

# Wideband Characterisation of the Dispersive Effects on Isolated Mature Trees for 2-GHz Band Urban Microcells

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## ABSTRACT

An important part of the modelling process applied to vegetation effects is aimed at analysing the radio propagation modes and the identification of individual signal contributions to the scattered signal caused by various elements of the tree. The paper describes detailed studies aimed at the wideband characterisation of propagation mechanisms arising in single trees. It explores effects of geometrical and physical properties of the tree on radiowave propagation modes arising specifically, i.e. absorption, scatter and depolarisation. Wideband channel measurements performed at 2 GHz provided valuable information on the dispersive effects of single trees, whose subsequent analyses revealed the sources of scattering, effects of tree elements, e.g. leaves and branches, and wind effects.

## INTRODUCTION

Propagation effects on terrestrial communications systems in the microwave and millimetre wave frequency bands have been the subject of considerable study in the last few years. The modelling of absorption and scatter due to the presence of vegetation represents a significant problem in macro- and micro-cellular geometries, in which errors yielded by prediction models amount to several dB [1]. This paper addresses the need to characterise their influence on the various propagation modes based on a deeper understanding of the causes giving rise to them. Studies around the 2 GHz were performed on a mature deciduous tree in order to characterise the complex propagation modes emanating from a single tree for 2-GHz Band Urban Microcells. Various measurement campaigns were conducted in Autumn/Winter and Spring/Summer on the same tree. A measurement system has been developed for short-range outdoor radio channels incorporating a vector network analyser (VNA), configured for swept frequency measurements [2]. Results of an investigation based on the measured complex impulse response (CIR) at various positions around the tree for both co-polar and cross-polar received signal components, are presented. A discrete mathematical model is used to compute rms delay spread of the power delay profiles (PDP) for both foliated and de-foliated states of the tree. Seasonal variations and the effects of leaf movement on the channel characteristics caused by wind, are also discussed.

## BISTATIC SCATTERING MODEL

### Wideband Model Development

The complex impulse response (CIR) is a wideband channel characterisation, which offers a complete description of the time-variant propagation radio channel characteristics [3]. In such a multipath environment, the radio signals are received via a scattering mechanism caused by the individual components in the canopy, resulting in multiple propagation paths with different time delays, attenuation and phases of the transmitted signal. The CIR of a multipath channel can be modelled mathematically in the time domain as in (1) [4], where  $N(t)$  is the total possible number of

$$h(t, \tau) = \sum_{i=0}^{N(t)-1} a_i(t, \tau) \exp(j\Phi(t, \tau)) \delta(t - \tau_i(t)) \quad (1)$$

multipath components received,  $a_i(t, \tau)$  and  $\tau_i(t)$  are, respectively, the real amplitudes and excess delays of the  $i^{\text{th}}$  multipath component at time  $t$ . The  $\Phi(t, \tau)$  is the phase term of a single multipath component, and  $\delta(t - \tau_i(t))$  is the unit impulse function which determines the specific multipath component at time  $t$  and excess delay  $\tau_i$ . The behaviour of the channel can be described in terms of rms delay spread of the power delay profile (PDP), providing an insight into the physical mechanisms in single trees.

## Measurement Description

Measurements were performed on an isolated deciduous mature tree found in Tredegar Country Park, at Newport - UK. The tree had an average height of 9 m and a trunk width of 0.4 m with foliage spread of 6 m covering the top 8 m of the tree height. Its leaves had an average of 10 cm length and 5 cm width. The geometry set-up is shown in Fig.1. The transmitter was kept stationary on top of a 4.5 m mast, and at a distance  $r_1 = 8$  m from the centre of the tree. The mobile receiver station was made to rotate around the tree in the angular range of  $-135^\circ \leq \phi < +135^\circ$  in discrete increments of  $5^\circ$ . The rotation path was circular of radius  $r_2 = 6.64$  m, during which the receiver was kept stationary while acquiring the measurement data. The main component in the system is a HP8714C economy VNA, which performs the frequency domain transfer function ( $S_{21}$  parameters), by sampling the channel at uniformly spaced frequencies between 1720 and 2000 MHz. A bandwidth of 280 MHz, with a step size of 350 KHz, was used in the experiments, that resulted in a time domain (Fourier) resolution of around 3.57 ns when using a rectangular window, and a time profile that is 1.428  $\mu$ s in length. This time resolution is equivalent to a spatial resolution of 1.07 m, i.e. a minimum detectable path difference between two multipath components. To mitigate the effects of Doppler shift, 10 consecutive sweep measurements (profile) were obtained for each position of the receiver. These were averaged out. Thus, space and time averaged power delay profiles could be measured [5]. Wind speed was assumed to be below 0.4 ms<sup>-1</sup> for most of the entire measurement periods.

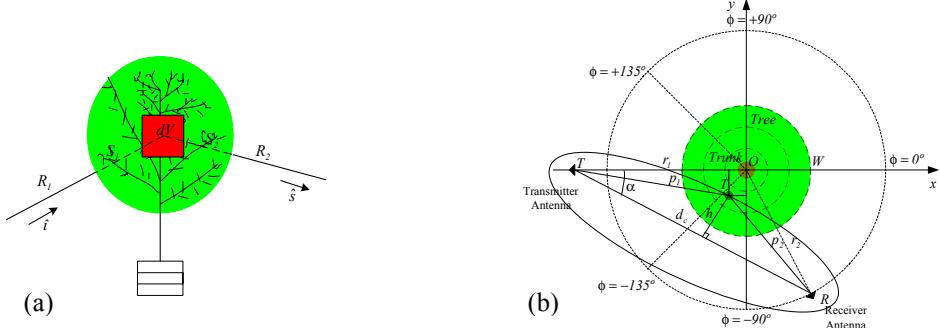


Fig. 1. Bistatic scattering model geometry showing the direction of the incident field and scatter from the tree canopy and (b) the path of geometry for a single scattering of the canopy.

## ANALYSIS AND DISCUSSION OF RESULTS

### Wind effects

Each measurement was repeated several times to check repeatability and hence to characterise the effects of the foliage movement due to the wind in the received signal level. All measurements were performed on a calm day, assuming wind speeds below 0.4 ms<sup>-1</sup>. Fig.2 show the standard deviation ( $\sigma$ ) of the received signal level of the complex transfer function (CTF) around its mean, for each position of the receiver. Results are presented for both co-polar and cross-polar components in both foliation states of the tree canopy.

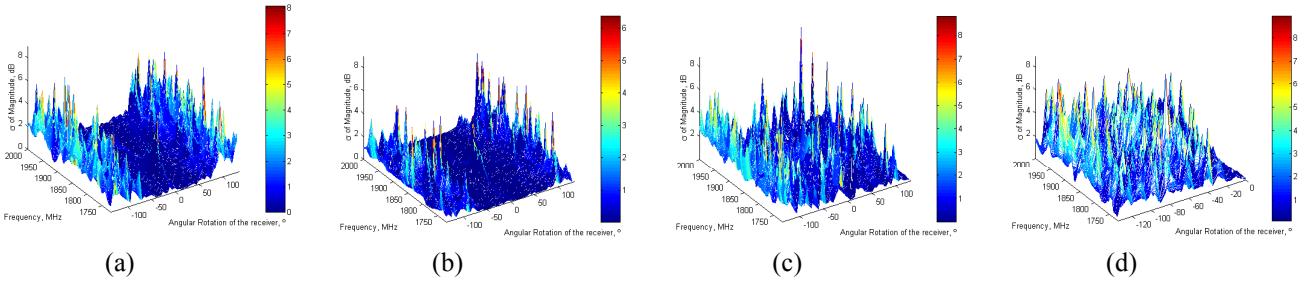


Fig. 2. Effect of the wind on the received scatter received signal for tree (a) in-full-leaf (co-polar), (b) out-of-leaf (co-polar), (c) in-full-leaf (cross-polar) and (d) out-of-leaf (cross-polar), as a function of receiver rotation angle  $\phi$ .

The variation observed is attributed to wind induced movement of the large number of branches of various lengths and leaves with different orientations, which vibrate at different natural frequencies. Of special note is the forward region of the co-polar scatter signal, which is characterised by a relatively small value of the standard deviation below 1 dB. This

is in good agreement with results obtained in [84], which suggested a maximum variation of the signal level of 1.12 dB at 2 GHz, for wind speeds up to 20 knots. In regions away from the boresight of the antennas, the standard deviation was observed to increase progressively as the receiver was made to rotate around the tree. Higher variation was observed however, for the tree in full leaf (Fig.2a), with peak variations of 8 dB when compared to 6 dB for the case of the tree out-of-leaf (see Fig.2b). Leaves are expected to vibrate at higher natural frequencies than the branches, due to their smaller physical size. This may explain the effects of leaf movement on the received co-polar signal level, especially in the regions between  $-100^\circ \leq \phi \leq -50^\circ$  and  $50^\circ \leq \phi \leq 100^\circ$ , where the dominant mode is the diffused scatter signal re-radiated from the tree.

Interestingly, the cross-polar component yielded a completely different behaviour from the co-polar component. The effects of depolarisation were more visible when the leaves were out (see Fig.2d), as expected due to currents induced in the branches which re-radiate the signal in random directions. These signals experienced further attenuation in the case when the tree was in-full-leaf, due to absorption by the leaves, which results in reduced variability of the received signal, as observed in Fig.2c. In general, the amplitude spread of the measured frequency points of the 10 consecutive CTFs, obtained at each location of the receiver, can largely be attributed to the movement of canopy elements caused by wind.

### Time Domain Analysis of the Averaged PDP

Delay spread analyses were performed on the average power delay profiles presented in Fig.3, in order to give an estimation of the time dispersive properties of the vegetation channel [3]. The rms delay spread was computed at all 54 measurement locations of the receiver, for both polarisation and foliation states of the tree. Three predefined thresholds were used in the computation to differentiate between genuine multipath components and thermal noise. These were -28 dBf, -25 dBf and 22 dBf, giving in the worst case scenario a 7 dB threshold above the noise level. This was well above the 3 dB minimum threshold margin recommended in [6].

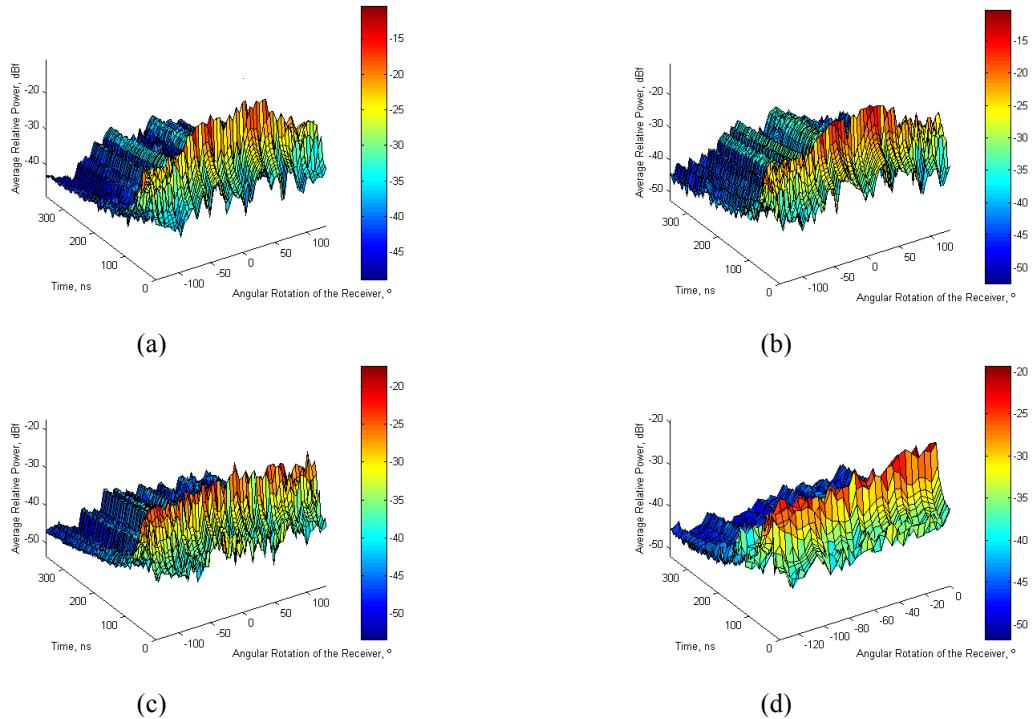


Fig. 3. 3-Dimensional plot of the average power delay profile of the received scatter signal for tree (a) in-leaf (co-polar), (b) out-of-leaf (co-polar), (c) in-leaf (cross-polar) and (d) out-of-leaf (cross-polar), as a function of receiver rotation angle  $\phi$ .

Three distinct regions were identified here from the analysis of the processed results. Statistical analyses of the processed results were applied to each region of interest. These were obtained in terms of cumulative distribution function (CDF) for each threshold applied over the rotation angle of the receiver, as given in Table 1.

Table 1. CDF for 90% of the RMS delay spread of the co- and cross polar received signals in the regions around the tree for both in-leaf and out-of-leaf states of the tree foliage.

Polarisation	Leaf State	Back and Side Region ( $\phi < -60^\circ$ and $\phi > +60^\circ$ )			Transitional Region ( $+20^\circ < \phi \leq +60^\circ$ & $-60^\circ \leq \phi < -20^\circ$ )			Forward Region ( $-20^\circ \leq \phi \leq +20^\circ$ )		
		-28-dBf	-25-dBf	-22-dBf	-28-dBf	-25-dBf	-22-dBf	-28-dBf	-25-dBf	-22-dBf
Co-polar	In	9.98	7.20	5.76	17.32	10.18	6.45	7.22	3.49	2.59
	Out	10.53	8.67	6.49	19.01	11.52	6.31	12.04	7.21	4.05
Cross-polar	In	6.53	n/a	n/a	7.40	n/a	n/a	5.44	n/a	n/a
	Out	7.97	n/a	n/a	6.99	n/a	n/a	5.85	n/a	n/a

In the region characterised by the strong *forward scatter signal*, as predicted by the RET theory, the computed delay spread values were observed to be relatively small. This was due to the limited spatial resolution of the measurement system and hence, signal components with differential delays less than the time resolution could not be resolved and were detected as single components. Most of the signal components experienced absorption and attenuation caused by the tree, and therefore, non-line of sight propagation was assumed, except in the case where large gaps existed in the canopy. The dispersive effects of the single tree in this region were observed to be more severe when the leaves were out. The delay spread parameters were in most cases twice as high as in the foliated state (see Table 1). Such behaviour of the delay spread parameters suggests that leaves play an important role in the propagation modes, exercising a strong influence on the received signal level and subsequently, on wideband channel performance.

In the *transitional scatter region*, the received signal is gradually changing from one dominated by the coherent component to that mostly scattered from the tree, defined in [1] and [2] by the diffused scatter component. High spatial fluctuations in the delay-spread parameter were observed in this region, indicating a relatively large number of scatter components arriving at the receiver. This was due to the possible direct coupling of the antennas, exhibiting a higher line-of-sight signal contribution, in addition to the scatter contributions from the tree. Although a considerably large number of multipath components were observed here, their influence on the channel performance was indicated by the computed rms delay spread to be not as significant, as initially thought. This is confirmed by computed values ranging between 6.45 - 17.32 ns (depending on the threshold applied) in the case of the foliated state (see Table 1).

At last, the *back and side scatter region* is mostly dominated by the signal re-radiated from the tree (incoherent component), in addition to any possible contribution from coupling between antennas via a side lobe, which in turn is relatively much reduced by the antennas directivity. The same is also applicable to contributions from ground reflection, investigated further in [2]. Spatial fluctuations of the delay spread were also observed in this region, especially when the receiver was moved further towards the back scatter areas of re-radiated signal, defined by  $\phi < -90^\circ$  and  $\phi > +90^\circ$ , indicating the strong backscatter from the tree. The scattering process was however enhanced in the out-of-leaf case, with delay spread parameters assuming relatively higher values, compared to the in-leaf situation.

The effects of depolarisation were observed to be more severe for the out-of-leaf case, except in the transitional region, whose statistics yielded smaller delay spreads. Furthermore, the rms delay spread statistical results have shown it to be independent of the measurement location, yielding a variation between 5 ns and 8 ns.

### Direction of Arrival of Multipath Components

A physical based model for propagation modes arising from a tree illuminated by an incident radiowave was developed based on measurements of the channel characteristics. This was carried out at the level of the individual multipath components, in particular, by separating the multipath waves using their different propagation delay times and directions of arrival. Scatterers comprising leaves, branches and trunk, are assumed to lie in the plane which includes the transmit and receive antennas. Only the azimuthal plane (XOY-plane) was used in the computation of direction of arrival of the various multipath contributions. If single scattered paths are considered in the canopy, then all scatterers associated with a certain path length can be located on an ellipse with the transmitter and receiver placed at its foci [2], as shown in Figure 1b. The individual scatterers or region of scatterers in the tree canopy were then located on the ellipse drawn for each path delay, at each measurement location of the receiver, in the form of a scaled map overlay on the measurement geometry. Resulting interceptions provided information about the significant single scatterer or scatter areas of the tree canopy, as shown in Fig.4. A ray-tracing tool has been developed to assist in the identification of the direction-of-arrival (DOA) of individual contributions from different regions of the tree canopy, as a function of

receiver angular position around the tree. The analysis tool considered ground reflections, direct coupling between transmitting and receiving antennas, and the physical dimensions of the mature deciduous tree under investigation [2].

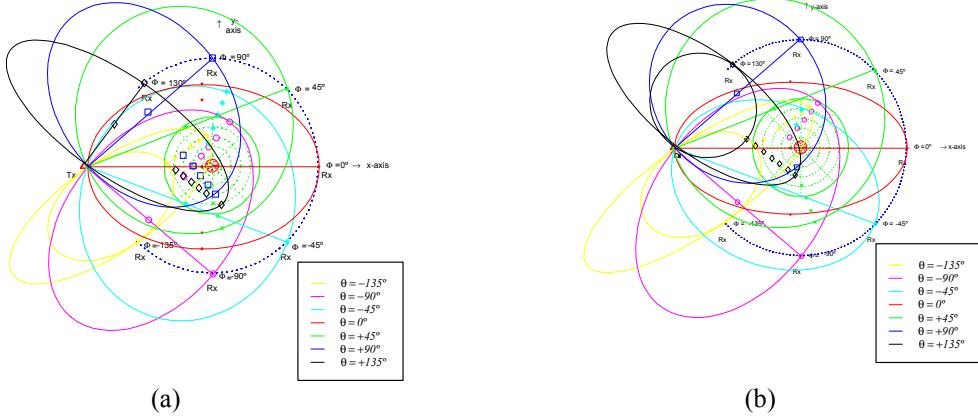


Fig. 4. Scaled diagram showing the each possible confocal ellipse around the tree based on the measured co-polar multipath delays when the tree is (a) in-full-leaf and (b) out-of-leaf.

Visual observation of the map overlay shows that at certain positions of the receiver, the ellipses do not intersect the tree canopy, suggesting an internal multiple scattering modes occurring within the canopy. This gives rise to multipath components arriving with rather longer path delays, which accord with the long tails observed in the CIRs. The multiple internal scattering was however mostly observed in the forward scattering regions, where strong coherent components predominate. In the regions away from the boresight of the antennas, the scatter from the tree is the dominant mode. At shorter path delays, the scattering regions may be clearly identified to be the outer boundary of the tree canopy, which consists of a mixture of leaves and branches. As the multipath delays increase, these regions will be located more into the canopy, until the trunk region is reached. It is believed that after the trunk region, the multipath components will experience severe attenuation due to the trunk, in addition to the attenuation caused by leaves and branches, and hence no contributions from these were expected to reach the receiver. The large path delays observed, which extends beyond the trunk region, were assumed to be caused by significant multiple scattering and subsequently dispersion caused by the leaves.

## CONCLUSIONS

The complex characterisation of the dispersive effects from single trees addressed in this paper represents an important contribution to the literature, especially for wideband channel performance. A physical based model for propagation modes emanating from a single tree was developed based on the complex impulse response measured at various positions around the tree, for both co-polar and cross-polar received signal components. These have demonstrated the sources of scattering in a single tree, and subsequent effects exercised by tree components such as leaves, twigs and branches, in addition to wind effects. An important further extension is the use of this near-field model to analyse the effects of single trees at frequencies covering both *BFWA* and *MBS* system applications.

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