

# Modelling and Measurements of the Directional Spectra of Scatter Signals Inside a Formation of Tree Trunks

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**Abstract**—This article proposes a method to predict the scattered signal inside and around a tree trunk formation. The method presented here is based on an empirical model that characterises the re-radiation patterns of both dielectric and metallic cylinders for three spot frequencies, 9.4, 18.8 and 37.6 GHz and, resorting to dRET (discrete Radiative Energy Transfer) model to gather all the interaction between trunks within a formation, the received signal can be predicted. Presented empirical model was developed based on both dielectric and metallic re-radiation pattern measurements in an anechoic chamber and it is used as an input parameter of dRET model, characterising the trunk cells. This paper also contemplates measurements within a tree trunk formation in order to assess the values extracted from dRET model.

## I. INTRODUCTION

In recent decades, the expansion of mobile communications has surpassed all expectations and that growth promises to continue strong at least in a near future. It is expected therefore, a new world of opportunities not only in voice communications, but also in broadband applications and multimedia services.

The planning, design and implementation of such systems is based on the availability of propagation models. These models are needed to describe and characterise with some precision the interaction of radio waves with the air interface, and in particular, with a number of obstacles that may exist in the radio path. Indeed, coverage prediction tools are indispensable for designers of mobile networks to obtain a proper coverage planning, namely predicting tools to identify the modes of propagation present in a determinate channel and the estimation of mutual interference between existing and future connections. In the particular case of land mobile communication systems, groups of trees may influence the radio waves propagation, causing its attenuation and dispersion.

Because of that, in recent years many measurement campaigns and research effort have been developed to address

the vegetation issue. Such work was mainly focused in modelling effects caused by the foliage present in trees canopies. However, there are many forests with raised canopy trees, so modelling the tree trunks influence in radio wave propagation becomes important for a proper coverage planning.

The Radiative Energy Transfer (RET) [1] based models have successfully been used to simulate radio wave propagation and scattering in vegetation environments, as presented in [2] and [3]. However, the existing models, which can be used for ground-to-ground propagation, do not account the propagation mechanisms in the trunk layer of raised canopy trees. Thus, the objective of this paper is to continue the work done in [4] and [5], by modelling the trunk layer using dRET model [6].

## II. dRET MODEL APPLICATION

The discretization of the RET model presented in [6], consists in modelling the computational volume as an amount of non-overlapping cubic cells. Such discretization process allows defining geometries with different vegetation volumes and propagation characteristics. Each cell within the structure is characterised by a set of input parameters which include:

$k_a$ , which is the absorption coefficient;

$k_e$ , which is the extinction coefficient;

$k_s$ , which represents the scattering cross section.

and a scatter function which is an angular function describing the re-radiation function of each cell.

The extinction coefficient  $k_e$  is given by the sum of absorption coefficient and scattering cross section  $k_a = k_e + k_s$ .

There is many work done in order to effectively extract dRET parameters for foliage structures, namely in [2] and [3], however there is no developed method to extract the parameters for trunks, thus, and due to the difficulty of extracting these parameters, the values of  $k_a$  and  $k_s$  used in this work were adjusted using a simple trial and error method.

### III. EMPIRICAL MODEL DEVELOPMENT

In [4] and [5] it was studied the possibility of using a far field Radar Cross Section (RCS) model [7] to characterise dRET trunk cells. However, those models presented a low level of accuracy predicting the radiation patterns of tree trunks. It was concluded that this accuracy problem arises from the fact that the trees present in a tree trunk formation are in the near field of each other. Thus, in [4] and [5] that characterisation was performed by measuring the re-radiation pattern of both metallic and dielectric cylinders, and using the measured functions as dRET input parameters. In this paper an empirical model was developed based in those re-radiation measurements.

#### A. Cylinder re-radiation measurements

For the development of an empirical model some measurements were made. Measurements were intended to record the re-radiation pattern of a single tree trunk. These measurements were realized in a controlled environment in an anechoic chamber, in order to minimize interferences such as ground reflection. Fig. 1 depicts the geometry used during these measurements. The transmitter was directed to the cylinder under measurement at a distance of 1.85 meters, distance enough to ensure that the cylinder was illuminated by a plane wave. The receiver, at a constant distance of 0.7 meters, was rotated around the cylinder from  $\Delta\Phi = -135^\circ$  to  $\Delta\Phi = 135^\circ$ , with an angular resolution of one degree. This rotation was fully controlled by a software application, eliminating possible human errors while changing the receiver position.

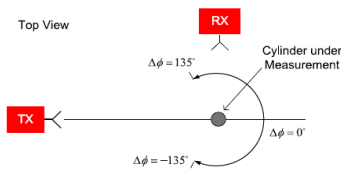


Fig. 1 – Cylinder re-radiation pattern measurement geometry (Top view)

Measurements illustrated in Fig. 1 were performed for both dielectric and metallic cylinders with 2m of height and 3cm of radius, at frequencies of 9.4, 18.8 and 37.6 GHz.

#### B. Model development

The developed empirical model is based on an existing function presented in [3], the phase function. Phase function is a Gaussian function superimposed to an isotropic background level, and has the format depicted in (1), where  $\alpha$  is the ratio of the forward lobe scattered power to the total power of the phase function,  $\beta$  represents the half power beamwidth of the forward lobe and  $\gamma$  is the azimuth angle between transmitter and receiver.

$$\rho(\gamma) = \alpha \times \left(\frac{2}{\beta}\right)^2 \times e^{\left(-\frac{\gamma}{\beta}\right)^2} + (1 - \alpha) \quad (1)$$

This function was widely used to model re-radiation patterns of trees in foliage layer. However, to the purpose of

this paper, this model was adapted in order to produce more accurate values while characterising tree trunks.

The function of measured cylinders re-radiation patterns is slightly similar to a phase function shape, however there are some differences namely in backscattering region in the case of dielectric cylinders and in the shadow region. To overcome these differences, phase function was adapted with a Root Mean Squared Error (RMSE) minimizations process.

The result of such process was the final version of the developed empirical model, presented in (2), where  $\Delta\Phi$  is the azimuth angle between transmitter and receiver and, similar to phase function,  $\alpha$  is a constant and  $\beta$  is function of the cylinder material and of radio wave frequency. Variable  $k_m$  is also a function of the cylinder material.

$$EM(\Delta\phi) = \left[ \alpha \times \left(\frac{2}{\beta}\right)^2 \times e^{\left(-\frac{2\Delta\phi}{\beta}\right)^2} + (1 - \alpha) \right] \times \sin(\Delta\phi \times 10^{-3}) \times e^{\left(\frac{\Delta\phi}{55k_m}\right)} \quad (2)$$

The functions of the empirical model input parameters are depicted in Table I.

TABLE I. EMPIRICAL MODEL INPUT PARAMETERS

Re-radiation case		$\alpha$	$\beta$	$k_m$
Frequency	Cylinder material			
9.4GHz	Dielectric	0.93	$109\lambda 0.4656$	0.55
	Metallic	0.93	$63.25\lambda 0.3592$	2.5
18.8GHz	Dielectric	0.93	$109\lambda 0.4656$	0.55
	Metallic	0.93	$63.25\lambda 0.3592$	2.5
37.6 GHz	Dielectric	0.93	$109\lambda 0.4656$	0.55
	Metallic	0.93	$63.25\lambda 0.3592$	2.5

#### C. Model analysis

Posterior to the development of intended model, a performance analysis was performed in order to assess the model accuracy. Thus, the extracted values from the empirical model were compared with the measurement results. Figs. 2, 3 and 4 depict both measured and model extracted results at 9.4, 18.8 and 37.6 GHz respectively, for both dielectric and metallic cylinders. The values of the RMS error obtained for both dielectric and metallic cylinders characterisation at 9.4, 18.8 and 37.6 GHz are shown in Table II, where it is possible to observe that the developed empirical model presents a relatively good performance while characterising the re-radiation pattern of both metallic and dielectric cylinders.

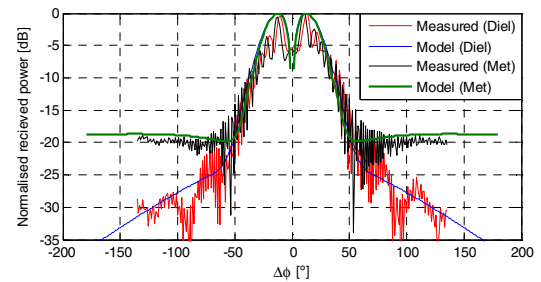


Fig. 2 – 9.4 GHz re-radiation measurement and model prediction

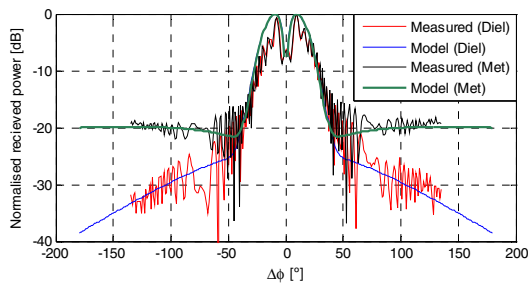


Fig. 3 – 18.8 GHz re-radiation measurement and model prediction

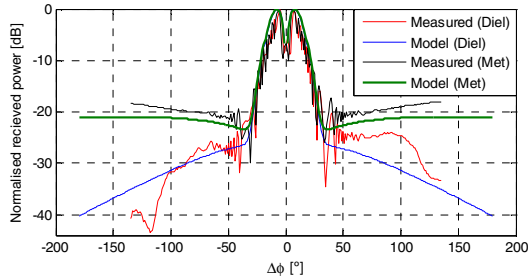


Fig. 4 – 37.6 GHz re-radiation measurement and model prediction

TABLE II. EMPIRICAL MODEL PERFORMANCE

Re-radiation case		RMSE (dB)
Frequency	Cylinder material	
9.4GHz	Dielectric	3.2242
	Metallic	2.7341
18.8GHz	Dielectric	3.5192
	Metallic	3.0239
37.6 GHz	Dielectric	4.0426
	Metallic	2.5355

#### IV. METHODOLOGY AND MEASUREMENT GEOMETRY

For the purpose of this paper, a regular geometry was considered so that simulations could be validated with appropriate measurements in the anechoic chamber, however, the existing dRET framework would allow for the simulation of any geometry, including randomly distributed trunks.

Trunk formation mimicked in dRET configuration was defined in a matrix of 13x13 square cells with 0.3m<sup>2</sup>, as depicted in Fig. 5, where trunk cells, represented with the blue coloured cells, were disposed in a 3x3 matrix spaced out 1.2m. Each one of the trunk cells was characterised with the developed empirical model, defining their scatter function.

Simulations were performed at three spot frequencies corresponding to the frequencies used during measurements, 9.4, 18.8 and 37.6 GHz, for both dielectric and metallic cylinders.

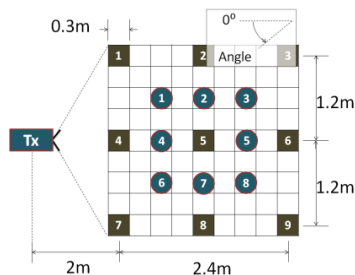


Fig. 5 - dRET simulation configuration

Several measurements were performed with the intention to assess the results extracted from dRET simulations. Realised measurements were repeated for frequencies at 9.4, 18.8 and 37.6 GHz for both dielectric and metallic cylinder formation. The geometry adopted during these measurements is very similar to dRET geometry configuration, where cylinders under measurement, represented by grey coloured circles, are disposed in a 3x3 matrix and spaced out 1.2m, as illustrated in Fig. 6.

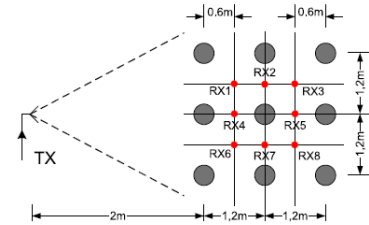


Fig. 6 – Tree trunk formation measurements geometry

This matrix was illuminated using a broad beamwidth antenna, placed at 2m from the structure, which ensures that the formation is uniformly illuminated.

The receiver antenna was placed at each one of the 8 measurement locations shown in Fig. 6 represented by the red points. At each of these locations, the receiver antenna was rotated around its vertical axis, in a  $\pm 180^\circ$  range, with an angular resolution of  $1^\circ$ . Thus, in each one of the measurement points, the incoming signal was measured in all directions.

#### V. MEASUREMENT SYSTEMS

The 9.4GHz transmitter comprised of a signal generator (SG) which created a 9.4GHz continuous-wave (CW) tone with 13dBm of output power, connected to a 20dBi standard horn antenna via coaxial cable.

To receive the 9.4GHz signal, it was used a 20dBi standard horn antenna connected to a frequency mixer. This mixer was also connected to a 6GHz phase-locked loop (PLL) oscillator in order to down-convert the radio frequency (RF) received signal to an intermediate frequency (IF) signal.

Regarding the 18.8GHz system, it was used an 18.8GHz PLL oscillator connected to a 10dBi standard horn antenna to transmit the signal. Similar to the 9.4GHz receiver, the 18.8GHz receiver was also composed by a 20dBi standard horn antenna connected to a frequency mixer. Also connected to the mixer, was a PLL tuned to 18.2GHz. Once again, the mixer was used to down-convert the received RF signal to an intermediate frequency (IF) of 600MHz.

The 37.6GHz measurement system was very similar to the 18.8GHz one, where the only difference is the addition of a frequency multiplier (2x). Thus, in the transmitter, it was used an 18.8GHz PLL connected to a frequency duplicator, which generated a 37.6GHz signal. This signal was radiated by a 20dBi standard horn antenna.

The receiver follows the same principle as the previously described receivers. It was composed by a PLL tuned to

18.5GHz, a frequency multiplier, a mixer and a 20dB horn antenna. The frequency of the receiver PLL's output signal, 18.5GHz, was duplicated by the frequency multiplier generating a 37GHz signal which was sent to the LO input of the mixer. The RF signal received by the antenna was carried to the RF port of the mixer. This way, the IF port of the mixer presented the received signal down-converted to a 600MHz signal.

To record the IF received power it was used a spectrum analyser (SA).

## VI. MEASUREMENTS AND SIMULATIONS RESULTS

Simulation results were obtained for the geometry depicted in Fig. 5 for both dielectric and metallic cylinders at 9.4, 18.8 and 37.6 GHz. Such results were then subjected to a comparison with the measurement results in order to analyse the proposed model performance. In Fig. 7 it is possible to observe both measured and predicted signal obtained in position 8 at 9.4GHz using dielectric cylinders, in Fig. 8, received signals at position 3 at 18.8 GHz with metallic cylinders and in Fig. 9 the results at position 1 at 37.6 GHz using metallic cylinders. In those figures it is possible to observe a relatively good agreement between measured and predicted results. In order to further analyse the performance of the proposed model, the RMS error obtained in all measurement cases was calculated. The results of these calculations are shown in Table III.

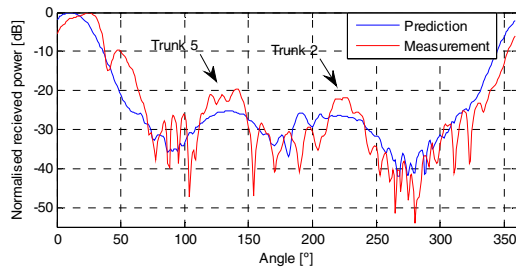


Fig. 7 – Received signal at position 8 at 9.4 GHz with dielectric cylinders.

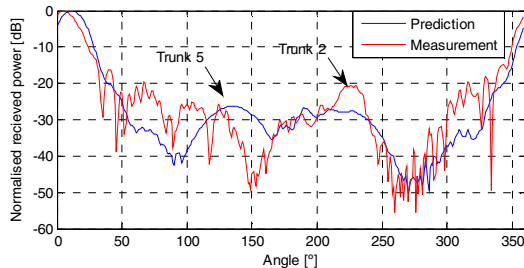


Fig. 8 – Received signal at position 3 at 18.8 GHz with metallic cylinders.

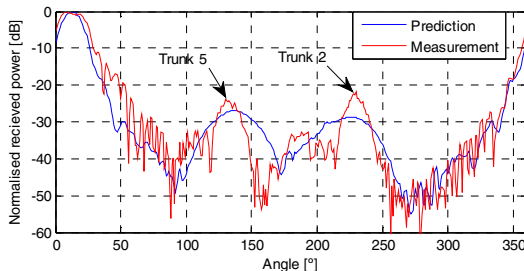


Fig. 9 – Received signal at position 1 at 37.6 GHz with metallic cylinders.

TABLE III. RMS ERROR OBTAINED AT 9.4, 18.8 AND 37.6 GHz

Position #	RMS error (dB)					
	9.4 GHz		18.8 GHz		37.6 GHz	
	Diel.	Met.	Diel.	Met.	Diel.	Met.
1	6,7503	5,5730	4,9018	7,3809	3,9044	6,1785
2	5,2454	5,2189	5,4706	6,2871	7,3498	8,2148
3	5,7176	5,9166	6,7307	6,6464	7,9285	10,3634
4	6,5766	7,0506	11,8515	16,0954	9,5441	9,9482
5	9,8788	11,5166	9,2773	12,3977	8,9196	7,9146
6	5,6235	5,9219	4,9367	6,9852	4,6826	6,3389
7	5,8875	5,0630	5,9624	5,7579	8,4100	9,0852
8	4,9183	4,4283	6,4776	6,0640	9,1544	9,9702
Average	<b>6,3248</b>	<b>6,3361</b>	<b>6,9511</b>	<b>8,4518</b>	<b>7,4867</b>	<b>8,5017</b>

## VII. CONCLUSIONS

The proposed extension of the dRET model to the trunk layer proved to be an additional step in terms of modelling radio propagation through a forest environment. The empirical model developed, based on re-radiation measurements, shows a relatively good performance characterising cylinders re-radiation patterns. In a tree trunk formation environment, a relatively good agreement between measured and predicted signals was achieved, at all studied frequencies, for both dielectric and metallic cylinders formation. Regarding this fact, it was also shown that dRET model is a practical alternative to the implementation of more complex models, such as the use of a Geometric Theory of Diffraction/Uniform Theory of Diffraction (GTD/UTD) based models, to estimate the scattering phenomena emanating from the tree trunks.

Further work will be required in an effort to improve the developed empirical model, in order to characterise cylinders of different dimensions and take into account different distances between trunks belonging to a trunk formation under measurement. It is also scheduled an extension of the 3D dRET model to a 2-layer stratified model, so therefore allowing the prediction of the interactions between trunk and canopy layer.

## VIII. REFERENCES

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