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24 GHz cmWave Radio Propagation Through Vegetation: Suburban Tree Clutter Attenuation

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***Abstract*—This paper presents a measurement-based analysis of cm-wave radio propagation through vegetation at 24 GHz. A set of dedicated directional measurements were performed with horn antennas located close to street level inside a densely-vegetated area illuminated from above. The full azimuth was examined for the elevation range from +10 to +30 degrees at each of the measurement positions in order to explore the directional characteristics of the channel. The detailed analysis of the spatial multipath components scattered from the trees suggests, in average, the presence of 5 strong tree-scattered components per location with an azimuthal deviation of approximately 20 degrees between the strongest and the direct transmitter-receiver components. A diversity gain of approximately 7 dB is estimated, plus 2 dB extra in the case of considering multi-beam combining techniques. Tree clutter attenuation was found to be in the range 2.6-3.8 dB/m for the first meters inside the vegetated area. This attenuation can be predicted by the current ITU-R models, although some modifications are suggested. Single-tree attenuation was estimated to be approximately 20 dB. The different models and observations presented along the paper are useful for simulation and radio network planning of future wireless systems operating at 24 GHz in presence of vegetation.**

***Keywords*—cmWave, 24 GHz, Radio Propagation, Suburban, Spatial Multipath, Vegetation, Tree Clutter, Attenuation.**

I. Introduction

Vegetation is an inherit component of most outdoor environments, and its effect on radio propagation has been investigated for decades. Usually, foliage attenuation is modeled as excess loss in addition to the free space path loss, divided by the total length of the path traveled by the radio signal inside the vegetated area. The relationship is found to be non-linear, since vegetation loss grows rapidly in the first few meters inside the tree clutter due to the high attenuation of the main direct path. Beyond, a lower loss rate is experienced due to the multiple contributions from different scatterers [1]. Carrier frequency is a key aspect that needs to be considered by the different foliage attenuation models. In comparison to the traditional frequencies (below 6 GHz) used in cellular systems nowadays, foliage-induced attenuation increases at cm-wave (3-30 GHz) and mm-wave (30-300 GHz) frequencies. The reason is that at smaller wavelengths fixed-size obstacles, such as a tree trunk or a leaf, cause higher blockage of the Fresnel clearance zone [2].

Several non-linear attenuation models with different frequency application ranges have been reported in the literature. The ITU-R Recommendation P-833-8 [3] proposes two models for the range from 30 MHz to 60 GHz: an exponential slant path model with elevation angle correction, and a terrestrial non-zero gradient model. Other widely used attenuation models are the exponential models proposed in [4], [5], and [6], which are said to present frequency application ranges up to 57.6, 95 and 40 GHz, respectively. However, the coefficients of these models have been mainly computed from limited sets of data obtained at frequencies close to 2 GHz. Therefore, there is still a need for verification measurements which prove correct their applicability for the higher frequencies. The lack of experimental studies specifically targeting foliage attenuation in the cm-wave frequency band serves as the first motivation for this paper.

The second motivation for this work is the limited knowledge about the interactions in the radio channel at higher frequencies in the presence of vegetation. As pointed out in [7], some of the specific measurement campaigns performed in the past explored only the obstructed link between two directional antennas aligned in boresight. This procedure provides a good estimate for the low frequency bands, where diffraction around the trunk or canopy of the trees is the main propagation mechanism. However, in higher frequency bands, where larger azimuth spreads are experienced due to the dominant contributions of the reflection and scattering mechanisms, the previous approach is not appropriate. In this case, directional analyses are better suited in order to fully capture the rich spatial multipath characteristics of the vegetation scenario at higher frequencies [7].

This multipath-rich behavior due to the trees was already observed in our previous work reported in [8], where a comparison of radio propagation in urban and suburban scenarios was presented. Based on a directional analysis of the outdoor radio channel, it was found that, in non-line-of-sight conditions, the number of spatial multipath components in the suburban scenario with strong presence of vegetation was 1.23 times higher compared to the non-vegetated urban scenario.

In order to fill in the gaps observed in the literature and complement the previous work, this paper addresses the propagation through vegetation at 24 GHz by means of a set of dedicated directional measurements. A detailed analysis of the spatial multipath components coming from the foliage is presented. This approach also permits the evaluation of the potential spatial diversity and beam combining gains that would be achievable in similar scenarios. Furthermore, based on the dedicated measurements, tree clutter attenuation is estimated and compared to that from the models reported in the literature in order to provide some insight on their behavior for the higher frequency bands.

The rest of the paper is organized as follows: Section II introduces the different aspects related to the measurement campaign. Section III presents the measurement results and the directional multipath analysis. Section IV presents the tree clutter attenuation computation and a comparison with different models and, finally, Section V concludes the paper.

II. Measurement Campaign

A. Measurement Setup

In order to perform the measurements, a 24 GHz continuous-wave (CW) setup with directional antennas at both the transmitter (TX) and receiver (RX) sides was used. As it can be seen in Fig. 1, the TX antenna was deployed on the flat rooftop of a 4-storey building at approximately 15 m above ground level with the aim of illuminating the vegetated area of interest. At the RX side, the antenna was mounted on a rotating pedestal close to street level, at 1.75 m height. Both the TX and RX antennas were pyramidal horns with 22 dBi gain and 25 degree half-power beamwidth (HPBW). By using this setup the maximum measurable path loss was estimated to be approximately 170 dB. Only vertical polarization was considered. Further details on the measurement equipment and overall setup can be found in [8].

B. Measurement Scenario

The measurement campaign was performed at the Fundação Centro de Análise, Pesquisa e Inovação Tecnológica (FUCAPI) campus in Manaus, Amazonas, Brazil. The scenario is a suburban area conformed by open spaces, scattered buildings and strong presence of vegetation. The area selected for the measurements is a densely-vegetated area with different types of trees: Seringueira, Abieiro, Mangueira and Palheteira.

Fig. 1. Directional measurement setup with TX antenna deployed above rooftop illuminating the densely-vegetated area of interest, and RX antenna mounted on a rotating pedestal close to street level.

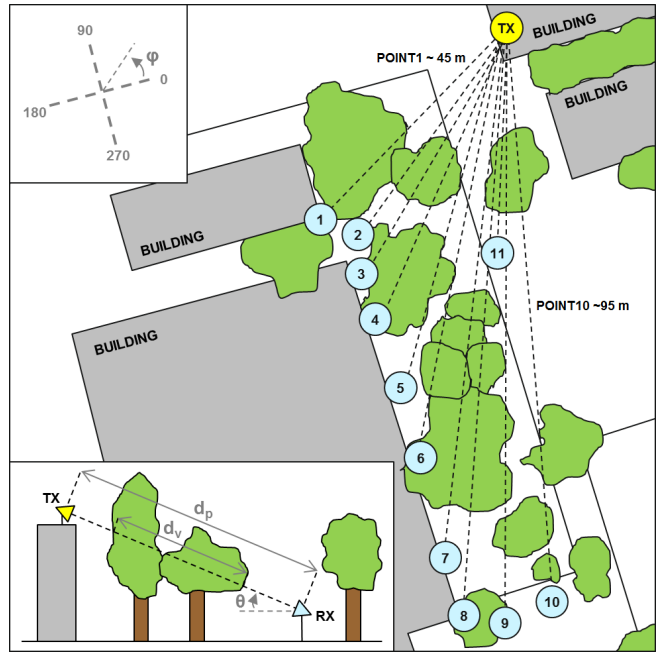

Fig. 2. Overview of the vegetated scenario, measurement positions and geometry considered.

Seringueira (rubber tree) is almost exclusive from the Amazon region, while Abiero and Mangueria trees can be found in different regions of the world. Palheteira trees are very common in Brazil and can be found in forestry roads, squares, gardens and car parks. The average tree height in this area is approximately 9 m. The diameters of the tree canopies are quite different and range approximately from 3 to 13 m. The estimated average leaf size is 15 cm. The measurements were performed at the end of the rainy season (mid-April) in dry conditions, when all the trees were in-leaf.

With the aim of exploring the propagation through vegetation, a total of 11 foliage-obstructed TX-RX radio links were studied. The different measurement positions were selected with TX-RX distances (d_p) ranging between 45 and 95 m, as illustrated in Fig. 2. The vegetation depth (d_v), defined as the length of the direct TX-RX paths running through vegetation as detailed in Fig. 2, ranged up to approximately 10 m. This set of measurements allowed to perform a detailed analysis of the first few meters inside the tree clutter, which are proven to be the largest contributors to the foliage-induced attenuation [1]. Moreover, typical vegetated areas inside cities can easily present vegetation depth ranges in the same order to the ones presented in this paper, so the different observations provided in the following sections could be applied to those scenarios as well.

C. Measurement Procedures

At each of the selected measurement points, the entire azimuth (0-360 degrees) was swept for the elevation range from +10 to +30 degrees. The selected angular steps were 9 and 10 degrees in azimuth (ϕ) and elevation (θ), respectively, resulting in a total of 120 (40x3) directional power samples recorded per position. With this resolution, smaller than half

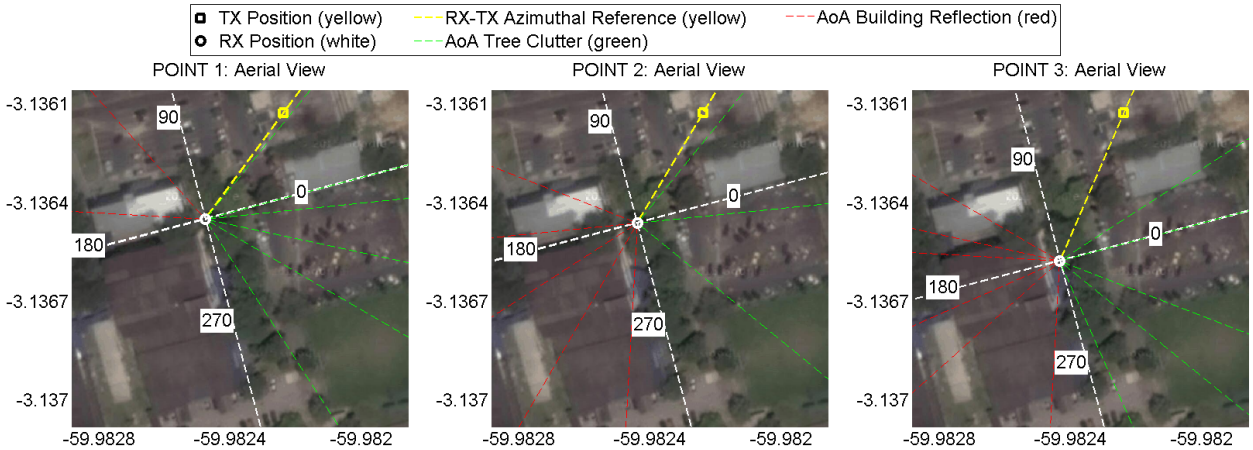

Fig. 3. Azimuthal references and AoA for the different detected tree-scattered and wall-reflected multipath components at measurement positions 1-3.

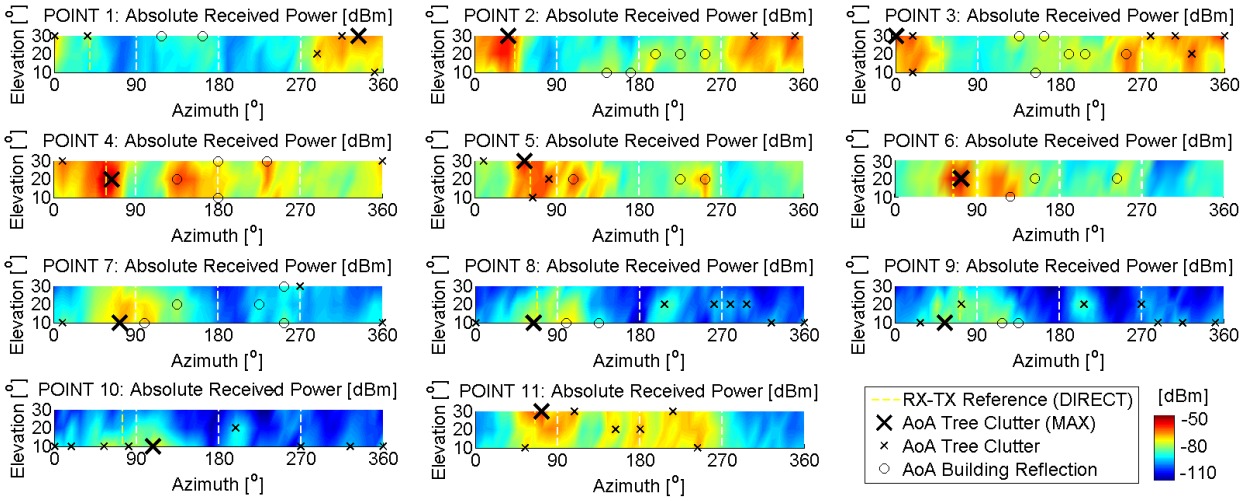

Fig. 4. Measurement results for all the considered positions: AoA and directional absolute received power values.

of the HPBW in both dimensions, a correct sampling and peak power detection is ensured. Following the procedures described in [8], peak/lobe detection was performed over the different sets of directional power data. Lobes are identified by applying a threshold of 20 dB from the strongest received component, considering a minimum signal-to-noise ratio (SNR) of 10 dB.

III. Measurement Results and Directional Multipath Analysis

The aerial views in Fig. 3 present the angle-of-arrival (AoA) of the power peaks/lobes detected at the three first measurement positions. The yellow dotted lines depict the azimuthal reference direction between TX and RX. The green dotted lines represent the different AoA of strong received (scattered) power components that are originated in the tree clutter. The red dotted lines represent power components originated (reflected) on the walls of the adjacent buildings. These plots serve as a clear example of the rich spatial multipath characteristics of the scenario caused by the presence of foliage.

Fig. 4 illustrates the directional power measured at each of the 11 measurement positions. The azimuth reference angles (white dotted lines) can be directly related to ones given in Fig. 2, i.e. the 90-270 degrees direction is always parallel to the large building on the left. The tree-scattered components (x) are presented together with the building wall-reflected components (o), which have been excluded from the following analysis. From the heat-maps it is relevant to observe that, in many cases, the levels of the tree-scattered power components are, if not higher, at least comparable to the power levels of the wall-reflected components. Another important observation, is that the AoA of the strongest received component (X) does typically not match with the TX-RX direction (yellow dotted line). This provides further validation to the observations reported in [7], which already suggested directional analyses to correctly characterize the channel, instead of using limited explorations of the obstructed TX-RX link with antennas aligned and fixed in boresight direction.

Table I contains the different scenario parameters and measurement values for each of the 11 points. Together with d_p and d_v, the number of trees (# tr) is given. This estimation of the natural number of tree canopies obstructing the line-of-sight (LOS) between TX and RX gives further indication on the vegetation obstacle density (1-3 trees) present in the scenario. The number of strong spatial multipath components (# SC) is a direct count of the number of the tree-originated peaks/lobes found by the peak detection algorithm (i.e. within 20 dB from

TABLE I
SUMMARY OF THE DIFFERENT SCENARIO PARAMETERS AND MEASUREMENT VALUES

#	d_p [m]	d_v [m]	# tr	P_{LOS} [dBm]	P_{DIRECT} [dBm]	P_{MAX} [dBm]	DG [dB]	P_{COMB} [dBm]	BCG [dB]	ΔAZ [^{o}]	# SC
1	46.1	9.3	1	-39.1	-84.5	-64.6	19.1	-61.4	3.2	66	6
2	45.0	4.7	1	-38.9	-58.7	-58.7	0	-56.0	2.7	8	3
3	55.7	7.2	1	-40.7	-71.2	-59.9	11.3	-55.7	4.2	52	7
4	65.4	5.1	1	-42.1	-61.2	-52.4	8.8	-52.0	0.4	5	3
5	78.7	3.6	1	-43.7	-58.1	-58.2	0	-55.4	2.8	7	3
6	85.3	6.2	2	-44.5	-64.1	-54.8	9.3	-54.8	0	9	1
7	92.6	9.3	3	-46.2	-73.5	-67.6	5.9	-67.4	0.2	7	4
8	97.6	9.8	3	-45.2	-75.9	-74.1	1.8	-73.6	0.5	5	8
9	97.4	9.9	2	-45.6	-83.2	-76.0	7.2	-73.2	2.8	17	8
10	95.8	8.2	2	-45.6	-75.7	-72.8	2.9	-70.0	2.8	34	9
11	45.8	6.6	1	-39.0	-66.6	-60.2	6.4	-58.6	1.6	8	7
							AVG: 6.7 dB		AVG: 1.9 dB	AVG: 19.6^o	AVG: 5

the strongest component) and represented on the heat-maps in Fig. 4. An average #SC of 5 per measurement position was found, which serves to quantify the aforementioned multipath-rich behavior experienced at this frequency due to the dominant contributions of reflection and scattering. ΔAZ is the estimated azimuthal deviation between the main TX-RX direction and the AoA of the strongest power component. From the measurements, it was found to be as large as 66 degrees (in position 1), and 20 degrees in average considering all the positions. This azimuth spread suggests a large spatial diversity of the scenario.

Diversity gain (DG) is defined in (1) as the difference between the power detected at the geometrical TX-RX direction (P_{DIRECT}) and the strongest peak power component measured (P_{MAX}). DG was found to be 6.7 dB in average. This is consistent with the findings in [9], that reported diversity gains in vegetation of 6-8 dB using 4 degrees HPBW cassegrain antennas at 26 GHz. DG can also be seen as a measure of how different the results obtained can be by performing the measurements with two directional antennas aligned in boresight and receiving the direct TX-RX power component (P_{DIRECT}), or by performing a directional analysis and finding the strongest power component (P_{MAX}). The results from the directional analysis, and P_{MAX} in particular, are more representative of the real-world propagation that an omnidirectional receiver would experience inside of the vegetation clutter.

The multipath-rich characteristics of the vegetated scenario could be exploited by using smart receivers with adaptive antenna systems in order to improve the experienced signal strength inside the clutter. In order to evaluate the potential achievable gains, beam combining gain (BCG) is also evaluated. This is defined in (2) as the gain experienced by considering the combined power sample resulting from the non-coherent addition of the three strongest received components (P_{COMB}), compared to the power of the single strongest component (P_{MAX}). The results show that spatial multipath could be exploited to achieve average gains of approximately 2 dB. It should however be noted that, in 6 out of 11 positions, BCG reached higher values up to 3-4 dB.

$$DG = P_{MAX} - P_{DIRECT} \qquad \text{[dB]} \tag{1}$$

$$BCG = P_{COMB} - P_{MAX} \qquad \text{[dB]} \tag{2}$$

IV. TREE CLUTTER ATTENUATION

From the different power measurement values reported in Table I (P_{DIRECT}, P_{MAX} and P_{COMB}), it is possible to compute the corresponding attenuation due to vegetation (L_v) by simply subtracting these values from the calibrated free space LOS reference power (P_{LOS}) [8] as indicated in (3).

$$\left.\begin{matrix} L_{v,DIRECT} \\ L_{v,MAX} \\ L_{v,COMB} \end{matrix}\right\} = P_{LOS} - \left\{\begin{matrix} P_{DIRECT} \\ P_{MAX} \\ P_{COMB} \end{matrix}\right. \qquad \text{[dB]} \tag{3}$$

Following the definition in [7], tree clutter attenuation is calculated as L_v/d_v in dB/m. If $L_{v,DIRECT}$ is considered, this results in 3.8 dB/m. This attenuation is representative of single azimuth measurements with boresight-aligned antennas, similar to the ones described in [10], which reported attenuations of 3.5-4.2 dB/m at 35 GHz. By considering the values derived from the directional analysis, $L_{v,MAX}$ or $L_{v,COMB}$, the calculated attenuation rate is reduced to 2.9 dB/m and 2.6 dB/m, respectively. These values are closer to the 2.5 dB/m reported in [11] for multi-directional measurements at 20 GHz.

Also from the measurements, single-tree attenuation was estimated, as $L_v, DIRECT/\#tr$, resulting in a value of 19.9 dB/tree. This value is aligned with the different literature results for frequencies close to 24 GHz. [11] estimated a single-tree attenuation of approximately 23 dB at 20 GHz, while [12] reported an attenuation of 19-26 dB at 28 GHz.

A. Comparison with Existing Models

Table II details the different existing foliage-induced attenuation models, where the formulations have been adjusted to match a common reference notation, where frequency (f) is considered in MHz and d_v in m. According to the definition of the models, all of them are applicable at 24 GHz. As it can be seen in Fig. 5, the predictions from these models are quite different. One of the reasons for this is that measurements were done by following very dissimilar procedures and, as it was verified in this study, attenuation values can be very different depending on the measurement technique used. Nevertheless, both the COST 235 [4] and the ITU-R slant path [3] models are able to predict, at least for the short vegetation depth explored, the measured attenuation with an average root-mean-square error (RMSE) of approximately 6.9 dB.

TABLE II
SUMMARY OF THE CONSIDERED FOLIAGE ATTENUATION MODELS

MODEL	FORMULATION	OBSERVATIONS	RMSE [dB] DIRECT	MAX	COMB	AVG
COST 235 [4]	$L_v[dB] = 13.77 \cdot f^{-0.009} \cdot d_v^{0.26}$	in-leaf, $d_v \leq 200$ m, 9.6 GHz $\leq f \leq$ 57.6 GHz	9.8	5.4	5.4	6.9
Weissberger [5]	$L_v[dB] = 0.187 \cdot f^{0.284} \cdot d_v^{0.588}$	14 m $< d_v \leq 400$ m, $f \leq 95$ GHz	18.5	11.7	9.8	13.3
FITU-R [6]	$L_v[dB] = 0.39 \cdot f^{0.39} \cdot d_v^{0.25}$	in-leaf, 10 GHz $\leq f \leq$ 40 GHz	8.2	12.6	14.2	11.7
ITU-R Slant Path [3]	$L_v[dB] = 0.25 \cdot f^{0.39} \cdot d_v^{0.25} \cdot \theta^{0.05}$	considers elevation (θ), 30 MHz $\leq f \leq$ 60 GHz	8.2	5.9	6.7	6.9
ITU-R Terrestrial [3]	$L_v[dB] = A_m \cdot (1 - exp(-d_v \cdot \gamma / A_m))$ $A_m[dB] = A_1 \cdot f^{\alpha}$	(S0) $A_1 = 1.37$ dB, $\alpha = 0.42$, $\gamma = 4.8$ dB/m	4.7	9.0	10.6	8.1
		(S1) $A_1 = 1.02$ dB, $\alpha = 0.49$, $\gamma = 4.25$ dB/m	4.5	x	x	
		(S2) $A_1 = 1.53$ dB, $\alpha = 0.51$, $\gamma = 2.98$ dB/m	x	3.9	x	
		(S3) $A_1 = 1.60$ dB, $\alpha = 0.41$, $\gamma = 2.95$ dB/m	x	x	3.4	

According to ITU-R Recommendation P-833-8 [3], the terrestrial model is the recommended one to be applied to the explored scenario. In order to apply this model, 3 sets of coefficients are calculated over the different attenuation samples. (S1), (S2) and (S3) are calculated for $L_{v,DIRECT}$, $L_{v,MAX}$ and $L_{v,COMB}$, respectively. Even though all the calculated values fall into the range of the original coefficients of the model (S0) calculated at 2.1 GHz [3], by observing the non-saturating trends of the model represented in Fig. 5, it seems clear that this model overestimates attenuation for larger vegetation depths. This is due to the definition of the maximum attenuation term (A_m). f^{α} is a good approach for the low frequency bands at which the original coefficients were calculated, but not for higher frequencies where this value becomes too large (i.e. 44 at 2 GHz, and 155 at 24 GHz, considering $\alpha = 0.5$). The observed trend suggest that this factor needs to be modified in order to correct the model for high frequencies. However, to verify this, measurements for larger vegetation depths need to be performed.

V. CONCLUSIONS

This paper presented a measurement-based study of 24 GHz cm-wave propagation through vegetation, with transmitter antenna deployed above average tree level and receiver antenna located close to ground level. A set of directional measurements exploring the full azimuth from 0° to 360° and the elevations between +10° and +30° were performed at different positions inside the tree clutter. The directional analysis provides insight on the limited knowledge reported in the literature about the interactions in the radio channel at higher frequencies in presence of vegetation. The measurement results show an average of 5 strong spatial multipath components originated in the tree clutter per explored location, with approximately 20 degrees of azimuthal deviation between the strongest and the direct transmitter-receiver components. Diversity gain was estimated to be approximately 7 dB, which could be increased 2 dB by applying multi-beam combining techniques. Tree clutter attenuation was found to be 2.6-3.8 dB/m for the first few meters inside the vegetated area. Single-tree attenuation was estimated to be approximately 20 dB. The predictions done with existing ITU-R models match the measurements with an average RMSE of 6.9-8.1 dB, which can be reduced to 3.4-4.5 dB by estimating new sets of coefficients. Based on the different observations, it is shown that the ITU-R terrestrial model needs to be revised in order to correct the trends for higher frequencies.

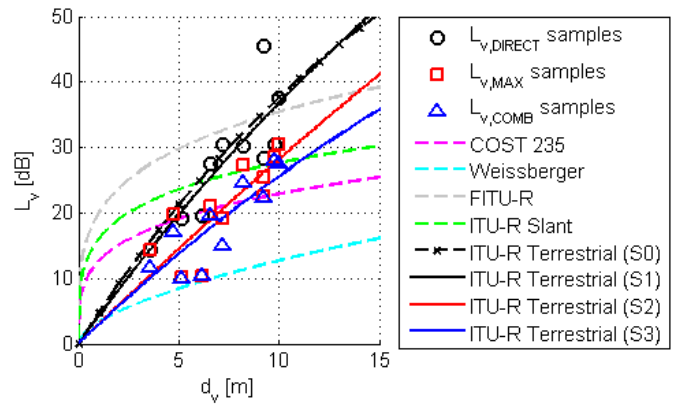

Fig. 5. Tree clutter attenuation samples and comparison with existing models.

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