DIRECTIONAL SPECTRUM MODELLING IN INHOMOGENEOUS FORESTS AT 20 AND 62.4 GHZ

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Abstract: This paper presents a radiowave propagation model for inhomogeneous forests based on the Radiative Energy Transfer theory (RET) model. This model, which is a discretised version of the RET, is able to simulate the behaviour of radiowaves inside a forest which contains various types of vegetation and free space gaps. The forest is divided into non-overlapping square cells, each one with different propagation characteristics. The propagation properties of each cell rely on specific propagation parameters, which are extracted from vegetation using an appropriate measurement method which is also described. The model performance is assessed through comparison between predicted values and directional spectrum measurements carried out in an isolated inhomogeneous forest at 20 and 62.4 GHz. This forest, located in South Wales, is formed by 6 different species of trees of various sizes and leaf types. The measurements were performed with the trees in-leaf.

1 INTRODUCTION

The growth of fixed and mobile radio networks experienced in the last decades, has led to an increased need for cost effective, and enhanced utilisation of the available bandwidth and system coverage. This enhancement can be accomplished through a more efficient use of the available radio spectrum. A more efficient use of the radio spectrum relies on accurate radio planning tools which allow system planners to effectively predict the behaviour of their radio communication systems in terms of coverage and interference on existing systems.

The radiowaves interact with the obstacles and surrounding environment present in the radio path creating undesirable effects which need to be accurately modelled. From these obstacles, vegetation is very likely to be present in sub-urban and rural environments, causing degradation in the performance of the radio systems. To this extent, the understanding of the interaction between radiowaves and vegetation media is very important.

Various propagation models have been applied to vegetation with different degrees of success (Rogers et al., 2002). From these, the *Radiative Energy Transfer* theory (RET) has yielded good results for micro- and millimeter wave frequencies (Rogers et al., 2002; ITU-R, 2005). In (Rogers et al., 2002), results from an extensive measurement campaign are used to compare the predictions of the RET with actual measurement data in the 1 to 60 GHz frequency band. This work has established a generic model for radiowave propagation in vegetated areas which was recently appended to the ITU-R recommendation in force (ITU-R, 2005). Although this model is based on three different propagation mechanisms, it is reported that the scattered component, which is modelled with the RET, is dominant in terms of the received signal level.

The first known application of the RET theory to model the radiowave propagation in vegetation media was reported in (Johnson and Schwering, 1985) which is based on the RET modelling presented in (Ishimaru, 1997). Both of these RET formulations present some approximations which limit the applicability of the model, *e.g.* the model considers a homogeneous medium; the medium is not physically limited and special geometry conditions must be met. The vegetation media is normally inhomogeneous in nature as leafs tend to grow more in the periphery of the forest due to the increased sunlight exposure. Another limitation is that vegetation normally appears in limited or isolated groups, and forest volumes are nor-

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mally limited by the ground and the top of the vegetation.

To overcome the issues presented above, a discretised version of the RET (dRET) was presented in (Didascalou et al., 2000). A development of this model as well as a complete assessment was performed in (Fernandes et al., 2005) using an idealised scaled-down version of a forest formed by 16 *Ficus Benjamina* plants inside an anechoic chamber at 20 and 62.4 GHz.

In order to apply the dRET, the vegetation volume is divided into non overlapping square cells each one presenting distinct propagation characteristics. The signal flow in each of the cells is subsequently calculated using an iterative algorithm which evaluates the interactions between the different cells.

In this paper, the dRET formulation is used to simulated the behaviour of a full scale outdoor forest formed by 6 different species of trees. The assessment of the model is performed by comparing the predicted values with the actual measurement data obtained from outdoor measurements at 10 locations inside the test forest.

In section 2, the RET based scattering propagation models which are used during this paper as well as the differences between the original RET and its discretised version are presented. The model input propagation parameters are also described. The site specifics, including both the geometry and the tree characteristics, used to validate the proposed model is also presented. The experimental procedures used to extract the vegetation parameters as well as the overall model validity in terms of excess attenuation caused by tree is also outlined. Section 4 presents and discusses the measurement results. Finally in section 5 the conclusions of the paper are presented.

2 THE SCATTERING PROPAGATION MODELS

2.1 The Radiative Energy Transfer (RET)

The RET models vegetation as a homogeneous medium randomly filled with similar scatterers, which are characterised by the following set of parameters:

- The **Extinction Coefficient** or k_e. This parameter specifies the amount of energy which is lost due to absorption and scattering;
- The **Scattering Coefficient**, k_s, which specifies the scattered energy;
- The scatter directional profile $p(\hat{s}, \hat{s}')$, known as **Phase Function** (Ishimaru, 1997), with $\hat{s}'$ and $\hat{s}$ representing the directions of the energy entering and emanating from each scatterer, respectively.

The phase function is normally modelled according to Eq. 1 (Johnson and Schwering, 1985; Ishimaru, 1997) which represents a Gaussian function superimposed to an isotropic background level:

$$p(\gamma) = \alpha \left(\frac{2}{\beta}\right)^2 e^{-\left(\frac{\gamma}{\beta}\right)^2} + (1-\alpha), \qquad (1)$$

where α is the ratio between the forward lobe power and the total power of the phase function, β represents the half power beamwidth of the forward lobe and γ is the angle subtended by $\hat{s}$ and $\hat{s}'$.

The RET equation is normally expressed in its differential form, presented in Eq. 2.

$$\frac{dI}{ds} = -k_e I + k_s \int_{4\pi} p(\hat{s}, \hat{s}') I dw, \qquad (2)$$

where the left hand side (LHS) describes the spatial variability (*i.e.* derivative) of intensity over one scatterer, while the first term on the right hand side (RHS) accounts for the reduction in intensity due to the absorption and scattering. The second term on the RHS represents the increase of intensity resulting from the scattering contributions of surrounding scatterers (Johnson and Schwering, 1985). In (Johnson and Schwering, 1985), the overall intensity I is divided into two different intensities: the reduced intensity, I_{ri} and the diffuse intensity I_d. I_{ri} is the attenuated incident intensity whereas I_d accounts for the contributions from incoherent scattered components inside the vegetation medium.

2.2 The Dret Formulation

The discrete RET (dRET) was originally proposed by (Didascalou et al., 2000), as a method to overcome the RET limitations in terms of applicability to isolated vegetation volumes. In the dRET modelling, the vegetation volume is divided in non-overlapping square cells and an iterative algorithm is used to gather all the interactions between these primary cells, allowing for the computation of the intensity across the entire tree formation. This approach of splitting the vegetation in discrete elementary volumes, allows one to assign different scattering parameters to every cell, consequently enabling an inhomogeneous vegetation volume to be more accurately represented. This is depicted in Fig. 1.

The dRET approach presented in (Fernandes et al., 2005) and used here, comprises 4 major improvements compared to the algorithm given in (Didascalou et al., 2000). These are summarised as follows: (i) the improved dRET version yields results for angles other than those which are integer multiples of $45°$; (ii) it accounts for the effect of the receiving antenna radiation pattern; (iii) the dRET differential equation is more readily solved, which means that piecewise linear approximation is no longer needed, so that the algorithm can cover larger cell sizes; and (iv) the cell parameters can be defined individually, thus allowing one to define inhomogeneous scenarios.

3 EXPERIMENTAL PROCEDURE

An experimental program was designed to evaluate the performance of the dRET model in a real outdoor environment. This program involved two main tasks: the dRET parameter extraction and the evaluation of the excess attenuation caused by trees at several locations inside the test forest.

3.1 Description of the Measurement Site

The measurement site is located in the North-East of Cardiff in South Wales. The test forest is an isolated group of trees formed by 6 different species. To completely characterise the test forest, precise locations of each tree and the mean canopy diameters were measured using a theodolite. Using this data, a 2D representation of the forest is presented in Fig. 2. The transmitter location (TX) and the direction where it was pointed in the measurements are also presented. The red dots which are labeled *Mpx*, represent the received signal measurement locations. The tree species present in the test forest as well as the dimensions of the trees are presented in Table 1.

For each of the species, the leaf size parameters were measured. These mean sizes are presented in Table 2.

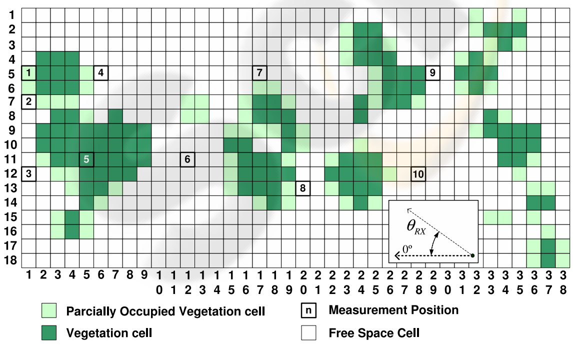

Figure 1: 2D cell structure.

Table 1: Tree species of Wyevale Garden Center site.

Tree Label	Common Name	Canopy Diameter (m)	Tree Height (m)
T1	Oak	11.4	10.9
T2	Oleaster	12.1	16.5
T3	Ornamental Cherry	6.1	3.5
T4	Oleaster	14.0	17.7
T5	Ornamental Cherry	5.2	3.5
T6	Ornamental Cherry	6.0	3.5
T7	Ornamental Cherry	6.0	3.5
T8	Ornamental Cherry	3.0	3.0
T9	Silver Birch	4.5	8.4
T10	Silver Birch	6.5	6.4
T11	Silver Birch	10.0	10.0
T12	Oleaster	12.5	15.6
T13	Silver Birch	5.6	5.5
T14	Oleaster	12.0	15.0
T15	Oak	5.6	2.5
T16	Oak	10.1	7.2
T17	Gean	9.6	7.3
T19	Pecan	3.9	8.9
T20	Oak	8.0	9.6
T21	Pecan	8.3	5.2
T22	Pecan	7.0	7.0
T23	Oak	6.1	7.8
T24	Oak	7.2	6.8
T25	Pecan	6.8	13.0
T26	Pecan	6.2	14.3
T27	Pecan	3.9	4.3

3.2 Directional Spectrum Measurements

To evaluate the excess attenuation caused by the vegetation, the RX antenna was placed at each of the locations shown in Fig. 2 and the directional profile of the received signal was evaluated. This evaluation was performed positioning the receiver antenna at 5.5 m high, which represent approximately one half of the mean canopy height of the trees which form the test forest. At each location, the RX antenna was rotated clockwise $360°$ around its vertical axes (θ_{RX}) in $1°$

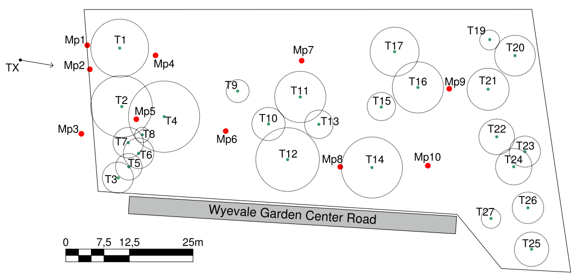

Figure 2: Scaled drawing of the Wyevale Garden Center test site.

Table 2: Tree leaf sizes of Wyevale Garden Center site.

Common Name	Leaf Size	
	Length (cm)	Width (cm)
Oak	13	8
Oleaster	9	0.8
Ornamental Cherry	10	6
Silver Birch	4	2.5
Gean	15	6
Pecan	9	3

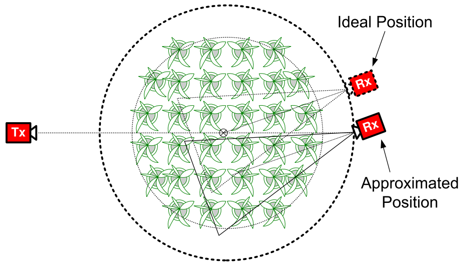

Figure 4: Approximated method to measure parameter β.

incremental steps.

The TX antenna was placed outside the forest in the position shown in Fig. 2 at 13 m distance from the air to vegetation interface. To achieve an almost uniform illumination of the interface, very broad 50° (10 dBi) half power beamwidth antennas were used at both test frequencies. At the receiver side, high gain directional antennas were used. At 20 GHz the RX antenna was of the lens horn type with 33 dBi and 4° of HPBW, while at 62.4 GHz a lens horn antenna with 36 dBi and 2.8° of HPBW was used.

3.3 Parameter Extraction and Scaling

The dRET input parameters must be extracted from specific measurement data. This data is obtained from received signal measurements in specific locations around the tree as explained in Fig. 3. The distances $d_{1,2,3}$ were chosen so that 100% of the canopy width could be illuminated within the HPBW of the TX antenna, and at the same time, the RX antenna was placed as close as possible to the tree canopy. At each of the 3 measurement locations presented in Fig. 3 (labeled M_n) the receiver antenna was rotated around the vertical axes in a $\pm 45°$ range in $1°$ steps.

The extraction of k_e was based on the measurement of the insertion loss caused by the tree, and consequently relied on measurements M_1 and M_3. The ratio between the maximum received powers at these locations was used to calculate k_e using Eq. 3.

$$\frac{P_{3\,\max}}{P_{1\,\max}} = e^{-k_e(d_3-d_1)} \left(\frac{d_3}{d_1}\right)^2, \qquad (3)$$

where $P_{1\,\max}$ and $P_{3\,\max}$ are the maximum receiver powers at positions M_1 and M_3, respectively, and d_n is the distance between the TX and the n^{th} measurement location in meters.

To extract the phase function parameters α and β, a modified version of the re-radiation indoor measurement procedure (Fernandes et al., 2005) was used. This modified version overcomes some of the inaccuracies reported in (Richter et al., 2002) and is simpler to carry out. The β optimisation is based in measurement M_3, where the ideal measurement position is replaced by a more convenient approximated position, as explained in Fig. 4. The optimisation of α uses the side scatter level of the tree obtained from measurement M_2, which is subsequently used to optimise α in Eq. 1. Finally, k_s is extracted by modelling the tree as a single dRET cell. As there are no interactions involved between cells a simple version of the dRET diffuse intensity equation (Fernandes et al., 2005) is used to optimise k_s, providing the measured side scatter level.

The parameter extraction was performed for 5 of the 6 species present in the test forest. The trees chosen to carry out the parameter extraction were: T_1, T_3, T_{11}, T_{12} and T_{17}. These were chosen due to their location at the border of the forest, thus avoiding the possible contamination of measured results caused by interference from the other species. The extracted parameters are presented in Tables 3 and 4 for 20 and 62.4 GHz respectively. Some parameters were impossible to calculate, specially for the larger trees, due to the high attenuation of the coherent signal component. In these cases average parameter values were assigned to the corresponding trees.

To limit the *stair case* error due to the discretisation of the forest, while maintaining a reasonable computational time, a 2.5 m vegetation cells division was used, as depicted in Fig. 1. In order for the phase

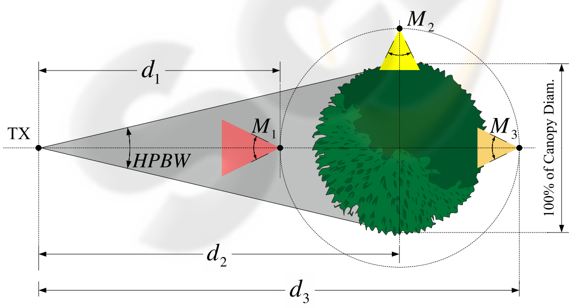

Figure 3: Parameter extraction measurement setup.

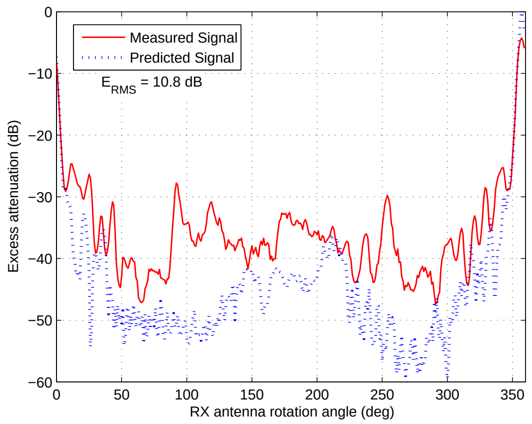

Figure 5: Measured and predicted signals in MP_2 at 20 GHz.

function parameters to remain valid, these have to be adapted to the new vegetation volumes by performing an appropriate scaling. The scaling method used here is explained in (Fernandes et al., 2006), which suggests a linear behaviour of α and β with the variation of the vegetation volume.

4 MEASUREMENT RESULTS

The assessment of the dRET propagation model results was performed comparing the predicted results with directional spectrum measurements were carried out at 10 locations inside the forest according to the procedure explained before. The measured excess attenuation can subsequently be compared with the predictions calculated by the dRET algorithm for the test forest depicted in Fig. 2 when modelled with the cell structure presented in Fig. 1.

A comparison between the measured received signal and the predicted signal values obtained at MP_2 is presented in Figs. 5 and 6, at 20 and 62.4 GHz, respectively. In these measurements, which were performed at the air to vegetation interface, the RX signal level is strongly influenced by the direct path between the TX and the RX antennas. Hence, the plots present a signal shape which is very close to the radiation pattern of the receiver antennas, particularly in the angular region around 0° where the RX antenna is pointing to the TX. Although a good overall agreement between predicted and measured curves can be observed, specially when the RX and TX antennas are aligned, a slightly increased error is present in the prediction of the signal which is scattered from the forest. This may be explained due to some inaccuracy in the estimation of k_s parameter corresponding to the surrounding trees during the parameters extraction phase.

Figs. 7 and 8, present the results for MP_4, which is located behind tree number 1. The results for 20 GHz (Fig. 7) also present a good agreement between the measured and the predicted received signal values. Nevertheless, there is a tendency to underestimate the scattered signal from tree number 1. This effect is present in the 220 to 330° angular range and might be due to the incorrect estimation of the beamwidth

Table 3: Input parameter values extracted from selected vegetation blocks at 20 GHz.

Tree Label	20 GHz k_e	k_s	α	β
T_1	0.38	0.28	0.36	10.7°
T_3	0.99	0.25	0.13	7.0°
T_{11}	0.75	NA	0.05	13.7°
T_{12}	0.68	NA	NA	15.9°
T_{17}	0.45	NA	0.13	19.5°
Mean	**0.65**	**0.26**	**0.17**	**13.4°**

Table 4: Input parameter values extracted from selected vegetation blocks at 62.4 GHz.

Tree Label	62.4 GHz k_e	k_s	α	β
T_1	0.31	0.13	0.08	4.7°
T_3	1.26	1.02	0.07	15.5°
T_{11}	0.81	NA	NA	12.1°
T_{12}	0.51	0.10	0.15	14.9°
T_{17}	0.50	0.38	0.04	11.1°
Mean	**0.68**	**0.41**	**0.09**	**11.7°**

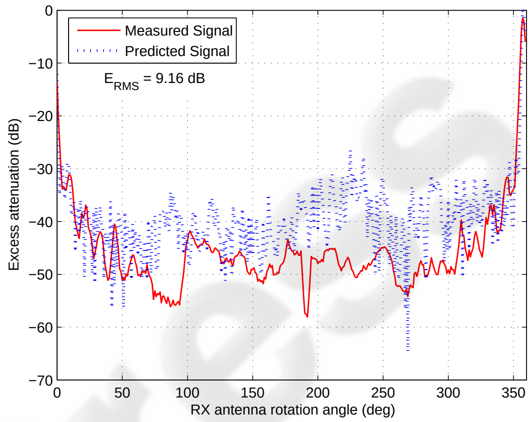

Figure 6: Measured and predicted signals in MP_2 at 62.4 GHz.

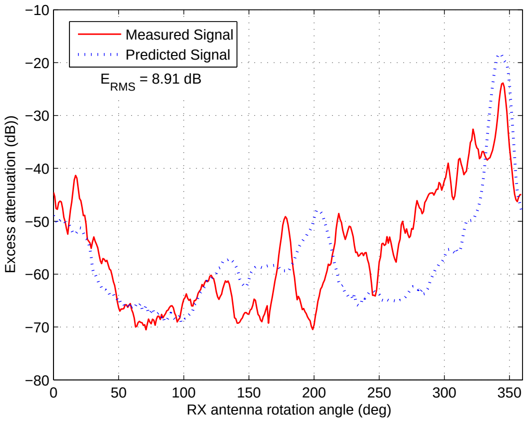

Figure 7: Measured and predicted signals in MP_4 at 20 GHz.

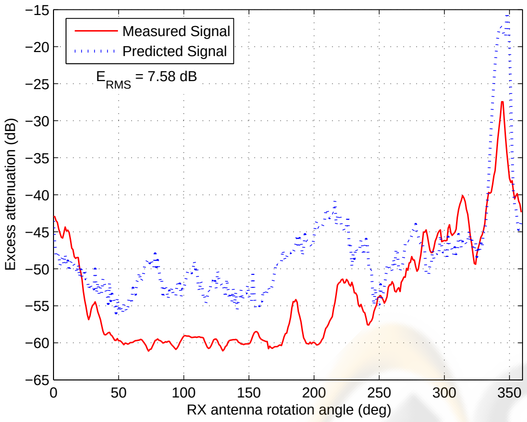

Figure 8: Measured and predicted signals in MP_4 at 62.4 GHz.

of the scattering profile of tree number 1. The underestimation of this parameter will concentrate the scattered radiation in the forward scattering region ($\theta_{RX} = 340°$) leading to the mentioned inaccuracy. Around $\theta_{RX} = 200°$ the dRET model predicts a peak in the received signal which corresponds to the signal scattered from tree number 9. The misalignment between this peak and the correspondent peak in the measured signal is likely to be due to the approximation in discretisation of the tree position inherent to the cell division process.

The 62.4 GHz plot (Fig. 8) presents an absolute error of 10 to 13 dB in the forward scattering region (around $340°$). This can be due to some blockage which was taken into account in the k_e extraction. In fact, k_e is extracted by measuring the excess attenuation caused by the tree, using a radial path which is different from the line used to measure the attenuation. Attenuation differences between different radial paths of 20 dB have been published in literature (Caldeirinha, 2001). This may help to explain this discrepancy.

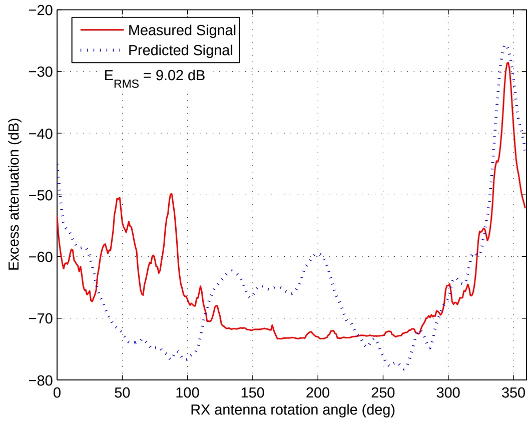

Figure 9: Measured and predicted signals in MP_9 at 20 GHz.

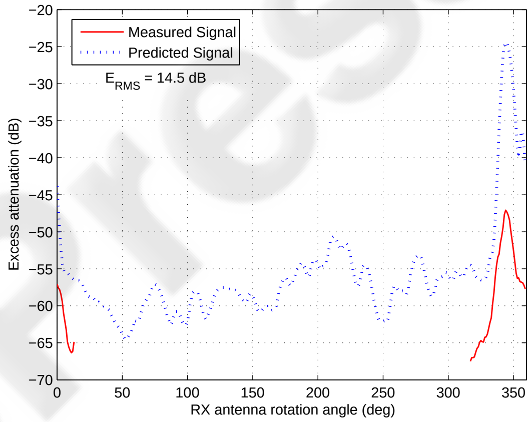

Figure 10: Measured and predicted signals in MP_9 at 62.4 GHz.

Figure 9 presents the measured and predicted received signal values in position MP_9 at 20 GHz. A good correspondence between the two values is present in the forward scattering region around $\theta_{RX} = 330° \pm 70°$. In the angular region where the RX antenna is pointing away from the test forest, i.e. $30° \leq \theta_{RX} \leq 110°$ the measured signal shows an increased received signal level which appears to be due to scattering in the vegetation structures surrounding the test forest. These structures, lying outside the

Table 5: Model performance assessment using the RMS error criterion.

Measurement Position	RMS error (dB) 20 GHz	62.4 GHz
MP_1	11.8	9.0
MP_2	10.8	9.2
MP_3	13.9	7.8
MP_4	8.9	7.6
MP_5	12.5	16.5
MP_6	13.5	13.5
MP_7	9.6	6.7
MP_8	18.7	11.8
MP_9	9.0	14.5
MP_{10}	13.2	NA
Mean	**12.2**	**10.7**

test forest were not modeled and consequently are not taken into account by the dRET modelling thus explaining why the model seems to be unable to predict accurately the signal level within this angular region.

At 62.4 GHz the signal level in position MP_9 was relatively low and could only be measured for a narrow angular region. Outside this region the received signal was too close to the receiver noise level, which is around -70 dBm, to be measured. The measured and predicted values seem to exhibit a level offset which seems to be due to a vertical misalignment of the RX antenna. This offset generates a larger RMS error when compered with the remaining measurement positions.

The overall RMS error for the complete set of measurement performed at 20 and 62.4 GHz is shown in Table 5. The RMS error is consistently below 15 dB except at a few locations in the forest. The mean overall RMS error is 12.2 and 10.7 dB at 20 and 62.4 GHz, respectively. Although the RMS error values are slightly above figures found in other published results, these can be considered reasonably low. They also demonstrate the benefits of dRET modelling, particularly when considering inhomogeneous media.

5 CONCLUSIONS

This paper presents a model for radiowave propagation in inhomogeneous vegetation media for micro and millimeter waves, which is based on the RET. The model relies on 4 vegetation dependent propagation parameters and a method to extract and scale these parameters is also presented. The input parameters are extracted from the different vegetation volumes forming the test forest using the proposed method at 20 and 62.4 GHz. Subsequently these parameters are used in the model to generate excess attenuation predictions at several locations inside the test forest. Finally, the predicted and measured results are compared using the RMS error criterion. This is shown to be consistently below 15 dB. Although this RMS error value is within the range of other published results, in some measurement locations the error was found to be as high as 18.7 dB. This is thought to be due to localised blockages, inaccuracies in the parameter extraction method and also misalignment of the RX antenna during the attenuation measurement phase. An improved parameter extraction method is thus being investigated to eliminate higher error discrepancies.

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