Investigation of a Radio Propagation Model for Vegetation Scatter Dynamic Channels at BFWA Frequencies

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Abstract: The successful deployment of wireless technologies in the micro- and millimetre frequencies relies on the understanding of radio channel propagation and accurate radio propagation models. To this extent, the dynamic effects of vegetation on radio signals are investigated, as a function of wind direction, receiver location and vegetation depth. Furthermore, a radio propagation model, based on the RET, is investigated as an approach to predict the channel dynamic effects of vegetation scatter at 20 GHz. The model is evaluated for a structured forest medium, and its performance is assessed through the use of primary, secondary and error quantification statistics.

1 INTRODUCTION

Growing demand for bit stream access to provide multimedia services, at fixed and mobile locations, have led the industry to continue to develop new technological solutions capable of surmounting the technical hurdles involved. Broadband Wireless Access (BWA) systems envisage the use of the frequency band from 2 to 60 GHz (IEEE 802.16, 2011); (Mehmet et al., 2006). The IEEE Standards Association has standardized a suite of 802.16 standards to cover LOS and non-LOS connectivity covering the 2 to 10 GHz and 10 to 60 GHz frequency bands, respectively (IEEE 802.16, 2011). The 20 to 40 GHz frequency band is to be used for BFWA (Broadband Fixed Wireless Access) systems. The successful deployment of technologies in the micro- and millimetre frequency bands relies, amongst other factors, on the precise planning, design and successful implementation of the communication systems. In order to achieve this, in depth understanding of the radio channel propagation phenomena and consequent accurate radio propagation models are essential.

Within the many obstacles, that may be present in the propagation path in rural, sub-urban and urban scenarios, several studies have shown that vegetation can critically affect the received radio signal (Meng et al., 2009); (Violette et al., 1985); (Schwering et al., 1988); (Caldeirinha, 2011); (Al-Nuaimi and Hammoudeh, 1993). The effects of absorption and scattering of static vegetation have been considered, while relatively few studies have considered the effects of wind induced vegetation movement. These studies show that wind causes the foliage medium to move to an extent that results in significant temporal variations of the received signal (Naz and Falconer, 2000); (Kajiwara, 2000); (Perras and Bouchard, 2002); (Hashim and Stavrou, 2006); Crosby et al., 2005). The recommended model for vegetation attenuation is the ITU-R P833 (ITU), of which the latest version has been updated to include results of measurements made in the UK and Norway for both attenuations and to include the dynamic effects caused by wind induced foliage movement.

The work presented in this paper aims to contribute to the modelling of the dynamic effects covering the micro- and millimetre frequency bands. A model is proposed as a reasonable approach to predict the time-variant scattered signal from vegetation. The proposed model is based on the Radiative Energy Transfer (RET) theory.

This paper is structured as follows. In section 2 the results from an investigation on the dynamic effects of vegetation on radio signals, are presented. Two sets of measurements were performed at 20

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GHz. One set of measurement on single trees, and the other on a structured formation of trees. The results are analysed as to the impact of wind incidence on single trees, and the interrelated impact of wind direction, vegetation depth and location of radio receiver on received signals inside a forest medium. Section 3 describes the proposed model rationale and formulation. A brief description of the RET and dRET theories is provided as well as the reasons leading to consider the dRET model to predict time-varying estimates of received radio signals inside forest media. The proposed modelling methodology makes use of the dRET input parameters to extend the dRET to consider channel dynamics. Both the model input parameters and intensity equations, used to calculate the received scatter signal, are expressed in equations. Section 4 presents the model assessment results. A simulation structured tree formation scenario is used to validate the proposed modelling approach against measured data. The model is assessed against various receiver positions and wind directions. Primary and secondary statistics are used to evaluate the model performance. In addition, ERMS errors are calculated for a number of scenarios to quantify the performance of the model. The model is shown to be a reasonable approach to model the dynamic effects in foliage channels. Section 5 concludes the paper. A summary of the findings is presented as well as suggestions for further model improvements and validation processes.

2 STATISTICAL CHARACTERISATION OF THE DYNAMIC EFFECTS IN FOLIAGE MEDIA

The investigation of the dynamic effects of vegetation on propagating radio signals in single trees and groups of trees is essential to understand the behaviour of scattered signals from foliage under wind induced movement. The propagation of radio signals through and scattered from foliage is expected to vary according to the change of wind speed, wind incidence in reference to the point of illumination of the air-to-vegetation interface and position of the receiver inside a forest medium, i.e. vegetation depth.

Specific measurements were performed to investigate these matters, and to enable the assessment of the proposed model performance.

2.1 Measurement Geometry

Radio measurements were performed on two distinct scenarios, inside an anechoic chamber. The measurements were executed using a Continuous Wave (CW) measurement system operating at a fixed frequency of 20 GHz.

The single tree scenario measurements were performed on one downscaled tree, of the *Ficus* species, where the time-varying re-radiation pattern of the tree was recorded. The experiment geometry is depicted in Figure 1 a). The re-radiation pattern was recorded over an angular range of 240º, with an angular resolution of 2º. Both the transmitter and receiver were placed in far field region of the antennas, illuminating around 90% of the centre canopy. This guarantees the received signal originates either from scattered signals from the foliage or signals propagating through the foliage medium. In these experiments a horn antenna of 10 dBi gain was used on the transmitter side, and a 20 dBi Gaussian antenna, with a 4º beam width, was used at the receiver. The dynamic signal envelope was recorded over a period of 10s at a sampling rate of 1 kHz, per scatter angle. The wind induced effects were simulated with a household fan, placed in four distinct locations around the tree, as depicted in Figure 1 a). The fan produced wind at a constant speed of 4.7 m/s, and illuminated the full extent of the canopy.

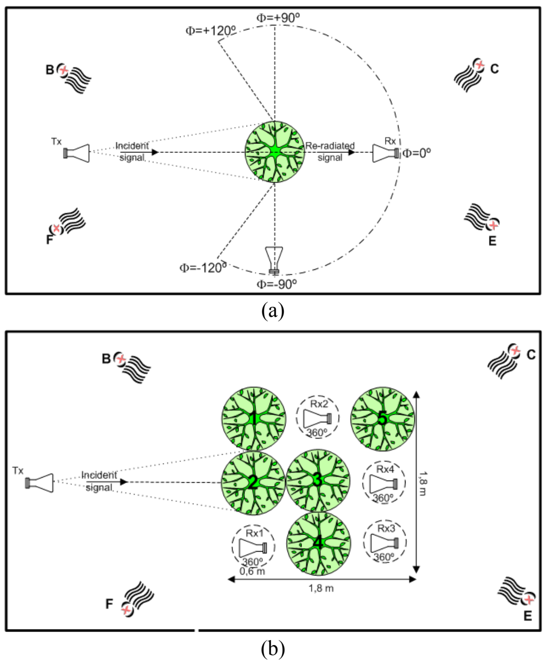


Figure 1: Measurement geometry of the: a) single tree and b) tree formation scenarios.

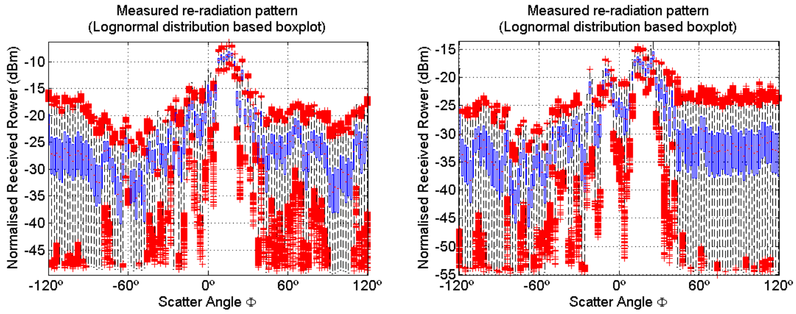
The tree formation measurements were performed on trees of the *Ficus* species, where the directional spectrum was recorded at four specific positions inside the forest medium. The experiment geometry is depicted in Figure 1 b). The directional spectrum was recorded by rotating the receiver around its own axis, in the azimuth plane, over a range of 360º with an angular resolution of 2º. The transmitter was placed conveniently to guarantee the illumination of 90º of the air-to-vegetation interface. The 10 and 20 dBi antennas used in the single trees measurements, were also used in these measurements, on the transmitter and receiver side, respectively. The received time-series were recorded over a period of 10s, per angle, with a sampling rate of 1 kHz. Once again the wind induced effects were simulated with a household fan, placed in four distinct locations around the tree, as seen in Figure 1 b). The fan produces a wind front at the air-to-vegetation interface with relative narrow width illumination (around 2 trees), in comparison to wide uniform wind illumination observed in outdoor forest geometries. However, given the small dimensions of the indoor measurement geometries, the employed method to generate artificial wind is found to be suitable.

2.2 Statistical Analysis

A statistical analysis was performed on the single tree and tree formation measurements. The ensuing results are presented. The single tree results focus on the effects of different wind incidences on the scattered radio signals. The tree formation results aim to investigate the effect of vegetation depth on the received signal, as wind induced vegetation movement causes channel dynamics across the foliage medium, from different incidences.

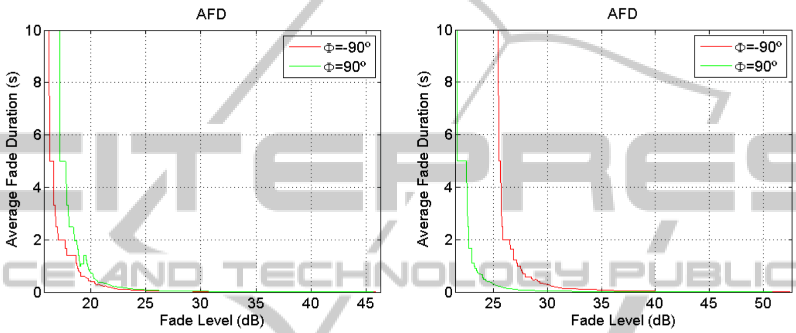
The analysis of the single tree results is done through the appreciation of the re-radiation pattern through a skewed box plot based on a Lognormal distribution, and second order statistics Average Fade Duration (AFD) and Level Crossing Rate (LCR). Concerning the box plot depictions, on each blue box the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers (dotted line) extend to the most extreme data points, and the outliers (red dots) are plotted individually. The box plot enables the analysis of the following information about the data: position, spread, skewness and tails. The measured radio signal scattered from the vegetation volume is shown to be influenced by the direction of the artificially generated wind. As wind is blown on to a single tree from a specific direction, two areas of vegetation motion need to be considered. One area of the tree, where the wind incises directly on the foliage (active area), and another area opposite to the first (quiet area). The foliage dynamics in the quiet area are observed to be reduced in comparison to the active area, as a result of wind speed decay through the vegetation media. A comparison between measured re-radiation patterns obtained with opposite wind directions is depicted in Figure 2. The active area is considered to be from Φ=-120º to Φ=-50º and Φ=50º to Φ=120º, for wind directions B and F, respectively. The quiet area may be defined as the opposite, in reference to the wind direction. For both wind incidences in analysis, the received signal in the active area presents an increased standard deviation in comparison to the quiet area. This is indicated by the lack of outliers in the active area below the mean level. The increased number of outliers in the quiet area below the mean level shows that the received signal seldom falls into signal levels as low as the ones observed in the active area. In addition, analysis of the AFD and LCR statistics, depicted in Figure 3 and Figure 4, show that the deep fades in the active area as well as the fast-fading signal variation are greater compared to the quiet area results. Furthermore, analysis of the results in Figure 5, show that a distinct differentiation can be made on whether the wind incidence is on the transmitter or receiver side. The depicted results relate to AFD and LCR statistics, obtained at Φ=-90º and Φ=90º, for wind incidences of B and C. These show lower signal fades and signal crossing rates observed in results from wind direction B, against wind direction C. When the direction of wind illuminates the tree canopy in the same direction of the propagating radio wave, the received signal presents smaller signal fades and lower signal variation compared to wind illumination from the receiver (opposite) side.

The investigation of the tree formation results is done through the analysis of the re-radiation pattern and its corresponding boxplot. The measured directional spectrum inside a forest medium is shown to be influenced not only by the direction of wind illumination, but also the amount of vegetation between the source of wind and position of the receiver. Analysis of the results depicted in Figure 6, show that the origin of measured scatter dynamics varies according to the wind source of illumination. For instance, Figure 6 a) shows the re-radiation pattern relative to wind direction B. In this case the measured dynamics observed from Φ=-100º to Φ=50º (except in the main lobe region where the



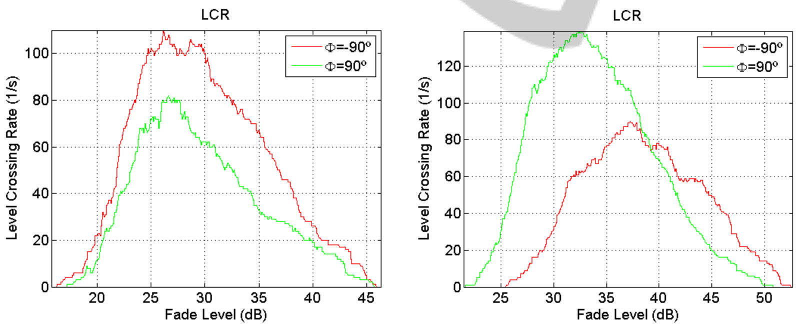
(a) (b)

Figure 2: Measured re-radiation boxplot patterns for wind incidences from: a) B and b) F.



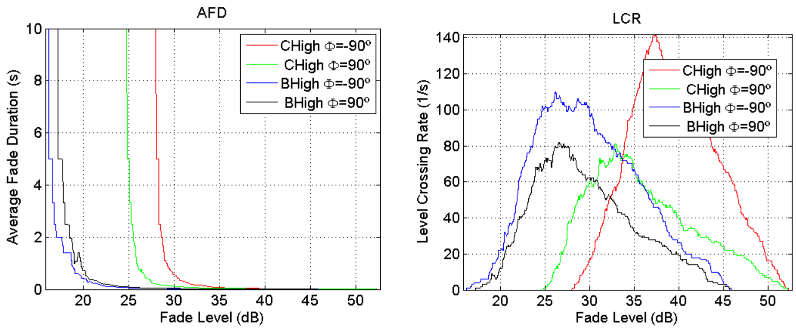
(a) (b)

Figure 3: Measured AFD statistics at Φ=-90º and Φ=90º, for wind incidences from: a) B and b) F.



(a) (b)

Figure 4: Measured LCR statistics at Φ=-90º and Φ=90º, for wind incidences from: a) B and b) F.



(a) (b)

Figure 5: Measured statistics at Φ=-90º and Φ=90º, for wind incidences from B and C, concerning: a) AFD and b) LCR.

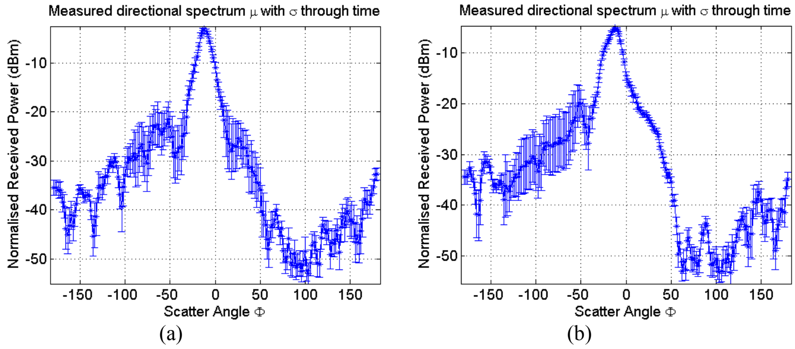


Figure 6: Measured directional spectrum from position Rx2, with wind incidence from: a) B and b) F.

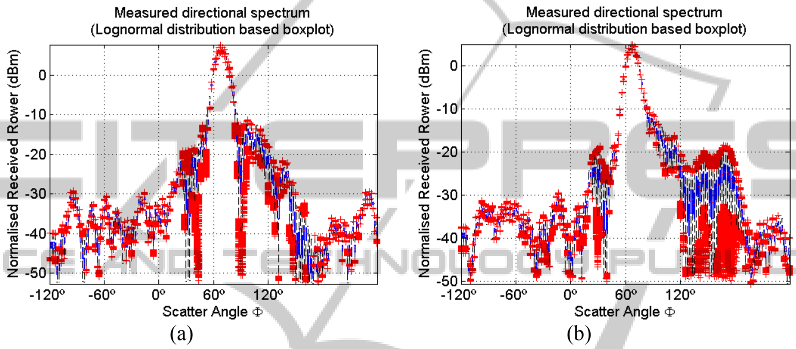


Figure 7: Measured directional spectrum from position Rx3, with wind incidence from: a) B and b) C.

received signal is coherent and presents little or no variation at all) are relative to the time-varying scatter originating from trees 1, 2 and 3 (as signalled in Figure 1 b)). Given this geometry, these are the trees most affected by the incidence of wind, and more prone to generate dynamic scattering of propagating signals. On the other hand, through analysis of Figure 6b), the change of wind source from B to F, results in increased dynamic scatter from trees 2, 3 and 4, indicated by the standard deviation observed around $-125^{\circ} \leq \Phi \leq 50^{\circ}$. These results show that the change of wind direction does not have a significant impact on the averaged directional spectra. However change of wind incidence does account for a change in measured dynamics in specific angular regions, depending on the wind direction.

Vegetation depth is expected to play a significant role on the effect of wind on foliage and its effect on propagating radio signals. As wind propagates through vegetation its force decreases as a result of wind decay and dispersion. As a consequence, wind induced vegetation movement will decrease resulting in lower channel dynamics. Results shown in Figure 7 allow the observation of this. The standard deviation observed in the measured directional spectrum at Rx3 with wind from position B, is close to neglectible. The depth of 2 to 3 trees is too great for wind to have a noteworthy impact on trees 3 and 4, and cause significant channel dynamics. The change of wind direction from B to C, results in high scatter dynamics from tree number 5 (region $50^{\circ} \leq \Phi \leq 90^{\circ}$) and mild effects from trees 3 and 4 (region $-50^{\circ} \leq \Phi \leq -10^{\circ}$). These results show that the wind point of source, forest geometry and position of radio receiver are all intrinsically interrelated. These variables need to be considered collectively when investigating the modelling methodology and developing the propagation model rationale.

3 MODEL RATIONALE AND FORMULATION

The channel characterisation discussed in the previous section, has shown that the propagation phenomena of radiowaves in forest media, under time-varying conditions, depends extensively on the geometry of forest, location of receiver and source of wind variation in reference to the receiver position. The considered modelling approach must take into account these deciding factors and provide not only insight into radio propagation physical phenomena in forested scenarios but also enable geometrical consideration of the scenario variables. To this extent the model is based on the RET theory, more specifically one of its derivatives, the dRET.

The RET theory, or energy transport theory, models vegetation as a random homogeneous medium comprised of small discrete scatterers. The RET has been shown to be a good solution to predict the complex phenomena of radio propagation through vegetation, as it provides accurate evaluation of the through vegetation attenuation with both horizontal and slant foliage paths (Johnson and Schwering, 1985); (Meng and Lee, 2010); Rogers et al., 2002). In spite of this, the RET has a crucial shortcoming. It assumes the forest as a homogeneous medium, and that it extends to infinity. In order to overcome these limitations, an improved version named the discrete RET (dRET) was proposed by Didascalou (Didascalou et al., 2000) and further enhanced by Fernandes (Fernandes et al., 2007).

In the dRET the vegetation volume is divided into non-overlapping cubic cells. This is particularly beneficial in dealing with inhomogeneous media. The process of splitting a forest formation into discrete elementary volumes allows the assignment of different scattering parameters to each cell. Each cell may be represented by four input parameters (Didascalou et al., 2000); (Fernandes et al., 2007): the absorption coefficient (σ_A, in *Np/m*), the scattering cross section per unit volume (σ_S, in m^{-1}), and the phase function parameters α and β. The phase function may be understood as the cell radiation pattern, with a pronounced forward lobe in the direction of signal propagation, and an isotropic background (Johnson and Schwering, 1985). The input parameters of each cell are used to calculate the incident intensity (the RET uses intensity as a fundamental quantity). An iterative algorithm is used to gather all the interactions between the cells, to perform the computation of intensity across the forest formation. The total specific incident intensity, in each cell, can be decomposed into the reduced intensity I_{ri} and diffuse intensity I_d. While both the input and output coherent intensities I_{ri} exhibit the same definite direction, each input diffuse intensity component I_d^{IN} generates several output components due to the scattering process (Johnson and Schwering, 1985); (Fernandes et al., 2007), as depicted in Figure 8.

The reduced and diffuse intensity were originally expressed in (Johnson and Schwering, 1985), and further discretised by (Didascalou et al., 2000); (Fernandes et al., 2007), to allow discrete formulations for losses due to absorption, scattering , increase of intensity resulting from scattering contributions from surrounding cells.

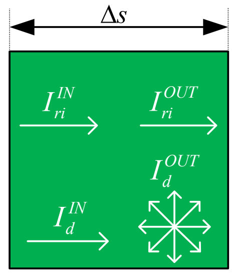


Figure 8: Representation of a single cell with size Δs.

The dRET enables insight into the complex propagation phenomena in scatter media, based on physical attributes of the vegetation (e.g. phase function). Furthermore, due to its discretised formulation it allows the enhanced resolving of the various directional intensities originating from individual vegetation cells. For these reasons, the proposed modelling methodology will be based on the dRET to provide time-varying estimates of received signal inside forest medium.

Since the dRET, in its current rationale, is only applicable to static conditions, the extension of the dRET to consider channel dynamics will be done through the time-variation of its input parameters. Analysis of the dRET input parameters time-varying properties, and its impact on the dRET predicted directional spectra, has been conducted (Morgadinho et al., 2011); (Sergio et al., 2011). The published results have shown that the dRET parameters vary over time with wind induced foliage movement, as the branches, twigs and leaves move and sway to the wind (Sergio et al., 2011). In addition, variations of the dRET input parameters are directly correlated to variations observed on the directional spectrum (Sergio et al., 2011). The extraction of the dRET input parameters for a single tree is done from its measured re-radiation pattern. The re-radiation pattern is the convolution of the tree scatter profile (phase function) and the receiver antenna pattern. Although the measured re-radiation pattern differs from the tree real radiation pattern, due to the receiver antenna distortion effect, it is considered a valid approximation of the tree scatter pattern. For time-invariant conditions, a single averaged re-radiation pattern is obtained, and an optimum Gaussian function is fitted against it (Johnson and Schwering, 1985). However, to ensure the parameters may be retrieved as a function of time, multiple re-radiation patterns are recorded over a period of time, each one corresponding to a specific time instant. Single Gaussian curves are estimated for each instant, from which the input parameters are retrieved, Figure 9. dRET parameters α and σ_S are estimated according to the backscatter level; β is calculated from the Gaussian function HPBW; σ_A is estimated from the difference between the phase function main lobe signal level and the corresponding line-of-sight level. These parameters may be expressed as:

$$\sigma_E(t) = \sigma_A(t) + \sigma_S(t) \tag{1}$$

$$P(t,\psi) = \alpha(t)\left(\frac{2}{\beta(t)}\right)^2 e^{-\left(\frac{\psi}{\beta(t)}\right)^2} + \left(1-\alpha(t)\right) , \tag{2}$$

where Ψ is the angle subtended by the input and output directions, and σ_E is the extinction coefficient.

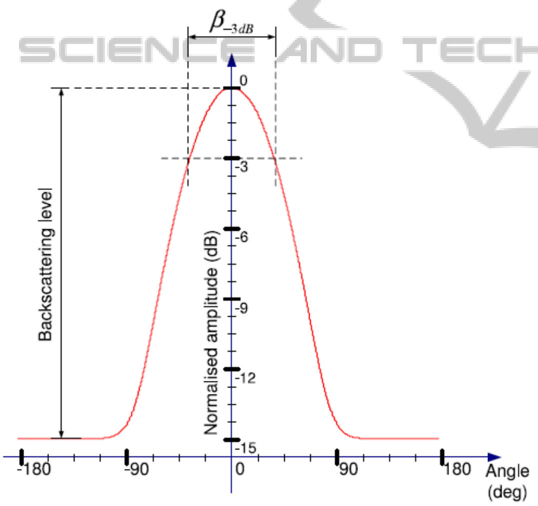


Figure 9: Gaussian phase function.

These parameters may be extracted under different wind conditions, i.e. wind speeds and incidences, to be later used in tree formation simulations under corresponding wind conditions.

Parameters α and σ_S are particularly sensitive to any changes in the side scatter level as they are estimated accordingly from the backscatter level. Under time-static conditions these parameters are extracted from an averaged backscatter level. However, under time-varying conditions, averaging the backscatter level will decrease both angular and time variations. Therefore, both parameters are extracted from a backscatter level estimated for a single angle of Φ=|90º|, where the recorded signal is expected to originate from tree scattering alone (Sergio et al., 2011).

In addition, the discretised intensities, depicted in Figure 8, expressed in (Didascalou et al., 2000), used to estimate the output radiation of each cell may be re-written as a function of time:

$$I_{ri}^{OUT}(t,\gamma_0) = I_{ri}^{IN}(t,\gamma_0) - \sigma_E(t) I_{ri}^{IN}(t,\gamma_0)\Delta s , \tag{3}$$

$$I_d^{OUT}(t,\gamma) = I_d^{IN}(t,\gamma) + \left[-\sigma_E(t) I_d^{IN}(t,\gamma)\right]\Delta s + \left[\sigma_S(t)\sum_{\gamma'=1}^{26} P(t,\gamma,\gamma') I_d^{IN}(t,\gamma') + \sigma_S P(t,\gamma,\gamma_0) I_{ri}^{IN}(t,\gamma_0)\right]\Delta s \tag{4}$$

where I_{ri}^{IN} and I_{ri}^{OUT} are the input, and output reduced intensities, I_d^{IN} and I_d^{OUT} are the input and output diffuse intensities, and P represents a discrete version of the phase function. Thus, the total output intensity is defined as:

$$I_T^{OUT}(t,\gamma) = I_{ri}^{OUT}(t,\gamma_0)\delta(\gamma-\gamma_0) + I_d^{OUT}(t,\gamma) , \tag{5}$$

4 ASSESSMENT OF THE DYNAMIC MODEL PERFORMANCE

The tree formation measurement scenario, depicted in Figure 1 b), was used as a reference for the assessment of the proposed modelling approach performance. To this extent, the simulation scenario, depicted in Figure 10, enabled a comparison between resulting modelled data and acquired data, for different wind incidences. This assessment aims to investigate the model performance as a function of: wind incidence and receiver position inside the forest media.

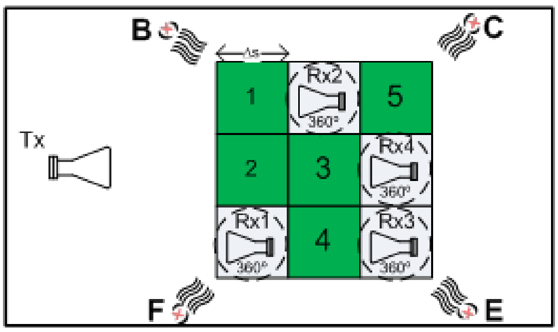


Figure 10: Simulation geometry of the tree formation depicted in Figure 1 b).

The evaluation between modelled and measured data is done through the consideration of the averaged directional spectra and its corresponding standard deviation. The averaged directional spectrum depicts the standard deviation information through the use of an errorbar. Furthermore, secondary statistic AFD is used to evaluate the ability of the model to predict deep fades throughout the bi-static scatter angle. The performance of the proposed model is quantified by the calculation of the ERMS (Root-Mean-Square) error, between simulated and measured data. The ERMS errors are provided in two ways: ERMS D-S is the averaged error from directional spectra through time, and ERMS T-S is the averaged error from time series as a function of the receiver scatter angle Φ.

The time-varying model input parameters, for the *Ficus* tree, were extracted from the measurement set depicted in Figure 1 a). The parameters were extracted for a period of 10 seconds, consequently resulting in a simulation time frame of 10 seconds.

Table 1: Averaged ERMS error statistics.

	Rx1	
Wind incidence	ERMS D-S (dB)	ERMS T-S (dB)
B	1.3	4.3
C	2.6	5.3
E	1.6	4.4
F	1.1	4.2
	Rx2	
B	6.5	8.8
C	4.0	7.3
E	5.7	8.0
F	5.5	8.9
	Rx3	
B	3.1	7
C	2.9	6.1
E	2.3	6.8
F	2.5	4.8
	Rx4	
B	7.0	16
C	1.2	8.4
E	1.8	9.1
F	2.8	9.9

The presented results indicate that the model is able to predict the directional spectra envelope and its variation with time, with relative agreement. The simulation results obtained from receiver positions Rx1 and Rx2 are assessed with more detail. A comparison between measured and simulated directional spectra and AFD statistic from Rx1 is provided in Figure 11 and Figure 12. These results show that the model is able to provide estimates of the signal averaged directional spectra standard deviation, where the envelopes of the measured and simulated fit accordingly, as observed in Figure 11 a) and b), respectively. In addition, given the wind incidence from C, the model accurately estimates the resulting signal variation from trees 2, 3 and 4, although it tends to underestimate the occurring magnitude of signal variation (see Figure 11 b)). The AFD statistics, depicted in Figure 12, show that the model underestimates the duration of fades in the order of 1 to 2 seconds, but is able to predict the fade level magnitude with satisfactory agreement. Similar behaviour is observed in simulated results obtained from Rx3, with wind incidence from E, depicted in Figure 13 and Figure 14. The model estimates the signal variation originating from trees 3 and 4 with relative accuracy, in both envelope and magnitude. Although the duration of simulated fades underestimate the deep fades observed in measured data, a comparison between measured and simulated time series (Figure 13 b)) shows the model is able to predict, with relative accuracy, time series with significant variation through time (in the order of 15-20 dB).

A set of averaged ERMS are presented in Table 1, for all wind directions and receiver positions. Relatively low ERMS D-S and ERMS T-S errors are observed for all wind incidences and receiver positions. These results suggest the model performs with relative agreement when estimating both the envelope of the directional spectra as well as its time variation due to wind induced vegetation scatter.

5 CONCLUSIONS

A radio propagation model for dynamic channel vegetation scatter effects has been investigated as to its feasibility. In order to understand the foliage channel behaviour under wind induced effects, a study has been conducted on single trees and structured forest medium measurements. Results for single tree measurements showed that as wind is blown on to a single tree from a specific direction, two areas of vegetation motion need to be considered. One area of the tree, where the wind incises directly on the foliage (active area), and another area opposite to the first (quiet area). The foliage dynamics in the quiet area are observed to be reduced in comparison to the active area, as a result of wind speed decay through the vegetation media. Additionally, when the direction of wind illuminates the tree canopy in the same direction of the propagating radio wave, the received signal presents smaller signal fades and lower signal variation compared to wind illumination from the receiver (opposite) side. Furthermore, tree formation results indicate that change of wind incidence results in a change in measured dynamics in specific angular regions, depending on the wind direction. The wind point of source, forest geometry and position of radio receiver are all intrinsically interrelated and need to be considered collectively when considering the modelling methodology.

For this reason the investigated modelling approach must provide not only insight into radio propagation physical phenomena in forested scenarios but also enable geometrical consideration of the scenario variables. To this extent, modelling of the dynamic effects in vegetation is done through the use of the dRET theory because of its ability to resolve various directional intensities originating from different directions. The proposed dynamic model makes use of the dRET time-variant input parameters properties to predict time-varying scatter from wind induced vegetation movement. Model assessment results show that the model tends to underestimate the time-variation and duration of signal fades. In spite of this, the presented model is able to perform with relative agreement when estimating the directional spectra and time-variation envelopes, as well as the fade level magnitude.

Further work is expected to encompass the validation of the investigated model against measurement data collected in outdoor environment.

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APPENDIX

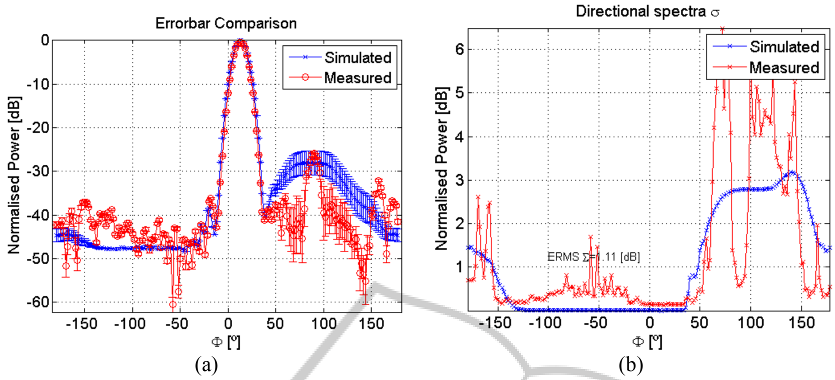

Figure 11: Comparison between measured and simulated data from position Rx1, with wind incidence C, considering: a) directional spectra errorbar and b) directional spectra standard deviation.

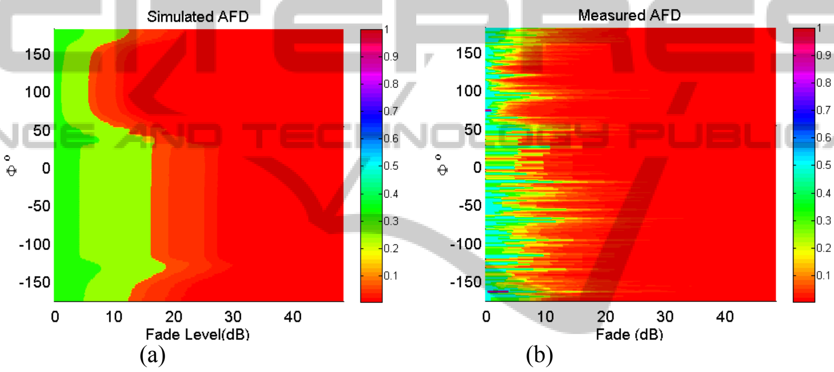

Figure 12: Comparison of data from position Rx1, with wind incidence C, between: a) simulated and b) measured data sets.

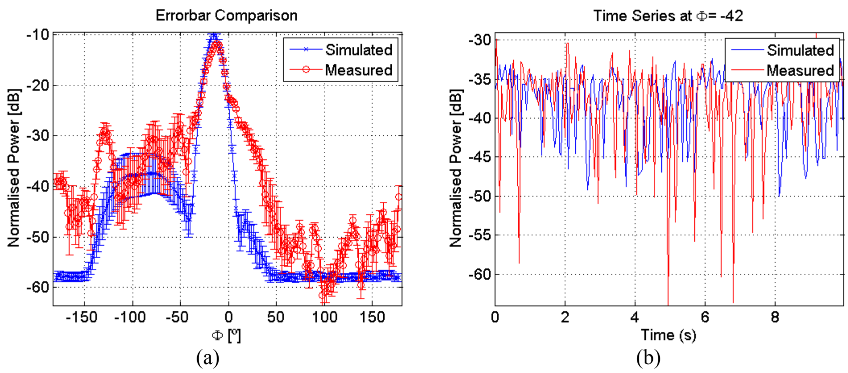

Figure 13: Comparison between measured and simulated data from position Rx2, with wind incidence E, considering: a) directional spectra errorbar and b) time series at Φ=.

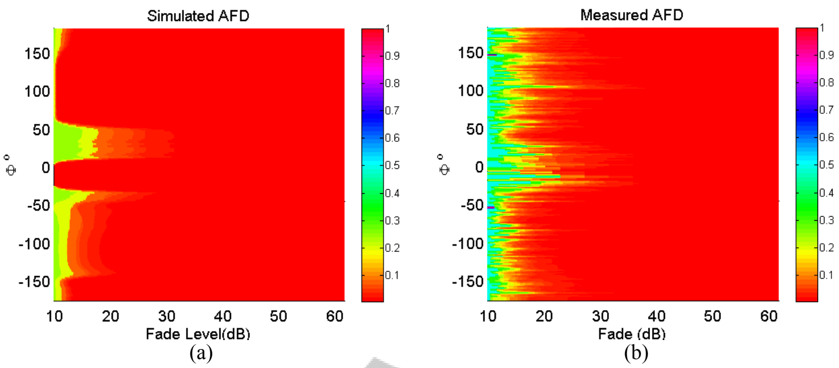

Figure 14: Comparison of data from position Rx2, with wind incidence E, between: a) simulated and b) measured data sets.