A Simplified Model for Path Loss Estimation in Citrus Plantations at 3.5 GHz

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Abstract— **Agriculture 4.0 represents a considerable increase in the number of sensors, as well as the appearance of new wireless technologies, which will meet the need to efficiently plan radio communication systems in agricultural environments. In this work, a simplified model for path loss estimation in citrus plantations is proposed. The model assumes that, for long distances, the physical mechanism is a parallel transmission path over the treetops that can be modelled by multiple-knife-edge diffraction. In our scenario, where the height of the transmitter is above the height of the trees, we proposed to estimate the multiple-knife-edge diffraction contribution by the settled field defined by Walfisch and Bertoni. In this way, the propagation losses estimated by the model have been compared with measurements carried out at 3.5 GHz in a lemon plantation before and after the fruit was collected. It has been observed that the slope of the regression line of the measurements yields values of 3.6 (with fruit) and 3.7 (without fruit), which are close to the value estimated by the model (3.8). The standard deviation of the prediction error given by the difference of the observed and estimated values, is 4.5 dB (with fruit) and 3.2 dB (without fruit).**

Index Terms—**Radiowave propagation, precision agriculture, radio planning**

I. INTRODUCTION

Wireless technologies have undergone great development in recent years for short-distance communications, such as Bluetooth technology; mid-range, like ZigBee; and long distance, such as WiFi, GSM/GPRS (2G), UMTS (3G) or LTE (4G) [1]. In agriculture, medium and long-distance wireless technologies have been combined to remotely send parameters captured in localized areas. Agriculture 4.0 [2] will mean a considerable increase in the number of sensors, as well as the appearance of new wireless technologies that will facilitate, for example, the automatic guidance of tractors, the monitoring of the state of the fruit over time before harvesting, the automation of the fertilizer or the harvesting of fruits, etc., which will mean the need to efficiently plan the radio communication systems in these environments.

Fig. 1. Lemon tree plantation, location of the transmitter and measurement routes.

The planning of these radio communication systems is carried out using computer tools [3] that incorporate propagation models [4]. Most of the propagation models incorporated into these tools can be applied in rural, urban, suburban and indoor environments, due to the massive deployment of systems such as GSM, UMTS or LTE. The massive use of sensors and actuators expected in Agriculture 4.0 will require a large deployment of wireless systems in other environments. In this sense, it is necessary to propose propagation models for specific agricultural environments according to the type of plantation (citrus, vineyards, cereals, vegetables, etc.).

In the agricultural sector, citrus plantations also have a special relevance. In 2019, the world's total citrus fruit area harvested, and production quantity were estimated at 9.92 million hectares and 158 million tons, respectively [5] [6]. With these numbers, the significant increase in radio communication systems in these plantations to be at the level of what Agriculture 4.0 assumes, increasingly requires the efficient planning of these systems.

Citrus plantations (lemon, orange, mandarin and grapefruit) follow a plantation framework that is defined by the distance between rows and the distance between the trees in the same row (see Fig. 1). This planting is usually done so that the distance between rows is greater than the distance between trees, resulting in the branches of consecutive trees touching, leaving a path (street) between rows that is used mainly for fumigation, tree trimming and to collect the fruit.

In this context, the model presented in [7] suggests that, after

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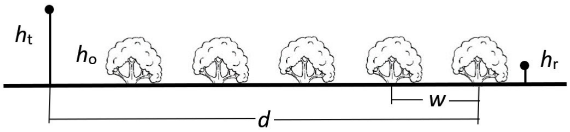


Fig. 2. Vertical profile with equally spaced trees.

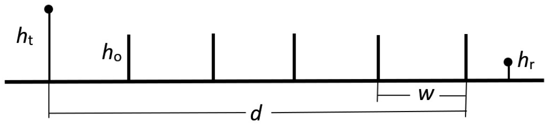


Fig. 3. Idealized vertical profile with equally space knife-edges.

doing a comparison with measurements, for short distances, there is direct transmission through the foliage, however, for long distances, which is the case of our scenario, the physical mechanism is a parallel transmission path over the treetops that can be modeled by multiple knife-edge diffraction. In [7], a series of equally-spaced trees with the same height with respect to the transmitter height (Fig. 2) are modeled as a series of knife-edges (Fig. 3).

On the other hand, it can be noted that, in [7], the transmitter is located below the height of the trees, and that is why the well-known theoretical model for multiple-diffraction over a series of knife-edges presented by Lee [8] is applied. However, in our scenario, where the height of the transmitter is assumed to be above the height of the trees, it is more appropriate to apply the expression for multiple knife-edge diffraction achieved by Walfisch-Bertoni [9].

In the work presented here, the profile of Fig. 2 for citrus plantations has been considered and the applicability of the settle field defined by Walfisch and Bertoni in [9] has been studied, which is of great interest since this model is already incorporated into radio planning tools.

In this letter, we first describe the propagation measurements carried out in a lemon plantation (before and after harvesting) at 3.5 GHz, one of the 5G bands [10]. Then, a simplified propagation model is proposed. Finally, the results obtained with the model are analyzed and compared with measurements and we sum up with the conclusion.

II. PROPAGATION MEASUREMENTS

A. *Propagation environment*

The measurements were made in a 200x300 m area of a lemon grove belonging to the FRUCA company located in the Carrascoy valley in the Region of Murcia, Spain (see Fig. 1). The planting frame is 7.5x5.5 m, that is, 7.5 m between rows (w) and 5.5 m between lemon trees in the same row. Lemon trees are very leafy, their average height and width are 2.5 m and 5 m, respectively, so the width of each path (street) between rows is around 2.5 m.

B. *Measurement system*

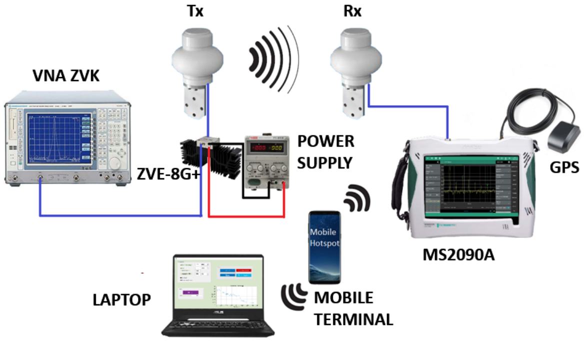
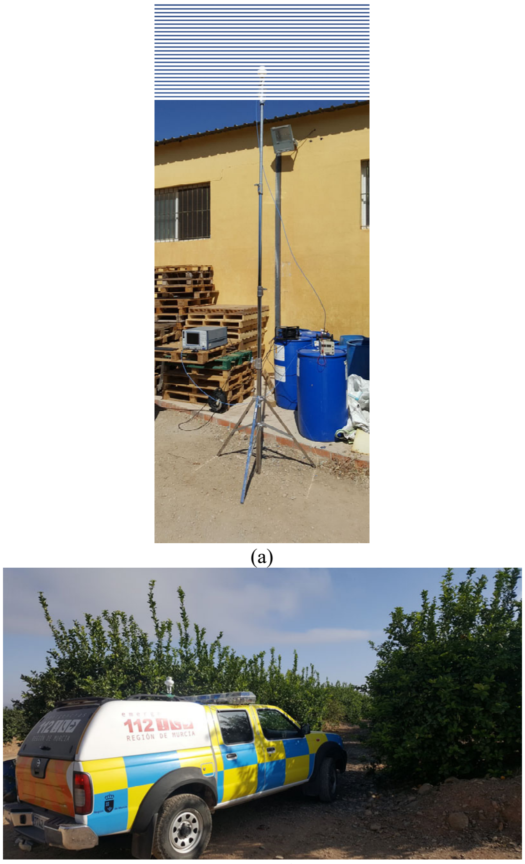


Fig. 4. Scheme of the measurement setup.



(a)

(b)

Fig. 5. Transmitter (a) and Receiver (b).

The measurement system used (Fig. 4) is based on the Rhode & Schwarz VNA ZVK (10MHz–40GHz) network analyzer used as the transmitter (Tx) and the Anritsu MS2090A (9kHz–26.5GHz) handheld spectrum analyzer used as the receiver (Rx). In addition, the ZVE-8G+ (2-8GHz) amplifier in transmission (which is properly powered by a POWER SUPPLY), 2 STEATITE Q-PAR ultra-wideband antennas (0.8–40GHz), a GPS, cables and connectors have been used. A MATLAB program has also been developed to automate the measurement process (which is running in a LAPTOP wirelessly connected to the VNA ZVK through a MOBILE TERMINAL).

In transmission, the network analyzer generates a tone at the frequency of 3.5 GHz that is amplified and transmitted with vertical polarization by an antenna located on a mast at a height $h_t = 4.2$ m (Fig. 5(a)).


(a) (b)

Fig. 6. One of the path of the measurement campaings without fruit in the trees (a) and with fruit (b)

The receiving system is mounted on a vehicle (Fig. 5(b)) with the receiving antenna at a height $h_r = 1.8$ m and located at a distance from the last tree of 1.25 m (half the width of each street). The developed program allows selection of the frequency to be measured, the bandwidth, the time between samples, etc. of the portable spectrum analyzer and stores a set of samples for each route. For each sample, the geographical position, the received power and the time (hour, minutes and seconds) are also available.

To consider the effect of all the equipment on the measurement, a calibration process was carried out with a set of measurements in direct vision paths between the transmitter and receiver.

Two measurement campaigns were carried out, the first one with fruit in the trees (before harvesting, Fig. 6(a)) and the second one without fruit (after harvesting, Fig. 6(b)). Fig. 1 shows the location of the transmitter and the 21 runs, each one of them on a path (street) with a length of 200 m. The number of samples per route was 116 on average per street, with the total number of samples being 2448.

III. PROPAGATION MODEL

Following [7], we propose a model that assumes the profile of Fig. 2 and the path loss is estimated by the sum in dB of the path loss between antennas in free space, the multiple diffraction over treetops and an additional contribution obtained from the measurements, that takes into account the local variations in the mean value due to various propagation media factors: species, foliage densities, seasons, and different frequencies.

The free space path loss is calculated by:

$$L_o(dB) = 32.44 + 20log10(d) + 20log10(f) \quad (1)$$

where d (see Fig. 3) is expressed in km and f is the frequency expressed in MHz.

The multiple-diffraction contribution is calculated with the following expression [9]:

$$L_{msd}(dB) = -20\log(Q) \quad (2)$$

where Q is the settled field defined by Walfisch and Bertoni in [9] for a series of knife-edges (Fig. 3):

$$Q = 0.1\left[\frac{\alpha\sqrt{w/\lambda}}{0.03}\right]^{0.9} \quad (3)$$

and can be applied if h_t-h_o>0 and $\alpha\sqrt{w/\lambda} \leq 0.4$. In (3),

$$\alpha \approx \frac{h_t - h_o}{d} \quad (4)$$

From (2) and (3), the multiple-diffraction contribution is calculated by

$$\begin{aligned} L_{msd}(dB) = 68.87 - 9log10(f) - 9log10(w) \\ - 18log10(h_t - h_o) + 18log10(d) \end{aligned} \quad (5)$$

where f is expressed in MHz and d in km.

We want to point out that (1) and (5) fixed a variation of the path loss (in linear units) with the distance between the transmitter and receiver of $d^{3.8}$ [9].

It should be noticed that the proposed model, in order to include the so-called Q factor, assumes a small angle of incidence over the trees (almost grazing incidence). On the other hand, it is worth noting that such assumption is particularly appropriate and realistic in citrus plantations, where the transmitter can be typically located over a hut which bears a height above the treetop height so that, for long distances between the Tx and Rx, a small angle of incidence is achieved. Moreover, the receiver could be placed, for example (as mentioned in the Introduction section), over an automatically guided tractor (for fumigation) with a typical height slightly below the treetop height. Finally, please note that the variation of the distance of the receiver from the trees could have an impact on the previously mentioned additional contribution.

IV. RESULTS AND DISCUSSION

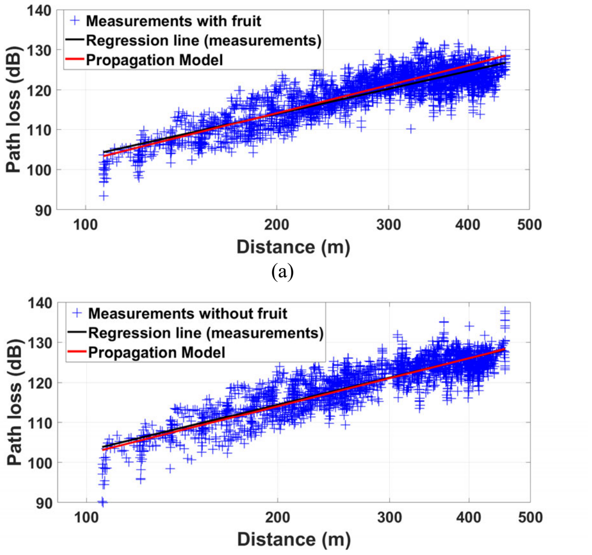
In Fig. 7 the measured losses (in dB) are represented as a function of distance. The regression lines of the measured losses and the losses estimated by the model have also been represented. In our scenario, the additional contribution (offset) in the model that obtains a better fit with the measured loss was 16.3 dB.

These regressions have been obtained using the FI (Floating Intercept) adjustment method.

$$L_{FI}(dB) = \alpha + \beta 10log10(d) + \chi_\sigma \quad (6)$$

where α (in dB) and β (slope) are adjustment parameters, d the distance between the transmitter and receiver in meters, and χ_σ a Gaussian random variable with zero mean and standard deviation σ in dB.

Table I shows the parameters used in the calculations. It should be noticed that, considering these parameters, typical in other citrus plantations, $\alpha\sqrt{w/\lambda}$ varies between 0.0412 and 0.1703 for the distance range of the measurements (which is clearly smaller than 0.4, for which almost grazing incidence can be assumed), (5) can be applied to estimate the multiple diffraction contribution.



(a)

(b)

Fig. 7. Path loss versus distance (a) with fruit (b) without fruit.

TABLE I
PARAMETERS FOR THE CALCULATIONS

f (GHz)	3.5
h_t (m)	4.2
h_r (m)	1.8
h_o (m)	2.5

TABLE II
FI PARAMETERS AND STANDARD DEVIATION

	With fruit			Without fruit		
	α	β	σ (dB)	α	β	σ (dB)
Measurements	32.3	3.6	3.2	29.0	3.7	3.2
Propagation Model	22.7	3.8	0.9	22.5	3.8	1.0

TABLE III
MEAN ERROR AND STANDARD DEVIATION

	With fruit		Without fruit	
	ME (dB)	σ_{error} (dB)	ME (dB)	σ_{error} (dB)
Propagation Model	0.7	4.5	-0.2	3.2

Table II shows the slopes and standard deviations in every case. From the results, it is observed that the slope of the regression line of the measurements is 3.6 (with fruit) and 3.7 (without fruit), close to the value of 3.8 estimated by the model. This result confirms that the variation of the path loss with the distance between the transmitter and receiver is mainly due to the free space and the multiple-diffraction contributions.

Table III shows the mean and the standard deviation of the prediction errors of the models from the measured values, where the prediction errors are given by the difference between the predicted and measured values.

The mean error (ME) is estimated by

$$ME(dB) = \frac{1}{N}\sum_{i=1}^{N}(L_{pi} - L_{mi}) \quad (7)$$

where L_{pi} (in dB) and L_{mi} (in dB) are the predicted and the observed value of the i-th sample, respectively, and N the number of samples.

The standard deviation of the error σ_{error} is calculated by

$$\sigma_{error}(\text{dB}) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\left(L_{pi} - L_{mi}\right) - ME\right]^2} \quad (8)$$

As can be observed in Table III, the standard deviation of the error is 4.5 dB in the case 'with fruit' and 3.2 'without fruit'.

V. CONCLUSION

In this work, a simplified model for path-loss estimation in citrus plantation environments has been proposed. To do this, a measurement campaign has been carried out at a frequency of 3.5 GHz in a lemon plantation in two situations: with lemons in the trees and without lemons once they have been harvested. The height of the transmitter is above the height of the trees and the receiver height is below the height of the trees. In these conditions, it has been observed that the slope of the regression line of the measurements has a value of 3.6 (with fruit) and 3.7 (without fruit), which are close to the value estimated by the model (3.8). Furthermore, the standard deviation of the prediction error of the model from the observed values in both cases is 4.5 dB (with fruit) and 3.2 dB (without fruit). Therefore, the results shown in this work point to the possibility of considering a multiple-knife-edge diffraction model for path loss estimation in citrus plantations.

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