS</td>
<td>Extended Empirical Roadside Shadowing</td>
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<tr>
<td>ERS</td>
<td>Empirical Roadside Shadowing</td>
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<tr>
<td>FITU-R</td>
<td>Fitted ITU-R</td>
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<tr>
<td>FSL</td>
<td>Free Space Loss</td>
</tr>
<tr>
<td>FWA</td>
<td>Fixed Wireless Access</td>
</tr>
<tr>
<td>GEO</td>
<td>Geostationary Earth Orbiting</td>
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<tr>
<td>GPIB</td>
<td>General Purpose Interface Bus</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile</td>
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<tr>
<td>GTD</td>
<td>Geometrical Theory of Diffraction</td>
</tr>
<tr>
<td>ITU-R</td>
<td>International Telecommunication Union of Radiocommunication</td>
</tr>
<tr>
<td>LCR</td>
<td>Level Crossing Rate</td>
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<tr>
<td>LEO</td>
<td>Low Earth Orbiting</td>
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<tr>
<td>LOS</td>
<td>Line of Sight</td>
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<tr>
<td>MDF</td>
<td>Maximum Doppler Frequency</td>
</tr>
<tr>
<td>MED</td>
<td>Modified Exponential Decay</td>
</tr>
<tr>
<td>MEO</td>
<td>Medium Earth Orbiting</td>
</tr>
<tr>
<td>MITU-R</td>
<td>Modified ITU-R</td>
</tr>
<tr>
<td>MLE</td>
<td>Maximum Likelihood Estimation</td>
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<tr>
<td>MMSS</td>
<td>Maritime Mobile Satellite System</td>
</tr>
<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>MoM</td>
<td>Method of Moment</td>
</tr>
<tr>
<td>MSS</td>
<td>Mobile Satellite System</td>
</tr>
<tr>
<td>NLOS</td>
<td>Non Line of Sight</td>
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<tr>
<td>NZG</td>
<td>Non Zero Gradient</td>
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<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
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<tr>
<td>PO</td>
<td>Physical Optic</td>
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<tr>
<td>PSD</td>
<td>Power Spectrum Density</td>
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<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RA</td>
<td>Radiocommunication Agency</td>
</tr>
<tr>
<td>RAL</td>
<td>Rutherfold Appleton Laboratory</td>
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<tr>
<td>RET</td>
<td>Radiative Energy Transfer</td>
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<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>SUI</td>
<td>Stanford University Interim</td>
</tr>
<tr>
<td>UTD</td>
<td>Uniform Theory of Diffraction</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>WLL</td>
<td>Wireless Local Loop</td>
</tr>
<tr>
<td>XPD</td>
<td>Cross Polarisation Discrimination</td>
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Chapter 1

1 Introduction

This dissertation is submitted for the fulfilment for the degree of Doctor of Philosophy on the Study of Dynamic Impact of Vegetation on Wireless Communication Systems. Research work was carried out within the Centre for Communication System Research at University of Surrey, United Kingdom.

1.1 Motivations

Wireless communications have now become part of many users' everyday life with the number of users constantly on the increase. The crucial areas for future improvements by network operators are the Quality of Service (QoS) and network capacity. In order to meet the capacity demands, there is a tendency to shift the operating frequency towards higher frequency bands [Rogers2002]. In addition, there is also a drive to move from a macrocell type network to a microcell type network [Graham1998]. The advantage of microcell type network is primarily to increase the network capacity with the possibility of more dense frequency re-use. However, this move will put microcell base stations at a level below the tree/building height and therefore, the
previously insignificant shadowing effects will become more pronounced. Consequently, better modelling of radio propagation through this type of medium is highly desired.

In both rural and urban environments, one of the significant problems affecting radiowave propagation is the issue of shadowing by trees or vegetation. Signal amplitude attenuation due to absorption and scattering by the tree trunks and vegetation bulk, has been extensively investigated [Al-Nuaimi1998], [Stephens1995] [Al-Nuaimi1993a], [Seker1988], [Tamir1977], [Tamir1967], and the effect of multiple scatterings and attenuation by the leaf canopy has also been studied [Jong2000], [Dilworth1996], [Torrico1996], [Campbell1988]. It is well known that, the received signal for a mobile receiver moving behind the vegetation bulk will experience two types of superimposed attenuation mechanisms [Saunders1999]: (a) a slow variation component produced by absorption through the bulk of trunks, and (b) a faster variation associated with the multiple scattering through the leaves and smaller tree structures. Furthermore, under the influence of wind, the movement of vegetation structures will introduce an additional adversity for the transmitted signal that can degrade the quality of signal transmission even when the transmitter and receiver are in stationary positions [Randle1999]. In general, the dynamics of the received signal can cause significant channel impairment and affect system parameters such as power control [Ledl2003], transmission bit rates, packet length and coding [Parsons2000], [Fungi1994]. Accurate modelling of these impairments is particularly relevant to services operating at frequency higher than 1 GHz, such as Wireless Local Loop (WLL), any Broadband Wireless Access (BWA) system and Digital Video and Audio Broadcasting systems. It is primarily this problem, which was investigated and reported in this particular research work.

1.2 Aims and Objectives

The main aims of this research work were to study the effects of vegetation structure and its movements onto radiowave propagation, and to develop a new model in predicting the fade characteristics of radiowaves propagating through vegetation under
various wind conditions. The new model should be able to describe qualitatively the main mechanisms involved in the process and provide quantitative predictions of their effects on wireless channel parameters. The development of the new model was based on an empirical approach derived from the measured data and can be used along with the existing vegetation attenuation models to predict wireless communication system performance.

A sequential approach was used to carry out this investigation, where the following intermediate objectives were identified corresponding to different stages of the investigation.

- To study the fading mechanisms in a wireless propagation channel and carry out a comprehensive literature survey on the existing work describing fading caused by vegetation and its movement. The information concerning previous measurements and modelling of vegetation effects on the propagated waves is of prime interest.

- To design an experimental methodology and identify relevant equipment to capture variations of the received signal. Two separate measurement campaigns were planned and conducted.

- To analyse the collected data statistically in order to characterise and produce a dynamic representation of the fading channel parameters at various wind conditions. The signal characteristics are presented in terms of their first- and second-order statistics.

- To develop radio propagation models that can represent the signal behaviour when propagating through vegetation based on the analysed data. The new model would be proposed as an additional new tool in order to evaluate the effects on the wireless channel to accurately predict the resultant system performance.

- To provide suggestions for plausible propagation mechanisms involved in this type of environment as well as recommendations for further investigations in the related areas. This investigation should serve as one of the initial attempts of its kind to ultimately produce a generalised propagation model for radiowaves propagating through vegetation in the future.
1.3 Thesis Structure

Chapter 2 provides a brief insight to the physics and statistics of radiowave propagation in a wireless channel. It describes various signal component contributions towards the total received signal in unshadowed and shadowed environments. In addition, it also presents commonly known statistical representations of radiowave propagation in terms of the first- and second order statistics and their usefulness.

Chapter 3 investigates and reports the impact of vegetation on radiowave propagation. Various related propagation mechanisms are discussed. A review of existing vegetation propagation models is presented. This chapter also discusses the dynamic effects of vegetation movement on the wireless channel, presents a survey of the related work carried out in the area and finally identifies the main mechanisms to be incorporated in the modelling process.

Chapter 4 and 5 present a series of propagation measurement campaigns that had been carried out. The measurement campaigns were divided into two separate campaigns: a) controlled, and b) outdoor environments. The controlled environment campaign was a series of experimental work conducted inside an anechoic chamber. On the other hand, the outdoor campaign was conducted outdoor in a real environment. Details of measurement campaigns, measurement approaches adopted and the main results obtained are described in this chapter.

Chapter 6 of this thesis discusses the statistical characteristics of the received signal in various windy conditions as recorded in the measurement campaigns. The analysis is presented in terms of their first- and second-order statistics. The relationship of fade characteristics with the wind speed, vegetation size, blockage configuration and operating frequencies are also addressed. In addition, an empirical model of the received signal statistics for radiowaves propagating through vegetation in association with the blockage configuration and wind speed conditions was developed and presented. The model was also tested against a new set of measurement data.

Finally, the last chapter explains the overall conclusions that were drawn from this particular research work and elaborates on recommendations for future works that can be
taken forward. This work has provided new insights on the dynamic characteristics of radiowaves propagating through vegetation. Therefore, further investigations are crucial for optimising the existing models as well as developing new algorithms that would consider this type of adversity in relevant applications.

1.4 Achievements

The major achievements of this work can be summarised as follows:

- Confirmation of the wind dependency for radiowaves propagating through different vegetation structures.

- Recognised the changing trend of the fast-fading statistics of the received signal by recording and correlating these changes with the changes in wind speed.

- Development of empirical propagation models for statistical characteristics of radiowaves propagating through mainly deciduous vegetation.

The results of these work have been published in several learned journals and presented at an international conference.

**Journal publications (IEEE):**


- M. H. Hashim and S. Stavrou, ‘Measurements and Modelling of Wind Influence on Radiowave Propagation Through Vegetation’ Accepted for publication in IEEE Transaction on Wireless Communication.
• M. H. Hashim and S. Stavrou, 'Wind Influence on radiowaves propagating through vegetation at 1.8 GHz', Accepted for IEEE Antenna and Wireless Propagation Letter.

Conference publications (IEE):

• M. H. Hashim, D. Mavrakis and S. R. Saunders, 'Measurement and analysis of temporal fading due to moving vegetation', IEE International Conference on Antenna and Propagation, University of Exeter, March-April 2003
Chapter 2

2 Radiowaves Propagation Mechanisms in Wireless Communication Systems

2.1 Introduction

This chapter presents descriptions of existing wireless communication network systems, their types, operations and main radio propagation mechanisms associated with each of them. The following sections in the chapter describe the physics and statistics of radiowaves propagation in such systems. A generic architecture of a communication system as described by [Shannon1948] is illustrated in Figure 2-1. The source block represents the information to be transmitted, such as a speech signal, a television signal or a stream of binary ones or zeros. The transmitter operates on the source output and prepares it for propagation through the channel. It is noted that the illustrated channel applies to all kinds of systems, which may consist of a pair of wires, coaxial cable, optical or microwave links. On the other end of the system, the receiver attempts to retrieve the source output from the channel output and presents the resulting signal to the users at the destination.
2.2 Wireless Communication Systems

A wireless communication system refers to a system where information is transmitted in the form of electromagnetic radiowaves through free space often called a wireless channel. A sound understanding of a wireless channel is essential in designing and analysing the operation of any wireless communication system. In a wireless channel, the noise source can be divided into two types: a) Additive and b) Multiplicative effects [Saunders1999]. The additive noise arises from the noise generated within the receiver itself, such as thermal and shot noise in passive and active devices, and also from the external sources, such as atmospheric effects, cosmic radiation and interference from the transmitter and other electrical appliances. On the other hand, the multiplicative noise arises from various processes encountered by the transmitted radiowaves in the channel. Wireless systems are generically categorised into, satellite and terrestrial systems. Description of each system and its propagation mechanisms are discussed in the next following sections.
2.2.1 Satellite Systems

Satellite Fixed Links

The satellite fixed link systems normally involve communications between geostationary earth orbiting (GEO) satellites and fixed earth stations. In this type of systems, the base stations are carefully sited to avoid local obstructions and large aperture antennas dish, which are broadly fixed to pointing direction, are used. Thus, the satellite fixed links are, most of the time, able to provide high reliability communications by relying on the line of sight (LOS) paths and high gain antennas. Due to the large separation distance, satellite are located in orbits about 36000 km above the earth’s surface, the propagation effects can be classified into three categories: a) Ionospheric, b) Tropospheric and c) Local obstruction effects. The dominant propagation mechanisms are the path loss, due to interactions between radiowaves and particles at different layers of earth’s atmosphere, and the free space loss (FSL), which is due to the large separation distance between the transmitter and the receiver.

Mobile Satellite Links

Mobile satellite links as it is referred as megacell systems [Saunders1999], provide communications between satellites and mobile users. The Mobile Satellite System (MSS), can be divided into three distinct groups [Buttl1992]: a) Maritime Mobile Satellite Systems (MMSS), b) Aeronautical Mobile Satellite Systems (AMSS) and c) Land Mobile Satellite Systems (LMSS). Maritime Mobile Satellite Systems (MMSS) offer communications between shores or coastal earth stations, gateways to the terrestrial networks and terminal on-board the ships, boats and many others, via satellites. Likewise, the Aeronautical Mobile Satellite Systems (AMSS) provide communications links between gateway earth stations and aeronautical terminals. Similarly, Land Mobile Satellite Systems (LMSS) facilitate communications between the base stations and the
land mobile terminals through the satellites. Since the main source of path loss in Geostationary Earth Orbiting (GEO) satellite systems is the FSL, satellite systems operating in Low Earth Orbiting (LEO) and Medium Earth Orbiting (MEO) constellations are found to be more attractive for mobile-satellite communication systems, because of the shorter distance between the satellites and the mobile terminals. Like in satellite fixed link systems, the main propagation effects are subjected to the atmospheric interactions. In addition to that, the surrounding objects near the mobile terminals are also significantly affecting the radiowaves propagation. Consequently, the line of sight (LOS) condition is no longer a usual condition as the mobile terminals may be shadowed by local obstructions such as terrain, vegetation or man-made structures. Therefore, the channel prediction must combine the prediction of shadowing and fast variation effects, caused by signal interactions with local obstructions, in addition to the usual path loss approximation.

2.2.2 Terrestrial Systems

Terrestrial Fixed Links

The terrestrial fixed links are defined as communication links between fixed points on earth. The individual link for a particular radio system in this category consists of a pair of transceivers, which are normally mounted on masts, on top of high buildings or towers, tens of metre above the earth's surface and usually separated by tens or even hundreds of kilometres. The terrestrial fixed links are commonly used for very high data rate systems such as telephone trunk lines, as well as data services to residential and commercial buildings in urban and suburban environments. Since the transceivers in this type of system are not as high as in satellite fixed links, the main propagation mechanisms, on top of FSL, are weather effects depending on the frequency of operation, and in certain occasions, loss can be also due to local obstructions.
**Macrocells**

Macrocell networks are designed to provide communication services to mobile users, particularly outdoor environments with medium traffic densities. The base station antennas are mounted on masts or buildings at heights higher than surrounding obstructions such as buildings and trees. A typical cell radius can range from 1 km to tens of kilometres. The propagation effects in this type of system are mainly the FSL, due to the distance between the transmitter and receiver, as well as the local obstructions losses.

**Microcells**

The microcell networks are mainly designed to increase the number of users that can access the system by reducing the cell size. The deployment of microcell networks is intended for high traffic densities, usually in urban and suburban environments. In a microcell system, the base station is mounted below the height of surrounding buildings, 3-6 metres above the ground level with the cell shape determined by the surrounding buildings. Therefore, the dominant propagation mechanisms include free space propagation, multiple reflections and scatterings within the cell coverage area, and diffraction around the vertical edges and over the rooftops of the surrounding buildings.

**Picocells**

The picocell systems are intended for very high traffic densities and high data rate communications, where a base station antenna is placed inside a building. Picocell are increasingly used in cellular telephony for high traffic areas such as railway stations, office buildings and airports. Users of picocell systems may be mobile or stationary. An example of a stationary user is a Wireless Local Area Network (WLAN) between computers in an office. The propagation mechanisms in this type of environment are...
influenced by the shape and characteristics of the room, the presence of furniture and people in the vicinity.

2.3 Propagation Mechanisms in Unshadowed Environment

The unshadowed propagation refers to the condition when there is a clear LOS between the transmitter and the receiver. In addition to that, a direct signal component is normally received with other multipath contributions, resulting from wave interactions with local scatterers as shown in Figure 2-2. Thus, the unshadowed received signal is composed of: a) Direct, b) Specular Reflection, and c) Diffuse components [Bart1992]. In the following sections, each one of the components is explained and the related propagation effects are highlighted.

Figure 2-2: Illustration of signal components for unshadowed radio propagation environment
2.3.1 Direct Component

It is now obvious that the direct component of the received signal, in an unshadowed environment, refers to the LOS propagation component. In a wireless channel, the direct signal is affected by the path loss exerted in the particular system. The path loss involved is very much dependent on the type of the wireless channel. The basic path loss is the FSL, which is related to the distance between the transmitter and the receiver, as well as the operating frequency. In addition to that, in satellite systems such as satellite fixed link or megacell systems, the attenuation of the direct LOS signal is also influenced by the interactions between the transmitted radiowaves and the particles in the ionospheric and tropospheric layers of the earth's atmosphere, or just tropospheric layer for the terrestrial fixed links. Examples of ionospheric effects include faraday rotation, group delay, dispersion and ionospheric scintillation, and the tropospheric effects, are absorption and scattering by atmospheric gases and raindrops, refraction, scintillation, depolarisation and sky Noise [Saunders1999]. Furthermore, for terrestrial fixed link propagation over a very long path, the shape of the earth must also be considered in calculating the shortest distance between the two terminals. Most of the time, the earth is assumed to be spherical, but for high accuracy predictions one must consider the earth's bulge [Jakes1974]. Most atmospheric effects had been investigated and presented in the past, [Butt1992], [Evans1991], [Allnutt1989], hence they should be incorporated, where applicable, into the system design in order to ensure adequate coverage in any particular area of interest. On the other hand, for systems in macrocell, microcell or picocell, the propagation loss, that is typically associated with the unshadowed direct signal component, is mainly FSL, although the signals are also attenuated by the presence of rain, snow and fog. These losses depend on the frequency and upon the amount of moisture in the path [Hogg1969].
2.3.2 Specular Reflection Component

The specular reflection component is commonly termed as the phase coherent reflected wave from points within the first Fresnel zone of the receiver [CCIR1986]. In such cases, the reflections are often referred to the ground reflection from assumed smooth earth's surface. It is noted that the polarisation state is not preserved following the reflection of the wave [Saunders1999]. In the case of reflection from the ground, waves of random polarisation incident at Brewster angle will be reflected to have a purely horizontal component. Therefore, for angle of incidence, between the incident wave and the earth's horizontal, greater than the Brewster angle, the reflected wave undergoes 180° phase change [Saunders1999]. Thus, it can be shown that the reflections of circularly polarised waves incident below the Brewster angle will be polarised in the same sense as the incident wave, while the reflections of circularly polarised waves incident above the Brewster angle will be in the opposite sense of the incident wave with respect to the ground [Beckmann1967]. In [Bart1992] referring to [Vogel1985], the authors have shown that satellite systems are usually operating at high elevation angles, thus the incident is greater than the Brewster angle, the specular reflection component will be opposite sense polarised. Based on this factor, the specular reflection component in satellite systems can be rejected by using an off-angle antenna discrimination, which makes it insignificant and often negligible. However, in systems such as macrocell and smaller, i.e. microcell and picocell, the specular ground reflected component should be taken into consideration in planning and designing the wireless network appropriately. In this situation, the propagation is referred to propagation over a plane earth, which loss can then be estimated. The analytical results was originally derived by [Norton1947], [Norton1937], [Norton1936], and simplified by [Bullington1957], [Bullington1947].
2.3.3 Diffuse Component

The diffuse component is a phase incoherent multipath wave due to reflections and scattering from points outside the first Fresnel zone of the receiver [Beckmann1963]. The diffuse component is termed for the large number of individual scatterers around the receiver. Usually no individual scatterer dominates for a statistically significant amount of time [Vogel1988a]. The relative phase shifts of various multipath components may lead to constructive and destructive interference in the received signal. Experiments by [Campbell1988] discussed in [Bart1992] showed that the diffuse component had no preferred directivity. It is uniformly distributed angularly around the receiver. Interference between the direct and diffuse component causes rapid fading of the received signal [Beckmann1963]. The diffuse component is usually indicated to be 12 to 20 dB below the direct component [Bart1992].

2.3.4 Total Unshadowed Signal

The total received signal in the case of unshadowed radio propagation is the phasor sum of the three components described in the previous sections [Bart1992].

\[
R_{\text{unshadowed}} = R_{\text{direct}} + R_{\text{specular}} + R_{\text{diffuse}}
\]  

(2-1)

\(R_{\text{unshadowed}}\) is the total unshadowed received signal, and \(R_{\text{direct}}\), \(R_{\text{specular}}\) and \(R_{\text{diffuse}}\) are direct, specular reflection and diffuse components respectively as explained in the previous sections. An illustration of the signal components for the unshadowed propagation is shown in Figure 2-2.
2.4 Propagation Mechanisms in Shadowed Environment

Another scenario of the radiowave propagation is when the receiver is located in a shadowed region as shown in Figure 2-3. The occurrence of a shadowed environment may be due to the obstruction of the direct LOS signal by buildings, terrain or vegetation structures. For example, when the mobile receiver moves into the shadowed region along roadside trees. In any of these scenarios, the direct LOS signal is either completely blocked or partly attenuated from the loss exerted by the obstructions.

![Illustration of signal components for shadowed radio propagation environment](image)

If the direct wave from the transmitter to the receiver is completely obstructed, then non-line of sight (NLOS) radio propagation occurs. Then, the main mechanisms would be multipath propagation from diffuse components. On the other hand, when the direct wave
is partly attenuated by the primary obstruction, the propagation mechanisms in equation (2-1) can be rewritten as below for shadowed environment [Barts1992].

\[ R_{\text{Shadowed}} = R_{\text{Shadowed Direct}} + R_{\text{Specular}} + R_{\text{Diffuse}} \] (2-2)

\( R_{\text{Shadowed}} \) is the total received signal in shadowed environment. The \( R_{\text{Shadowed Direct}} \) represents the direct component that is attenuated by the obstruction loss, such as diffraction loss from buildings or foliage absorption, and scattered by the vegetation structures within the canopy. On the other hand, \( R_{\text{Specular}} \) and \( R_{\text{Diffuse}} \) components are identical in form to the ones in unshadowed propagation.

### 2.4.1 Attenuated Direct Component

In the shadowed propagation scenario, the LOS path between the signal source and the receiver is frequently affected by the presence of obstructions such as buildings and roadside trees. The extent of the influence of the shadow loss on the link reliability is directly related to the type of the environment in which the receiver operates at any given instant. For example, in built-up urban areas, the attenuation of the direct signal due to diffraction by the high-rise buildings could be several dBs for significant percentages of time and the shadow loss due to a building had been shown in the literature to be well predicted by the knife-edge diffraction model [Butt1992].

Apart from obstruction by buildings, the vegetation blockage can also be a limiting factor in link reliability in many suburban and rural areas [Seville1995a], [Butt1992]. The shadowed direct component is generated when the LOS signal from the transmitter passes through vegetation and is attenuated and scattered by the leaves, branches and limbs of the vegetation. Thus, the shadowed direct component can be modelled as the sum of an attenuated LOS signal and a random forward scattered field [Barts1992].
\[ R_{\text{ShadowedDirect}} = \alpha_{\text{attenuation}} R_{\text{Direct}} + R_{\text{RandomForwardScattered}} \] (2-3)

\( R_{\text{ShadowedDirect}} \) represents the total attenuated received signal, whilst \( \alpha_{\text{attenuation}} R_{\text{Direct}} \) is the attenuated coherent direct signal component and \( R_{\text{RandomForwardScattered}} \) is the term for the random forward scattering components from vegetation structures. Vegetation attenuation of the direct LOS signal depends on the path length through the vegetation and can be estimated by models similar to the Modified Exponential Decay (MED) model adopted by [CCIR1986] or [Al-Nuaimi1998] and its derivatives.

### 2.4.2 Random Forward Scattered Component

When the propagated radiowave passes through a vegetation block, the attenuated direct signal is received along with the random forward scattered field as expressed in equation (2-3). The random forward scattered component interferes with the direct component causing it to fade and lose its phase coherency. The distinction between the random forward scattered component and the diffuse component from the vegetation shadowing is somewhat arbitrary [Bartl1992]. Both components are incoherent multipath signals and are responsible for signal fading. It is noted that, the vegetatively shadowed random forward scattered components, \( R_{\text{RandomForwardScattered}} \), are assumed to be from approximately in the same angular direction as the direct component. In contrast, the diffuse components, \( R_{\text{Diffuse}} \), are assumed to be from all angular directions [Barts1992]. While both may behave similarly, this work assumes that the effects of the vegetatively shadowed random forward scattered signal, \( R_{\text{RandomForwardScattered}} \), is included in the shadowed direct, \( R_{\text{ShadowedDirect}} \), component and the diffuse, \( R_{\text{Diffuse}} \), component is included as the effects of all other scatterers.
2.4.3 Total Shadowed Signal

The total received signal for vegetatively shadowed propagation is the sum of shadowed direct, specular reflection, and diffuse components. Therefore, the propagation mechanisms in shadowed environment can be re-expressed as below.

\[ R_{\text{shadowed}} = \alpha_{\text{attenuation}} R_{\text{direct}} + R_{\text{random forward scattered}} + R_{\text{specular}} + R_{\text{diffuse}} \]  

\[ (2-4) \]

where \( R_{\text{shadowed}} \) is the total shadowed received signal, and \( \alpha_{\text{attenuation}} R_{\text{direct}} \), \( R_{\text{random forward scattered}} \), \( R_{\text{specular}} \) and \( R_{\text{diffuse}} \) are attenuated coherent direct, random forward scattered, specular reflection and diffuse components respectively as explained in the previous sections. The general shadowed propagation environment is illustrated in Figure 2-3.

2.5 Statistical Representation of Radiowave Propagation

2.5.1 Importance of Statistical Representation

The wireless system performance is governed, not only by transmission loss, but also by the temporal and spatial variability of the signal and noise. This variability originates from the changes in transmission loss arising from the nature of the random processes of the multipath propagation, the movement of system terminals and any other movement of contributing objects between the antennas within the channel. Due to their randomness in nature, these processes are normally described by their statistical characteristics.
The statistical information of fading in the received signal can be represented in terms of first- and second-order statistics. The first-order statistics, which are normally expressed in terms of Probability Density Function (PDF) and Cumulative Density function (CDF), give the probability that the signal is above or below a certain level. The information of the signal level exceeded for large percentages of time or location is used to determine the quality and link reliability of the wanted service or of the service area. In addition, the information of the signal level which occurs for small percentages of time is crucial in determining the significance of potential interference or the feasibility of frequency re-use. On the other hand, the second-order statistics explain how rapidly the signal level changes between different levels. They are concerned with the distribution of the signal’s rate of change, rather than with the signal itself. This provides a valuable aid in selecting transmission bit rates, word lengths, coding schemes and forward error correction schemes for the system [Saunders1999]. These dynamic effects are commonly described in terms of Level Crossing Rate (LCR) and Average Fade Duration (AFD) of a specified level. Therefore, knowledge of the statistical characteristics of a received signal is required in the assessing of the performance of wireless communication systems. In addition to that, the statistics of the signal variability are also required as tools for spectrum planning and system designing [Parsons2000].

2.5.2 First-Order Statistics

The first-order statistics are mathematical concepts that describe the occurrence probability of certain signal levels. The occurrence probability is normally expressed in terms of the distribution of the overall percentage of time or locations, for which the received signal lies above or below a specific level. It is noted that time or distance is not a factor for the first-order statistics, thus the probability distributions do not provide any indication of signal dynamics between different levels. Some of the most commonly known distributions associated with radiowave propagation in wireless communications, include the Gaussian, Rice, Rayleigh, Nakagami and Weibull distributions, are described
below. These distributions would be compared to the distribution of the measured data in Chapters 4 and 5.

The mathematical expressions for each distribution are shown in the following equations [Raju2002].

Gaussian distribution [Saunders1999]:

\[
p(r) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(r-\mu)^2}{2\sigma^2}}
\]

(2-5)

where, \( \mu \) and \( \sigma \) are the mean and standard deviation of the random variable \( r \).

Rice distribution [Rice1944]:

\[
p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2+sr^2}{2\sigma^2}} I_0 \left( \frac{sr}{\sigma^2} \right)
\]

(2-6)

where, \( s \) is the amplitude of the coherent/dominant component, \( \sigma^2 \) is the variance of either the real or imaginary terms, of the random multipath component and \( I_0(\cdot) \) is the modified Bessel function of the first kind and zeroth-order.

Nakagami distribution [Nakagami1960]:

\[
p(r) = \frac{2m^m}{\Gamma(m)2^m} r^{(2m-1)} e^{-\frac{mr^2}{\Omega}}
\]

(2-7)
where, \( m \) and \( n \) are the shape and scale parameters respectively, and \( \Gamma(\cdot) \) is the gamma function.

Rayleigh distribution [Strutt1880]:

\[
p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}
\]  

(2-8)

where, \( \sigma \) is the standard deviation of either the real or imaginary parts of random multipath components.

Weibull distribution [Weibull1951]:

\[
p(r) = \frac{b}{a} \left( \frac{r}{a} \right)^{b-1} e^{-\left( \frac{r}{a} \right)^b}
\]  

(2-9)

where, \( b \) and \( a \) are the shape and scale parameters respectively.

The estimation of the parameters for all the known distributions could be performed by using the Maximum Likelihood Estimation (MLE) method, in which the set of parameters maximizes the likelihood function [Raju2002].

For the Gaussian and Rayleigh distributions, the parameters were estimated using the readily available function in MATLAB. In the case of other distributions, the optimisation procedure was implemented using the Nelder-Mead Simplex method available in the MATLAB optimisation toolbox [Raju2002], [Nelder1965]. This method requires an initial guess of the parameters. The guessed parameters, denoted with
subscript 0, were obtained using the Method of Moments (MoM) approximation [Raju2002]. For the Rician and Nakagami distributions, the initial guesses were calculated using the estimated second and fourth moments of the measured data. \( E(r) \) represents the mean of the random variable \( r \) and is taken to be equal to the sample mean.

Rician distribution:

\[
\begin{align*}
\sigma_0 &= \sqrt{\frac{E(r^2) - s_0}{2}} \\
E(r^2) &= s_0^2 + \sigma_0^2
\end{align*}
\]  

(2-10) 

(2-11)

where, \( s_0 \) and \( \sigma_0 \) are the initial guesses for the amplitude of the coherent/dominant component and the standard deviation of the random multipath component specified in equation (2-6). \( I_0(\cdot) \) is the modified Bessel function of the first kind and zeroth-order.

Nakagami distribution:

\[
\begin{align*}
\Omega_0 &= E(r^2) \\
m_0 &= \frac{\left[ E(r^2) \right]^2}{E(r^4) - \left[ E(r^2) \right]^2}
\end{align*}
\]  

(2-12) 

(2-13)

where, \( m_0 \) and \( n_0 \) are the initial guesses for the shape and scale parameters respectively specified in equation (2-7), and \( \Gamma(\cdot) \) is the gamma function.
On the other hand, for the Weibull distribution, an iterative procedure was used to compute the initial guess $b_0$ by solving the following equation.

$$\frac{\Gamma\left(1 + \frac{2}{b_0}\right)}{\Gamma^2\left(1 + \frac{1}{b_0}\right)} \frac{E(r^2)}{[E(r)]^2} = \frac{E(r^2)}{[E(r)]^2}$$

(2-14)

Once $b_0$ was obtained from above equation, $a_0$ was obtained from the expression below.

$$a_0 = \frac{E(r)}{\Gamma\left[1 + \frac{1}{b_0}\right]}$$

(2-15)

where, $b_0$ and $a_0$ are the initial guesses for the shape and scale parameters respectively as specified in equation (2-9).

After the initial guesses of the parameters of the Rician, Nakagami and Weibull distribution were obtained as described above, the MLE was implemented using the Nelder-Mead technique.

2.5.3 Second-Order Statistics

The second-order statistics describe the rate at which fades of any depth occur and the average duration of a particular fade below any given depth level. The statistics are expressed in terms of the LCR and AFD. Hence, the second-order statistics provide quantitative information on the effects of the fast varying signal. In wireless
communication systems, this form of statistical information is used to explain the
dynamic effects on the received signal in an environment that is dominated by multipath
signals. The quantitative description is particularly useful for the system designers in
selecting the transmission bit rates, word lengths, coding or error correction schemes and
it is also important for the dynamic power control planning.

\[ d = v \Delta t \]

\[ \Delta l = d \cos \alpha \]

Figure 2-4: Doppler shift scenario

In a mobile receiver situation, the spatial variation is translated into a time variation when
either end of the link is in motion. The dynamic changes in the propagation path lengths can be
directly related to the motion of the receiver and indirectly to the Doppler effect that arises. The
rate of change of phase, due to motion, is apparent as a Doppler frequency shifts in each
propagation path. The phase change is illustrated by Figure 2-4, and the Doppler shift is
described by equation (2-20) and (2-21) below [Parson2000].

\[ \Delta \phi = \frac{2\pi}{\lambda} \Delta l = \frac{2\pi}{\lambda} v \Delta t \cos \alpha \]  \hspace{1cm} (2-16)

\[ \Delta f = \frac{1}{2\pi} \frac{\Delta \phi}{\Delta t} = \frac{v}{\lambda} \cos \alpha \]  \hspace{1cm} (2-17)
The maximum rate of change of phase is when the waves arrive from directly ahead, or directly behind the receiver, which gives the Maximum Doppler frequency shift, \( f_m = \pm \frac{v}{\lambda} \).

**Level Crossing Rate (LCR)**

The level crossing rate (LCR) at any specific level is defined as the expected rate at which the envelope of the signal crosses a threshold level, \( R \), in a positive- or negative-going direction in a given time period. The manner in which, this parameter is derived is illustrated in Figure 2-5.

![Figure 2-5: Derivation of LCR and AFD from a fast varying signal](image)

The analytical expression for level crossing rate (LCR) is shown in equation (2-18) as given by [Jakes1974].

\[
N_R = \int_0^\infty r' P(R, r')dr'
\]

(2-18)
\( r \) is the signal level, \( r' \) is the time rate of change of the envelope, and \( p(R, r') \) is the joint PDF of \( r' \) and \( r \) at \( r = R \).

For a Rayleigh distributed fading envelope of a signal in mobile wireless systems, the expected (average) level crossing rate (LCR) at level, \( R \), which the expression for \( p(R, r') \) was given by [Rice1948], can be expressed as in equation (2-19) [Jakes1974].

\[
N_R(R) = \sqrt{\frac{\pi}{\sigma^2}} R f_m \exp \left( -\frac{r^2}{2\sigma^2} \right)
\]

(2-19)

It is known, as derived in [Parsons2000], that \( 2\sigma^2 \) is the mean square value, then \( \sqrt{2\sigma} \) is the RMS value of the signal. The equation (2-19) above can be rewritten as below,

\[
N_R(\rho) = \sqrt{2\pi} f_m \rho \exp(-\rho^2)
\]

(2-20)

where,

\[
\rho = \frac{R}{\sqrt{2\sigma}} = \frac{R}{R_{RMS}}
\]

In both equations, (2-19) and (2-20), \( f_m \) is the Maximum Doppler Frequency shift associated with the Rayleigh distributed signal. It is noted that the above expression gives the value of LCR in terms of the average number of crossings per second. Therefore, it is apparent from the appearance of \( f_m \), that LCR is a function of mobile speed. Normally, it is convenient to express the LCR in terms of the average number of crossings per wavelength. Then, equation (2-20) is normalised by \( f_m \).
**Average Fade Duration**

The Average Fade Duration (AFD) is the average length of a fade below any specified level, $R$, as shown in Figure 2-9. The analytical expression for the AFD is shown in equation (2-21) [Parson2000].

$$L_R(R) = \frac{Prob[r \leq R]}{N_R(R)}$$

(2-21)

$Prob[r \leq R]$ is the cumulative probability function (CDF) of $r = R$ and $N_R(R)$ is the LCR as shown in the previous section.

Thus, the AFD for a Rayleigh distributed signal can be expressed as below.

$$L_R(R) = \frac{\exp\left(\frac{R^2}{2\sigma^2}\right) - 1}{\sqrt{\frac{\pi}{2}} \frac{Rf_m}{\sigma}}$$

(2-22)

Alternatively, the AFD is also expressed in terms of the RMS value.

$$L_R(\rho) = \frac{\exp(\rho^2) - 1}{\rho f_m \sqrt{2\pi}}$$

(2-23)

It is also noted that the LCR expressions for Rician, Log-Normal and Nakagami distributions are derived in [Rice1958], [Loo1985] and [Youssef1996] respectively.
2.6 Interim Conclusions

A review of typical existing wireless communication systems was presented in this chapter. In addition to that, various propagation mechanisms in different types of environment as well as the associated signal’s statistical representation have also been studied and presented. Generally, wireless communication can be categorised into either satellite or terrestrial systems. Each system, satellite or terrestrial, can be further separated into fixed or mobile network systems. It has been shown that the propagation mechanisms involved, are very much dependent on the type of wireless system and the surrounding environment.

However, the main radiowave propagation environment was categorised as Unshadowed or Shadowed. Unshadowed radio propagation occurs when the direct LOS, is present between the transmitter and the receiver. On the other hand, Shadowed propagation is when the LOS is obstructed by structures located on the earth’s surface, such as buildings, trees or relevant terrain. In Unshadowed propagation, the direct LOS is limited mainly due to FSL and loss due to any interactions between radiowaves and atmospheric particles. Other propagation mechanisms include a specular ground reflection component and the incoherent diffuse component, originating from multipath propagation as a result of reflections and scatterings from objects surrounding the receiver. However, apart from specular and diffuse components, in a shadowed propagation environment, the shadowed direct signal component is limited, not only by free space loss and atmospherics loss, but also due to obstructions loss. In the case of vegetation shadowing, the attenuated direct signal component is also affected by the random forward scattering components resulting from multiple reflections and scatterings from individual leaves and branches within the vegetation structure.

The final section in this chapter, discussed the statistical representations, which are commonly used to describe the fading signal behaviour in wireless communication systems. It was shown that the knowledge of signal’s statistical behaviour is important in assessing the performance of any particular wireless communication system. Investigating the propagation mechanisms in different environments and the statistical
representations of the received signal provides useful background information and valuable assistance in understanding the radiowave propagation as well as their applications in the subsequent analysis sections.
Chapter 3

3 Impact of Vegetation on Radiowaves Propagation

3.1 Introduction

It is well established in the literature, by various researchers that the presence of foliage along the propagation path can cause significant signal degradation [Al-Nuaimi1998], [Barts1992], [Bello1998], [Bello2000], [Caldeirinha2001], [Goldhirsh1998], [Perras2002], [Randle1999], [Schwering1988], [Stephen1998], [Vogel1995]. Furthermore, the growing number of users has resulted in network planners increasing the system capacity by locating transmission antennas at heights that are comparable or lower than surrounding trees and buildings intended for smaller cell size [Graham1998]. The advantage of a small cell is primarily to increase the network capacity with the possibility of more dense frequency re-use. In addition to that, there is also a tendency to shift the operating frequency towards higher frequency bands [Rogers2002]. Therefore, the transmission loss due to trees will be more pronounced. Propagation algorithms that determine path loss and predict signal coverage are essential.
for planning and designing wireless networks for cellular mobile, terrestrial or satellite communication services. Vegetation obstructing or close to the LOS propagation path causes absorption, scattering, diffraction and depolarisation [Rogers2002]. Knowledge of this type of channel characteristics enables the wireless communication system designers to predict the signal loss more accurately. A detailed study of the propagation effects through vegetation is required.

One typical example in which vegetation fading occurs is depicted in Figure 3-1, showing a receiving scenario for a mobile-satellite link transmission. In satellite-fixed link, the receiving antenna can be to some extent directive in elevation, such that multipath from lower elevation angles is filtered out by the antenna gain pattern characteristics. The multipath contributions may originate from various other azimuths, but the shadowing from tree canopies can still be one of the major attenuation contributions.

Figure 3-1: LMSS propagation path shadowed by one or two trees

In contrast, Figure 3-2 shows the configuration of a system operating where the transmitter and receiver are both located near the ground. The propagation takes place at low elevation angles and through a grove of trees. In this particular propagation scenario,
the radiowaves propagate through series of non-attenuating space in between vegetation. Thus, the attenuation rate, of those derived for path length intersecting one or two contiguous canopies in scenarios like LMSS, may overestimate the attenuation rate derived from measurement through the grove of trees [Goldhirsh1998]. The signal fading for both cases are primarily due to combined effects of absorption and scatterings from the trunks as well as branches and leaves within the tree canopies.

Figure 3-2: Low elevation ground-to-ground propagation through a grove of trees

This chapter discusses various propagation effects, previously investigated and reported in the literature, as the radiowaves propagate through a volume of vegetation. The scatterings and multiple reflections by vegetation components may also result in considerable change in the polarisation of the incident signal. In addition to that, under the influence of wind, the scattered and multiple reflected radiowaves by moving leaves and branches give rise to fast variation component in the received signal. The second part of the chapter examines and presents the existing propagation models associated with a vegetation environment. These models are in the form of empirical, semi-empirical and analytical models. The chapter also reports on the work that had been carried out in regards to the dynamic impact under the influence of wind, and describes the area in which this research can serve as a new addition to the existing knowledge. Finally, the
conclusions about the vegetation impacts onto radiowaves propagation and the related existing work are given at the end of the chapter.

3.2 Static Vegetation Impact

3.2.1 Attenuation Through Vegetation

As it was mentioned in the introduction, foliage is one of the major features that affect the radio propagation channel characteristics. Vegetation can be found mostly in rural and residential as well as in some urban environments. The incidence of blockage by vegetation will be very site dependent and varies in different locations. From an investigation of two United Kingdom towns, trees obstructed 10-20% of buildings. Ironically, the percentage of buildings blocked by trees is actually on increase as the transmitter is increased [ITU-R2000]. In addition, tree attenuation is severe at millimetre wavelength and the attenuation rate depends on tree type, moisture content, and path geometry. Planners of radio systems need to account satisfactorily for the propagation effects of vegetation, the levels of wanted signal and co-channel interference associated with a particular radio link. Trees, singly or as a group in the radio path of a point-to-point or point-to-multipoint link can influence the level of the received signal directly by providing an additional or excess attenuation to that caused by free space propagation [Rogers2002].

It is recognised that the propagating of radio waves through vegetation is, in its very nature, complex. Some of the investigations like [McPetrie1946], [LaGrone1961] and [Dilworth1996] are mainly concentrating on the study of absorption and diffraction due to a single tree for ground-to-ground propagation. The effects of isolated trees for LMSS had also been investigated by examining the attenuation, additional to that of free space at UHF, L-, S- and K-band by [Butterworth1984a], [Butterworth1984b], [Vogel1985], [Vogel1986], [Goldhirsh1987], [Yoshikawa1989], [Vogel1993], [Benzair1991], [Cavdar1994] and [Vogel1995]. Isolated trees can cause significant
shadowing in a small area directly behind the tree, and it was found that the maximum shadowing occurred when the signal path intersects with the centre of the tree [LaGrone1961] and [Vogel1986]. It was also observed and reported in the literature that at higher elevation angles, the path attenuation reduces rapidly [Goldhirsh1998]. This occurs because at these higher angles, the propagation path skims through the top of the trees where the path length through the foliage is significantly less than at the smaller angles. At smaller angles, both the foliage density levels and the path length through the foliage presumably influence the attenuation level.

On the other hand, for a signal propagating through a grove of trees, the path length is usually estimated to be the grove thickness. Series of measurement campaigns had been reported on this issue by [Al-Nuaimi1993a], [Al-Nuaimi1993b], [Al-Nuaimi1994], [Stephens1995], [Vogel1993], [Seville1995a], [Seville1995b], [Seville1997], [Al-Nuaimi1998] for a signal transmission at 11.2, 20 and 38GHz. The [ITU-R1994], referred to attenuation through vegetation of ground-to-ground measurements over paths of approximately 100m or more, in woodland, forest or jungle areas, with antenna heights of 2-3m above the ground and only part of the ray passing through foliage, as long-path. A short-path attenuation is designated to short ground-to-ground propagation distance or slant-path through the foliage with depths of no more than 10-15m [Goldhirsh1998]. Results from [ITU-R1994] are shown in Figure 3-3 of attenuation rate for short- and long-path attenuation.

As it can be seen from Figure 3-3, the long-path attenuation rate, dB/m, is significantly smaller than the short-path. For the long-path propagation, the thickness may encompass a proportionately large interval of non-attenuating space between the trees. Hence, the attenuation rate, of those derived for path length intersecting one or two contiguous canopies in scenarios like LMSS, may overestimate the attenuation rate derived from measurement through the grove of trees. It is also reported in [Al-Nuaimi1998] that the attenuation rate is generally much higher for small value of vegetation depths than that observed at larger depths. The initial high attenuation rate is caused by the significant reduction of the coherent component of the propagating wave. As the vegetation depth increases, the received wave changes from one predominantly influenced by a coherent component to one which consists mostly of the incoherent

Dynamic Impact of Vegetation on Wireless Communication Systems

47
components due to the forward scattering caused by leaves and branches, which tends to counteract the loss due to absorption, hence the much lower attenuation rate.

Figure 3-3: Attenuation rate (dB/m) for short- and long-path propagation through vegetation reported by ITU-R for vertical (V) and horizontal (H) polarisation

Apart from the attenuation caused by single individual trees and the grove of trees, the network and system planners are also interested in the shadowing caused by other trees configuration like a line of trees, where the receiver moves along a roadside. Series of measurements had been conducted and reported in the literature for this configuration [Goldhirsh1987], [Goldhirsh1989], [Vogel1990], [Vogel1992], [ITU-R1994], [Vogel1995] and [Goldhirsh1995]. The results of these measurements had led to the derivation of models like the Empirical Roadside Shadowing (ERS) model and the Extended Empirical Roadside Shadowing (EERS) model. These studies indicate that the roadside tree attenuation statistics have demonstrated that significant reduction in fade was observed if the vehicle is driven on the side of the road corresponding to minimum shadowing, meaning the system is more vulnerable to fast variation signal in high shadowing regions. Therefore, changing the lane driven on the road, for mobile receiver,
may lead to a considerable fade reduction. The worst case of fades due to shadowing is at the smaller elevation angles. This attributed to the fact that more trees are intercepted along any given road and the path lengths through the trees are greater.

In addition to the different configurations of vegetation structures, the shape of the individual leaves and branches as well as the seasonal effect are also considered important parameters in predicting the channel characteristics. It was reported in [Goldhirsh1987] for single tree measurements, that attenuation was higher during the Spring season, when the deciduous type leaves and branches tend to achieve maximum moisture content, than during Autumn towards Winter. Figure 3-4 shows the corresponding results for the two seasons during which the tree was in full foliage and without leaves [Goldhirsh1998].

![Figure 3-4: Static tree attenuation versus elevation angle at 870 MHz.](image)

Green Triangle = full foliage  
Blue Diamond = no-foliage case  

Similar observations, the losses and attenuation rates measured for trees without leaves were smaller than those obtained for trees in full leaf for the same foliage depth, were also reported in [Al-Nuaimi1993a]. This phenomenon is due to a much higher scattering and less signal absorption of the signal per unit volume, when propagating through defoliated vegetation.

Dynamic Impact of Vegetation on Wireless Communication Systems
The impact of vegetation attenuation had been extensively studied and analysed by many researchers in recent years. This section has presented an overview of the work that had been conducted and reported in the literature, specifically on the subject of vegetation attenuation. It can be seen that, accurate fade statistics such as average or median attenuation level in a certain type of vegetation environment, is necessary for predicting the appropriate link margin for any wireless communication system.

### 3.2.2 Depolarisation

Another important aspect of radiowave propagation in wireless communication links is the change of polarisation of the incoming signal. Depolarisation of the incident signal arises when it encounters a scattering medium such as vegetation. Models are available for predicting depolarisation from backscattered signals such as those encountered in remote sensing. However, a limited number of works has been reported in the literature on the depolarisation effect due to radiowave transmission through a volume of vegetation. The work reported in [Caldeirinha2001] showed a considerable influence of depolarisation on the level of received signal as a result of tree re-radiation even in the direction of propagation of the incident wave. The degree of depolarisation depends strongly on the wavelength and on the dimension of the tree structure. It was found that the intensity of the received signal is the sum of the fields re-radiated by individual scatterers having random orientations and variable electromagnetic properties [Caldeirinha2001]. In addition to that, a significant reduction was observed in the co-polarised component signal level as reported in [Caldeirinha2000]. This can be explained by the enhancement of the cross-polarised component observed in the forward region that was accompanied by a consequent reduction of the co-polarised component causing considerable reduction in Cross Polarisation Discrimination (XPD). The XPD when the leaves are wet is always less than the dry condition. Broad leaves result in smaller XPD than smaller leaves, due to the capability of the surface of the broader leaves to hold more water by surface tension [Dilworth1996]. It is clear that depolarisation and the reduction of XPD have important implications on the design of both terrestrial and satellite radio...
links whose paths include vegetation [Rogers2002]. Thus, depolarisation effect is also an important factor in the prediction model, for propagation through vegetation in addition to absorption and scattering.

3.3 Existing Vegetation Attenuation Models

For successful network planning and basic system design, propagation algorithms that determine the path loss, fade characteristics and signal coverage are critical to successful system deployment. These prediction algorithms are also highly desirable for predicting and controlling mutual co-channel interference between existing and new radio links. In the case of land mobile systems as well as fixed wireless access systems, trees may be present singly or in a group within a radio cell. These obstructions may then give rise to both absorption and scattering of the radio signals. Therefore, it is these absorption and scattering effects that must be investigated and predicted if the accuracy of the planning tools and spectrum utilisation, which is required for mobile and fixed-link radio communication services, are to be improved and optimised. Most of vegetation models found in the literature are classified as a static or mobile case [Goldhirsh1998]. The mobile case refers to the situation where the receiver is moving in the shadowed regions, and static refers to the case where both the environment and receiver are assumed stationary. In both cases, the trees are represented as non-moving obstructions. A review of existing vegetation attenuation models available in the literature is given in the following sections [Rogers2002]. These models are applicable to the static case and the best possible optimisation would be to combine these, with the dynamic effects of movement in the environment.
3.3.1 Empirical Models

Empirical models are mainly the outcome of series of measurement campaigns, where the model parameters are often optimised to the collected data. The main advantage of this type of model lies in the simplicity of the mathematical expression describing them. However, one of the drawbacks of empirical modelling is that the formulated models are strictly related to specific measured datasets. Hence, these models usually fail to give any indication on the physical processes involved [Karaliopoulos1999]. Such models are usually attempting to predict the mean attenuation of the propagated signal, caused by vegetation, or to calculate the link budget needed to compensate for the propagation losses and deep fades caused by vegetation. The parameters for these models are normally determined through regression curves fitted to the measurement data, providing quick and general estimates of the amount of excess attenuation caused by a particular vegetation medium.

The Modified Exponential Decay Model (MED)

The Modified Exponential Decay Model (MED) was developed by Weissberger after reviewing several exponential decay models [Rogers2002]. The model expresses the specific attenuation, in $dB/m$, of path length through the vegetation medium. It was based on several sets of available measured attenuation data carried out in different environment in the United States at frequency ranges from 230MHz to 96GHz. It was noted that an exponential decay model was appropriate for situations where the propagation occurred through a grove of trees rather than by diffraction [Weissberger1982]. The functions describing the MED are shown in equations (3-1) and (3-2).

\[
L = 1.33 f^{0.284} d^{0.588} \quad \text{for} \quad 14m \leq d \leq 400m \quad (3-1)
\]

\[
L = 0.45 f^{0.284} d \quad \text{for} \quad 0m \leq d \leq 14m \quad (3-2)
\]
\( L \) is the loss in dB, \( f \) is the frequency in \( \text{GHz} \) and \( d \) is the path length through the trees in metres. It was reported in [Weissberger1982] that the path loss is 3 to 5dB higher for trees with full foliage. The MED prediction was also tested for its performance in [Al-Nuaimi1993b] and showed poorer fit to measured data at 11.2 and 20GHz than that obtained at UHF and VHF bands.

**ITU-R Model and its Derivatives**

An attenuation model was developed within the International Telecommunication Union of Radiocommunications sector for radio propagation through vegetation [ITU-R1994b]. The recommendation was proposed for communication links operating at frequencies between 200MHz – 95GHz, such that the majority of the radio path falls within the vegetation medium with assumed maximum depths of 400m. The modelled excess loss \( L \) can be expressed as in equation (3-4).

\[
L = 0.2 f^{0.3} d^{0.6}
\]  

(3-4)

\( f \) is the frequency in MHz and \( d \) is the depth of vegetation in metre.

Then, the ITU-R model was modified to the Modified ITU-R (MITU-R) model, which the excess loss \( L \) is expressed in the form shown by equation (3-5) [Al-Nuaimi1998].

\[
L = k d^n
\]  

(3-5)
$k'$ is a constant at a specific frequency and other parameters are as in ITU-R model above. The model was established by optimising the values $k'$ and $n$ in order to obtain a best fit with the measured data at 11.2GHz [Al-Nuaimi1994]. Thus, equation (3-5) was expressed as in equation (3-6) and (3-7) for in-leaf and out-of-leaf cases respectively.

\[
L = 11.93d^{0.398} \quad \text{in-leaf} \quad (3-6)
\]
\[
L = 1.75d \quad d \leq 31m \quad \text{out-of-leaf} \quad (3-7)
\]

It was reported in [Al-Nuaimi1993] and [Al-Nuaimi1993b], due to an abrupt change in the attenuation rate of trees without leaves during measurements, that the excess loss could not be represented accurately by a single curve of the form $L = k'd^n$.

An excess loss model was also proposed in COST 235 [COST1996] for the case of vegetation in both foliated and defoliated states. The model can be written as in equation (3-8) and (3-9).

\[
L = 15.6f^{-0.009}d^{0.26} \quad \text{In-leaf} \quad (3-8)
\]
\[
L = 26.6f^{-0.2}d^{0.5} \quad \text{Out-of-leaf} \quad (3-9)
\]

The frequency $f$ is expressed in MHz and distance $d$ is in m.

The constants in the ITU-R model were further optimised using measured data in [Seville1995b], [Stephens1995], [COST1996] and [Al-Nuaimi1998] to derive the Fitted ITU-R (FITU-R) model. This has resulted in the following formulas for foliated and defoliated scenarios.

\[
L = 0.39f^{0.39}d^{0.25} \quad \text{In-leaf} \quad (3-10)
\]
The frequency $f$ is expressed in MHz and distance $d$ is in m [Al-Nuaimi1998].

All of the empirical models listed above indicate that the signal level received at small foliage depths decays at a considerably faster rate than the one at larger foliage depths. This observation is in a good agreement with the theoretical predictions based on the Radiative Energy Transfer (RET) theory described in [Al-Nuaimi1994], [Schwering1988]. This phenomenon can be explained by the interplay between coherent or direct path component, dominating at short distances into vegetation depth but is strongly attenuated, and the incoherent or scattered component, which takes over at relatively larger depths and is less attenuated. In addition to that, the foliage attenuation is shown to be higher for trees with leaves, due to the higher absorption per unit volume, and the comparable dimensions of individual leaves and branches at higher frequencies.

### 3.3.2 Semi Empirical Models

Semi-empirical models were initially developed to postulate a dual-slope characteristic of the attenuation function revealed by the measurement data [Al-Nuaimi1993], [Al-Nuaimi1993b], [Seville1995a], [Seville1995b], [Al-Nuaimi1994], and [Schwering1988]. The measured data appeared to level to a near zero gradient having a non-zero final attenuation rate. A more general three-parameter model, with the freedom of an unfixed final slope called Non-Zero Gradient (NZG) model was developed [Seville1995b]. The model gives a different shape for the attenuation versus vegetation depth, which is more representative of the dual-slope nature of the measured curves. However, this model only gives a fit to specific individual data sets, and further scaling to measurement frequency and geometry was required. In order to account for the site geometry, a Dual Gradient (DG) model was developed and proposed [Seville1997]. The descriptions of both semi-empirical models are given in the following sub-sections.
Non Zero Gradient Model (NZG)

The attenuation of trees as a function of vegetation depth has been shown in the literature to be more accurately represented by dual-slope attenuation functions [Al-Nuaimi1993] and [Al-Nuaimi1993b]. A model developed at Rutherford Appleton Laboratory (RAL) was intended to accommodate this dual-slope attenuation function known as the NZG model [Seville1995b], [Seville1997]. The initial slope describes the performance due to the coherent propagating component whereas the second slope, which is of a much reduced value, describes the behaviour of the weaker scattered incoherent component. The NZG model considers both of these components to give a good fit with measurement results at 11.2 and 20 GHz. Its attenuation function is expressed in equation (3-12) [Al-Nuaimi1998].

\[
L = R_0 d + k \left(1 - e^{-\frac{(R_0 - R_\infty) d}{k}} \right) \tag{3-12}
\]

\(L\) is the excess loss in dB, \(R_0\) and \(R_\infty\) are the initial and final attenuation rate in dB/m respectively, \(d\) is the vegetation depth in m and \(k\) is the final attenuation offset in dB. The values for parameters \(R_0\), \(R_\infty\) and \(k\) are given in Table 3-1 [Al-Nuaimi1998].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>In-leaf</th>
<th>Out-of-leaf</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_0) (dB/m)</td>
<td>19.82</td>
<td>6.25</td>
</tr>
<tr>
<td>(R_\infty) (dB/m)</td>
<td>0.33</td>
<td>0.24</td>
</tr>
<tr>
<td>(k) (dB)</td>
<td>37.87</td>
<td>6.45</td>
</tr>
</tbody>
</table>

Table 3-1: Parameters values for NZG model
Dual Gradient Model (DG)

A DG model is a further development of NZG model carried out by researchers in RAL [Seville1997] in order to account for the site geometry. The model considers the extent of illumination of the vegetation, which can be characterised by the illumination width, $W$ as shown in Figure 3-5.

![Vegetation geometry for DG model](image)

Figure 3-5: Vegetation geometry for DG model

$r_1$, $r_2$, $d$, $\beta_{tx}$, $\beta_{rx}$ and $\omega$ are the distance between the transmitter and vegetation structure, distance between vegetation structure and the receiver, vegetation width, transmitter beamwidth, receiver beamwidth and length of vegetation structure respectively. The excess loss predicted by the DG model can be expressed in equation (3-13).

$$L = \frac{R_0}{f^a W^b} d + \frac{k}{W^c} \left( 1 - e^{\left( \frac{(r_2 - r_1)\omega}{k} \right)} \right)$$  (3-13)
where, \(a\), \(b\), \(c\), \(k\), \(R_0\) and \(R_\infty\) are constants described in [COST1996], [Seville1997] and given in Table 3-2. Frequency \(f\) is in GHz.

\[
W = \min \left( \frac{(r_1 + d + r_2) \tan(B_\alpha) \tan(B_{rx})}{\tan(B_\alpha) + \tan(B_{rx})}, \frac{(r_1 + d) \tan(B_\alpha)}{(d + r_2) \tan(B_{rx})} \right)
\]

\((3-14)\)

\(W\) is the maximum effective coupling width between the transmit and receive antennas, that lies within the vegetation medium defined as equation (3-14).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>In-leaf</th>
<th>Out-of-leaf</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>0.7</td>
<td>0.64</td>
</tr>
<tr>
<td>(b)</td>
<td>0.81</td>
<td>0.43</td>
</tr>
<tr>
<td>(c)</td>
<td>0.37</td>
<td>0.97</td>
</tr>
<tr>
<td>(k)</td>
<td>68.80</td>
<td>114.70</td>
</tr>
<tr>
<td>(R_0)</td>
<td>16.70</td>
<td>6.59</td>
</tr>
<tr>
<td>(R_\infty)</td>
<td>8.77</td>
<td>3.89</td>
</tr>
</tbody>
</table>

Table 3-2: Parameters values for DG model

As can be seen in equation (3-13), the DG model is frequency dependent. The inverse relationship with frequency \((f^a \text{ and } a > 0)\) suggests a decreasing attenuation as frequency increases. This behaviour appears to contradict the outcome of the ITU-R models and what is observed in measured data [Stephens1998]. Furthermore, a clear trend, consistent but not necessarily uniform fashion, of increasing in attenuation with
frequency was observed and reported from the vegetation propagation measurement campaigns conducted at 9.6, 28.8 and 57.6GHz in [Schwering1988]. The foliage loss was shown to increase substantially as the frequency is raised from 9.6 to 28.8GHz, but the attenuation increment was happening at much reduced rate for frequency between 28.8 to 57.6GHz [Rogers2002].

Other prediction models to characterise signal attenuation as a function of vegetation depth, mainly for frequencies lower than 1GHz, have also been developed and are available in the literature. Series of extensive tree attenuation measurement campaigns were reported in [Vogel1986], [Vogel1988a] for Land Mobile Satellite System (LMSS). The results were derived from experiments performed using a helicopter and remotely piloted aircraft as the source platform at L-band and UHF frequencies. The attenuation was calculated by comparing the power changes for a scenario in which the receiving antenna was placed in front and behind a particular tree.

3.3.3 Analytical Models

In contrast to empirical or semi-empirical models described in previous sections, analytical models offer an insight into the physical processes involved during radiowave propagation through vegetation. However, they usually require the use of numerical analysis methods to provide solutions to the complex analytical formulations [Caldeirinha2000]. The available theoretical models, on radiowave propagation through vegetation, in the literature are analysed and presented in the form of; i) Geometrical and Uniform Theory of Diffraction (GTD/UTD) [Matschek99], [Li1998], [Tamir1967], ii) Radiative Energy Transfer Theory (RET) [Al-Nuaimi1994], [Schwering1988], [Ishimaru1978], iii) Full Wave Solutions [Ishimaru1978], [Schwering1988], [Al-Nuaimi1994], [Chiu2000], [Didascalou2000], and iv) Physical Optics (PO) [Torrico1996], [Torrico1998].

Out of these models, the Radiative Energy Transfer (RET) model was found to offer a highly effective vegetation attenuation and scatter model, which can be applied in
a variety of radio path geometries and frequencies above 1GHz [Rogers2002]. The RET model requires a few parameters which can be determined by measurements. The model itself requires the evaluation and solution of a number of equations, when compared to those involved in empirical models, appear to be quite complex. However, because the RET considers the physical processes involved in propagation through vegetation, solutions obtained from the model were expected to yield more accurate results for the attenuation and scatter components of the propagating signals [Rogers2002]. Brief description of basic RET model concepts are provided in the following section.

The Radiative Energy Transfer Theory

An analytical model based on the theory of Radiative Energy Transfer (RET) may be used to predict the attenuation curves and directional spectra due to propagation of a microwave signal through vegetation [Al-Nuaimi1994], [Schwering1988], [Ishimaru1978].

![Figure 3-6: Scattering from a homogeneous random medium of scatterers \( ds \)](image)

The vegetation medium is modelled as a statistically homogeneous random medium of scatterers with unit cross section and length \( ds \). As shown in Figure 3-6, the model considers a plane wave incident \( s' \) from an air half space upon the planar interface of a
vegetation half space and \( s \) is the scattered wave. The volume \( ds \) contains \( \rho \, ds \) particles, where \( \rho \) is the number of particles in a unit volume. Each particle absorbs the power \( \sigma_a \, I \) and scatters the power \( \sigma_s \, I \), where \( \sigma_a \) and \( \sigma_s \) are the absorption and scatter cross section respectively. The basic equation of the RET theory, expressed in terms of the specific intensity \( I \) and the phase or scatter function \( \rho(\hat{s}, \hat{s}') \), is given in equation (3-15) [Rogers2002].

\[
\mathbf{s} \cdot \nabla I(\hat{r}, \hat{s}) + (\sigma_a + \sigma_s)I(\hat{r}, \hat{s}) = \frac{\sigma_s}{4\pi} \int p(\hat{s}, \hat{s}')d\Omega
\]  

With regards to the phase function of the vegetation medium, a few assumptions had been made [Schwering1988]. Since the scattering surfaces in vegetation are practically random orientations, it was assumed that the scatter function is isotropic. Furthermore, since all scatter objects in vegetation including leaves and pine needles have dimensions comparable to a millimetre wavelength, the vegetation medium will produce strong forward scattering with a certain amount of scattering in all other directions. Therefore, the scatter function is assumed to consist of a strong narrow forward lobe and an isotropic background [Schwering1988].

For the solution of the transport equation in (3-15), the specific intensity, \( I \), at a given point within the vegetation medium is divided into two parts [Rogers2002].

\[
I(z, \theta) = I_n(z, \theta) + I_d(z, \theta)
\]  

This represents the sum of a coherent component, \( I_n \), which is reduced in intensity due to absorption of the incident wave, an incoherent diffuse component, \( I_d \), due to the scattered wave and \( z \) is the distance into the medium [Rogers2002], [Schwering1988]. For convenience, the term \( I_d \) was further split into two parts to represent the forward lobe.
scatter function, $I_1$, and $I_2$ for scattering into the isotropic background. Equation (3-16) can be re-expressed as in equation (3-17) below.

$$I = I_{ri} + I_1 + I_2$$

(3-17)

The resulting equation simplifies considerably for normal incidence of the propagation signal to the air-vegetation interface, and for an aligned transmitter and receiver configuration. Thus, the excess attenuation due to vegetation is by equation (3-18) [Rogers2002].

$$\frac{P_R}{P_{\text{Max}}} = e^r$$

$$+ \frac{\Delta \gamma^2}{4} \left[ \left( e^{-r} - e^{-r}\right) \cdot q_M + e^{-r} \cdot \sum_{m=1}^{\infty} \frac{1}{m!} (\alpha W r)^m (q_m - q_M) \right]$$

$I_{ri}$ part

$$+ \frac{\Delta \gamma^2}{4} \left[ -e^{-r} \cdot \frac{1}{P_N} \sum_{k=N+1}^{\infty} A_k e^{\frac{-r}{P_N}} \cdot \sum_{n=0}^{\infty} \frac{1}{1 - \frac{\mu_n}{S_k}} \right]$$

$I_1$ part (3-18)

$I_2$ part

$P_R$ is the received power by the receiving antennas with its gain pattern, and $P_{\text{Max}}$ is the received power in the absence of vegetation. $S_k$ and $A_k$ are the attenuation coefficient and amplitude factor respectively. Both terms were determined numerically in [Rogers2002]. $\Delta \gamma_R$ is the beamwidth of the receiving antenna, and $m$ is the order of the term $I_1$. The term $I_1$ is more accurately evaluated for higher values of $m$, however it will not change significantly for $m > 10$. $N$ in $I_2$ has to be an odd number larger than 1, with reasonable values were found to be between $11 < N < 21$ [Rogers2002]. Other relations and parameters related to equation (3-18) are as follow:
\[ \tau = (\sigma_a + \sigma_s) \cdot z = \sigma_t \cdot z \quad \tau \text{ is the optical density and } z \text{ is the distance in metres.} \]

\[ \bar{q}_m = \frac{4}{\Delta y^2 + m \beta^2} \]

\[ \mu_n = -\cos\left(\frac{n\pi}{N}\right) \]

\[ P_n = \sin^2\left(\frac{\pi}{2N}\right) \quad \text{for } n = 0, N \]

\[ P_n = \sin\left(\frac{\pi}{N}\right) \cdot \sin\left(\frac{n\pi}{N}\right) \quad \text{for } n = 1, 2, ..., N - 1 \]

\[ \hat{\tau} = (1 - \alpha W) \tau \]

\[ \hat{W} = \frac{(1 - \alpha) W}{1 - \alpha W} \quad \hat{W} \text{ is referred to the reduced albedo} \]

\[ (3-19) \]

\[ (3-20) \]

The parameters \( \sigma_a, \sigma_s, \alpha, \text{ and } \beta \) are specific to a vegetation medium and can be estimated for the medium under investigation by comparison of experimental and predicted results [Stephens1995], [Al-Nuaimi1994]. The relative magnitude of \( \sigma_a \) and \( \sigma_s \) are described in terms of the albedo, \( W \) as shown in equation (3-20).

\[ W = \frac{\sigma_s}{\sigma_a + \sigma_s} \]

(3-20)

The implementation of this deterministic approach using numerical techniques gives a good understanding of the physical processes affecting propagation through vegetation. This theory predicts the dual slope nature of the measured attenuation versus vegetation depth curves and provides a physical interpretation of the scenario [Stephens1998], [Hammoudeh1996]. For the initial part of these curves, the received signal is reduced linearly due to scattering and absorption of the incident signal. As the receiver is moved deeper into the vegetation, and the direct coherent component is reduced further, the isotropically scattered component becomes significant. Due to the increasing scatter volume as we move deeper into the medium, the scatter signal level tends to be
maintained, leading in turn to an attenuation rate which is significantly reduced at these depths [Rogers2002].

**Generic Vegetation Attenuation Model**

A generic model for radiowaves propagation through vegetation had been proposed in [Rogers2002]. The model is valid for operating frequencies between 1 and 60GHz. The model was developed to overcome the limiting factor, such as parameters relating to vegetation medium, path geometry, system configuration and seasonal effects, and to predict the attenuation of narrowband radio signals for a full range of propagation geometries and propagation characteristics appropriate to vegetation common to the United Kingdom (UK). The extent of the vegetation is modelled as a rectangular hexahedrons, as shown in Figure 3-7.

![Figure 3-7: Consideration of three modes of propagation through and around vegetation](image-url)
The generic model combines the effects of three individual propagation modes: (a) Diffraction from the sides and top of the foliage, (b) Ground reflections, and (c) direct or through vegetation propagation. Diffraction is model using up to two \textit{knife-edges} in accordance to ITUR Recommendation 526-3 [ITU-R2000a], ground reflection is modelled according to ITU-R Recommendation 527-3 [ITU-R2000b] and the direct or through vegetation propagation ray is modelled using the RET theory, which accounts for both scattering and absorption of radiowaves. Thus, the total predicted loss, $L_{\text{Total}}$, experienced by a signal propagating through vegetation is given by the combination of the loss terms, expressed in equation (3-21).

$$L_{\text{Total}} = -10 \log_{10} \left[ 10^{-L_{\text{side},a}} + 10^{-L_{\text{side},b}} + 10^{-L_{\text{top}}} + 10^{-L_{\text{ground}}} + 10^{-L_{\text{direct}}} \right]$$

(3-21)

### 3.4 Dynamic Effects of Vegetation

When considering the effects of vegetation, it is clear that the environment will not remain static at all times. A receiver may be obstructed by one or more trees along the signal propagation path that would not give a sufficient mean attenuation to take the received signal below the system margin. However, it has been found that as the tree moves, the signal level varies dynamically over a large range making the provision of service is unfeasible, even if the sufficient mean power is obtained at the receiver [ITU-R2000], [Ledl2003]. In addition, although it was not consistent, it was reported in [Seville2003] that the television picture was lost when the signal level, propagating through tree channel, went into deep fades. Utilising a higher operating frequency or lowering the base station heights, previously insignificant vegetation-shadowing effects will now become more pronounced. As most neighbourhoods have some sort of vegetation that can expand or grow over the years, it is not always possible to guarantee a clear LOS propagation path [Perras2002]. Thus, characterising radiowave propagation...
through this type of dynamic medium is vital and a better understanding of the dynamic vegetation effects will help in finding solutions to this problem. While literature includes many investigations on the effects of absorption and scattering effects of assumed static vegetation bulk as explained in previous sections, relatively few studies have dealt with the effects of moving vegetation under the influence of wind [Randle1999], [Perras2002] and [Ledl2003]. The motion of leaves and branches within the vegetation structure in response to wind is thought to introduce temporal variation of the relative phases of the multipath components resulting in faster variations of the received signal than its shadowing loss. For accurate channel prediction, this adverse condition should be taken into consideration.

Several authors had also acknowledged the effects of the wind-induced motion of foliage onto propagating radiowaves as a result from their measurement campaigns [Vogel1995], [Goldman1999], [Bello2000]. However, the work did not specifically study the wind-induced impact. Simultaneous measurements at L- and S-band frequencies were conducted to study the time, space and frequency variability in the received signal of tree shadowing condition [Vogel1995]. The results indicated that the time variations are slow if there is little wind and the receiver is stationary. Another measurement campaign through a cottonwood plantation was reported in [Goldman1999] at VHF and UHF bands suggesting that significant short-period fluctuations were evident in the received signal. Signal power variations were also recorded in the propagation studies in an urban forested park area for frequencies ranging from 0.9 to 1.8GHz [Bello2000]. The fading evident in the recorded data was thought to result from the temporal variation of the relative phase of multipath components resulting from motion of leaves and branches in response to wind, and to some extent, from the motion of people in the vicinity of the receiver. Most of the studies and models available are on static trees or group of trees. In the case of channel prediction, it is usually the best policy to predict the channel performance under adverse conditions. For example, examining and predicting the minimum environmental circumstances that would break the communications link. Therefore, modelling the trees as a static source of scattering would not produce adverse conditions as the vegetation components, such as leaves and branches are subjected to movement under strong wind influence.
3.4.1 Bistatic Scattering Effects

As it has been addressed in the previous section, modelling the effects of trees that are set in motion by strong wind is important and would account for frequency shift and other modulating effects on the carrier. The modulating effect represents an additional concern for wireless network planners, particularly those who are concerned about the different use of radio spectrum [Randle1999]. The application of such a model is suitable for assessing how dynamic foliage scattering will affect certain modulation schemes. In addition, it may also assist with the general planning of a wireless network topologies and power budgets.

Series of measurement campaigns on dynamic foliage scattering at 1.529 GHz were reported in [Randle1999]. The measurements were focused on characterising the spectral shifting effects on the bistatic scattering of the RF signal in the forward direction as well as correlating them with the wind speed, from moving foliage. Both the transmitter and receiver were stationary and within the line of sight of each other. The report presents the spectral analysis of averaged light and strong wind conditions of 1.024 mph and 3.844 mph respectively. It was reported that the carrier modulation effects were easily noticeable over a band of 0 – 200 Hz and they occurred more frequently and significantly during strong wind condition, as oppose to little spectral activities during light wind condition. Thus, higher wind speeds generate a larger spread in modulating frequency component. The results were used in the development of Dynamic Foliage Modulation (DFM) model proposed in [Randle1999] to include the effects of foliage on the transmitted signal. Figure 3-8 is a sample diagram representing the additional modulation of incoherent scattering from foliage. On the left of Figure 3-8 is the transmitted power, $P_t(t)$, that enters the stationary scattering model. This produces a received coherent voltage contribution, $V_c(t)$, that is then modulated with the dynamic scattering channel characteristics of the foliage, $V_m(t)$. The output of the model is $V_r(t)$,
the total received voltage across the receiving antenna. The modulating voltage contribution is shown in equation (3-22).

\[ V_m(t) = 2A \sum_{j=1}^{200} K_j(f) \cos(2\pi ft + \psi) \]  

(3-22)

\( V_m(t) \) is the baseband modulating contribution to form the incoherently received voltage contribution, \( V_{ic}(t) \) as depicted in the figure. Note that \( \psi \) is the phase of each spectral contribution and was found by [Randle1999] to have a uniform distribution between \(-\pi\) and \(+\pi\) radians. Coefficient, \( K_j(f) \), is the Rayleigh distributed weight, chosen according to the spot frequency of the modulating voltage and \( A \) is a constant that represents the magnitude of scattering which is related to the received ratio of incoherent to coherent field. The variables \( K_j(f) \) and \( A \) are represented as below:
$$K_f(f) = \frac{R_f(f)}{\langle R_f(f) \rangle}$$  \hspace{1cm} (3-23) \\

$$A = \frac{\langle R_f(f) \rangle}{V_c^{ref}}$$  \hspace{1cm} (3-24) \\

$R_f(f)$ is the mean incoherent spectral voltage level at a particular frequency and $V_c^{ref}$ is a coherent spot frequency voltage. The distributions of $K_f(f)$ for light and strong wind conditions, derived from measurement data, are shown in Figure 3-9(a) and (b) respectively [Randle1999].

![Figure 3-9: Distribution of $K_f(f)$, Rayleigh distributed weight](image)

(a) Light wind condition       (b) Strong wind condition
From the measurements, the parameters values for equations (3-23) and (3-24) are summarised in Table 3-3.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Light Wind Condition</th>
<th>Strong Wind Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{c}^{ref}$</td>
<td>35.44 µN</td>
<td>35.44 µN</td>
</tr>
<tr>
<td>$&lt;R_f(f)&gt;$</td>
<td>0.258 µN</td>
<td>0.45 µN</td>
</tr>
<tr>
<td>$A$</td>
<td>0.0073</td>
<td>0.0127</td>
</tr>
</tbody>
</table>

Table 3-3: Related parameters values for DFM

The time domain response of an arbitrary coherent voltage, $V_c$, at a frequency, $f_c$, and stationary phase is defined as:

$$V_c(t) = V_{c}^{ref} \cos(2\pi f_c t)$$  \hspace{1cm} (3-25)

Therefore, the general form of the incoherent voltage contribution can be expressed as equation (3-25).

$$V_K(t) = V_c A \sum_{f=1}^{200} K_f(f) \cos[(2\pi ft + \psi) - 2\pi f_c t] + V_c A \sum_{f=1}^{200} K_f(f) \cos[(2\pi ft + \psi) + 2\pi f_c t]$$  \hspace{1cm} (3-26)

Thus, it provides a spectrum that is mirrored about $f_c$. At the final stage of the simulation in Figure 3-6, the coherent contribution will be unsuppressed at the antenna side of the receiver. Therefore, the coherent and incoherent voltages undergo
superposition as represented in equations (3-27) and (3-28), assuming no other power losses.

\[ V_r(t) = V_e(t) + V_k(t) \quad (3-27) \]

\[ P_r(t) = \frac{V_r(t) \times V_r^*(t)}{Z_0} \quad (3-28) \]

This initial empirically generated model proposed in [Randle1999] relates the activity of dynamic scatter to the stationary electromagnetic contribution. Furthermore, the findings of this work showed that the dynamic scattering ratio, \( A \), is proportionally related to the wind speed and that higher wind speeds generate a larger spread in modulating frequency components.

### 3.4.2 Variation of Direct Signal

As it has been addressed earlier, blockage by trees can severely limit the availability of a particular service in a given location, so it is very important to evaluate the fading characteristics caused by trees. Beside the variation of multipath scattering contributions arising from the surrounding foliage as explained in the previous section, the movement of the blocking trees, during a windy environment, can also be an additional fading contribution to the received signal. This additional attenuation over traditional LOS attenuation is then necessary to be compensated by an increased power margin or using an appropriate power control scheme. Furthermore, in some cases, even if the sufficient mean power is obtained at the receiver, the desired quality of service is not obtained because of deep fades in the received signal [ITU-R2000], [Ledl2003]. Therefore, it is desirable to evaluate this dynamic impact as accurate as possible.

One aspect of the problem that is lacking in most investigations is the signal dynamics caused by vegetation movement under the influence of wind, given that both...
the amplitude and phase of radiowaves will be affected. Limited number of studies has been found in the literature regarding this issue. The temporal variations characterisation for fixed wireless system at 29.5GHz was conducted and reported in [Naz2000]. The work discusses the general effect of foliage movements due to wind, and nearby passing vehicles on the radio propagation link. In addition to that, a comparison of various temporal characteristics of radio channels for a broad range of frequencies, including 2.45, 5.35, 29 and GHz, was reported in [Perras2002]. It was shown that RF propagation transmission through trees between 2 and 60GHz is strongly frequency and wind speed dependent. A time-series prediction of attenuation caused by trees during windy conditions intended for Fixed Wireless Access (FWA) systems operating in millimetre waveband was presented in [Ledl2003]. The simulation results at 38 GHz were compared to the results of measurements conducted in the anechoic chamber. Both results showed good qualitative agreement with each other and that the signal amplitude distribution resembles Rayleigh distribution during high wind speed. Nevertheless, the observed fading depth from the anechoic chamber measurement conducted in [Ledl2003] was much less than the simulation.

It has been reported in the previous work that radiowave propagation through vegetation structures is strongly wind speed dependent. The effects of multiple scattering can be originated from the multipath contributions surrounding the receiver as well as scattered components generated within the direct blocking tree structures. Therefore, the main focus of this work is to investigate the fast variation of the direct signal effects due to moving foliage as well as to characterise its attributes over different wind conditions. The outcome of this work is an empirically generated dynamic fading model that describes the variation of the direct signal reaching the receiver during different wind conditions.
3.5 Interim Conclusions

The impact of vegetation on propagating radiowaves in various vegetation shadowing scenarios have been described in this chapter. Attenuation of the propagating signal through a vegetation medium is clearly very important in the design of radio links, where vegetation forms part of the radio propagation path. The attenuation of the signal depends on the physical extent of the medium and the attributes of the trees in the medium. Prediction models, which estimate the excess attenuation and dynamic effects due to vegetation are critical to the wireless network providers, for not only planning radio networks, but also for optimising spectrum utilisation by accurately predicting the system performance. A number of propagation prediction models available in the literature had been summarised. Most of them can be used to provide estimates of the excess attenuation due to static vegetation structures at specified frequency bands. However, it is usually the best policy to predict the channel operating under adverse conditions. Modelling the trees as a static source of scattering would not represent adverse conditions, as the components within the tree structure such as leaves and branches are subjected to movement in the real environment. Since limited work investigated this issue, the measurement campaigns and the analysis of the results reported in the following chapters are involved in characterising and predicting the signal behaviour under various wind conditions.
Chapter 4

4 Measurement Campaign I:
Controlled Environment Experiments

4.1 Introduction

This chapter outlines series of experiments that had been conducted as part of the dynamic impact of vegetation onto wireless systems. The aims of the measurement campaign were to investigate the influence of vegetation movements onto radiowave propagation and characterise the received signal behaviour under various wind conditions. The movement of vegetation was assumed to have a direct relation with the wind speed projected onto it. Measurements were carried out in a controlled environment of an anechoic chamber. A wind generator was implemented as a wind source, and vegetation samples were used as scatterers. This approach provides flexibility in controlling the wind speed and minimising interference from other reflected waves. The main results and initial analysis of the experiment are presented at the end of this chapter. Further analysis of fast fading analysis is given in chapter 6, where the controlled environment and outdoor environment data would be processed and compared co-currently.
4.2 Specific Experimental Objectives

The general aim of the experiments was to characterise the radiowaves propagating through the moving vegetation. The wind speed was measured for every level of the speed settings on the wind generator. Therefore, the following objectives were of interest throughout the measurement campaign.

- To record the received signal power variations in the time domain through various vegetation samples during different wind speed conditions.
- To compile a wind speed profile for each of the level settings on the wind generator representing the wind speed projected onto the vegetation samples.
- To analyse the recorded data in order to describe the statistical characteristics of fading in windy conditions.
- To observe any relation between the wind speed and the statistical trends of received signal during various windy conditions at different frequencies.

4.3 Measurement Approach

4.3.1 Anechoic Chamber and Measurement Set-up

An anechoic chamber is a laboratory environment that is used for indoor measurements to enable experiments to be performed under controlled conditions. It constitutes of rigid absorbing foams (RAM) in order to curtail the reflections of waves present during the experiments, thus minimises electromagnetic interference with the transmitted waves that are under investigation. The utilised chamber had a length of 5.82 m, a width of 3.08 m and a height of 2.67 m. The outside walls including the roof and the floor of the chamber are lined with metal plates that prevent any outside electromagnetic influence on what is occurring within the chamber. In addition, the inner walls, floor and
ceiling of the chamber are bonded with absorption foam panels. The panels were designed to have series of pyramidal shaped absorption cones. The specific frequency range that can be operated within this chamber is between 0.4 to 60GHz. Housed within the chamber, is an automated turntable, which is normally used for measuring the radiation pattern of an antenna and various propagation measurements. A computer located outside the chamber is used primarily to control the automated measurements performed inside the chamber. This has the additional advantage of eliminating the need for human presence inside the chamber while measurements are in progress.

For this particular study, a vegetation sample was placed within the propagation path. Special care was given to the distance between the vegetation sample and the transmitting or receiving antenna in order to carry out the measurements in the far-field region.

Figure 4-1: Experimental configuration for controlled environment measurements

Figure 4-1 shows the layout of the experimental design. The wind generator was implemented on one side of the anechoic chamber together with the transmitting and receiving antennas, where other equipment were placed outside of the chamber. Each of the vegetation samples was placed in between the transmitter and receiver antennas, which were at equal height with each other.
4.3.2 Experimental Equipment

The equipment used to conduct the controlled environment scattering measurement can be grouped into three categories:

a) Transmission
b) Receiving and data acquisition
c) Wind speed profiling

Figure 4-2 shows the diagram of the experimental set up.

![Diagram of experimental equipment](image)

Figure 4-2: Experimental equipment for controlled environment measurements

The measurements were performed using a Continuous Waves (CW) transmission at four different frequencies. These include signals at 0.9 and 2GHz generated from a Rohde & Schwarz SMIQ03B (R&S) and, 12 and 17GHz signals were generated from a Hewlett Packard 83650L (HP) signal generator. The output of the signal generator was amplified through an RF amplifier in order to deliver 18 dBm to the transmitting antenna to make sure that a sufficient amount of power would be detected at the receiver side. The equal height of the transmitting and receiving antennas were adjusted so that the
maximum irradiation was oriented to the centre of the vegetation canopy. Standard horn antennas for transmission and, horn and dipole antennas, depending on the frequency, for reception were used during the measurements. The list of antennas used in the experiments and their basic characteristics are summarised in Table 4-1 below.

<table>
<thead>
<tr>
<th>Type</th>
<th>Frequency Range</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn 1</td>
<td>600 – 900MHz</td>
<td>Tx (900MHz)</td>
</tr>
<tr>
<td>Horn 2</td>
<td>1 – 18.0GHz</td>
<td>Tx (2GHz)</td>
</tr>
<tr>
<td>Horn 3</td>
<td>11.9 – 18.0GHz</td>
<td>Tx &amp; Rx (12 &amp; 17GHz)</td>
</tr>
<tr>
<td>Tunable Dipole</td>
<td>0.75 – 2.0GHz</td>
<td>Rx (900MHz &amp; 2GHz)</td>
</tr>
</tbody>
</table>

Table 4-1: List of antennas used in the controlled environment experiments

On the receiver side, the received signals were recorded using a R&S FSEK spectrum analyser. The spectrum analyser was set to zero-span, as it was carried out in [Perras2002], in order to record the time series signal at a sample rate of 1000 samples per second. Using the General Purpose Interface Bus (GPIB) cable, the spectrum analyser was connected to the computer, where a labview program calculated and saved the signal variations into data files for further analysis. The transmission and receiving equipment were synchronised with each other by connecting to the same 10 MHz reference from the signal generator.

![Figure 4-3: Anemometer used for wind speed profiling](image)
The last pieces of the experimental equipment were the wind generator and the wind speed metre used for the wind speed profiling, prior to the actual radiowave scattering measurements. An industrial wind generator was positioned in the way illustrated in Figure 4-1, inside the anechoic chamber. There were four speed levels identified. The wind speed produced at each level was measured using a simple analogue anemometer, which constitutes of a rounded tip sensor, a metre and a power supply. The anemometer was able to measure the wind speed in metre per second. Figure 4-3 shows a schematic diagram of the anemometer used in this measurement campaign.

4.3.3 Vegetation Samples

The scattering measurements in the controlled environment were performed on two types of vegetation samples. These vegetation samples had different sizes and shapes of leaves and branches. The leaves of Tree 1 were much longer and broader than those of Tree 2, which were mainly small with an elliptical shape. Similarly, the branches of Tree 1 were much more sturdy compared to the smaller and more flexible branches of Tree 2. The two samples of vegetation are shown in Figure 4-4(a) and (b).
4.3.4 Experimental Procedures

As an initial calibration, a CW signal was transmitted in a LOS condition, without any vegetation present, and the mean received signal was used as a reference in the fading calculations. This process was repeated for every frequency tested before starting the scattering measurements. Both transmit and receive antennas were vertically polarised. Prior to the actual vegetation scattering measurements, the profile of wind speed projected onto the vegetation sample was compiled for every speed level. A simple analogue anemometer, described and illustrated in Figure 4-3, was used to measure the wind speed at various points around the position where the vegetation sample would be placed. Then, the average wind speed was taken to represent the projected wind speed at every level setting. Four speed settings generated from the wind generator were identified and summarised in Table 4-2 below.

<table>
<thead>
<tr>
<th>Level</th>
<th>Wind Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.51 m/s</td>
</tr>
<tr>
<td>2</td>
<td>1.65 m/s</td>
</tr>
<tr>
<td>3</td>
<td>4.07 m/s</td>
</tr>
<tr>
<td>4</td>
<td>7.10 m/s</td>
</tr>
</tbody>
</table>

Table 4-2: List of speed level generated from wind generator

Speed level 1, 2, 3 and 4 represent calm, low, medium and high wind speed conditions respectively. For the scattering measurement, one of the vegetation samples was placed in the propagation path and the wind generator was set to level 1 on the dial. The wind generator was left to continue blowing for a while, so that a constant speed could be achieved before the receiving system started recording the data. The speed was then changed to a higher setting and similar procedures were followed. Table 4-3 summarises the number of experiments conducted. The recorded signal was then normalised to the LOS value to represent the fades caused by vegetation samples.
<table>
<thead>
<tr>
<th>Experimental Parameters</th>
<th>Tree 1</th>
<th>Tree 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>0.9, 2.0, 12, 17</td>
<td>0.9, 2.0, 12, 17</td>
</tr>
<tr>
<td>Polarisation</td>
<td>Vertical</td>
<td>Vertical</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>1, 2, 3, 4</td>
<td>1, 2, 3, 4</td>
</tr>
</tbody>
</table>

Table 4-3: List of experiments conducted during controlled environment measurement campaign

4.4 Main Results

For each scenario the same set of measurement was repeated at least 20 times in order to collect enough data for fast fading analysis purposes. That was because the spectrum analyser recorded 500 samples per cycle of 0.5 second in zero-span mode. The recorded received signal from all experiments were combined and sorted according to the wind speeds, vegetation types and frequencies. The main results of the measurement campaign are presented in terms of the power variations relative to the LOS level. Figures presented in the next sections show typical time dependent received signals recorded during every wind speed set [Hashim2003a].

4.4.1 Measurement Data at 900MHz

Figure 4-5(a), (b), (c) and (d) show the normalised power variations recorded at 900 MHz for Tree 1. From the figures, there was about -6 to -7 dB of almost constant loss caused by Tree 1 regardless of the wind conditions. The results recorded for smaller size Tree 2 shows insignificant loss.
From these results, it implies that the impact due to vegetation is more significant when its size is comparable to the signal’s wavelength, and the signal fluctuation caused by the two vegetation samples is insignificant at 900 MHz for this particular controlled environment experiment.
4.4.2 Measurement Data at 2.0GHz

Figure 4-6(a), (b), (c) and (d) show the power variations recorded at 2 GHz for Tree 1. It can be deduced from the plots that during a windy environment the signal fluctuations became more prominent.

![Graphs showing power variations over time for Tree 1 at 2 GHz](image_url)

(a) Wind speed = 0.51 m/s  
(b) Wind speed = 1.65 m/s  
(c) Wind speed = 4.07 m/s  
(d) Wind speed = 7.1 m/s

Figure 4-6: Power variations over time for Tree 1 at 2 GHz
However, these variations were concentrated around the constant mean value of -6 to -7 dB except for signal recorded during speed level 4 as shown in Figure 4-6(d). The mean value had increased slightly to about -5 dB. This suggests, as if, lower loss during high wind speed at during the highest wind speed level. This phenomenon is due to the limitation of the experimental set-up. During the measurements inside the anechoic chamber, the wind generator was implemented on one specific corner as shown in Figure 4-1. This configuration created a single direction of wind, projected onto the vegetation sample. Consequently, when high wind speed was applied, the single direction of wind speed had pushed the tree to be skewed to the opposite side, which then allowed a stronger dominant signal to be present. Similar to signal at 900 MHz, the results for Tree 2 show insignificant loss and fluctuations.

4.4.3 Measurement Data at 12.0GHz

Figure 4-7(a), (b), (c) and (d) and figure 4-8(a), (b), (c) and (d) show the power variations recorded at 12 GHz for Tree 1 and Tree 2 respectively.

![Graphs showing power variations at 12.0GHz](image)

(a) Wind speed = 0.51m/s  
(b) Wind speed = 1.65m/s
Figure 4-7: Power variations over time for Tree 1 at 12 GHz

(a) Wind speed = 0.51 m/s
(b) Wind speed = 1.65 m/s
(c) Wind speed = 4.07 m/s
(d) Wind speed = 7.1 m/s
It can clearly be seen from the figures that deep fades in the received signal had been augmented during windy conditions and the rate of signal's variation had also increased with wind speed. In addition, the plots indicate reduction of mean signal level when the wind speed was increased up to level 3 and increased when the wind speed was at its highest level, which is more obvious for Tree 1. Consistently, the effect caused by larger size Tree 1 was more significant than Tree 2.

4.4.4 Measurement Data at 17GHz

Figure 4-9(a), (b), (c) and (d) and figure 4-10(a), (b), (c) and (d) show the power variations recorded at 17 GHz for Tree 1 and Tree 2 respectively.
Figure 4-9: Power variations over time for Tree 1 at 17 GHz

(a) Wind speed = 0.51 m/s
(b) Wind speed = 1.65 m/s
(c) Wind speed = 4.07 m/s
(d) Wind speed = 7.1 m/s
The results plotted in this section show a consistent behaviour and confirm the findings of the previous sections in terms of the received signal behaviour over various wind speed conditions and two different vegetation samples, including the increment of the mean level during the highest wind speed condition.
4.5 Initial Analysis of Propagation Data

The radio propagation measurement recordings consist of two types of main data: (a) Signal received power, and (b) Wind speed. The raw measured datasets were sorted according to the different scenarios, averaged wind speed, frequency and vegetation sample. Then, the received level of each dataset was normalised to the mean power level in order to extract the fast variation component of the received signal, and its fade amplitude was calculated. This pre-processing of the propagation data was designed to achieve an appropriate form for the analysis, where the statistical information of fast variation component was the parameter of interest.

4.5.1 Comparison to Known Distributions

As explained in Chapter 2, the distributions of the fast fading signal, from the measurement data, were compared to the commonly known distributions. Figures 4-11, 4-12, 4-13, 4-14, 4-15, 4-16, 4-17 and 4-18 show the examples of PDF comparison of the measured data, from the experiments, against the five mentioned distributions.
As indicated by Figures 4-11 and 4-12 for all measured datasets at 0.9 and 2.0GHz the Gaussian distribution is the closest distribution to represent the data. It was not possible to estimate the distribution using other distributions. This is well explained by the nature of the concentration of the received signals around the strong mean value due to the insignificant impact of the vegetation sample at these frequencies.

(c) Medium wind speed condition  
(d) High wind speed condition

Figure 4-11: PDF comparison of measured data at 0.9 GHz of Tree 1 in controlled environment with known distributions

(a) Calm wind speed condition  
(b) Low wind speed condition
Figure 4-12: PDF comparison of measured data at 2.0 GHz of Tree 1 in controlled environment with known distributions

On the other hand, as can be seen in Figures 4-13, 4-14, 4-15 and 4-16, all of measured data at 12 and 17 GHz can be well represented by Gaussian, Rice or Nakagami distribution, except for measured data during low wind speed using the relatively smaller Tree 2 as a vegetation sample. For these datasets, the closest distribution is still the Gaussian distribution.
Figure 4-13: PDF comparison of measured data at 12.0 GHz of Tree 1 in controlled environment with known distributions

(a) Calm wind speed condition

(b) Low wind speed condition

(c) Medium wind speed condition

(d) High wind speed condition
Figure 4-14: PDF comparison of measured data at 12.0 GHz of Tree 2 in controlled environment with known distributions

(a) Low wind speed condition

(b) Medium wind speed condition

(c) Medium wind speed condition

(d) High wind speed condition

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Figure 4-15: PDF comparison of measured data at 17.0 GHz of Tree 1 in controlled environment with known distributions

Dynamic Impact of Vegetation on Wireless Communication Systems
4.5.2 Error Analysis

In order to assess the closeness of the measured data PDF to the known distributions, calculation of the root mean square (RMS) error was carried out as in [Al-Nuaimi1998] for the modelled and measured attenuation curves. The RMS error is defined as:

\[ E_{RMS} = \sqrt{\frac{\sum_{i=1}^{N} E_i^2}{N}} \]  

(4-1)

\( N \) is the number of PDF sample points and \( E_i \) is the difference between measured and theoretical PDF values at the same fading level. The theoretical curve with the least RMS
error value would be considered as the representation of the measured fast fading amplitude distribution.

<table>
<thead>
<tr>
<th>Speed Level</th>
<th>Average $E_{\text{RMS,Gaussian}}$</th>
<th>Average $E_{\text{RMS,Rician}}$</th>
<th>Average $E_{\text{RMS,Rayleigh}}$</th>
<th>Average $E_{\text{RMS,Nakagami}}$</th>
<th>Average $E_{\text{RMS,Weibull}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm</td>
<td>1.19</td>
<td>0.69</td>
<td>6.25</td>
<td>0.69</td>
<td>6.78</td>
</tr>
<tr>
<td>Low</td>
<td>0.55</td>
<td>0.52</td>
<td>2.71</td>
<td>0.52</td>
<td>3.18</td>
</tr>
<tr>
<td>Medium</td>
<td>0.23</td>
<td>0.21</td>
<td>0.95</td>
<td>0.22</td>
<td>1.27</td>
</tr>
<tr>
<td>High</td>
<td>0.22</td>
<td>0.21</td>
<td>1.06</td>
<td>0.21</td>
<td>1.41</td>
</tr>
</tbody>
</table>

Table 4-4: Average $E_{\text{RMS}}$ values for each distribution compared to measured data from controlled environment measurements.

Since the measured data at 0.9 and 2 GHz were clearly shown to follow Gaussian distribution, the calculations of $E_{\text{RMS}}$ were carried out on measured data at 12.0 and 17.0 GHz. Table 4-1 summarises the average $E_{\text{RMS}}$ values calculated from measured data at 12 and 17 GHz during each wind speed level, and it was found that the measured data can be represented by Rice and Nakagami distributions almost equally well based on the average $E_{\text{RMS}}$ over frequency and vegetation type.

### 4.6 Interim Conclusions

Series of controlled environment measurements had been conducted as part of the dynamic vegetation impact investigation on radiowave propagation. The main objective was to study and characterise the radiowave behaviour when radiowaves propagate through vegetation under the influence of wind. The controlled experiments of various
wind speed levels projected onto two different types of vegetation samples at four different frequencies had been carried out. The main results indicated a strong wind speed dependency for radiowaves propagating through vegetation. The contributions of multipath, due to multiple reflections and scattering from the leaves and branches, have led the received signal to be mostly Rician or Nakagami distributed. The experimental set up in this measurement campaign also provides the flexibility in controlling the wind speed level projected onto the vegetation sample and minimising other contributions that might be present in a real environment. However, a peculiar increase of mean signal level during wind speed level 4, the highest wind speed level, was also noted. This phenomenon can be explained by the nature of the experimental set-up of this study. In the experimental configuration shown in Figure 4-1, the wind generator was placed on one side. Consequently, the wind was blowing from one direction. During high wind speed level, the generated wind had pushed the vegetation sample to be skewed to the opposite side, which then allowed a stronger dominant signal to be present. As a result of this, the mean signal level was higher during the highest wind speed. Finally, it is confirmed that the impact caused by moving vegetation also became more pronounced when the vegetation size and the wavelength of the signal are comparable to each other. This can be implied from the significant effect caused by the larger vegetation sample and for experiment conducted at higher frequencies. Further analysis of various statistical characteristics of measured data is examined in Chapter 6.
Chapter 5

5 Measurement Campaign II: Outdoor Environment Experiments

5.1 Introduction

The second phase of the measurement campaign, and as a complement to the measurements conducted in the anechoic chamber, series of outdoor measurements were also carried out. The aim of the measurement campaign was broadly similar to the one explained in the previous chapter, to investigate the influence of vegetation movement onto radiowave propagation and characterise the received signal behaviour under various wind conditions. However, in this measurement campaign the transmitted signals from an existing mobile base station, propagating through a block of vegetation, were recorded. Shadowed regions of various configurations were identified and used as experimental locations. The main findings and initial analysis of the experiment are presented at the end, and further fast-fading analysis of the results are given in Chapter 6, where the
controlled environment and outdoor environment data would be processed co-currently and compared.

5.2 Specific Experimental Objectives

The specific aim of this measurement campaign were to study and compare the results from this measurement campaign and the ones from the controlled environment. During the data recording process, the wind speed in the area of interest was measured simultaneously with the received signal. Therefore, the intermediate objectives identified previously were still valid with a slight modification as follows.

• To acquire the signal strength of propagating radiowaves through a single tree, line of trees and group of trees during various conditions up to a wind speed of Beaufort number 7.

• To record the wind speed simultaneously during the conducted propagation measurements.

5.3 Measurement Approach

In general the experiments were conducted outdoor in a real environment. During the measurements, the transmitter and receiver were set to be in a stationary position. This part of experimental design was intended to allow the recording of temporal variations in received signal due to the movement of the vegetation structures. The transmitted signal was provided by an existing mobile base station, operated at 0.9 and 1.8GHz.
5.3.1 Experimental Sites and Set-up

Figure 5-1 illustrates the general geometry of the experimental set-up.

![Diagram](image)

Figure 5-1: Geometry of the outdoor experimental set-up

In investigating the influence of vegetation shadowing and the effects of its movements, the environment can be categorised into the following scenarios [Bello2000]:

(i) Isolated individual tree

(ii) Line or multiple lines of trees

(iii) Small forest, well defined park or group of trees, and

(iv) Relatively large forest

Ideally, all scenarios should be investigated and studied. However in this measurement campaign, a single tree, a line of trees and a group of trees were considered. As part of the measurement preparation, the mobile base station identification was carried out based on the Radiocommunication Agency (RA) database. One base station for GSM-900 and two GSM-1800 base stations were identified to be suitable for the experiments. Figure 5-2(a), (b), (c) and (d) show the photographs of the experimental sites for GSM-900
(isolated tree), GSM-1800 (isolated tree), GSM-1800 (line of trees) and GSM-1800 (group of trees) configurations respectively.

Figure 5-2: Experimental sites for outdoor measurement campaign

(a) Site 1 for GSM-900  
(b) Site 1 for GSM-1800  
(c) Site 2 for GSM-1800  
(d) Site 3 for GSM-1800
However after a series of trial measurements, the sample data recorded at the GSM-900 experimental site showed insignificant loss and fading variation regardless of wind speed influence. As shown in Figure 5-2(a), the tree canopy was quite high compared to the receiver, which may have caused stronger dominant signal relative to multipath contributions to be present. Therefore, the continuation of the measurement was then concentrated on the 1800MHz signal characteristics.

The first site of GSM-1800 experiments was an isolated tree on the Guildford Cathedral ground. It was an open area with minimal disturbances from vehicles or people walking in the vicinity. A mobile network base station was located on top of the cathedral tower that was used as the transmission source for this site. A stretched line of trees on the same cathedral ground formed the vegetation blockage for Site 2 of GSM-1800 measurements. The transmitting source used was still the same base station as Site 1. The last experimental site was a group of trees configuration. The site was in the middle of Stoke Park in Guildford, where a mixed of different vegetation types were found. The mobile network base station for this site was located on a building next to the park.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height: Tx (hTX)</td>
<td>49</td>
<td>49</td>
<td>21</td>
</tr>
<tr>
<td>Height: Rx (hRx)</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Distance: Tx – Rx (dTX-Rx)</td>
<td>130</td>
<td>110</td>
<td>335</td>
</tr>
<tr>
<td>Distance: Tree – Rx (dTree-Rx)</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Vegetation depth (Wtree)</td>
<td>7</td>
<td>7</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 5-1: 1.8 GHz experimental parameters

As for previous sites, the park was mainly quiet when the measurements were conducted. The average height of the vegetation structures was about 13m, blocking out any direct line of sight (LOS) path. Experimental parameters are expressed in metres and summarised in Table 5-1. All of vegetation structures were broad leaf deciduous type except for Site 3, which was a mixture of deciduous and some coniferous vegetation.
5.3.2 Experimental Equipment

Since an existing transmitted signal from a GSM-1800 base station was recorded, only a receiver system was required for the data collection. A Seegull dual-band scanning receiver manufactured by Dynamic Telecommunication Incorporated (DTI) was used. The receiver operates at Global System for Mobile (GSM) and Digital Cellular System (DCS) frequencies of 900 and 1800 MHz. The typical scanning speed of the scanning receiver was 300 samples per second. The receiver could be battery powered at +8 to +16 V (negative ground).

The operation of the scanning receiver was supported by data acquisition and analysis software, which was supplied by Cellular Design Services (CDS) Limited, UK. The software controls the scanning receiver and downloads the recorded data to the hard drive of the laptop or personal computer (PC) as well as presents it in real time for on-site monitoring. The last piece of equipment for the receiver system was the antenna. Since the main focus of this investigation was to investigate the signal variations caused by the movement of obstructing vegetation, a directional radiation pattern antenna was
considered. A dual-band low profile patch antenna with two ports, one for each frequency, was used. The beamwidth was 80° x 80°. The components of the receiving system are illustrated in Figure 5-3.

The second part of the equipment was for recording the environmental data. The aim was to have a system that can record the wind speed at the experimental site simultaneously during the propagation measurement. A Weather Wizard III weather station from Davis Instrument was used. The weather station consisted of an anemometer to measure wind speed, a wind vane to record the wind direction and a temperature sensor. The recorded environmental data was stored at 10 seconds interval. The environmental data recording system components are illustrated in Figure 5-4.

![Figure 5-4: Environmental data recording system](image)

5.3.3 Experimental Procedures

This section discusses the aspects of experimental design and procedures in conducting the measurements. Wind speed can be categorised into 12 Beaufort number as shown in Table 5-1 [Beaufort1805]. Due to safety and endurance of the experimental equipment, the measurement campaign was targeting to acquire environmental and
propagation data that would reach up to number 7 on the Beaufort scale. Higher levels can possibly cause severe damage to homes and surrounding, thus, normal users are not expected to be using the service in these conditions.

<table>
<thead>
<tr>
<th>Beaufort Number</th>
<th>Wind Speed (m/s)</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0 - 0.5</td>
<td>Calm, smoke rise vertically</td>
</tr>
<tr>
<td>1</td>
<td>0.5 - 1.5</td>
<td>Smoke drift indicates wind direction, still wind vanes</td>
</tr>
<tr>
<td>2</td>
<td>2.1 - 3.1</td>
<td>Wind felt on face, leaves rustle, vanes begin to move</td>
</tr>
<tr>
<td>3</td>
<td>3.6 - 5.1</td>
<td>Leaves and small twigs constantly moving, light flags extended</td>
</tr>
<tr>
<td>4</td>
<td>5.7 - 8.2</td>
<td>Dust, leaves, and loose paper lifted, small tree branches move</td>
</tr>
<tr>
<td>5</td>
<td>8.7 - 10.8</td>
<td>Small trees in leaf begin to sway</td>
</tr>
<tr>
<td>6</td>
<td>11.3 - 13.9</td>
<td>Larger tree branches moving, whistling in wires</td>
</tr>
<tr>
<td>7</td>
<td>14.4 - 17.0</td>
<td>Whole trees moving, resistance felt walking against wind</td>
</tr>
<tr>
<td>8</td>
<td>17.5 - 20.6</td>
<td>Whole trees in motion, resistance felt walking against wind</td>
</tr>
<tr>
<td>9</td>
<td>21.1 - 24.2</td>
<td>Slight structural damage occurs, slate blows off roofs</td>
</tr>
<tr>
<td>10</td>
<td>24.7 - 28.3</td>
<td>Seldom experienced on land, trees broken or uprooted,</td>
</tr>
<tr>
<td>11</td>
<td>28.8 - 32.4</td>
<td>N/A</td>
</tr>
<tr>
<td>12</td>
<td>32.9 &lt;</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 5-2: Beaufort wind scale

The wind speed at each experimental site was measured simultaneously with the radio propagation data. The anemometer was mounted on a mast at a height of 2 m and placed in an open area near the experimental site. The average wind speed for each 60 seconds block period of time was assumed to be the projected wind speed onto the vegetation block. As shown in Figure 5-1, during the measurements, the transmitter and receiver remained in stationary positions and the receiving antenna was placed in the shadowed region behind the vegetation block in-line with the direct path from the transmitter. The transmitted signal was measured using the dual-band scanning receiver. The data was sampled at 200 samples per second. At each experimental scenario, data was collected and assigned to the respective environmental condition based on the average speed.
Therefore, an extensive data collection was carried out in order to gather as much information as necessary to develop any correlation between wind speed and received signal’s fading statistics.

5.4 Main Results

Similar to the controlled environment experiments, samples of received power level, measured during the outdoor measurement campaign, are plotted over time for different experimental configurations during various conditions, calm, low, medium and high wind speed as tabulated in Table 5-3.

<table>
<thead>
<tr>
<th>Wind Speed Condition</th>
<th>Average Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm</td>
<td>&lt; 1m/s</td>
</tr>
<tr>
<td>Low</td>
<td>1 – 2m/s</td>
</tr>
<tr>
<td>Medium</td>
<td>3 – 4m/s</td>
</tr>
<tr>
<td>High</td>
<td>&gt; 5m/s</td>
</tr>
</tbody>
</table>

Table 5-3: Wind speed conditions recorded during outdoor measurement campaign

5.4.1 Measured Data at 0.9 GHz

The recorded examples of the received power level during calm and windy conditions from the outdoor experiments conducted for signal transmitted at 0.9 GHz are shown in Figure 5-5(a) and (b).
In general, the scale of received signal fluctuations has increased during windy condition as similarly observed in the controlled environment experiment. However, it is noted that the level of variations relative to mean is considerably low or rather insignificant. In addition to that, the mean level during a windy condition is observed to be higher than during a calm condition, which might have been due to the geometrical structure of the tree, and stronger direct component because the tree had moved to create a less obstructed propagation path.

5.4.2 Measured Data at 1.8GHz

Typical recorded examples of the received power level during calm and windy conditions from the outdoor experiments for received signal at 1.8GHz are shown in figure 5-6, 5-7 and 5-8. It can be clearly seen that the impact of vegetation movement is augmented during higher wind speed conditions. The level of fluctuations is also much larger than the one recorded at 0.9GHz for the outdoor environment measurement campaign and any of the controlled environment experiments at a similar frequency. This is clearly visible.
especially when comparing the main results of Site 1 at 1.8 GHz and the main result of 0.9 GHz. Although the experiments were conducted at different sites, the tree configurations of both sites are single-tree configurations.

Figure 5-6: Typical received signal variation for an isolated tree configuration – Site 1

Figure 5-7: Typical received signal variation for a line of trees configuration – Site 2
As in the controlled environment described in the previous chapter, the deep fades were augmented during windy condition as shown by all figures. Fades in the range of 5-7dB relative to the recorded mean, during low windy condition, and increased up to 30 dB relative to mean during windy condition. In addition to that, the rate of signal fluctuation has also increased, although the slower variation in the received signal was also apparent during both low and windy conditions in most samples, except the samples measured for the line of trees configuration. The slower fading occurrences were thought to be due to the slower movements of vegetation structures during a windy condition. For example, during a low wind speed condition, the leaves and branches are not static but moving slowly, which explains the slower fading. On the other hand, during a windy condition, the slow fading is now caused by the movement of larger vegetation structures, like larger branches or trees as a whole. In this state, the fast movements of leaves and small branches causes the fast fading to be superimposed onto the slow fading signal as explained earlier. In the line of trees configuration, the trees are very close to each other forming a vegetation blockage between the transmitter and receiver. The larger vegetation structures do not have room and flexibility to move even during a high wind condition. Therefore, the slow fading was not obvious during the windy condition.
5.5 Initial Analysis of Propagation Data

The raw measured datasets were sorted according to the different scenarios, averaged wind speed, frequency and vegetation sample. Then, the received level of each dataset was normalised to the mean power level in order to extract the fast variation component, and its amplitude was calculated. Similar to the controlled environment, the process prepares the raw data for further statistical analysis.

5.5.1 Comparison to Known Distributions

Due to the insignificant fluctuations recorded for the 0.9GHz received signals, comparisons to known distributions were carried out on the 1.8GHz datasets of the outdoor measurement. In this part of analysis, the distribution of the fades relative to mean, during each wind speed condition, was constructed from the collective measurement data of all sites. Since neither the transmitter nor the receiver was in motion, the coherent component was assumed to be constant. Therefore, the fast-fading component was extracted by normalising the received signal values to its mean, as in [Bello1998].
Dynamic Impact of Vegetation on Wireless Communication Systems
Figure 5-10: PDF comparison of measured data at 1.8 GHz of outdoor measurement data with known distributions – Site 2
Figures 5-9, 5-10 and 5-11 illustrate the distribution comparisons for measured data of outdoor measurement campaigns during different wind speed conditions. From Figure 5-9, it can be seen that the fast-fading distribution of radiowaves propagating through a single can be represented by Gaussian, Rice and Nakagami rather well. As the wind speed increases into medium and high wind speed, other distributions, mainly Rayleigh and Weibull distributions, started to appear and able to estimate the measured data with less accuracy. The figures indicate that a Weibull distribution is the least fitted distribution for all wind conditions. Similar observations can be deduced from distribution comparisons of measured data for line- and group-of-trees configurations as indicated by Figure 5-10 and 5-11 respectively. The appearance of Rayleigh distribution at higher wind speed is an indication that the fast-fading amplitude distribution is shifting towards Rayleigh distribution, although strong Gaussian, Rice or Nakagami was still apparent.
5.5.2 Error Analysis

Similar procedures were taken in numerically evaluating the closeness of the known distributions to the measured data for the outdoor environment measurements, as for the controlled environment measurements. All of the five distributions were tested for their closeness to the measured data. Table 5-4 summarises the average $E_{RMS}$ values for each wind speed level. It was found that the measured data could be represented by Rice and Nakagami distributions almost equally well based on the average $E_{RMS}$, over different vegetation structures of the experimental sites.

<table>
<thead>
<tr>
<th>Speed Level</th>
<th>Average $E_{RMS, Gaussian}$</th>
<th>Average $E_{RMS, Rician}$</th>
<th>Average $E_{RMS, Rayleigh}$</th>
<th>Average $E_{RMS, Nakagami}$</th>
<th>Average $E_{RMS, Weibull}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm</td>
<td>0.36</td>
<td>0.09</td>
<td>0.44</td>
<td>0.10</td>
<td>0.66</td>
</tr>
<tr>
<td>Low</td>
<td>0.10</td>
<td>0.08</td>
<td>0.21</td>
<td>0.08</td>
<td>0.36</td>
</tr>
<tr>
<td>Medium</td>
<td>0.07</td>
<td>0.04</td>
<td>0.16</td>
<td>0.04</td>
<td>0.29</td>
</tr>
<tr>
<td>High</td>
<td>0.09</td>
<td>0.07</td>
<td>0.10</td>
<td>0.07</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Table 5-4: Average $E_{RMS}$ values for each distribution compared to measured data from outdoor environment measurements

It is also noted from the above table, that the value of $E_{RMS, Rayleigh}$ has decreased as the wind speed increased towards a high level condition. This observation is suggesting that the fast-fading distribution is shifting towards a Rayleigh distribution during high wind speeds as it was observed in the controlled environment measurement campaign.
5.6 Interim Conclusions

Series of outdoor environment measurements had been conducted as part of the investigation of vegetation dynamic impact on radiowave propagation. The main objective was to study and characterise the radiowave behaviour when radiowaves propagate through vegetation under the influence of wind. Various wind speed conditions were investigated. The main results from the outdoor environment measurement campaign confirmed the wind dependency as it was observed in the controlled environment measurement campaign. A higher fading amplitude and rate of fluctuation in the outdoor measurements was also indicated. Thus, is expected to be more representative of the actual vegetation movement impact under wind influence. The initial analysis also demonstrated that the fast-fading amplitude is best represented by a Rice or a Nakagami distribution. This measurement campaign also revealed that the configuration of a vegetation blockage would have an effect on the fades behaviour. In addition to that, a slower fluctuation is suspected to be due to slower movement of larger components within the vegetation structure, but it is assumed to be negligible.
Chapter 6

6 Dynamic Impact of Vegetation: Fast-Fading Analysis and Modelling

6.1 Introduction

This chapter includes details of the statistical analysis of the fast fading characteristics present in the measured received signal. As explained in the previous chapter, the measurement campaigns were conducted using two different approaches. The main focus of the analysis is to inspect the fade amplitude statistics over various wind conditions. The discussion also covers the aspect of different frequencies, vegetation sizes and vegetation blockage configurations. The raw measured data underwent the pre-processing procedures and initial comparisons to the commonly known distributions, before further analysis could take place. The pre-processed data was then analysed for its first- and second-order statistics. The first-order statistics are presented in terms of the PDF and Rician k-factor analysis. On the other hand, the parameters of interest for second-order statistics are LCRs and the associated Maximum Doppler Frequency Shift.
6.2 First-Order Statistics Analysis

Although the fading distribution of measured propagation data through vegetation can be represented as a Rician or Nakagami distribution, it is more convenient to represent it by a Rician distribution. This is because a Rician distribution resembles a Gaussian or Rayleigh distribution depending on the level of dominant and random multipath components, where the ratio of these two components can be conveniently described by the physical interpretation of its k-factor. Therefore, the fast-fading information extracted from the measurement campaigns was analysed to generate the Rician PDF and its k-factor at each frequency for various scenarios inspected.

6.2.1 Probability Density Function

The first part of first-order statistics analysis was a comparison of fast-fading amplitude distribution over different wind speed conditions. Figure 6-1(a), (b) and (c) show the general plot of PDFs derived from the collective measurement data, during different wind conditions identified as calm, low, medium and high speed, for radio signals at 12 and 17GHz of the controlled, and 1.8GHz of the outdoor environment. Although the fast fading distribution of the measured data can be represented by a Rician distribution, it was observed that the characteristics of this distribution change over different wind speed conditions. PDFs derived from series of collective data for each measurement campaigns at different wind speed conditions were derived and plotted in Figure 6-1.
As it can be seen from the figures, fading distributions during a low wind speed condition, differ significantly from the medium and high wind speeds, for both measurement campaigns. The same observation was also reported in [Perras2002]. The widening and flattening of the PDF curves as wind speed increases suggest that the
mechanism has moved from a strong mean to a random multipath dominated, as the PDF starts to resemble a Rayleigh distribution.

In some cases of the controlled environment experiments, the fade distribution during the high wind speed condition appeared to be narrower than during a medium wind speed condition. This phenomenon arose due to one of the limitations of the experimental set up. As it can be seen from Figure 4-1 of previous chapter, during the measurements conducted inside the anechoic chamber, the wind generator was implemented on one specific corner. This configuration resulted a single direction of wind projection onto the vegetation sample. Consequently, when a high wind speed was applied, the single direction of wind had pushed the tree to be skewed to the opposite side, which then allowed a stronger dominant signal to be present. As a result of this, the direct signal became less obstructed by the tree sample, which led to a stronger dominant component and a reduction of the significance of the multipath contributions. Thus, increased k-factor values and less signal variations were observed.
In addition, a comparison of PDFs between two different configurations, Site 1 and Site 2, of the outdoor environment results are shown in Figure 6-2. It can be clearly observed that the PDF curve through a line-of-trees implies the received signal is initially more multipath dominated than the one through a single-tree configuration, during a calm condition. As the wind speed increases, the PDFs generated from both sites changed towards a Rayleigh-like distribution, with the single-tree configuration of Site 1 varied at a faster rate before they both stabilised to a fairly similar distribution at high wind speed. The faster rate of change observed at Site 1 is thought to be the result of higher multipath contributions due to the fact that a single-tree may have more flexibility in movement. This would increase its dynamic movement in response to wind, than trees that are in-line and close to each other, like in Site 2. However, this difference vanished almost completely during the high wind speed.

Figure 6-2: PDF comparisons over different vegetation blockage configurations
6.2.2 Rician K-factor Analysis

The PDF analysis in the previous section indicates a continuing increase of signal variations, and the Rician PDF curve starts to resemble a Rayleigh distribution during higher wind speed conditions. In order to quantitatively analyse this behaviour, the average Rician k-factor was calculated for each data. The k-factor is described as [Saunders 1999]:

\[
k = \frac{\text{Power in constant part}}{\text{Power in random part}} = \frac{s^2}{2\sigma^2}
\]  

(6-1)

The Rician parameters, \( s \) and \( \sigma \), were determined from the MLE procedures, as explained in Chapter 2. The k-factors were estimated for each measurement scenario at a particular frequency and wind speed then averaged out over the tree types or configurations depending on the campaign. The results were plotted against the wind speed. Figure 6-3 and Figure 6-4 illustrate the variation of calculated k-factor over wind speed for both measurement campaigns.

![Graph showing k-factor variations over wind speed](image)

Figure 6-3: k-factor variations over wind speed - Controlled Environment
It can be clearly seen, from both measurement campaigns, Figure 6-3 and Figure 6-4, that the k-factor decreases over increasing wind speed, confirming the transition towards a Rayleigh distribution. Since both the transmitter and receiver were set to be in static positions in all experiments, the reduction of the Rician k-factor suggests that the contributions of the random multipath had increased with increasing wind speed. Thus, it changes the fast-fading amplitude distribution characteristics according to the wind speed conditions. The increment is closely related to the increase of scatterings and multiple reflections caused by moving vegetation structures such as leaves and branches within the tree canopy during windy conditions. It is also noted that once in the windy state, any further increment in the wind speed has less of an effect on the received signal. However, the effect of one direction wind speed in the controlled environment can also be seen in the Rician k-factor as shown in Figure 6-3 at 17GHz. Apart of the variation over wind speed, Figure 6-3 also indicates that the average k-factor at 17GHz was lower than 12GHz during wind speed less than 2 m/s. The k-factor then converged to a similar value for both frequencies at a higher wind speed. The difference of Rician k-factors implies that the radiowave signal is more significantly affected at the higher frequency. The
effect was also more obvious during low wind speed, when the condition was changing from a calm to a windy condition. The k-factor continued to decrease at higher wind speeds but at a much slower rate, and the difference between frequencies was becoming less obvious.

In addition, Figure 6-5 plots the k-factor for two different samples of tree used in the controlled environment measurements at 12 and at 17 GHz.

![Figure 6-5: Variation of k-factor at 12 and 17 GHz](image)

The difference of the k-factor values between the two trees suggests that the broader and larger dimension of Tree 2 would result in a more evident impact than the smaller dimensions of Tree 1. The same observation was found from the propagation data at 17 GHz of the same measurement campaign.

One of the main findings that can be extracted from this part of analysis is that signal variations had increased as wind speed increases from a calm to a windy condition. Thus, it changes the fast fading amplitude distribution characteristics according to the wind speed conditions. In addition, the effect of vegetation on radiowave propagation was more obvious when the larger size of tree was used. Therefore, the analysis also conformed to the well known fact that the impact is more significant at higher frequencies.
and when the scatterers are comparable to the wavelength of the radiowave signal [Perras2002], [Schwering1988].

### 6.3 Second-Order Statistics Analysis

The propagation data was further analysed to evaluate the second order statistics. The LCR and the Maximum Doppler Frequency Shift, $f_m$, variation over wind speed were determined. Whilst the first-order statistics, in the form of PDF, provide valuable information on link availability, the second order-statistic parameters are concerned with the distribution of the signal's rate of change, rather than the signal itself. The LCR is defined as the number of positive or negative going crossings of a reference level in unit time as described in Chapter 2. In the past, these two statistical parameters were used to relate the rate of signal change to the speed of the mobile receiver movement. However, in this work the second-order statistics were used to investigate the impact of vegetation movement under the wind influence.

#### 6.3.1 Level Crossing Rate

The LCR at any specific level is defined as the expected number of times per second, the signal envelope crosses the specified level in a positive or negative direction. Therefore, the second-order statistics in the form of LCR had been derived from the similar collective measured data as for the PDFs.
The algorithm to calculate the LCR was then implemented in a MATLAB program. Results for the general LCR curves during different wind speed conditions from the measurement campaigns are shown in Figure 6-6. In all cases, the curves indicate the highest concentration of level crossings around the 0 dB level, indicating high signal activities at the mean signal value. The widening of the LCR curves over wind speed suggests that the mechanism had moved from a strong dominant to a multipath dominated
signal at a higher wind speed. These results reinforce the earlier findings about the PDF, where the Rician contribution could still be seen in the total signal, although the fade distribution changes towards a Rayleigh distribution with increasing wind speed. In addition to that, it can be clearly seen that the rate of level crossings has increased during the windy condition, although the effect of one wind direction in the controlled environment measurement campaign is still apparent from the narrowing of the LCR curve at high wind speed in Figure 6-6 (a) and (b).

### 6.3.2 Maximum Doppler Shift Analysis

Analogous to the k-factor of the first order statistics, the Maximum Doppler Shift, \( f_m \) is an indication of the range of frequency shift from the operating frequency, as a result of signal’s dynamic characteristics. It was established in the previous sections that the fast-fading is Rician distributed and, it is well known that the resultant time variations or dynamic changes in the propagation path lengths can be indirectly related to the Doppler effect. In Chapter 2, the general LCR expression for Rayleigh distributed signal of a Classical Power Spectrum Density (PSD) was given. The LCR expression for a Rician distributed signal is given in equation (6-2) [Rice1958] [Patzold2002],

\[
N_R = \sqrt{\frac{\beta}{2\pi}} \cdot p_{Rice}(r) = \sqrt{\frac{\beta}{2\pi}} \cdot \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} I_0 \left( \frac{r\sqrt{2k}}{\sigma} \right) \quad (6-2)
\]

where \( \beta \) is the short notation for the negative curvature of the autocorrelation functions \( r_{\mu_1}(\tau) \) and \( r_{\mu_2}(\tau) \) at the origin \( \tau = 0 \). The autocorrelation function is the inverse Fourier transform of the PSD of a specific random process. Thus, it is noted that the second-order statistics expressions of a dynamic multipath situation are specified by the signal’s PSD.
In order to evaluate the $f_m$ as a result of vegetation movement, the value of $f_m$ was calculated by optimising the theoretical LCR to the LCR generated from measured data. For the outdoor measurement campaign, it was assumed that the vegetation structure was large, thus it is assumed that the signal arrivals vary from $-\pi$ to $+\pi$ with respect to the direct path between the transmitter and the receiver. In addition, when the vegetation is in motion, the relative distance travelled by the scattered and reflected waves before reaching the receiver varies, which results in $\pm f_m$, as the mobile is moving towards and away from the source. Therefore, the impact can be approximated to be similar to the condition where the radiowaves are arriving from all horizontal angles around the receiver similar to Jakes PSD. Thus, the negative curvature of the autocorrelation functions $r_{\mu,j1}(\tau)$ and $r_{\mu,j1}(\tau)$ at the origin $\tau = 0$, $\beta$ is expressed in equation (6-4) [Jakes1974].

$$\beta = 2(\sigma^2_m, \sigma)^2$$

(6-3)

The resultant Doppler shift would be $-f_m \leq f_d \leq +f_m$. $-f_m$ and $+f_m$ are the maximum shifts when the receiver is moving away from (increase relative distance) and towards (decrease relative distance) the source respectively. Using the above expressions described in equation (6-2), (6-3) and (6-4) the value of $f_m$ for the outdoor measurement campaign data was calculated. The $f_m$ values extracted from the collective measured data of the outdoor measurement campaign using MLE optimisation are plotted in Figure 6-7 over different wind speed conditions.

Dynamic Impact of Vegetation on Wireless Communication Systems
One of the findings, which can be deduced from the figure, is that the resultant maximum Doppler shift, $f_m$ values caused by vegetation movement, under the wind influence, are fairly small, with an average of 0.3Hz, but consistent with the estimated value used in the Standford University Interim (SUI) channel models for Broadband Fixed Wireless (BFWA) applications [Erceg2001]. It is also noted that the values of $f_m$ slowly increased with an increment of the wind speed.

### 6.4 Fast-Fading Empirical Modelling

As it was demonstrated previously, the received signal of a narrowband radio channel can be represented quite generally as having a fixed component, plus a fluctuating or scatter component. The fixed component may be due to the coherent LOS or attenuated direct signal from the transmitter, and the fluctuating component is usually due to echoes from multiple local scatterers, which cause spatial and temporal variations.
of the summed multipath waves. If the scatter component has a complex Gaussian
distribution, as it does in the central limit theorem, where many echoes of comparable
wavelength, the time-varying magnitude of the complex received signal will have a
Rician distribution [Greenstein1999]. As it was proven from the results of measurement
campaigns [Ledl2003], [Hashim2003a], [Hashim2003b], the fast-fading of radiowaves
propagating through vegetation for a fixed link is indeed Rician distributed. The key
parameter of this distribution is the k-factor, which is the ratio of the fixed and scatter
component. It was also found that the behaviour of the Rician k-factor in this type of
environment is strongly dependent on the surrounding wind condition as well as the
vegetation blockage configuration. Therefore, a simple statistical model of the Rician k-
factor, derived from the measurement data of Site 1 and Site 2 of outdoor measurement
campaign, and its performance is presented in the next sections. These two sets of data
were chosen as each of them represents the two extremes of vegetation blockage
configurations. The modelling of $f_m$ is not considered, as its value is fairly constant over
wind speed and the variation is insignificant.

6.4.1 Dynamic First-Order Statistical Model

The first-order statistical model presented is a method in predicting the probability
distribution of k-factor over time, given the path parameters, such as blocking vegetation
configuration and surrounding wind speed. Similar approach to the one taken by
[Greenstein1999] was adopted. The model is based entirely on the database from the
outdoor measurement campaign at 1.8GHz, mainly the data recorded during experiments
conducted at Site 1 and Site 2, since these two sites differ in configuration of vegetation
blockage but are receiving from the same base station.

Firstly, the influence of vegetation blockage was examined. For the datasets of
four averaged wind speed conditions, each k-factor median was computed and compared
between the two sites. As shown in Table 6-1, from single-tree to line-of-tree
configuration, a 6.9 dB reduction of median k-factor during calm or no wind condition,
but a consistent increase in median k-factor during other windy conditions, ranging from
3.6dB (high wind) to 11.1dB (low wind), between a single-tree and line-of-tree configuration can be observed. However, the difference of the median k-factor between the two configurations is reduced as the condition changed towards a higher wind speed. The higher median k-factor of Site 1 is thought due to the higher contribution of fixed dominant component as a result of around tree diffraction and ground reflection. However, when the wind speed started to pick up, the impact of multipath contributions became more pronounced, as suggested by the lower median k-factors, through the single-tree configuration. As mentioned earlier, this is thought to be the result of higher flexibility in movement of its leaves and branches in response to wind speed, than the line-of tree configuration.

<table>
<thead>
<tr>
<th>Wind Speed Condition</th>
<th>Single Tree – Site 1</th>
<th>Line-of-Trees – Site 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm</td>
<td>24.0dB</td>
<td>17.1dB</td>
</tr>
<tr>
<td>Low</td>
<td>3.0dB</td>
<td>14.1dB</td>
</tr>
<tr>
<td>Medium</td>
<td>1.5dB</td>
<td>10.6dB</td>
</tr>
<tr>
<td>High</td>
<td>3.1dB</td>
<td>6.7dB</td>
</tr>
</tbody>
</table>

Table 6-1: Median k-factor for Site 1 and Site 2

The influence of wind speed was next considered, in the model development. It was noted in the analysis of the previous sections that the Rician k-factor decays exponentially with an increasing wind speed when radiowaves propagate through vegetation. Therefore, the above results led the modelling process to assume an exponential decay relationship as shown below,

\[ k \approx F_c k_0 e^{aw} \]  \hspace{1cm} (6-4)
where, \( v \) is wind speed in m/s and \( F_C \) is configuration factor. \( F_C = 1 \) is set for a single-tree configuration, as a reference, in all wind conditions. The \( F_C \) values for the Rician k-factor of radiowaves propagating through a line-of-tree configuration blockage are shown in Table 6-2. Referring to equation (6-5), \( k_0 \) and \( \alpha \), are constants that associate the impact of wind speed with the Rician k-factor and are optimised via exponential fitting of both data recorded from Site 1 and Site 2.

\[
Y = \frac{k}{F_C} \equiv k_0 e^{\alpha v}
\]  

(6-6)

<table>
<thead>
<tr>
<th>Wind Speed Condition</th>
<th>Configuration Factor, ( F_C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm</td>
<td>0.5</td>
</tr>
<tr>
<td>Low</td>
<td>3.6</td>
</tr>
<tr>
<td>Medium</td>
<td>2.8</td>
</tr>
<tr>
<td>High</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 6-2: \( F_C \) values for line-of-tree configuration

The optimisation was carried out by forming the data variable according to equation (6-6) for each datasets according to the wind condition categories in Table 6-1. For every \( k \) computed in the database, there is an associated vegetation configuration, and the computed values of \( Y \) were paired with measured \( v \). Then, an exponential fit between \( Y \) and \( v \) over the database was performed.
From Figure 6-8, the results indicated $k_0 = 18.19$ and $\alpha = -0.75$, where both the computed $Y$ and its exponential fit curve are shown. In addition, it was also observed that the instantaneous $Y$ values are lognormally distributed around the exponential fit curve with standard deviation of just over 10dB, as shown in Figure 6-9. The closeness to the theoretical Normal distribution curve implies a near lognormal distribution for k-factor over wind speed. Therefore, it is shown that the Rician k-factor of radiowaves propagating though vegetation can be modelled as a lognormal variable over wind speed, with a median value easily related to blockage configuration. Equation (6-5) can be re-expressed as shown below.

$$k = F_c k_0 e^{\alpha u} \quad (6-7)$$

$u$ is the lognormal variate with zero-mean and standard deviation, $\sigma = 10$dB.
6.4.2 Model Performance

A simple first-order statistical model that relates the Rician k-factor variation in relation to vegetation blockage configuration and wind speed dependence for radiowaves propagating through vegetation had been derived and proposed. In order to assess the robustness and reliability of the model, a series of predicted data were generated and compared to the results from the outdoor experiment at Site 3. The vegetation blockage configuration at Site 3 was a group-of-trees, where the receiver was placed in the shadowed area. It was expected that the fast-fading behaviour would closely resemble the behaviour of the line-of-trees configuration. The numerical value of constants $k_0$, $\alpha$ and $\sigma$ calculated from the datasets of Site 3 are 13.87, -0.75 and 9dB respectively. Figure 6-10 shows the comparison of measured and modelled Y value variations over wind speed.

Figure 6-9: CDF of k-factor variation about wind speed exponential fit curve
The value of $k_0$ calculated from measured data was found to be slightly lower than the predicted one. The lower $k_0$ may be due to the fact that the trees at Site 3 were not closely positioned as in the line-of-trees configuration as it was initially assumed. Thus, even during a calm condition, the multipath contributions, which are thought to be a result of leaves and branches movement, were more apparent in the overall $k$-factor. However, the exponent decay constant and standard deviation as well as the Lognormal distribution of Y values about the exponential fit curve of Site 3 are in consistent agreement with the predicted values. The 1dB difference of the standard deviation between the measured and predicted data, is perhaps mostly due to the simplification in the modelling of the median for each wind condition, including assuming a common median for all wind speed within the same category.

In order to assess the accuracy of the newly proposed model, predicted $k$-factor values were compared against the ones extracted from measured data of Site 3. Figure 6-11 and Table 6-3 show the simulated $k$-factor data points and its average values respectively, using the model as well as the results of measurements conducted at Site 3.
It can be observed from Figure 6-11 that the model agrees with the measurements at Site-3 rather well. The average values of k-factors from predicted data are also found to be in the same region as for the measured data as indicated in Table 6-3, thus confirms its validity.

<table>
<thead>
<tr>
<th>Wind Speed Condition</th>
<th>Simulated Average k-factor</th>
<th>Measured Average k-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm</td>
<td>21.1dB</td>
<td>20.7dB</td>
</tr>
<tr>
<td>Low</td>
<td>15.7dB</td>
<td>14.3dB</td>
</tr>
<tr>
<td>Medium</td>
<td>15.1dB</td>
<td>12.7dB</td>
</tr>
</tbody>
</table>

Table 6-3: Averaged k-factor comparison for Site 3
6.4.3 Model Application

One of the important factors in designing a reliable radio link is to have a tool that can accurately describe the channel. A wireless channel is characterised by parameters such as path loss including shadowing, multipath delay spread, fading characteristics, Doppler spread, and co-channel and adjacent channel interference [Erceg2001]. The newly developed model, as an outcome of this particular work, can be integrated into the channel models similar to the Standford University Interim (SUI) channel models [Hari2000], [Erceg2001], used for the development and testing of technologies suitable for Broadband Fixed Wireless Access (BFWA) applications. The multipath fading is modelled as a tapped-delay line with 3 taps of non-uniform delays. The gain associated with each tap is determined by the distribution, described by the Rician k-factor, and the Maximum Doppler Frequency (MDF) shift, \( f_m \). Therefore, the proposed model can be used as a tool to predict the fade characteristics of a tap that is suspected to be the one, which radiowaves are propagating through a block of vegetation structure. This can be regarded as an extension or a complement to the existing model [Greenstein1999] that predicts the narrowband Rician k-factor as one of the input parameters to the SUI models for various propagation scenarios.

6.5 Interim Conclusions

Analysis of the results from both measurement campaigns had been carried out and presented. From the analysis, it can be concluded that the distribution of fast-fading of the received signal propagating through vegetation can be represented by a Rician distribution. The characteristic of the distribution, mainly the Rician k-factor varies depending on the wind speed condition. The variation of k-factor may result in the fast-fading distribution shifting towards a Rayleigh distribution during a high wind speed condition. However, once in the windy state, any further increment in wind speed has less of an effect. Good qualitative agreements, in terms of k-factor varying trend,
between controlled and outdoor environments measurement campaigns were found, although higher frequency signals were used in controlled environment in order to investigated the impact as the vegetation were relatively smaller than in real outdoor environment. The analysis also pointed out that there was a possibility of a slower fading component to be present along with the fast fading as a result of slower movement of large scatterers within the vegetation structures. In addition to that, it was clear from both, the LCR and AFD, that the dynamic of the received signal had increased under the influence of strong wind influence. Although, the analysis of the Maximum Doppler Frequency shift, $f_m$, showed insignificant variation over increasing wind speed, the values were consistent with the estimated values used in the SUI channel models [Erceg2001]. As a continuation, the first-order empirical model that incorporates the impact of wind speed when radiowaves propagate through a vegetation structure, was developed and proposed. The performance of the newly proposed model was tested and proved to be in good agreement with the measurement data of Site 3, although slight differences were observed due to differences in configuration between the assumed and actual vegetation structures. This small degree of inaccuracy is viewed as a trade-off for obtaining a simple and user friendly model.
7 Conclusions and Future Work

7.1 Conclusions

In this research work, the importance of characterising and modelling the propagation channel for wireless communication had been highlighted. The main concentration was on the impact of vegetation movement under the influence of wind onto the propagated radiowaves. In environments like urban, residential or rural area, trees can be considered as one of many significant features. Especially, when the system is operating at high frequency band or the base station is implemented at the height below the tree line, or trees that grow over the years. In these scenarios, the previously insignificant tree impact will become more pronounced. Then, under the influence of wind, the movement of vegetation component would introduce an adverse condition on the propagating signal. The main aims of this research work were to study the effects of vegetation structure, its dynamics onto radiowaves propagation, and to develop a new model of predicting signal variation characteristics during radiowave propagation through vegetation, under various windy conditions.

Reviewing the existing wireless communication systems, the mechanisms involved from the perspective of radiowave propagation and examining the physics and
statistics of radiowave propagation started off the project. Generally, wireless communication system can be categorised into either satellite of terrestrial systems. The propagation mechanisms of each system vary from basic Free Space Loss (FSL) and loss due to interactions with atmospheric particles, to shadowing from local obstructions, depending on the type of the system. The fading signal behaviour is characterised statistically in terms of the first- and second-order statistics. The most common statistical parameters and their importance were identified and discussed. The gathered information had provided essential background knowledge and valuable assistance in understanding the wireless channel as well as the analysis methods to process the measured data. The literature survey was then narrowed down to review the existing work on the impact of vegetation on radiowave propagation. In the past, many researchers had extensively investigated the effects of absorption and attenuation by a vegetation bulk and various prediction models, for scenarios like single and group of trees in static condition and line of trees along the roadside for mobile scenario, had been proposed. Most of them can be used to provide estimates of the excess attenuation at specific frequency bands and environments to a certain accuracy. However, almost all prediction models treat the foliage as a static block and neglected the fact that trees are subjected to movement under the influence of wind. There are limited numbers of investigations available in the literature dealing with the issue and most of them are mainly in their initial stage of finding out the actual impact.

Therefore, two phases of measurement campaigns, controlled and outdoor environment, were conducted and the results were analysed to better understand this new propagation scenario. Series of controlled environment measurements had been conducted as part of the dynamic vegetation impact investigation on radiowave propagation. The main objective was to study and characterise the radiowave behaviour when radiowaves propagate through vegetation under the influence of wind. The controlled experiments of various wind speed levels projected onto two different types of vegetation samples at four different frequencies had been carried out. The main results indicated a strong wind speed dependency for radiowaves propagating through vegetation. The contributions of multipath, due to multiple reflections and scattering from the leaves and branches, have led the received signal to be mostly Rician or Nakagami
distributed. The experimental set up in this measurement campaign also provides the flexibility in controlling the wind speed level projected onto the vegetation sample and minimising other contributions that might be present in a real environment. However, a peculiar increase of mean signal level during wind speed level 4, the highest wind speed level, was also noted. This phenomenon can be explained by the nature of the experimental set-up of this study. In the experimental configuration shown in Figure 4-1, the wind generator was placed on one side. Consequently, the wind was blowing from one direction. During high wind speed level, the generated wind had pushed the vegetation sample to be skewed to the opposite side, which then allowed a stronger dominant signal to be present. As a result of this, the mean signal level was higher during the highest wind speed. Finally, it is confirmed that the impact caused by moving vegetation also became more pronounced when the vegetation size and the wavelength of the signal are comparable to each other. This can be implied from the significant effect caused by the larger vegetation sample and for experiment conducted at higher frequencies.

In addition to the controlled environment, series of outdoor environment measurements had been conducted as part of the investigation of vegetation dynamic impact on radiowave propagation. The main objective was to study and characterise the radiowave behaviour when radiowaves propagate through vegetation under the influence of wind. Various wind speed conditions were investigated. The main results from the outdoor environment measurement campaign confirmed the wind dependency as it was observed in the controlled environment measurement campaign. A higher fading amplitude and rate of fluctuation in the outdoor measurements was also indicated. Thus, is expected to be more representative of the actual vegetation movement impact under wind influence. The initial analysis also demonstrated that the fast-fading amplitude is best represented by a Rice or a Nakagami distribution. This measurement campaign also revealed that the configuration of a vegetation blockage would have an effect on the fades behaviour. In addition to that, a slower fluctuation is suspected to be due to slower movement of larger components within the vegetation structure, but it is assumed to be negligible.
One of the findings indicates that a radiowave transmission through vegetation is strongly dependent on wind speed. In addition to that, the size and geometry of the vegetation structure as well as the operating frequency of the propagating signal also influences this type of radiowave transmission. Both measurement campaigns show similar qualitative agreement in regards to the wind dependency. Further analysis of the results from both measurement campaigns had been carried out and presented. From the analysis, it can be concluded that the distribution of fast-fading in the received signal propagating through vegetation can be represented by a Rician distribution. The characteristic of the distribution, mainly the Rician k-factor varies depending on the wind speed condition. The variation of k-factor may result in the fast-fading distribution to shift towards a Rayleigh distribution during a high wind speed. In addition to that, it was clear from both, the LCR and $f_m$ analysis that the dynamic of the received signal, in terms of signal variations and deep fades, had increased under the influence of a strong wind. The analysis also pointed out that there was a possibility of slower fading component to be present along with the fast fading as a result of slower movement of large scatterers within the vegetation structures. The data from the outdoor measurement campaign was used to generate the empirical predictions of the first-order statistics of fast-fading for signal propagating through vegetation. One of the possible model applications was also described. Due to limited availability of similar work in the literature, the prediction outcomes were compared and validated to similar measurements conducted at a different site from the ones used for model development. The performance of the newly proposed model was proved to be in good agreement with the measurement data of Site 3, although slight differences were observed due to differences in configuration between the assumed and actual vegetation structures. This small degree of inaccuracy is viewed as a trade-off for obtaining a simple and user friendly model. The model serves as an initial attempt in describing the dynamic attributes of radiowaves in vegetated environment.
7.2 Future Work

This work had researched extensively the subject and the results had been reported. However there are other issues within the topic that are critical and need to be further investigated. The recommendations for future work are outlined as follows:

- Further measurements, in similar and various other configurations of trees positions, types and sizes especially for system operating at higher frequencies, should be conducted in order to acquire large collected datasets in which can be used to generalise the prediction models. Collected data can also be used in determining the cut-off speed that defines the starting of windy environment and when the impact is no longer depending on the increase of wind speed.

- To study and characterise the appearance of the slow fading component due to slower moving structures superimposed in the received signal.

- Should the measurements inside the anechoic chamber be carried out, the wind generator should be implemented such that it will cause random movements of the tree leaves and branches, so that it can be a closer representation of the real environment.

- Single anemometer could provide the general trend in the wind speed during a test period, but it could not record turbulences or different wind speeds with position or wind direction. Therefore, it could not provide an absolute correlation between wind speed and scattering characteristics. Future investigations should tackle these issues as well as investigate the impact of wind direction.
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