AFFIDAVIT

STATE OF NEW YORK)
) SS:
COUNTY OF ORANGE)

I, Matthew Waletzke, being duly sworn, deposes and states:

1. I am a certified Building Biology Environmental Consultant ("BBEC"). BBEC's are certified pursuant to the International Institute for Building-Biology and Ecology ("IBE"). In that capacity, I identify and direct remediation of mold, electromagnetic fields and other toxins in the indoor building environment. I am the founder and owner of Healthy Dwellings and have worked in this field for over a decade.

2. I have measured electromagnetic fields in Deborah Kopald's house on three separate occasions- Once in October 2014 and again in October 2019 after trees were cut on the subject property (Sec/Blk/Lot 11-1-1.52) below Ms. Kopald's house (Sec/Blk/Lot 20-2-5) and again in April 2020.

3. There was an increase in electromagnetic fields in Ms. Kopald's house between the times I took readings in 2014 and October 2019. While I did not take a reading directly before the subject construction began and many things could have accounted for some or all of the recent sudden increase that Ms. Kopald reported seeing on her Acoustimeter measuring device, I can specifically assert that trees attenuate, that is to say abate radiation, such as pulse-modulated microwave radiofrequency radiation (PM MW RFR) emitted by cell towers, Wi-Fi, smart meters and the like.

4. The major destruction of tree cover, such as occurred directly in front of Ms. Kopald's property involved a clear-cut that would give radiation a direct path, which did not previously exist, to her windows and house.

5. The International Telecommunications Union ("ITU") "Attenuation in

Vegetation" report ITU-R P.833-4 provides a model that can apply to frequencies between 30 MHz and 60 GHz which encompass cell tower and other wireless device frequencies in a forested area. It is my opinion based upon the literature and years of observation, that a significantly reduced forested area adjacent to a home would remove such attenuation. (Exhibit A). A forest is a natural shielding mechanism that accomplishes a reduction in exposure to PM MW RFR.

6. Forests attenuate many frequencies, including from high-powered Wi-Fi transmitters, that can send signal hundreds of feet. See especially: "Signal Distortion Caused by Tree Foliage in a 2.5 GHz Channel", 2003 MSc. Thesis of Eric Pelet submitted to the University of Saskatchewan, Canada, Department of Electrical Engineering. https://www.collectionscanada.gc.ca/obj/s4/f2/dsk3/SSU/TC-SSU-12122003093735.pdf (last viewed June 15, 2020). Another publication from the same year, Savage N, Ndzi D. et al. Radio wave propagation through vegetation: Factors influencing signal attenuation. *Radio Science.* Vol 38, Issue 5. October, 2003 (Exhibit B) suggests that any dense forest provides attenuation, not just those of a specific tree type:

> The results show that the leaf state, measurement geometry and vegetation density are more important factors influencing signal attenuation than tree species or leaf shape.

7. In the early days of wireless technology development, the Federal Communication Commission ("FCC") acknowledged the attenuating effects of foliage on PM MW RFR and the concomitant thwarting of signal connection. Please take administrative notice of FCC Office of Engineering and Technology, Bulletin Number 70, July 1997, "Millimeter Wave Propagation: Spectrum Management Implications." This report covers frequency bands from 30 GHz to 300 GHz, which encompasses the so-called "5G" frequencies: https://transition.fcc.gov/Bureaus/Engineering_Technology/Documents/bulletins/oet70/oet70a.pdf

(Last viewed, June 15, 2020). The U.S. government has been analyzing this phenomenon since the Cold War. Please also take administrative notice of the Department of Defense Electromagnetic Compatibility Analysis Center Annapolis, MD's July 1982 Report ESD-TR-81-101 "An Initial Critical Summary of Models for Predicting the Attenuation of Radio Waves By Trees" by contractor Mark A. Weissberger of the IIT Research Institute: https://apps.dtic.mil/dtic/tr/fulltext/u2/a118343.pdf (last viewed June 15, 2020)

8. The fact that foliage and forests significantly attenuate RF is accepted as scientific fact and continues to be analyzed in the literature. See e.g. Meng YS, Lee YH. Investigation of Foliage Effects on Modern Wireless Communication Systems: A Review. *Progress in Electromagnetics Research.* Vol. 105, 313-332, 2010. (Exhibit C)

> Discrete scatterers such as the randomly distributed leaves, twigs, branches and tree trunks can cause attenuation, scattering, diffraction, and absorption of the radiated waves. This will severely constrain the design of modern wireless communication systems.

9. To reiterate and in conclusion, destruction of a forest in front of a structure will increase PM MW RFR in front of that structure. The Building Biology profession recommends to all clients that they reduce exposure to PM MW RFR and avoid actions that permanently increase same.

/s/ Matthew Waletzke
Matthew Waletzke

Sworn to before me this
17th day of June 2020

Notary Public

LISA ALVARADO
Notary Public, State of New York
No. 01AL6101150
Qualified in Orange County
Commission Expires November 3, 2023

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[signature]

Matthew Waletzke

Sworn to before me this
17th day of June 2020

[signature]

Notary Public

LISA ALVARADO
Notary Public, State of New York
No. 01AL6101150
Qualified in Orange County
Commission Expires November 3, 2023

EXHIBIT A

RECOMMENDATION ITU-R P.833-4

Attenuation in vegetation

(Question ITU-R 202/3)

(1992-1994-1999-2001-2003)

The ITU Radiocommunication Assembly,

considering

a) that attenuation in vegetation can be important in several practical applications,

recommends

1 that the content of Annex 1 be used for evaluating attenuation through vegetation between 30 MHz and 60 GHz.

Annex 1

1 Introduction

Attenuation in vegetation can be important in some circumstances, for both terrestrial and Earth-space systems. However, the wide range of conditions and types of foliage makes it difficult to develop a generalized prediction procedure. There is also a lack of suitably collated experimental data.

The models described in the following sections apply to particular frequency ranges and for different types of path geometry.

2 Terrestrial path with one terminal in woodland

For a terrestrial radio path where one terminal is located within woodland or similar extensive vegetation, the additional loss due to vegetation can be characterized on the basis of two parameters:

– the specific attenuation rate (dB/m) due primarily to scattering of energy out of the radio path, as would be measured over a very short path;

– the maximum total additional attenuation due to vegetation in a radio path (dB) as limited by the effect of other mechanisms including surface-wave propagation over the top of the vegetation medium and forward scatter within it.

In Fig. 1 the transmitter is outside the woodland and the receiver is a certain distance, d, within it. The excess attenuation, A_{ev}, due to the presence of the vegetation is given by:

$$A_{ev} = A_m \left[1 - \exp\left(- d \gamma / A_m \right) \right] \tag{1}$$

where:

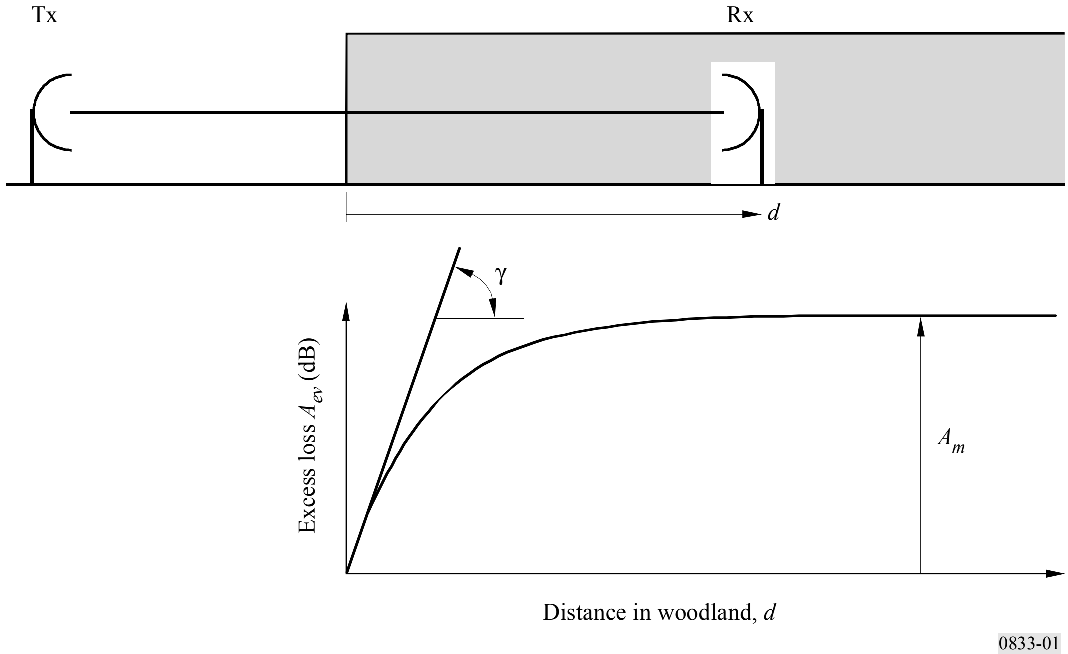
d: length of path within woodland (m)

γ: specific attenuation for very short vegetative paths (dB/m)

A_m: maximum attenuation for one terminal within a specific type and depth of vegetation (dB).

FIGURE 1

Representative radio path in woodland



It is important to note that excess attenuation, A_{ev}, is defined as excess to all other mechanisms, not just free space loss. Thus if the radio path geometry in Fig. 1 were such that full Fresnel clearance from the terrain did not exist, then A_{ev} would be the attenuation in excess of both free-space and diffraction loss. Similarly, if the frequency were high enough to make gaseous absorption significant, A_{ev} would be in excess of gaseous absorption.

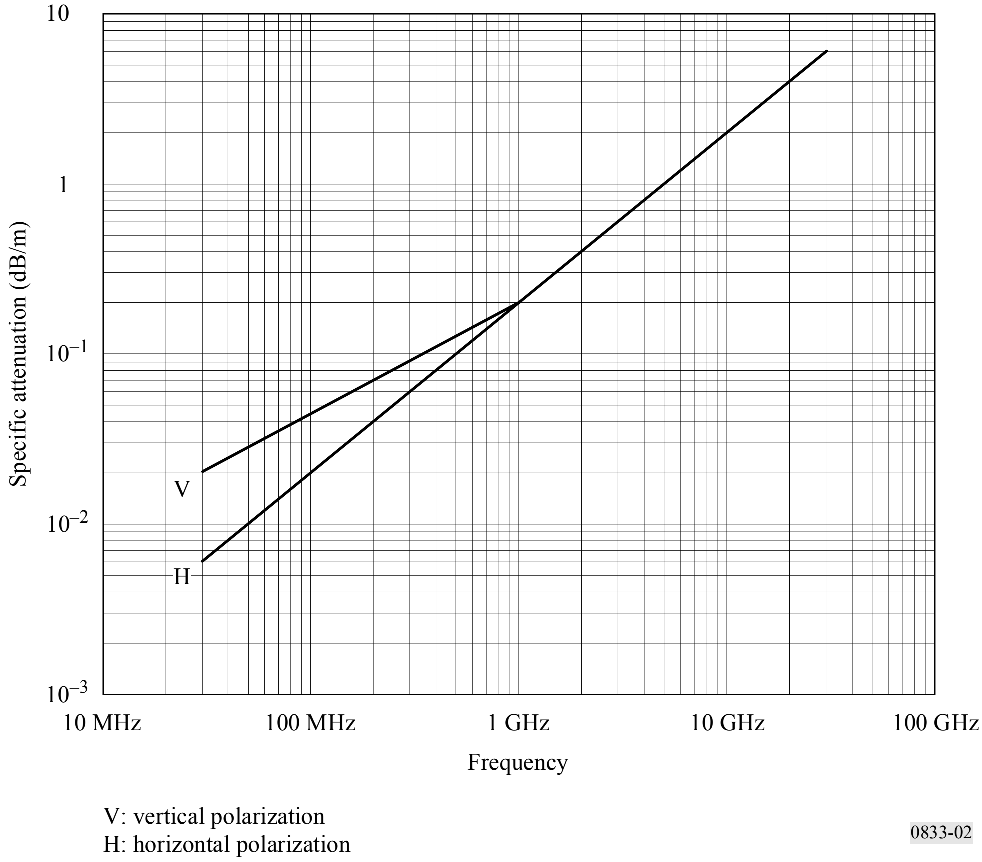
It may also be noted that A_m is equivalent to the clutter loss often quoted for a terminal obstructed by some form of ground cover or clutter.

The value of specific attenuation due to vegetation, γ dB/m, depends on the species and density of the vegetation. Approximate values are given in Fig. 2 as a function of frequency.

Figure 2 shows typical values for specific attenuation derived from various measurements over the frequency range 30 MHz to about 30 GHz in woodland. Below about 1 GHz there is a tendency for vertically polarized signals to experience higher attenuation than horizontally, this being thought due to scattering from tree-trunks.

FIGURE 2

Specific attenuation due to woodland



It is stressed that attenuation due to vegetation varies widely due to the irregular nature of the medium and the wide range of species, densities, and water content obtained in practice. The values shown in Fig. 2 should be viewed as only typical.

At frequencies of the order of 1 GHz the specific attenuation through trees in leaf appears to be about 20% greater (dB/m) than for leafless trees. There can also be variations of attenuation due to the movement of foliage, such as due to wind.

The maximum attenuation, A_m, as limited by scattering from the surface wave, depends on the species and density of the vegetation, plus the antenna pattern of the terminal within the vegetation and the vertical distance between the antenna and the top of the vegetation.

A frequency dependence of A_m (dB) of the form:

$$A_m = A_1 f^{\alpha} \tag{2}$$

where f is the frequency (MHz) has been derived from various experiments:

– Measurements in the frequency range 900-1 800 MHz carried out in a park with tropical trees in Rio de Janeiro (Brazil) with a mean tree height of 15 m have yielded $A_1 = 0.18$ dB and $\alpha = 0.752$. The receiving antenna height was 2.4 m.

– Measurements in the frequency range 900-2 200 MHz carried out in a forest near Mulhouse (France) on paths varying in length from a few hundred metres to 6 km with various species of trees of mean height 15 m have yielded $A_1 = 1.15$ dB and $\alpha = 0.43$. The receiving antenna in woodland was a λ/4 monopole mounted on a vehicle at a height of 1.6 m and the transmitting antenna was a λ/2 dipole at a height of 25 m. The standard deviation of the measurements was 8.7 dB. Seasonal variations of 2 dB at 900 MHz and 8.5 dB at 2 200 MHz were observed.

3 Single vegetative obstruction

3.1 At or below 3 GHz

Equation (1) does not apply for a radio path obstructed by a single vegetative obstruction where both terminals are outside the vegetative medium, such as a path passing through the canopy of a single tree. At VHF and UHF, where the specific attenuation has relatively low values, and particularly where the vegetative part of the radio path is relatively short, this situation can be modelled on an approximate basis in terms of the specific attenuation and a maximum limit to the total excess loss:

$$A_{et} = d\,\gamma \tag{3}$$

where:

d: length of path within the tree canopy (m)

γ: specific attenuation for very short vegetative paths (dB/m)

and $A_{et} \leq$ lowest excess attenuation for other paths (dB).

The restriction of a maximum value for A_{et} is necessary since, if the specific attenuation is sufficiently high, a lower-loss path will exist around the vegetation. An approximate value for the minimum attenuation for other paths can be calculated as though the tree canopy were a thin finite-width diffraction screen using the method of Recommendation ITU-R P.526, § 4.2.

It is stressed that equation (3), with the accompanying maximum limit on A_{et}, is only an approximation. In general it will tend to overestimate the excess loss due to the vegetation. It is thus most useful for an approximate evaluation of additional loss when planning a wanted service. If used for an unwanted signal it may significantly underestimate the resulting interference.

3.2 Above 5 GHz

Attenuation through vegetation is important for broadband wireless access systems. These systems are typically based on a star network, with a well positioned hub (or base station) serving many individual users with rooftop antennas. In many cases, signals will be obscured by vegetation close to the user antenna. For simplicity, the hub antenna will be referred to as the transmitter and the user antenna as the receiver.

An empirical model of propagation through vegetation has been developed for frequencies above 5 GHz. The model gives the attenuation through vegetation as a function of vegetation depth, taking into account the dual slope nature of the measured attenuation versus depth curves.

The model predicts the excess loss due to the presence of a volume of vegetative foliage which will be experienced by the signal passing through it. In practical situations the signal beyond such a volume will receive contributions due to propagation both through the vegetation and diffracting around it. The diffracted signal can be estimated using the method given in Recommendation ITU-R P.526, § 4.2. The dominant form of these two propagation mechanisms will then limit the total vegetation loss.

The model was derived from a database of measured data over a range of frequencies 9.6-57.6 GHz, but also takes into account the site geometry in terms of the extent of illumination of the vegetation, defined by the minimum illumination area, A_{min}. The attenuation for a vegetation depth, d (m), (in addition to free space loss) is given by:

$$A_{scat} = R_{\infty} d + k\left(1 - \exp\left\{\frac{-(R_0 - R_{\infty})}{k} d\right\}\right) \tag{4}$$

Here, the initial slope is:

$$R_0 = af \tag{5}$$

and the final slope is:

$$R_{\infty} = \frac{b}{f^c} \tag{6}$$

where f is the frequency (GHz) and the turnover value of attenuation, at which the scattered component of the received field becomes of the same order as the attenuated coherent component,

$$k = k_0 - 10 \log_{10}\left(A_0\left(1 - \exp\left\{\frac{-A_{min}}{A_0}\right\}\right)\left(1 - \exp\{-R_f f\}\right)\right) \tag{7}$$

and the parameters a, b, c, k_0, R_f and A_0 are given in Table 1.

TABLE 1

Parameter	**In leaf**	**Out of leaf**
a	0.2	0.16
b	1.27	2.59
c	0.63	0.85
k_0	6.57	12.6
R_f	0.0002	2.1
A_0	10	10

A_{min}, is the minimum illumination area defined as the product of the minimum width of illuminated vegetation, $\min(w_1,w_2,w_v)$ and the minimum height, $\min(h_1,h_2,h_v)$ which corresponds to the smaller of the two antenna spot areas on the front and rear faces of the vegetation. These heights and widths are determined by the elevational and azimuthal 3 dB beamwidths of the transmit antennas and the physical width, w_v, and height of the vegetation, h_v, shown in Fig. 3, where the vegetation is assumed to be a rectangular block. If the transmit antenna has elevational beamwidth, φ_T, and azimuthal beamwidth, θ_T, and the receive antenna φ_R and θ_R then the minimum illumination area is defined as:

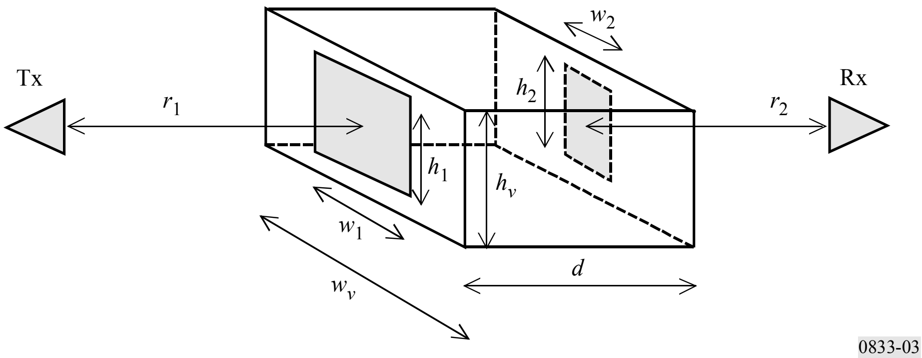
$$A_{min} = \min(h_1, h_2, h_v) \times \min(w_1, w_2, w_v)$$

$$A_{min} = \min\left(2r_1\, tan\left(\frac{\varphi_T}{2}\right), 2r_2 \tan\left(\frac{\varphi_R}{2}\right), h_v\right) \times \min\left(2r_1 \tan\left(\frac{\theta_T}{2}\right), 2r_2 \tan\left(\frac{\theta_R}{2}\right), w_v\right) \tag{8}$$

FIGURE 3

Geometry to determine the minimum illuminated vegetation area, A_{min}

(see equation (8))



In practice r_1>>r_2 and the beamwidth of the receiver, B_{rx}, is expected to be only a few degrees. Under these conditions the parts of equation (8) containing r_1 will not normally be required.

The diffraction loss for double isolated knife-edges A_{difw} due to diffraction around the sides of the vegetation and A_{difh} due to diffraction over the top of the vegetation is calculated as in Recommendation ITU-R P.526, § 4. The vegetation loss, A, which is then found as the minimum value of A_{difw}, A_{difh} and A_{scat}.

Figure 4 shows an example of the model for two cases of minimum illumination area (0.5 m^2 and 2 m^2) and three frequencies 5, 10 and 40 GHz for vegetation in and out of leaf.

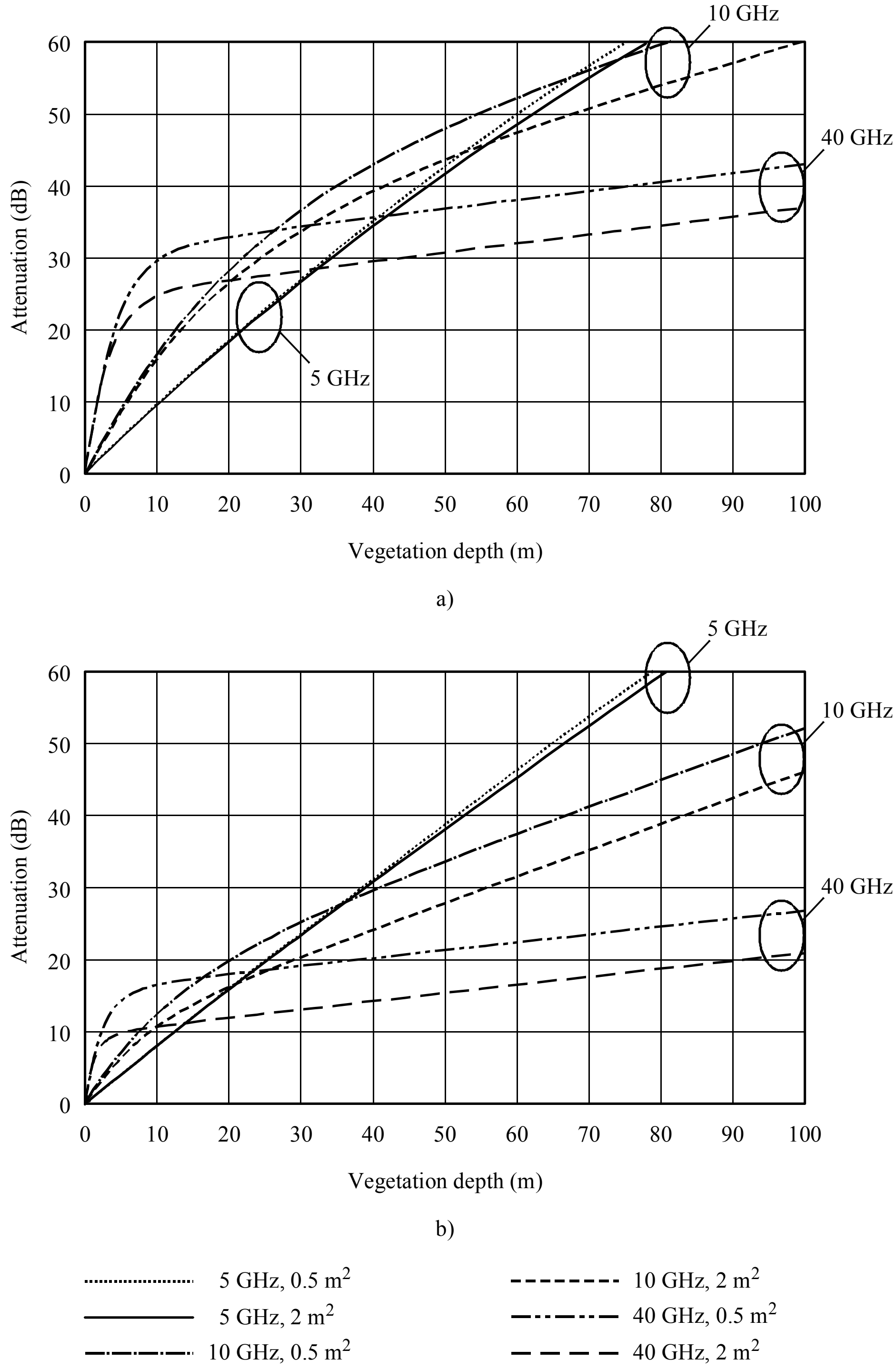
This model for the attenuation due to vegetation as a function of depth through the vegetation can be incorporated into deterministic models (such as ray-based tools using a 3D database of the local building and tree locations) to give a more realistic prediction of the extent of coverage for a given transmitter location.

4 Depolarization

Previous measurements at 38 GHz suggest that depolarization through vegetation may well be large, i.e. the transmitted cross-polar signal may be of a similar order to the co-polar signal through the vegetation. However, for the larger vegetation depths required for this to occur, the attenuation would be so high that both the co-polar and cross-polar components would be below the dynamic range of the receiver.

FIGURE 4

Attenuation for 0.5 m² and 2 m² illumination area, a) in leaf, b) out of leaf)*



* The curves show the excess loss due to the presence of a volume of foliage which will be experienced by the signal passing through it. In practical situations the signal beyond such a volume will receive contributions due to propagation both through the vegetation and diffracting around it. The dominant propagation mechanism will then limit the total vegetation loss.

0833-04

EXHIBIT B

RADIO SCIENCE, VOL. 38, NO. 5, 1088, doi:10.1029/2002RS002758, 2003

Radio wave propagation through vegetation: Factors influencing signal attenuation

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Received 9 August 2002; revised 10 June 2003; accepted 4 August 2003; published 7 October 2003.

[1] The paper describes an extensive wideband channel sounding measurement campaign to investigate signal propagation through vegetation. The measurements have been conducted at three frequencies (1.3, 2 and 11.6 GHz) at sites with different measurement geometries and tree species. The data have been used to evaluate current narrowband empirical vegetation attenuation models and study the prevailing propagation mechanisms. Evaluation of the modified exponential decay (MED), maximum attenuation (MA) and nonzero gradient (NZG) models show that on a site by site basis, the NZG model gives the best prediction of excess attenuation due to vegetation. The MA model has been found to be the worst of the three models. The studies have shown that the measurement site used to obtain the NZG model parameter values given in *International Telecommunication Union* (*ITU*) [2001] is influenced by metal lampposts and passing traffic, and thus was based on corrupted data. The results show that the leaf state, measurement geometry and vegetation density are more important factors influencing signal attenuation than tree species or leaf shape. Generally, the 11.6 GHz signal was attenuated much more than the 1.3 and 2 GHz signals by vegetation in-leaf, but the differences in attenuation were not significant in the out-of-leaf state. A successful excess attenuation model due to vegetation must consider the measurement geometry and vegetation descriptive parameters as well as any contributions from ground reflection and/or diffraction over the top or round edges of the trees. *INDEX TERMS:* 0634 Electromagnetics: Measurement and standards; 6964 Radio Science: Radio wave propagation; 6969 Radio Science: Remote sensing; *KEYWORDS:* vegetation, excess attenuation, delay spread, foliage, narrowband, wideband

Citation: Savage, N., D. Ndzi, A. Seville, E. Vilar, and J. Austin, Radio wave propagation through vegetation: Factors influencing signal attenuation, *Radio Sci.*, *38*(5), 1088, doi:10.1029/2002RS002758, 2003.

1. Introduction

[2] The reduction of cell size and basestation antenna heights in cellular networks has forced the telecommunication sector and spectrum licensing authorities to investigate the impact of vegetation on radiowave propagation. This knowledge will assist in optimizing spectrum utilization and enhancing the quality of services provided. The study of propagation through vegetation is challenging due to variations in vegetation density, measurement geometry, and vegetation composition. In addition, vegetation is prone to environmental effects, such as wind, that can introduce dynamic variations in the channel signature. The lack of extensive measurement campaigns to aid and verify model development means that empir-

0048-6604/03/2002RS002758

Table 1. Beam Widths of Antennas Used and Transmit Power

Frequency, GHz	TX Beam Width	RX Beam Width	TX Power
1.3 (yagi loop)	18°	18° (70° with RAL)	17 dBm
2 (horn)	40°	70°	22 dBm
11.6 (horn)	18°	20°	16 dBm

ical models have, historically, been based on small amounts of narrowband data and are often biased towards artifacts at the measurement site [*Vogel and Goldhirsh*, 1993; *Seville and Craig*, 1995; *Al-Nuaimi and Stephens*, 1998]. Analytical methods used to model radiowave propagation through vegetation often either grossly over-simplify the vegetation medium or require the use of numerical analysis to provide solutions to intractable formulations [*Brown and Curry*, 1982; *Tavakoli et al.*, 1991; *Tamasanis*, 1992; *Rikte et al.*, 2001].

[3] This paper presents the results of an extensive measurement campaign and the evaluation of current empirical models. The measurement sites are verified using wideband analysis to identify any artifacts and to study the predominant propagation mechanisms. During the investigation, signal propagation through different tree species, both in-leaf and out-of-leaf, and different measurement geometries were studied and the curves of the measured excess signal attenuation are presented. Although not fully discussed in the paper, the study also involved narrowband measurements for frequencies in the range 1 to 18 GHz.

2. Experimental System and Data Processing

[4] The investigation was conducted using a wideband channel sounder, the details and design principles of which are described in *Austin et al.* [1997]. The sounder has previously been used to characterize various channels, and details can be found in *Ndzi et al.* [2001] and *Savage et al.* [2002]. The sounder transmits a 31.25 MHz bandwidth pseudorandom Gaussian noise (PRGN) sequence simultaneously at 1.3, 2 and 11.6 GHz. However, only one frequency can be received at any one time. The noise floor of the receiver is −90 dBm. The received signal is averaged over 128 channel responses (all measured in 1 ms), thus improving the signal-to-noise ratio by 21 dB. The fast channel sampling enables dynamic variations in the channel, for example due to wind, to be measured.

[5] The power at the output of the transmitter, the antennas used and their beam widths are summarized in Table 1. The antennas were mounted on variable height masts. During the measurements, the transmitter was set up in a fixed location while the receiver, integrated in an experimental vehicle, was moved from one measurement point to the next. The transmitter and receiver were synchronized using a 10 MHz phase reference from global positioning system (GPS) receivers or connected to a common reference by a cable. At some measurement sites, the experiments were conducted in collaboration with Rutherford Appleton Laboratories (RAL), Didcot.

[6] Measurements were carried out at various sites, as listed in Table 2. At each site, the transmitter was located in a clearing in front of the vegetation. Figure 1 illustrates the geometries investigated and the measurement set up. A calibration file was measured at every site with the receiving antenna at the front edge of the vegetation, corresponding to zero vegetation depth as marked by the letter '*C*' in Figure 1. At each measurement position, the receiving and transmitting antennas were aligned. All of the measured channel frequency responses were calibrated to obtain the channel transfer functions. A single spectral line within the wideband spectrum was extracted from the transfer function and the power of this line was used to emulate a narrowband signal. Figure 2 shows the discrepancy between the power of the extracted spectral line and the average power across the bandwidth. The free space loss, calculated for each position, was removed from the measured signal power and the resulting excess attenuation was normalized to the level received at zero vegetation depth (position 'C' in Figure 1). The vegetation depth was measured from the front edge of the vegetation to the receiver antenna position, along the direct path from the receiver to the transmitter. The extraction and use of only a single frequency power allowed the database generated from the study to be used in the evaluation of narrowband channel models.

[7] The channel impulse responses were estimated from the measured transfer functions using the singular value decomposition prony (SVD-P) algorithm [*Hewitt et al.*, 1989; *Lau et al.*, 1991; *Lam*, 1995]. Given the transmitted signal bandwidth of 31.25 MHz, the delay resolution

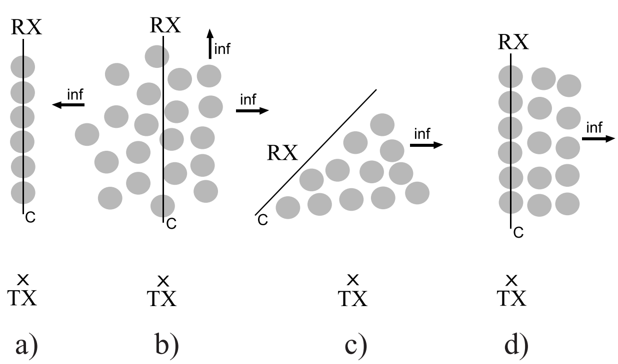

Figure 1. Measurement geometries. (a) Line of trees, (b) into vegetation, (c) through vegetation, and (d) edge of vegetation. See color version of this figure in the HTML.

Table 2. Geometry of the Measurements Conducted

Site	Tree Species (Scientific Name)	Geometry	Leaf Shape	Leaf State	Tree Height	TX Antenna Height	RX Antenna Height	Distance to Edge
Ravelin Park	Sycamore (Acer pseudoplantanus)	Into	Lobe	In	10 m	3 m	2.5 m & 7.5 m	13.8 m
RAL	Horse Chestnut (Aesculus hippocastanum)	Single	Lobe	In	8–9 m	3 m	5.3 m	26.2 m
RAL	Sycamore (Acer pseudoplantanus)	Edge	Lobe	In and Out	20–25 m	3.5 m	2.5 m & 7.5 m	11.4 m
RAL	Sycamore (Acer pseudoplantanus)	Through	Lobe	In	20–25 m	3 m	5.3 m	Approx 115 m
QECP	Lawson Cypress (Chamaecyparis lawsoniana)	Through	Needles	In	15 m	3.5 m	2.5 m & 7.5 m	18.1 m
QECP	Common Beech (Fagus sylvatica)	Into	Oval	In	15–20 m	3 m	2.5 m & 7.5 m	31 m
J.J.Nurseries	Silver Maple (Acer saccharinum)	Line	Lobe	In and Out	7–8 m	3 m	3 m	10.8 m
J.J.Nurseries	Common Lime (Tilia x Europaea)	Line	Oval	In and Out	7–8 m	3 m	3 m	4.4 m
J.J.Nurseries	London Plane (Plantanus x hispanica)	Line	Lobe	In and out	7–8 m	3 m	3 m	3.5 m

using Fourier transformation would be 31 ns. However, detail accuracy test results have shown that the SVD-P algorithm is able to successfully recover two rays that are separated by less than 5 ns with a signal to noise ratio of 24 dB. The technique has been proven to work very well with signal to noise ratios greater than 20 dB [*Shen*, 1995]. This high resolution enables a detailed study of the prevailing propagation mechanisms. The wideband channel characterizing parameter, root mean square (RMS) delay spread, has been calculated for all the measurements. RMS delay spread gives an indication of the time spread of the received signal, enabling an assessment of the channel quality for communication [*Rappaport and Sandhu*, 1994].

3. Measurement Sites and Geometries

[8] Measurement sites were selected based on accessibility, tree type and measurement geometry. Four geographical sites were chosen for the measurements: Ravelin Park - Portsmouth (single tree and wedge of trees), Queen Elizabeth Country Park (QECP) - Hampshire (a managed forest), RAL - Didcot (a line and wedge of trees) and J. J. Nurseries - Malvern, (a plantation of rows of immature trees), see Table 2. The measurements were conducted on eight different tree species. However, in-leaf and out-of-leaf measurements at the same site were only conducted on four tree species. To investigate the effect of different parts of the vegetation on signals, some measurements were conducted at more than one receiver antenna height.

[9] Four main measurement geometries were investigated; into forest, line of trees, along edge of forest, and through the forest, as illustrated in Figure 1. At each site, the transmitter was located outside the vegetation and the receiver was moved along the lines as shown in Figure 1. The receiver was positioned inside the vegetation and measurements taken at various points along the direction of signal propagation for all measurement geometries, except for the through vegetation geometry, as shown in Figure 1c.

4. Vegetation Attenuation Models

[10] The generation of an accurate model, either empirical or analytical, requires input parameters that are difficult to acquire. These parameters include any com-

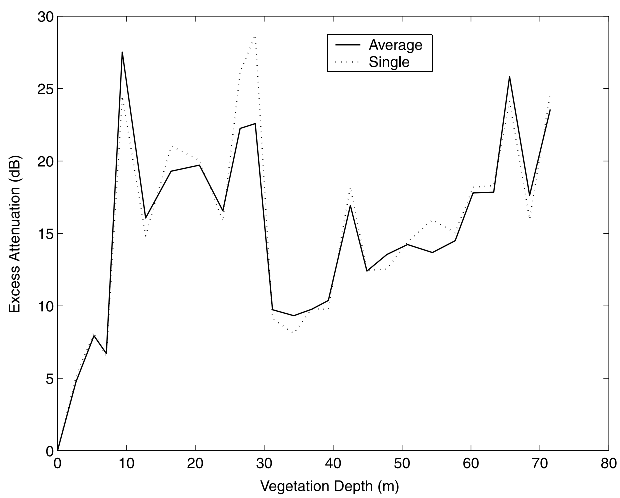

Figure 2. Comparison between a single extracted spectral line power and the power averaged over the bandwidth.

bination of the following: height of vegetation, leaf state, vegetation density, trunk size, leaf size, and canopy height [*Welch and Lemark*, 1995]. Some of these parameters are difficult to characterize and quantify in an understandable, easy to measure and relevant manner for use in a practical (engineering) model. Three models have been evaluated using the database of measurements; the modified exponential decay (MED) model, the maximum attenuation (MA) model, and the nonzero gradient (NZG) model [*ITU*, 2001]. Since the empirical models are generated from previous measurements, they model the combined effects of the different propagation modes, not only the through vegetation mode. It should be noted that these are not the only models that can be found in literature, there are also analytical models that attempt to model only the through vegetation signal. Among the analytical models that have been used and reported in literature are; the geometric and uniform theory of diffraction (GTD/UTD) [*Matschek and Linot*, 1999; *Sachs and Wyatt*, 1968], radiative energy transfer (RET) [*Al-Nuaimi and Hammoudeh*, 1994; *Ishimaru*, 1978] and full wave solutions (FWS) [*Didascalou et al.*, 2000] models. These models are mathematically and computationally intensive and have not been evaluated in this paper. However, it has been reported that the RET model offers the best results for attenuation and scattering due to vegetation and can be applied to a wide range of frequencies and geometries [*Qinetiq*, 2002].

4.1. Modified Exponential Decay Model

[11] This model was first proposed by *Weissberger* [1982], and a modified version was included in the *International Radio Consultative Committee* (*CCIR*) [1986] recommendations. It has been used to fit data from a variety of experiments, each resulting in different values of the fitted parameters [*Weissberger*, 1982; *COST 235*, 1996; *Al-Nuaimi and Stephens*, 1998]. Different parameter values have been proposed depending on the leaf state. The model is fitted to the measured data to estimate the values for X, Y and Z, in equation (1); where f is the frequency in megahertz (MHz) and d is the vegetation depth in meters. The advantage of the model lies in its simplicity, but it has a major drawback in that it does not take into account the measurement geometry or the propagation mechanisms.

$$\text{Atten} = Xf^{Y}d^{Z}. \qquad (1)$$

Table 3. Fitted Parameters for Fitted Modified Exponential Decay Model

	X	Y	Z
All	0.75	0.25	0.35
Edge	0.55	0.35	0.3
Into	0.05	0.15	1.3
Wedge	0.45	0.4	0.1
Line	1.3	0.25	0.2
Line_in	1	0.3	0.15
Line_out	2.45	0.15	0.25
Lobe	0.6	0.3	0.3
Oval	0.05	0.5	0.45
In-leaf	0.45	0.35	0.25
Out-of-leaf	3.95	0.05	0.35

Table 4. Fitted Parameters for Maximum Attenuation Model[a]

	Am (11.6)	Am (2)	Am (1.3)	R (11.6)	R (2)	R (1.3)
All	60.75	60.89	45.83	1.05	0.45	0.5
Edge	60.75	34.78	45.83	2.5	0.95	0.75
Into	43.91	42.69	38.44	0.8	0.4	0.6
Wedge	48.67	60.89	27.2	1.3	0.5	0.35
Line	54.5	37.66	30.16	1.05	0.6	0.55
Line_in	54.5	34.56	30.16	1.05	0.5	0.5
Line_out	35.12	37.66	30.08	1.5	1.05	0.8
Lobe	60.75	60.89	45.83	1.1	0.45	0.45
Oval	50.73	28.65	21.88	1.25	0.15	0.3
In-leaf	60.75	60.89	45.83	1.1	0.45	0.4
Out-of leaf	35.12	37.66	45.1	1.3	0.8	0.9

[a]Frequency given in parentheses.

4.2. Maximum Attenuation Model

[12] The maximum attenuation model involves the use of the maximum excess attenuation (A_m) measured and the initial gradient (R) of the excess attenuation curve as input parameters to equation (2). The calculation of the initial gradient is prone to errors because of variations in the data. The dependency of this model on fitted parameters from experimental measurements limits its application, as the parameters are often biased toward the measurement geometry and/or methodology. Another limitation of this model is that it has a fixed final attenuation gradient. The MA model is described by equation (2), where d is the vegetation depth in meters.

$$\text{Atten} = A_m\left(1 - \exp\left(-\frac{Rd}{A_m}\right)\right). \qquad (2)$$

4.3. Nonzero Gradient Model

[13] This model was proposed by *Seville and Craig* [1995] to overcome the zero final gradient problem associated with the maximum attenuation model, and it is the current ITU-R model for frequencies above 5 GHz [*ITU*, 2001]. As with the MA model, the NZG model requires input parameters to equation (3) that have been estimated from measured data. These include the initial gradient (R_0) and the final gradient (R_∞) of the attenuation curve, and the offset of the final gradient (k). The model also suffers from the problems associated with using values of parameters obtained from fitting curves to experimental data. However, the ITU recommenda-

Table 5. Fitted Parameters for Nonzero Gradient Model

	R_∞ (11.6)	R_∞ (2)	R_∞ (1.3)	R_0 (11.6)	R_0 (2)	R_0 (1.3)	k (11.6)	k (2)	k (1.3)
All	0	0.1	0.1	3.1	1.4	1.15	30	13	14
Edge	0.15	0.25	0.25	4	2.25	1.95	38	11	11
Into	0.55	0.25	0.35	0.65	0.4	0.45	6	37	34
Wedge	−0.1	−0.15	−0.1	3.95	1.65	3.85	33	24	13
Line	0	0.1	0.05	3.75	3.35	1.55	29	14	14
Line_in	−0.15	0.1	0.1	3.95	1.85	1.35	41	13	11
Line_out	0.1	0.05	1.65	3.65	3.95	1.05	20	18	18
Lobe	0	0.1	0.1	3.95	1.6	1.35	32	14	12
Oval	0.6	0.05	0.15	3.35	0.15	0.45	9	46	3
In-leaf	0	0.05	0.1	3.2	0.7	1	32	21	12
Out-of-leaf	0.1	0	0.25	3.85	2.85	1.8	19	18	13

tions do suggest parameters to be used in the model based on frequency and the minimum width of illuminated vegetation. An extension of this model that takes into account antenna beam width and frequency has also been proposed [*Seville*, 1997]. However, the proposed model has proved to have several inaccuracies [*Stephens*, 1998].

$$\text{Atten} = R_\infty d + k\left(1 - \exp\left(-\frac{(R_0 - R_\infty)}{k}d\right)\right). \quad (3)$$

5. Evaluation of Attenuation Models

[14] The three models introduced in Section 4 have been fitted to the measured data and the estimated values of the parameters of the models are given in Tables 3, 4, and 5. The mean square error (MSE) of the fittings is given in Table 6. To validate the importance of different measurement and vegetation description parameters, the data was divided into four categories based on, measurement geometry, tree species, leaf shape and leaf state. The models were also fitted to the whole database of measurements, disregarding differences in leaf state and geometry, but taking into account the frequency. The values obtained from fitting to the whole database are

Table 6. Mean Square Error From Fitting Data to Models

	MED	MA (11.6)	MA (2)	MA (1.3)	NZG (11.6)	NZG (2)	NZG (1.3)
All	9.72	13.41	9.67	8.79	11.4	9	8.3
Edge	7.84	12.16	6.37	6.9	10.5	5.6	6.4
Into	9.6	8.45	12.5	8.5	8.25	12.2	8
Wedge	8	10.66	10.07	8.04	7.7	8.8	7
Line	7.65	13.12	8.3	6.37	9.75	6.5	5.2
Line_in	8.2	15.84	6.73	5.5	10.8	5.85	4.53
Line_out	6.1	6.36	8.3	6.7	5	6.52	5.64
Lobe	9.7	15.03	9.24	8.34	12.1	8.3	7.64
Oval	10.5	13.04	9.81	6.18	12.6	9.65	6
In-leaf	10.24	14.74	9.72	8.11	12.4	9.38	7.66
Out-of-leaf	6.91	6.47	8.38	8.16	5.14	6.36	7.74

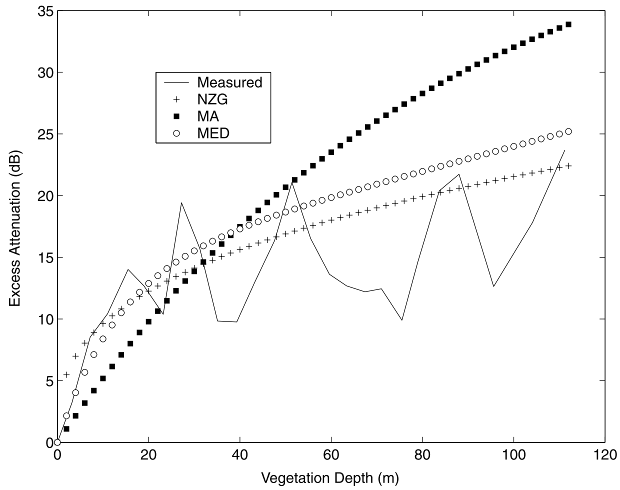

Figure 3. Fitting of the models to experimental data at 1.3 GHz from measurements on London Plane using parameter values estimated from all the experimental data at 1.3 GHz.

presented in Tables 3–6 in the row labeled "All." The rows labeled "Line-in" and "Line-out" refer to the measurements carried out on a line of trees in-leaf and out-of-leaf, respectively. Since the MA and NZG models do not have explicit frequency dependent terms, the fittings were carried out for each frequency, as stated in brackets in Tables 4, 5, and 6.

[15] Figures 3–5 illustrate a comparison between the fittings of the models to data for particular data sets. The

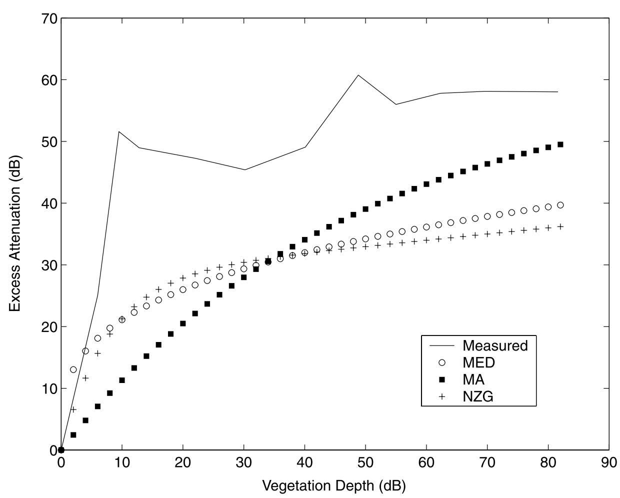

Figure 4. Fitting of the models to experimental data at 11.6 GHz from in-leaf measurements on Sycamore (edge geometry) using parameter values estimated from data not grouped according to vegetation geometry at 11.6 GHz.

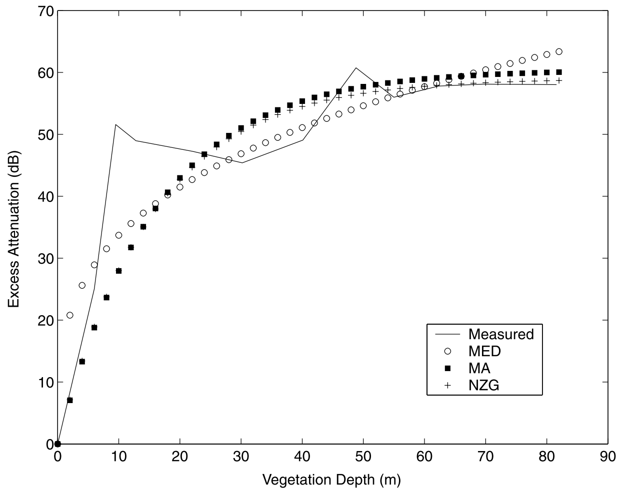

Figure 5. Fitting of the models to experimental data at 11.6 GHz from in-leaf measurements on Sycamore (edge geometry) using parameter values estimated from data grouped according to vegetation geometry at 11.6 GHz.

parameters of the models used in Figure 3 have been estimated from all the data irrespective of geometry or leaf state. Figure 4 shows the fitting of the models using values of parameters estimated from all the data measured in the in-leaf state, taking into account frequency. Figure 5 shows the fitting using parameter values obtained from a data set that takes into consideration the frequency and measurement geometry. Figure 3 shows that the MA model underestimates attenuation at short vegetation depths (<35 m) and overestimates at large depths. The MED model provides a consistently close fit at depths greater than 8 m. Analysis of the fitting of all of the models to all of the measurements conducted showed that overall, the NZG model provides a close fitting at all depths. As Figures 4 and 5 are the same measurement data, it shows that including the measurement geometry results in a much better fit to the measured data.

[16] When the data were grouped based on the measurement geometry, better fittings were achieved, in general, for all the models. This shows that measurement geometry is an important consideration for model development. The increase in accuracy is thought to be due to the fact that the propagation mechanisms depend on the measurement geometry. Better fits were also obtained for measurements that were conducted in the out-of-leaf condition. When the measurements were conducted in the out-of-leaf condition there were no leaves to attenuate the signal and no variations in the signal induced by changes in leaf density. This was especially noticeable at 11.6 GHz for measurements conducted on lines of trees. When the data was grouped based on the leaf shape there was no improvement in the accuracy of the fittings, indicating that the leaf shape has little influence on radiowave propagation through vegetation at the frequencies investigated.

[17] When the models were fitted to individual measurements, the NZG model gave the most accurate prediction of excess attenuation. This was expected as the NZG model has been developed based on individual site measurements. The values obtained at one site may not be used to predict attenuation at another because they encompass propagation anomalies that may not exist at both sites. Fitting the models to combined data from different sites will average out any anomalies and make the model parameter values more generic. When the models were fitted to the data sets listed in Table 6, the NZG model performed generally better than both the MED and the MA models by 1 dB and 2 dB on average, respectively, except for the measurements conducted at 11.6 GHz. At 11.6 GHz the best fit was obtained with the MED model. The MA model performed consistently worse than both the NZG and MED models.

6. Propagation Mechanisms and Wideband Analysis

[18] The current ITU-R recommendation [*ITU*, 2001] does not take into consideration all possible mechanisms involved in radiowave propagation through vegetation. The propagation mechanisms that can exist in the presence of vegetation include diffraction, reflection and scattering [*Tamir*, 1977; *Seker*, 1989], as illustrated in Figure 6. Detailed analysis of the measured channel responses, in both time and frequency, complemented by knowledge of the measurement set up can be used to identify these mechanisms. The identification of these mechanisms and knowledge gained from channel response analysis are essential to ensure that the received signal is dominated by through vegetation scatter.

[19] Assuming that the transmitting antenna illuminates just the vegetation, at short vegetation depth the signal is dominated by a coherent wave, with little

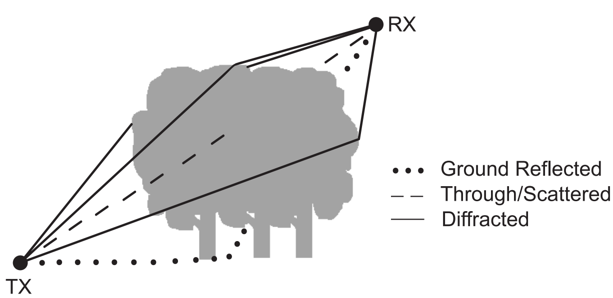

Figure 6. Possible propagation mechanisms in the presence of vegetation. See color version of this figure in the HTML.

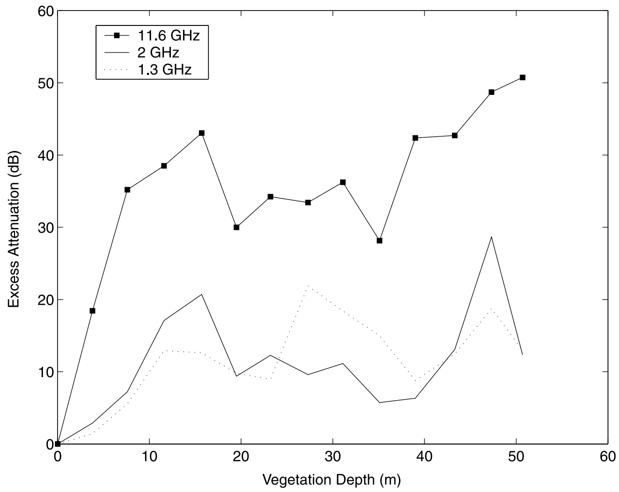

Figure 7. Silver Maple in-leaf excess attenuation for line of trees geometry (receiver antenna height: 3.5 m).

scattered power [*Schwering et al.*, 1988; *Ulaby et al.*, 1990; *Al-Nuaimi and Hammoudeh*, 1994]. The vegetation medium acts as randomly distributed scatterers and at greater depths the radiowaves become incoherent with random amplitudes and phases. Propagation is dominated by scattering and the signal level decrease with vegetation depth is slower than when the signal is coherent. This is exhibited in the signal attenuation against vegetation depth curve by a dual gradient characteristic. This represents the ideal case where only the effects due to vegetation exist. In practice, however, more than one propagation mode often exists. While the proposed empirical models represent attenuation by vegetation as a bulk effect encompassing all the propagation modes, analytical techniques often focus on the vegetation medium alone [*Brown and Curry*, 1982; *Tavakoli et al.*, 1991; *Tamasanis*, 1992; *Rikte et al.*, 2001].

[20] In the investigation, a case study of the prevailing propagation mechanisms involving detailed measurements and simulations were carried out on the sycamore wedge at RAL. The measurements were undertaken using a narrowband system for frequencies in the range 1 to 18 GHz at antenna heights from 5 to 19 m. The canopy height at this site was approximately 20 to 25 m. These studies were conducted to assess the impact of ground reflection, over-the-top and edge diffraction on the measure signal. Detailed simulations using equations in ITU-R Recommendation 526 for edge diffraction and equations in ITU-R Recommendation 527 for ground reflection were also carried out. The results from this study showed that over the top diffraction could only be received for receiver antenna heights of 17 m and above. However, edge diffracted components could potentially dominant the received signal at 1.3 and 2 GHz at all antenna heights when the receiver was positioned close to the edge of the wedge of trees. The edge diffracted components could not be avoided in the final wideband measurements because smaller vegetation depth could only be achieved close to the edges due to the shape of the plot of trees. The study also revealed that at small vegetation depths the ground reflected components were significant at all frequencies whereas at the larger vegetation depths they were only identifiable at 1.3 and 2 GHz.

6.1. Lines of Trees

[21] The measurements in this category include all those at J. J. Nurseries (on London Plane, Common Lime and Silver Maple trees) and Fermi Avenue (Horse Chestnut), see Table 2. The line of trees had clearance on both sides. Figures 7 and 8 show examples of excess attenuation curves for the two leaf states, both exhibiting dual gradient slopes. Using Silver Maple as an example, the figures show that higher excess attenuation was observed at 11.6 GHz than at 1.3 or 2 GHz for the in-leaf condition. In the out-of-leaf condition less excess attenuation was measured at 11.6 GHz whereas a general increase in excess attenuation was recorded at 1.3 and 2 GHz. The strong through vegetation component at 1.3 GHz and 2 GHz observed at JJ Nurseries is due to the fact that most of the branches were smaller than the wavelength of these signals. However, at 11.6 GHz, the branch dimensions are comparable to the wavelength of the radiowaves and the signal was significantly scattered by branches and attenuated by the leaves. In out-of-leaf condition the scattered components at

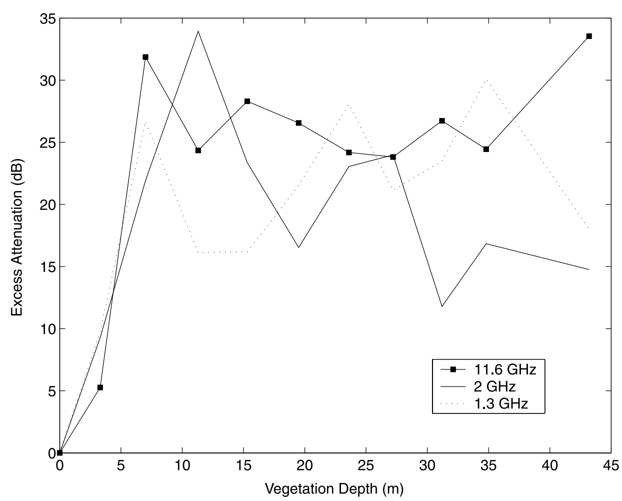

Figure 8. Silver Maple out-of-leaf excess attenuation for line of trees geometry (receiver antenna height: 3.5 m).

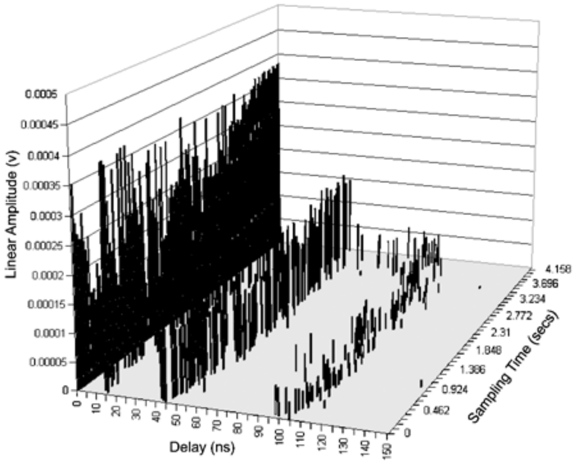

Figure 9. 1.3 GHz Silver Maple in-leaf estimated impulse responses (vegetation depth 18 m). See color version of this figure in the HTML.

11.6 GHz suffered very little absorption resulting in less excess attenuation. The smaller excess attenuation at 2 GHz compared to 1.3 GHz can be associated with the larger beam width of the 2 GHz antenna which is able to receive more paths than the 1.3 GHz antenna. The differences in excess attenuation between the two leaf conditions can be explained by considering the prevailing modes of signal propagation, which can be deduced with the aid of the estimated channel impulse responses, shown in Figures 9 and 10.

[22] Figures 9 and 10 illustrate the channel impulse responses measured at 18 m vegetation depth over a period 4.3 s for in-leaf and out-of-leaf conditions, respectively, at 1.3 GHz. The time delay axis has been normalized to the strongest received component and each received signal path is represented as an impulse. Figure 9 shows that there were four defined signal components reaching the receiver antenna and very few relatively insignificant scatter components within 150 ns time delay. However, Figure 10 shows that there was one strong path and numerous small scatter components.

[23] In the in-leaf condition, signal propagation in the line of trees geometry was significantly influenced by diffraction around the edges and top of the trees, especially at 1.3 and 2 GHz. Some of the diffracted signals arrived too close, in time, to the component that has propagated through the vegetation and hence could not be resolved by the SVD-P algorithm. In Figure 9, the signal impulse at 0 ns is the through vegetation component that is thought to be influenced by diffracted and ground reflected paths. A distinct diffracted signal component with time delay around 10 ns is also shown in Figure 9. Reflected and scatter components off adjacent lines of trees were received at 40 ns and 100 ns time delay. The scattering effects of leaves on the through vegetation signal and the influence of diffracted paths at 1.3 GHz can be seen by comparing the components at 0 ns for in-leaf (Figure 9) with that from the out-of-leaf (Figure 10) condition. The out-of-leaf impulse response shows the first received component with a stable power (amplitude), emphasizing the lack of influence from diffracted paths that can induce temporal variations in the received signal, for example, due to wind.

[24] While diffraction, scattering and reflections were the propagation modes observed at J. J. Nursery, the measurements conducted at another site (Fermi Avenue) demonstrated the importance of site selection in propagation studies. The line of Horse Chestnut trees was located adjacent to a busy road lined with metal lampposts. Detailed analysis of the measured data showed that the received signal suffered from strong reflections off the lampposts and passing traffic. The combination of these factors resulted in negative excess attenuation at certain points. The wideband analysis and the results obtained at this second site (Fermi Avenue) are important as the parameter values recommended in *ITU* [2001] were based on measurements conducted at this site, and so are contaminated by artifacts of the measurement site.

6.2. Through Vegetation Geometry

[25] In this geometry, the transmitter and the receiver were located outside the vegetation as shown in Figure 1c. This is the scenario most likely to be encountered with practical systems. The measurements in this category include those carried out on Lawson pine and the sycamore wedge at RAL. The receiver antennas were positioned close to the edge of the vegetation to discriminate against over the canopy diffracted signal components. For

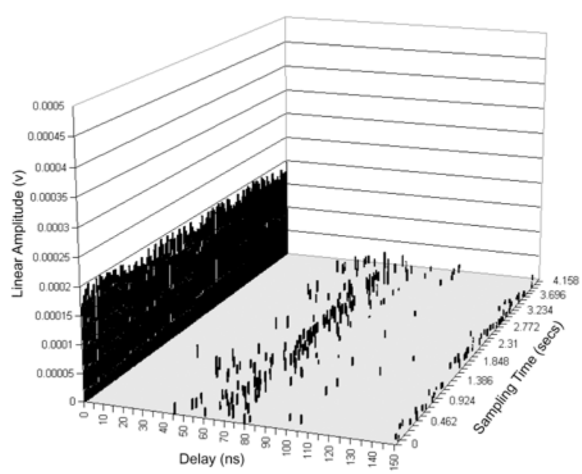

Figure 10. 1.3 GHz Silver Maple out-of-leaf estimated impulse responses (vegetation depth 18 m). See color version of this figure in the HTML.

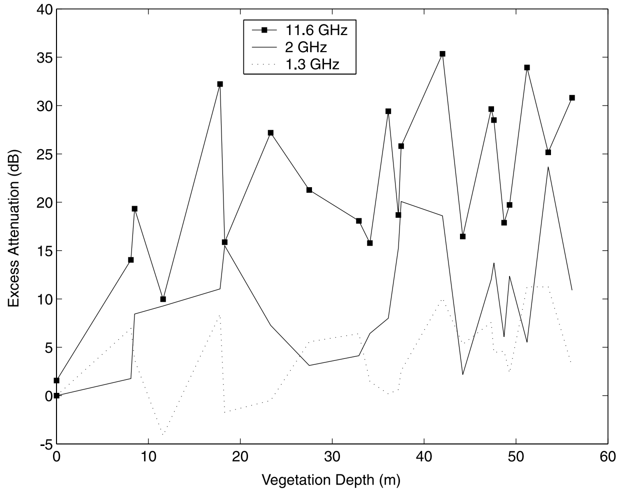

Figure 11. Sycamore in-leaf excess attenuation for through vegetation geometry (receiver antenna height: 7.5 m).

this geometry, two main characteristics of a group of trees are important. In a group of trees, trees in the middle or away from the edge have few branches that are often found close to the canopy. However, trees at the edges have numerous branches and leaves from ground level to the top of the canopy.

[26] Figure 11 shows the excess attenuation curves for the measurements conducted on the sycamore. The excess attenuation curves show that the dual slope characteristics is less defined and it exhibits an almost linear increase with vegetation depth, with a peak value of around 30 dB at 11.6 GHz. By comparison the results from the Lawson pine measurements had a steep initial gradient at all the frequencies before rapidly leveling off. For these measurements attenuation at two receiver heights was investigated. The results show that, overall, higher attenuations were measured at 7.5 m antenna height than at 2.5 m. This could be expected due to increased branch and leaf density at greater heights.

[27] The differences in the excess attenuation levels of the pine and sycamore can be explained by differences in tree densities. The pine forest was densely planted while the sycamore was sparse. After the initial slope of the excess attenuation curve for the Lawson Pine measurements, the signal reached the receiver by means of forward scattering. The trunk density ensured that all the frequencies were attenuated similarly. However, in the sycamore, the low trunk and branch density meant that 1.3 and 2 GHz signals suffered very little attenuation. For the through vegetation geometry, an increase in the received signal is expected as the antenna height approaches the top of the canopy. The dominant propagation mode in this case would be diffraction over the top of the trees. Detailed investigation, through measurements and simulations, showed that the absence of the steep initial gradient in the excess attenuation against vegetation depth curve for the sycamore measurements was due to edge diffraction.

6.3. Edge of Forest

[28] Only one site with this geometry was investigated, the Sycamore wedge at RAL. The measurements were conducted for both in-leaf and out-of-leaf conditions. This geometry allowed investigations to be conducted to greater vegetation depths and also at relatively high trunk and branch density. The measurements were taken at two receiver antenna heights along the edge of the wedge of trees.

[29] The excess attenuation curve for in-leaf measurements, Figure 12, exhibits dual slope characteristics. The peak attenuation for 11.6 GHz in-leaf condition is the largest for all measurements, approximately 60 dB, and has the steepest initial slope. The peak attenuation at 1.3 and 2 GHz is between 30 and 40 dB. The reason for the large attenuation values at this site is due to a high density of branches and leaves. The out-of-leaf measurements show much lower attenuation values, peaking at 35 dB for 11.6 GHz, 20 dB for 2 GHz and 15 dB for 1.3 GHz.

6.4. Into Vegetation

[30] This geometry includes the measurements conducted on Sycamore trees at Ravelin Park and Common Beech trees at QECP. Measurements were conducted at both 2.5 m and 7.5 m receiver antenna heights and only for the in-leaf condition. Analysis of the data showed only minor differences between the measurements at these

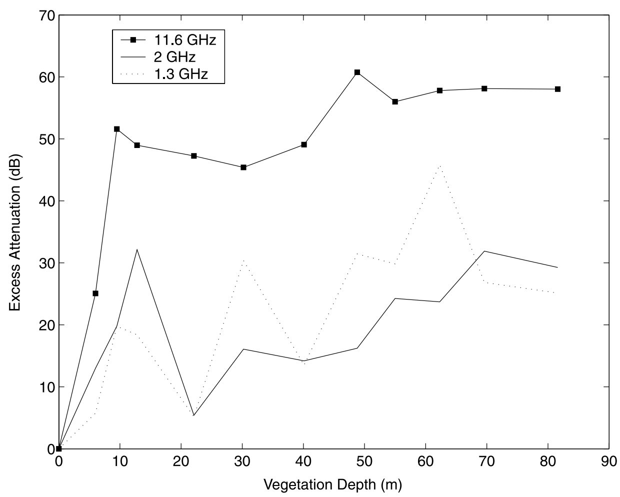

Figure 12. Sycamore In-Leaf excess attenuation for edge geometry (receiver antenna height: 5 m).

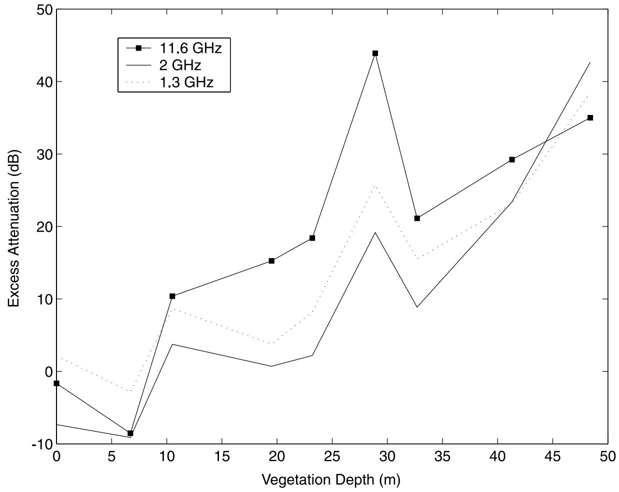

Figure 13. Beech in-leaf excess attenuation for through vegetation geometry (receiver antenna height: 7.5 m).

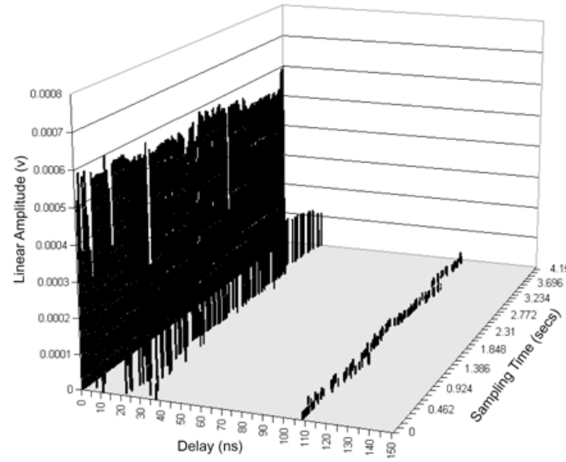

Figure 15. Sycamore 2 GHz estimated impulse responses without wind (receiver antenna height: 7.5 m). See color version of this figure in the HTML.

antenna heights. Figure 13 shows the excess attenuation from QECP beech trees at 7.5 m antenna height. There were not many differences between the three frequencies and no dual slope characteristic was identified. The results also show a linear increase in attenuation with vegetation depth. The large clearance below the high canopy for this particular geometry meant that mainly tree trunks and very few branches were in the line of sight path between the transmitter and the receiver antenna. Compared with other geometries the canopy for these sites were relatively flat and thin. This created suitable conditions for lateral wave propagation along the top of the canopy and in-ward propagation through gaps [*Tamir*, 1977]. This was more evident in the measurements carried out at QECP where less attenuation was recorded at 7.5 m receiver antenna height than at 2.5 m.

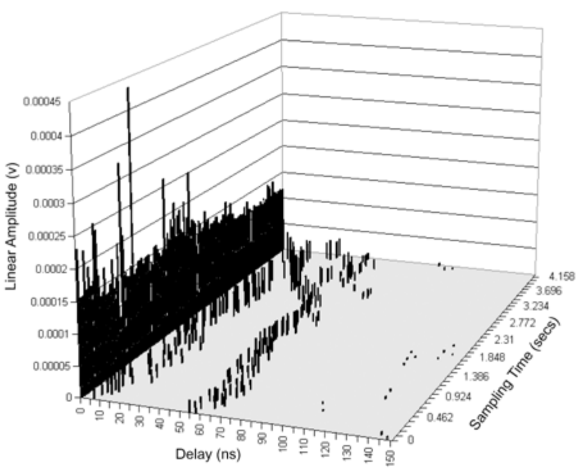

Figure 14. Sycamore 2 GHz estimated impulse responses with wind (receiver antenna height: 7.5 m). See color version of this figure in the HTML.

6.5. Effect of Wind

[31] Figure 14 shows the effect of wind on the impulse responses of the channel at 2 GHz and Figure 15 shows measurements carried out at the same site on a nonwindy day. The effect of the branches swaying in the wind on the channel response is pronounced at the receiver antenna height of 7.5 m, which was the canopy height for most of the trees. The movement of the branches causes fast variations in the amplitudes and phases of the received components that introduce fast variations in the signal envelope. At 11.6 GHz the effect of wind is more pronounced and does not result in the well defined components found at 1.3 and 2 GHz, but manifest as multiple scatter components. This is because most of the twigs and branches are of a size comparable to the wavelength of the signal, thus the random motion causes scattering. Figure 16 illustrates traces of the narrowband signal measured at different frequencies. It clearly shows that as the frequency increases the temporal variations become very rapid.

[32] Wideband channel parameters were calculated for all the measurements. While these results are not presented in this paper, some trends in the parameters were identified. Analysis of the data measured in windy condition showed that on average, the delay spread increased from approximately 12 ns to 16 ns at 2 GHz compared to measurements conducted in nonwindy condition.

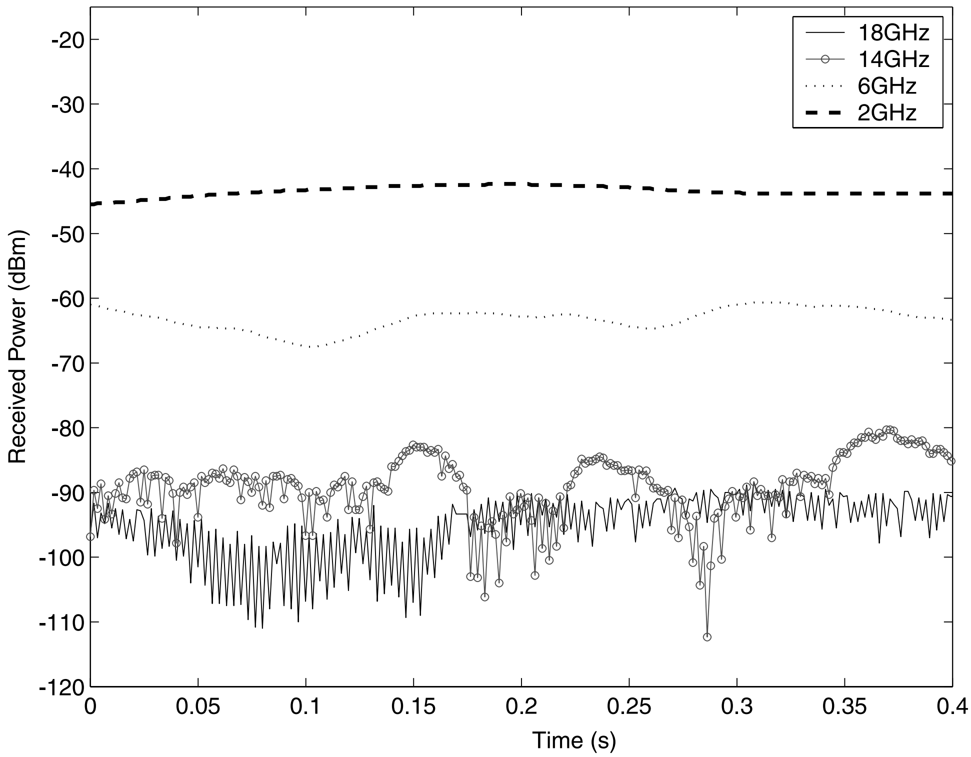

Figure 16. Frequency dependency of temporal signal variation. See color version of this figure in the HTML.

[33] Table 7 summarizes the excess attenuation and RMS delay spread at some vegetation depths for 1.3, 2 and 11.6 GHz measurements at a few sites. Generally, the delay spread for in-leaf measurements was greater at 11.6 GHz than results obtained from out-of-leaf investigations. However, this was not the case at 1.3 and 2 GHz where larger values of delay spread were measured in out-of-leaf state than in-leaf, except for London Plane.

7. Discussion and Conclusions

[34] This paper has reported an investigation to study signal propagation through vegetation and generate a

Table 7. Estimated Excess Attenuation and RMS Delay Spread at 1.3 GHz, 2 GHz, and 11.6 GHz

			Vegetation Depth, m								
			1.3 GHz			2 GHz			11.6 GHz		
Tree Type	Leaf State	Parameter Estimate	5 m	15 m	50 m	5 m	15 m	50 m	5 m	15 m	50 m
London Plane	In	Excess attenuation, dB	5	14	18	4	16	16	5	18	26
		Delay Spread, ns	*2*	*2*	*4*	3	16	14	10	*5*	*8*
	Out	Excess attenuation, dB	3	13	17	3	15	23	7	13	25
		Delay Spread, ns	*6*	*8*	*6*	2	10	10	5	*10*	*9*
Silver Maple	In	Excess attenuation, dB	*2*	*13*	*16*	5	16	19	20	35	40
		Delay Spread, ns	*4*	*5*	*9*	3	9	10	3	*6*	*70*
	Out	Excess attenuation, dB	15	16	25	15	24	16	15	26	35
		Delay Spread, ns	2	2	5	3	7	15	10	*16*	*20*
Common Lime	In	Excess attenuation, dB	5	12	18	8	14	24	22	38	58
		Delay Spread, ns	*4*	*4*	*18*	6	12	17	9	*8*	*100*
	Out	Excess attenuation, dB	6	12	10	15	17	20	8	11	23
		Delay Spread, ns	*3*	*2*	*4*	5	8	20	10	*4*	*14*
Horse Chestnut	In	Excess attenuation, dB	0	0	20	0	0	20	0	0	20
		Delay Spread, ns	*0*	*5*	40	0	5	40	*4*	*4*	*40*

database of measurements that can be used to evaluate existing narrowband vegetation attenuation models. The wideband study has shown that different combinations of diffraction, reflection and scatter propagation mechanisms are present at every site. The superposition of signal components propagating through these mechanisms results in significant frequency selective fading, manifested by variations in excess attenuation with measurement positions. The results have also shown that the measured signal levels exhibit spatial and temporal variations due to changes in vegetation density and movement of the vegetation components.

[35] Different measurement and vegetation geometries have been investigated. Of all the geometries, the into-vegetation geometry was found to be the only one that did not exhibit a distinct dual gradient characteristic. The rest of the geometries exhibited similar wideband characteristics and attenuation trends. Excess attenuation due to vegetation has been found to be affected mainly by the vegetation density and measurement geometry for a particular leaf condition. Although it could be deduced from the measurements that over the top diffraction and through canopy downward propagating components minimized the attenuation observed, further studies are required to confirm this assertion. This has implications in satellite communications where the ground station is located within trees.

[36] Three empirical vegetation attenuation models have been evaluated using the measured data. These models include the modified exponential decay (MED), maximum attenuation (MA) and the nonzero gradient (NZG) models. The fittings were carried out on (a) all the data and, data sets divided according to, (b) leaf state (in-leaf and out-of-leaf), (c) leaf shape, and (d) measurement geometry. The results show that (1) the models performed better in out-of-leaf than in-leaf state; (2) the NZG model performs best at 1.3 GHz, although it has been recommended only for frequencies above 5 GHz (the linear slope model proposed in *ITU* [2001] is considered inaccurate, as dual slope mechanisms have been noted at 1.3 and 2 GHz); (3) the shape of the leaves do not have a significant impact on attenuation, for the three frequencies investigated; (4) the MA model gives the worst fit to data of all the three models evaluated; (5) globally, the MED model gives more consistent results than the MA and NZG models, although higher accuracy could be achieved with the NZG model for some measurements; and (6) the measurement and vegetation geometries are a very important factor in the modeling and the determination of attenuation due to vegetation.

[37] The MED model has proved to be more consistent in predicting attenuation for a wide range of scenarios. In the *ITU* [2001] recommendations, into-vegetation geometry is separated from all other geometries, and the MA model is recommended for calculating the excess attenuation. However, the MA model was not found to perform distinctly better than the other models in this investigation. Based on the results from the measurements, it is proposed that a linear model will generate a better fit for this environment, although more studies are required.

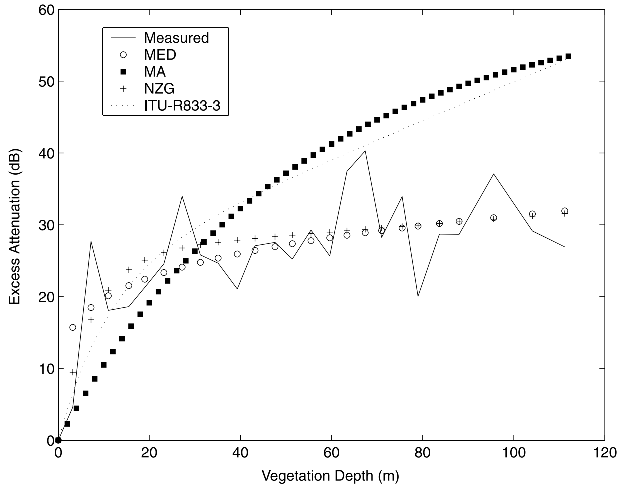

Figure 17. Comparison of the fitting of models to measured data using parameter values given in *ITU* [2001] and values estimated from "all" (Tables 3–5) data at 11.6 GHz.

[38] Figure 17 shows the fitting to one of the measurements (at 11.6 GHz) using the model parameters estimated from the whole database. The values are given in Tables 3–5 in the rows labeled "All." The values for the NZG model parameters as recommended in *ITU* [2001] have also been used to fit the model to the data set. The results indicate that better predictions of excess attenuation are obtained using the parameter values calculated using measurements from different sites. The large mean square error obtained (approximately 20 dB) by using parameter values in the ITU-R has been found to be due to the fact that signal propagation at Fermi Avenue, the site used to obtain the ITU-R parameter values, is significantly influenced by reflections from metal lampposts and passing traffic. Thus the authors advocate the use of different parameter values for NZG or MED model based on geometry and/or leaf condition, as given in Table 5, or the values given in the row labeled "All" if the geometry is not known for frequencies between 1 and 11 GHz.

[39] The study has revealed that there is a strong frequency dependency of signal attenuation by vegetation, with high frequencies experiencing more attenuation than low frequencies. Wind has been found to influence delay spread, but this will have a noticeable impact on a communication system only if the receiver is

located very close to or inside the vegetation. The effects at 1.3 and 2 GHz manifest as a variations in the amplitude and time delay of clearly defined multipath components. At 11.6 GHz, however, the wind scatters well defined signal paths (impulses) into random and severely attenuated components, especially in-leaf condition.

[40] Wideband analysis shows that RMS delay spreads were consistently less than 20 ns at 1.3 and 2 GHz for foliage depth less than 50 m. However, larger values were obtained at 11.6 GHz especially at large vegetation depths. There was a general lack of correlation between excess attenuation and delay spread. This means that, although a narrowband model may predict the reception of a strong signal, the signal may be rendered unintelligible for communication purposes by multipath.

[41] The results have emphasized the importance of careful site selection in signal propagation studies to ensure that appropriate measurement geometries are chosen and taken into account in the interpretation of the results. Most importantly, care needs to be exercised to ensure that site specific artifacts do not influence the spatial and temporal characteristics of the channel. The study has shown that a generic vegetation attenuation model must consider all modes of signal propagation by taking account of reflection and diffraction in addition to through-vegetation propagation, where necessary. This has culminated into a study aimed at developing a generic vegetation attenuation model, using the knowledge gained and data obtained from the measurement campaign reported in this paper. The model, while modeling ground reflection and diffraction based on the geometry, uses the radiative energy transfer (RET) technique to estimate the signal propagation through the vegetation medium. Preliminary results of this generic model development study are reported by *Qinetiq* [2002] and are beyond the scope of this paper.

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EXHIBIT C

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INVESTIGATIONS OF FOLIAGE EFFECT ON MODERN WIRELESS COMMUNICATION SYSTEMS: A REVIEW

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Abstract—In this paper, a large number of studies of the effect of the foliage on single or lines of trees on modern wireless communication systems are reviewed. The paper is focused on the experimental works mainly done for commercial applications such as cellular communication and high speed point-to-point fixed link at the microwave and millimeter wave frequencies. For this review study, the development of the foliage loss prediction methods and the factors influencing the tree-induced shadowing effect are highlighted. In view of current research work in this area, some possible future works are proposed to improve the performance of modern wireless communication systems with the effect of foliage.

1. INTRODUCTION

The appearance of the foliage medium in the path of the communication link has found to play a significant role on the quality of service (QoS) for wireless communications over many years [1–4]. Discrete scatterers such as the randomly distributed leaves, twigs, branches and tree trunks can cause attenuation, scattering, diffraction, and absorption of the radiated waves. This will severely constrain the design of modern wireless communication systems. From the open literature, considerable attention has been given to the influence of

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the foliage effect on the path loss, shadowing and multipath dispersion etc. Generally, the foliage effects on the wireless communications can be discussed in terms of the three following cases:

i. a tree;

ii. a line or multiple lines of trees;

iii. a forest.

The forest-induced effects on the radio-wave propagation have been studied in our previous work [4] due to the implementations of wireless sensor networks in forests recently, where the path loss prediction models are mainly discussed for long-range forested propagations in the VHF and the low UHF bands. However, the effects from a single tree and a line/multiple line of trees have not been thoroughly investigated, although some impressive studies have been conducted by several groups of researchers [1–3]. Karaliopoulos et al. [1] attempted to review some empirical foliage loss prediction models for the studies of the isolated foliage effect on a mobile-satellite channel. Bertoni [2] mainly contributed to the studies of the influence of lines of trees planted along the streets. Rogers et al. [3] performed an excellent work on the semi-empirical modeling of the foliage loss for the implementation of high speed wireless systems. It is found that these studies [1–3] focus on the investigation of the short-range foliage effect in terms of single tree/lines of trees at the microwave and millimeter waves mainly, for the commercial applications such as cellular application [1, 2] and high speed wireless communication links [3].

Recently, the rapid development of wireless sensor network [5], Multiple-Input-Multiple-Output (MIMO) [6] and Ultra Wideband (UWB) [7] techniques, and broadband high-altitude platforms (HAP) [8, 9] etc. require thorough understanding of the wireless communication channels. The above-mentioned foliage channel in terms of the single tree and line/multiple lines of trees is very common for such applicable scenarios [5–9] in rural, suburban, and urban areas. Therefore, the investigation of the foliage channel in terms of single tree/lines of trees at the microwave and millimeter waves or even higher frequencies becomes an interesting research topic.

In this paper, we will conduct a comprehensive review of the above-mentioned foliage channels at the microwave and millimeter wave frequencies. However, as the variety of operational contexts and physical situations for the foliage channels (in terms of single tree/lines of trees) are practically unlimited, the results from the many studies are often quite different. Summarizations and comparisons of the studies on the foliage loss prediction methods and the factors influencing the tree shadowing effect are carried out. This review should serve as a reference for future studies and also as a fundamental for the implementation of the modern wireless communication systems with the foliage effect. In the following, published results since 1980 are reviewed. Foliage loss prediction methods are studied in Section 2. In Section 3, tree shadowing effect and factors influencing the shadowing has been discussed. This is followed by a summarization of the wideband foliage channel information in Section 4. Finally, conclusions and some possible future works are given in Section 5.

2. FOLIAGE LOSS PREDICTION MODEL

As compared to the analytical works (mainly based on Radiative Energy Transfer (RET) theory and Wave theory) for the foliage loss predictions at the microwave and millimeter waves, there are much more empirical studies in the literature, and therefore they will be focused in the following part. Later, the analytical method will be introduced.

2.1. Empirical Method

Based on the ray geometry of the propagating wave, the foliage loss modeling and prediction with tree/lines of trees can be classified as,

i. horizontal path as shown in Fig. 1; the elevation angle is usually below 3°, and both the short foliage path through 1 or 2 trees and long foliage path through many trees (a line or several lines of trees but not form as a forest) can be experienced.

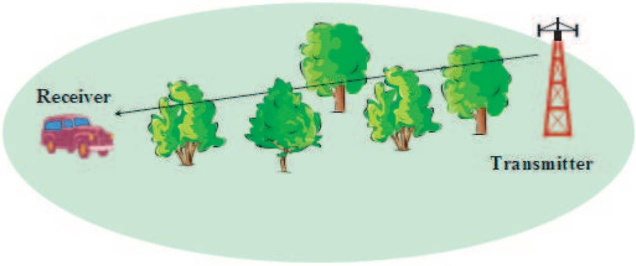

Figure 1. Schematic diagram of the horizontal foliage path.

ii. slant path as shown in Fig. 2; the elevation angle is usually above 10° and short foliage path through 1 or 2 trees.

These result in different methodologies in the modeling of the foliage-induced loss and are discussed in the following respectively.

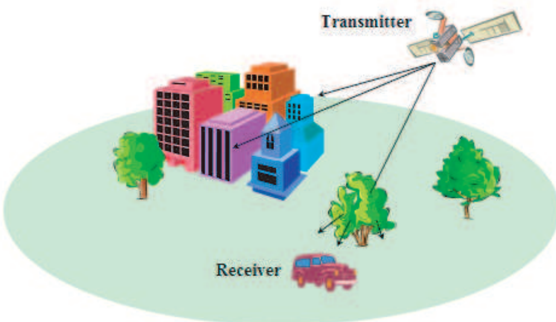

Figure 2. Schematic diagram of the slant foliage path.

2.1.1. Foliage Loss Model for the Horizontal Path

The proposed empirical foliage loss models for the horizontal propagation path can be classified as the modified exponential decay (MED) models, such as Weissberger model [10], ITU Recommendation (ITU-R) model [11], COST235 model [12] and fitted ITU-R (FITU-R) model [13]; the modified gradient model, such as Maximum attenuation (MA) model [14], Nonzero gradient (NZG) model [14], and Dual Gradient (DG) model [15]. These models are summarized in Table 1 for reference, and the review of comparative studies among these models is the focus of this subsection.

The exponential decay model was first proposed by Weissberger [10], and its main modified versions include ITU-R model [11], COST235 model [12] and FITU-R model [13] as shown in Table 1. In general, the exponential decay model has the following form,

$$L\,(\text{dB}) = A \times f^B d^C \tag{1}$$

where A, B, and C are the fitted parameters from a variety of experiments with regression techniques. Different parameter values have been proposed depending on the frequency, foliage type, and propagation mechanisms etc. The advantage of the exponential decay model lies in its simplicity, but it has a major drawback that it does not take into account the measurement geometry as indicated by Savage et al. in [19].

For the developments of the modified gradient models, the NZG model was proposed by Seville et al. in [14] to overcome the zero final-gradient problem associated with the MA model. Subsequently, DG model is proposed to take into account the antenna beamwidth and the operating frequency in [15], since there is no frequency information in both the NZG model and MA model as compared to the previously discussed modified exponential decay models. However, DG model

Table 1. Summary of the main empirical foliage loss models for the horizontal path.

Model	Expression
Weissberger model [10]	$L_W\,(\text{dB}) = \begin{cases} 1.33 \times f^{0.284} d^{0.588} & 14\,\text{m} < d \leq 400\,\text{m} \\ 0.45 \times f^{0.284} d & 0\,\text{m} \leq d < 14\,\text{m} \end{cases}$ f is frequency in GHz, and d is the tree depth in meter
ITU-R model [11]	$L_{ITU\text{-}R}\,(\text{dB}) = 0.2 \times f^{0.3} d^{0.6}$ f is frequency in MHz, and d is the tree depth in meter ($d < 400\,\text{m}$)
COST235 model [12]	$L_{COST}\,(\text{dB}) = \begin{cases} 26.6 \times f^{-0.2} d^{0.5} & \text{out-of-leaf} \\ 15.6 \times f^{-0.009} d^{0.26} & \text{in-leaf} \end{cases}$ f is frequency in MHz, and d is the tree depth in meter
FITU-R model [13]	$L_{FITU\text{-}R}\,(\text{dB}) = \begin{cases} 0.37 \times f^{0.18} d^{0.59} & \text{out-of-leaf} \\ 0.39 \times f^{0.39} d^{0.25} & \text{in-leaf} \end{cases}$ f is frequency in MHz, and d is the tree depth in meter
MA model [14]	$L_{MA}\,(\text{dB}) = A_m\,[1 - \exp(-R_0 d/A_m)]$ A_m is the maximum attenuation, R_0 is the initial gradient of the attenuation rate curve, and d is the tree depth in meter
NZG model [14]	$L_{NZG}\,(\text{dB}) = R_\infty d + k\left(1 - \exp\left\{\frac{-(R_0 - R_\infty)}{k} d\right\}\right)$ d is the tree depth in meter, R_0 and R_∞ are the initial and final specific attenuation values in dB/m, and k is the final attenuation offset in dB
DG model [15]	$L_{DG}\,(\text{dB}) = \frac{R_\infty}{f^a w^b} d + \frac{k}{w^c}\left(1 - \exp\left\{\frac{-(R_0 - R_\infty)}{k} w^c d\right\}\right)$ The same definition for d, R_0, R_∞, and k with NZG model, f is frequency in GHz, w is the maximum effective coupling width between the transmitting and receiving antennas, and a, b, c, are estimated constant.

is not recommended. This is because the inverse relationship with frequency (f^a and $a > 0$ as in [15]) suggests a decreasing attenuation as frequency increases, which appears to contradict both the anticipated behavior and that observed in the measured data as revealed in [3]. The Version 3 of the ITU Recommendation P. 833 [16] then suggested some parameters in the NZG model to consider the frequency and the minimum width of the illuminated foliage medium.

The performance comparisons between the NZG and MA models at 11.2 GHz and 20 GHz are conducted by Stephens et al. in [17]. They reported that both the models have near identical performance when the tree is not in-leaf, while the NZG model shows better prediction ability when the foliage depth is relatively small. The evaluation of the model performance at 11.2 GHz and 20 GHz among the ITU-R model, FITU-R model, and NZG model etc. is conducted by Al-Nuaimi et al. [13]. When assessing these models, they observed that the FITU-R model produces the best prediction ability for both in-leaf and out-of-leaf generic cases as compared to others. Similar measurements are conducted at 18 GHz and 38 GHz by Mosesen [18] later. From his results, the NZG model is shown to be a better model for the foliage loss prediction considering both the tree species and foliated state.

Recently, Savage et al. [19] have conducted impressive comparative studies among the MED model, MA model and NZG model at 1.2 GHz, 3 GHz, and 11.6 GHz. It is noted that they used the original exponential decay model as shown in Equation (1) to fit the measured data for the study of the MED model. In their investigations, the measurement geometry, tree species, leaf shape and foliated state have been considered when fitting the model with the measured data. The values of A, B, and C for different experimental cases (i.e., tree species, leaf shape *etc.*) have been estimated. They reported that, on a measurement site by site basis, the NZG model gives the best prediction of foliage loss. The MA model has been found to be the worst of the three models.

From these comparative works [13, 17–19], it can be found that taking into the consideration of the measurement geometry, tree species, leaf shape and foliated state, the NZG model is the better method of the foliage loss prediction at the microwave and millimeter wave as compared to other models in Table 1. However, as pointed out by Savage et al. [19], the values obtained at one site for the NZG model may not be used to predict attenuation at another because they encompass propagation anomalies that may not exist at both sites.

2.1.2. Foliage Loss Model for the Slant Path

The research on isolated trees-induced shadowing effect was first initiated by Vogel and Goldhirsh in [20]. They conducted investigations experimentally to model the tree shadowing effects on the land mobile-satellite system. Their subsequent works [21–24] have significant contributions to this research area. In [21–24], the tree shadowing effect on the slant path at UHF, L band, and K band has been investigated respectively. The model proposed for tree shadowing effect on the slant path is first developed at UHF (870 MHz) band as

$$L_{VG}\,(\mathrm{dB}) = \begin{cases} -0.35\theta + 19.2 & \text{out-of-leaf} \\ -0.48\theta + 26.2 & \text{in-leaf} \end{cases} \tag{2}$$

where L_{VG} is the attenuation in dB, and θ is the elevation angle in degree. This model is valid for elevation angles from 15° to 40°.

Based on the measurements at UHF, L band, and K band, frequency scaling formulation relating the median attenuations of tree canopies is then developed in [23] initially as

$$L_2\,(\mathrm{dB}) = L_1\,(\mathrm{dB})\sqrt{\frac{f_2}{f_1}} \tag{3}$$

where L_1 and L_2 are the equal probability attenuations in dB at the indicated frequencies between 870 MHz and 1.6 GHz with an assumption of a full in-leaf scenario. The expression in (3) was found also to be applicable for frequencies between UHF and S Band for mobile scenarios. Based on a large amount of measured data, they [24] derived a general formula for the transition from L band (1.6 GHz) to K band (19.6 GHz) attenuation and vice-versa.

$$L_2\,(\mathrm{dB}) = L_1\,(\mathrm{dB}) \exp\left\{ b \left[\frac{1}{f_1^{0.5}} - \frac{1}{f_2^{0.5}} \right] \right\} \tag{4}$$

where L_1 and L_2 are the attenuation in dB at frequencies f_1 and f_2, respectively, expressed in GHz, and $b = 1.173$. This relationship agrees well with the measured results to within 0.2 dB when scaled from L band up to K band and 0.1 dB when scaled from K band down to L band in [24]. The above relationship is found to be applicable in the frequency range of 870 MHz to 19.6 GHz.

Recently, another scaling factor from L band (1.6 GHz) down to UHF (800 MHz) band has been determined to be approximately 1.32 as reported by Cavdar [25] based on the measurements from 14 different types of trees in Turkey. This scaling factor expression is as shown in

$$L_L\,(\mathrm{dB}) = 1.32 L_{UHF}\,(\mathrm{dB}) \tag{5}$$

where L_L and L_{UHF} are the attenuation in dB at L band and UHF, respectively.

A comparative study between Vogel and Goldhirsh's model in Equation (2) and ITU-R model was conducted by Sofos and Constantinou [26] with the measurement results at 2.5 GHz. They reported that Vogel and Goldhirsh's model fits the measurement results better when the elevation angles are higher (25.49° and 39.35° in their study, which are within the applicable range of [15° 40°] for the Vogel and Goldhirsh's model), while the ITU-R model seems to fit the measurement results better when the elevation angle is 14.03° (which is out of the range of [15° 40°] for the Vogel and Goldhirsh's model).

2.2. Analytical Method

Physics-based models to predict the foliage loss have attained significant prominence recently. As discussed by Bertoni in [2], either Radiative Energy Transfer (RET) theory or wave theory can be used to develop a proper physics-based model. In the following, the developments of the foliage loss model with both the theories are introduced.

2.2.1. Radiative Energy Transfer Model

RET theory based model is shown to be a good solution to predict the foliage loss for a variety of vegetation geometries [3], since it is time-efficient and highly accurate for the evaluation of the through-vegetation attenuation with both the horizontal and slant foliage paths. From the open literature, the application of the RET theory to model the radio-wave propagation in foliage medium was first reported in [27] and later discussed by Schwering et al. [28] and Al-Nuaimi et al. [29]. However, it is noted that the RET approach is generally applied to a homogeneous medium. In order to overcome this limitation and make it applicable to inhomogeneous foliage medium, an improved version named the discrete RET model (dRET model) is proposed by Diadascalou et al. for isolated vegetation specimens [30] and further enhanced by Fernandes et al. [31]. Comparative study on the RET model and dRET model has been conducted at 11.2 GHz and 62.4 GHz by Fernandes et al. [32] on inhomogeneous vegetation recently. The proposed dRET model was observed to perform reasonably well in terms of signal level modeling.

St Michael et al. compared the RET model with various empirical models (see Table 1) in their study [33]. They found that the RET theory based model offered the best fit to measured data at 2 GHz, while at 11.2 GHz, the ITU-R model and FITU-R model gave better fits compared to other models but the RET model still gave a reasonable fit to the observations.

The RET based model has been deeply studied by Rogers et al. in [3] and is adopted in the current ITU recommendation [34] for the modeling of foliage loss at frequencies above 1 GHz. However, this method requires four input parameters which are extracted from the path-loss measurement data, therefore makes itself a semi-empirical model in essence. Typical values of the input parameters for different tree specimen have been summarized in the current ITU recommendation [34].

2.2.2. Wave Theory Based Model

The wave theory based model is believed to be more accurate for presenting the coherence effects and phase information as reported in [38]. Coherent wave propagation models based on Monte Carlo simulation of scattering from a realistic looking fractal trees are successfully used to obtain the statistics of wave propagation through foliage in [35] and [36]. The tree stands were generated with physical and structural parameters, such as tree density, height, mean trunk diameter, etc. For the estimation of the foliage attenuation, Koh et al. [37] applied a full-wave numerical technique, Method of Moments (MoM), to calculate the scattering from a cluster of leaves or needles at 35 GHz. They reported that the widely used Foldy's approximation in conjunction with the single scattering theory overestimates the forward scattering as high as 3–4 dB at 35 GHz. Wang and Sarabandi [38] later used the distorted Born approximation to macro-model the scattering pattern from the foliage dielectric objects. By including multiple scattering effects in the simulation model, much better agreement is obtained for both mean and standard deviation of the foliage loss. In their later work [39], the effort on the reduction of the computational resources for the simulation has been carried out.

In summary, as compared to wave theory based model, the RET theory based model is numerically intractable for large propagation distances as reported in [39] due to discretization of the foliage medium into small cells. However, the RET theory based model is an appropriate prediction tool for the short-range foliage loss in radio coverage planning for cellular, fixed and satellite communication systems since it is time-efficient and also highly accurate.

3. SHADOWING EFFECT AND ITS VARIATIONS

The tree shadowing effect [40–45] often affects the modern wireless communication systems. For example, at high elevation angles, attenuation due to trees on roadside dominates fade margin requirements for the land mobile-satellite systems [40–42], whereas the presence of one or more trees on the peak of a hill can shadow the signal propagation significantly [43, 44] and even can lead to a relative enhancement of the signal by at least 10 dB at 20 GHz as compared to the diffraction loss for a path obstructed by the hill as reported in [43]. Therefore, in this part, tree-induced shadowing effect will be discussed empirically and theoretically. The focus will be on the investigations of the factors such as wind and rain which can result in a variation of the shadowing.

3.1. Empirical Characterization of the Shadowing Effect

There are a lot of empirical works addressing the characterization of the tree shadowing effect [40–45]. Typically, the foliage environments can be classified as rural [40], suburban [41, 44], and dense urban [42, 45] etc. The tree shadowing effect in dB can be directly measured as in [43–45] and also roughly predicted by the previously mentioned foliage loss models. With either of these two solutions, a fade margin for the tree shadowing can then be estimated.

There are two important environmental factors which can influence the tree shadowing effect, wind and humidity of the foliage. The wind can cause the foliage medium to move and therefore, results in the temporal variations of the received signal. Unexpected deep fades can be experienced and lead to an unacceptable QoS degradation in spite of a fade margin. While the change in the humidity of the foliage medium can vary the dielectric parameters (conductivity and permittivity) of the trees and then influence the signal propagation. From the open literature, large amount of the empirical works have contributed to the investigations of the wind induced temporal power variation [19, 46–54] and humidity increased foliage attenuation [55, 56]. They will be discussed in the following respectively.

3.1.1. Wind Effect

The contributions to the investigations of the wind effect in the literature are mainly motivated by the implementation of local multipoint distribution services (LMDS). Lewenz [46] studied the effect of the foliage movement at 2 GHz with large transmission paths (approximately 4.5 km), where the propagation path is partially blocked by trees. Four categories of wind velocity range from low to high were analyzed. It is reported that the standard deviation of the attenuation variation about the mean does increase as the wind speed increases, and for 2 GHz radio service in rural areas, a fade margin of 3.4 dB should be allowed. Later, fading characteristics of a 6 MHz channel centered at 2.545 GHz were reported by Pelet et al. [47] with a variation of wind speed. They indicated that wind impinging on the trees at velocities as low as 15 km/h can cause significant fading. On a bluff of poplar trees about four trees deep, winds of 15 km/h caused fades of 15 dB with attenuation rates up to 50 dB per second. The fades occurred at intervals as short as 0.5 seconds apart.

Naz et al. [48] conducted an investigation of wind effect on different foliated states at a much higher frequency up to 29.5 GHz as compared to the work in [46, 47]. They found that trees with green foliage (in summer) produce less variation as compared to trees with yellow and dehydrated foliage (in fall), and dense trees cause attenuation but do not produce much variation. It is also observed that, coniferous (evergreen) trees when disturbed by wind produce slower fading, while deciduous trees produce faster fading. Kajiwara [49] found that swaying foliage in wind causes a significant channel fading at 29.5 GHz, ranging over 10 dB, while the fading depth at 5 GHz is approximately 2 dB with a foliage depth of 1.6 to 1.8 m. He also reported that the attenuation in dB can be treated statistically as Rician distribution. Perras et al. [50] then performed in-depth studies of winded foliage channels over a wide range of frequencies (2.45 GHz, 5.25 GHz, 29 GHz, and 60 GHz) at relatively small transmission distances up to 110 m, where the radio channels are statistically analyzed and compared against existing channel models. It is reported that the Extreme Value and Lognormal distributions best represent the data collected, and each distribution proves better than the other in different scenarios.

A more detailed statistical analysis of the wind-induced fading is subsequently examined through the commonly known distributions associated with radio channel as shown in Table 2, namely Gaussian, Rician, Rayleigh, Nakagami, and Weibull, by Hashim et al. [51]. The wind induced temporal variation (over a short period of less than 60 seconds) is found to be Rician distributed. Moreover, they reported that the Rician K factor was found to vary exponentially with wind speed at frequencies of 0.9 GHz, 2 GHz, 12 GHz and 17 GHz in the controlled (anechoic chamber) and outdoor environments. However, different from their observations, the median Rician K factor in [52] is found to be approximately inversely proportional to averaged wind speed empirically based on the outdoor experimental data for a link up to 17 km over a period of 1 year at 3.5 GHz. Similar work for statistical

Table 2. Summary of the statistical models for the characterization of the shadowing variation used in [51].

Model	Expression
Gaussian distribution	$P_r(r) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(r-\mu)^2}{2\sigma^2}}$
Rician distribution	$P_r(r) = \frac{r}{\sigma^2} e^{-\left(\frac{r^2+s^2}{2\sigma^2}\right)} I_0\left(\frac{sr}{\sigma^2}\right)$
Rayleigh distribution	$P_r(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}$
Nakagami distribution	$P_r(r) = \frac{2m^m}{\Gamma(m)\Omega^m} r^{(2m-1)} e^{-\left(\frac{mr^2}{\Omega}\right)}$
Weibull distribution	$P_r(r) = a \cdot b \cdot r^{b-1} \cdot \exp(-a \cdot r^b)$

characterization of wind-induced variation is reported by Dal Bello et al. in [53]. Recently, the relationship between the Rician K factor and averaged wind speed is found to be linear at 1.9 GHz as reported in [54].

From these works [46–54], it can be observed that the wind-induced motion of the foliage medium can vary the tree shadowing effect temporally, and the temporal variation of the shadowing can be statistically modeled. Rician K factor is usually used to characterize the temporal shadowing effect. However, the relationship of the Rician K factor referring to the wind speed is not conclusive at present, which seems to depend on the operating frequency from the literature.

3.1.2. Humidity Effect

The humidity in the tree is an important parameter which determines the dielectric constants (conductivity and permittivity) of the tree, and then influences the radio-wave propagation. Several experimental works have been conducted to investigate the humidity effect on the radio-wave propagation at different frequencies. Dilworth et al. [55] found that wet foliage produces about 6–8 dB attenuation per meter as compared to dry foliage which produces 2–4 dB per meter of attenuation. In their experiments, a variety of deciduous trees (Oak, Sycamore, and Ash) was used, and the experiment was conducted at 38 GHz. Subsequently, Seville [15] reported that there is very little difference between dry and simulated wet conditions (the water was sprayed onto the foliage to form a wet condition) on a ficus tree at 37 GHz. Dalley et al. [56] later reported that a wet leafy horse chestnut tree can produce an additional 7 dB loss at 13 GHz as compared to the dry condition.

Recently, Pelet et al. [47] observed that there was an additional attenuation of about 5 dB across a cluster of poplar trees at 2.5 GHz when there was a rain fall at a rate of 6 mm/hr. From these works [15, 47], and [55, 56], it can be found that higher humidity can increase the propagation attenuation. However, the amount of the increased attenuation is unpredictable, which depends on the operating frequency, tree specimen, etc.

3.2. Analytical Characterization of the Shadowing Effect

As compared to the empirical studies, there are limited analytical works related to the characterization of the tree shadowing effect, besides the previously discussed wave theory based method and RET theory based method. In this section, analytical methods to characterize the dynamic shadowing effect due to the swaying foliage medium by the wind and also the tree shadowing in dense urban areas, such as lines of trees planted along the streets etc., are mainly discussed.

3.2.1. Modeling of the Dynamic Shadowing Effect

Pechac et al. [57] introduced an analytical model based on a 3-D lattice, which features a flexibility to accurately simulate the temporal as well as spatial-temporal dynamic effects of a tree shadowed link. In their work, the simulated results are evaluated by both the laboratory and the outdoor measurements with dog-rose bush, apple tree, and pine. The measurement results show the efficiency of the proposed approach. The main advantages of the model are its universality and simplicity. It can be used either for the fade margin estimations for the required QoS or as a time-series generator for channel simulations as reported by Pechac et al. [57].

Another interesting work is conducted by Cheffena et al. [58] recently. They developed a new simulation model for generating signal fading due to a swaying tree, by utilizing a multiple mass-spring system to represent a tree and a turbulent wind model. The proposed model is validated with the measurements at 2.45 GHz, 5.25 GHz, 29 GHz, and 60 GHz. It is found that satisfactory agreement can be achieved.

3.2.2. Modeling of the Tree Shadowing Effect in a Street

Significant work has been contributed by Torrico et al. [59] and Bertoni [2] to model the tree shadowing effect in a street. In their works, a theoretical model is proposed to include the effects of trees as well as houses or buildings on the propagation loss in residential areas. The properties of a tree are characterized by the mean field, attenuation, and phase delay. Physical Optics (PO) method is then used to evaluate the diffracting field at the receiver by using multiple Kirchhoff-Huygens integration for each absorbing/phase half-screen combination. Trees are represented as an ensemble of leaves and branches, all having prescribed location and orientation statistics. Leaves are modeled as flat, circular, lossy dielectric discs and branches as finitely long, circular, lossy dielectric cylinders. The coherent field in the canopy is then computed by using an effective propagation constant that is determined by the medium's equivalent scattering amplitude per unit volume in the forward scattering direction. The incoherent scattered field outside the canopy is obtained in terms of an integral over the canopy volume. In this study, the effects of the trunk are neglected. A similar way to model the tree shadowing effect is recently conducted in [60, 61] up to 2 GHz. The analytical studies show good

Table 3. Characteristics of delay spread through vegetation#.

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

#The data in Table 3 was obtained for a 3.5 GHz carrier signal modulated with a 1.5 ns pulse. The 3 dB bandwidth of the resulting pulse-modulated signal is 0.78 GHz [34].

agreements with the results of scattering measurements for propagation through a tree canopy in a residential environment.

4. WIDEBAND FOLIAGE CHANNEL INFORMATION

Wideband foliage channel information was first investigated by Bultitude [40] for the satellite-mobile channels, where the channel impulse responses were estimated for the in-leaf and out-of-leaf conditions. However, there are limited works conducted in the literature, although the demand of the wideband foliage channel information increases recently due to the implementation of the high speed wireless systems based on the MIMO or UWB techniques. From the open literature, the most significant wideband characterizations of foliage channel are conducted by Savage et al. [19]. They investigated wideband foliage channel information with different measurement sites, different species of trees, and different measurement geometries for both the in-leaf and out-of-leaf conditions. It is found that, generally, the delay spread for in-leaf measurements was greater at 11.6 GHz than results obtained from out-of-leaf investigations. However, this was not the case at 1.3 and 2 GHz where larger values of delay spread were measured in out-of-leaf state than in-leaf, except for London Plane.

ITU Recommendation [34] has summarized some typical wideband parameters such as delay spread found for different tree specimens. These parameters are shown in Table 3 for reference.

5. CONCLUSIONS

In this paper, published works regarding the foliage effect on modern wireless communication systems have been reviewed. The foliage loss prediction model, shadowing effect and its variations, and wideband channel information are discussed both empirically and analytically.

The focus of this paper is on the development of empirical studies to date.

From the review, some possible research areas can be proposed. Since external factors such as wind, rain, etc. are found to cause the unexpected loss of the foliage shadowed links, mitigation techniques are suggested for the improvement of the reliability of these links. Some research works related to the studies of the spatial diversity have been conduced in [62, 63]. However, more research work on other diversity techniques such as depolarization [64] diversity or MIMO technique with foliage effect can be done. Moreover, for implementation of UWB techniques with the foliage effect, the wideband foliage channel information is needed to be investigated in more details.

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