WLAN IEEE 802.11b/g/n Coverage Study for Rural Areas

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Abstract - **With the boost of precision agriculture, Wi-Fi products have become very relevant due to their broad range of connectivity options. Nowadays, technology can improve many facets of farming practice by collecting data, such as weather conditions or soil quality. Moreover, they can better control the output of the production which would enhance business efficiency and lead to higher revenues. However, the lack of collated experimental data difficult the development of prediction procedures to determine the effects of vegetation in radio coverage. In this paper, an empiric radio coverage model for WLAN outdoor in agriculture scenarios is presented. This model is based on the free field propagation equation, taking into account the losses due to vegetation. To do this, experimental data was collected at an orange tree plantation. We measured the effects when there are trees, near the trees and far from the trees in order to compare the signal losses. Our experiments provided us the equation given by the signal losses in an orange tree plantation, which could be very useful for designing Wireless Sensor Networks in precision agriculture.**

Keywords - Wireless network coverage; IEEE 802.11; Propagation Loss; Precision agriculture; Wireless Sensor Networks.

I. INTRODUCTION

Precision agriculture uses multiple devices to analyse spatial, temporal and individual data to support management decisions. Improving the production capacity enhances business efficiency and leads to higher revenues, as well as reducing environmental impact. Moreover, as G. Yun et al. stated, the world population will exceed 9 billion people by 2050, which means that the agricultural sector needs to increase production by 70% [1]. To achieve this, present-day farmers need to integrate hardware and software systems to their set up. Among the necessary devices that farmers need to incorporate, sensing technologies are at the core of the structure [2]. Together with GPS tracking devices and communication technologies, farmers can get real-time information to prevent diseases or detect fires.

There are many types of emerging technologies that can be applied to improve agriculture performance [2]. Larger farmers may use drones and even satellite images to monitor their fields. Satellite crop monitoring facilitates real-time crop monitoring through spectral analysis of satellite images [3]. Thus, vegetation indexes give information about crop development proportions so that additional work can be carried out in particular areas of the field. A cheaper solution is agricultural drones. These aerial vehicles can help optimize agricultural operations by gathering information from sensors and taking high-resolution images. The unmanned aerial vehicles (UAVs) use wireless networks to send information to the controller and mobile devices, allowing the identification of stressed areas in real-time [4].

One of the most used ways to collect data is using Wireless Sensor Networks (WSNs) as a communication technology [5]. These networks are formed by a group of spatially distributed sensors dedicated to monitor and record the conditions of the environment. WSNs rely on wireless connectivity to communicate the gathered information to a central node. Therefore, most WSN uses IEEE 802.11 g/n standard, which provides a high data rate network access within approximately 300 meters outdoors, without path loss [6].

Many factors can affect the wireless coverage. E.g. inside cities wireless coverage is affected by the buildings, walls, cars in the streets, etc. In rural areas, there are many issues that can affect signal strength, such as trees and plants. Moreover, there are other factors to take into account such as the Fresnel zone, the scattering of energy out of the radio path, diffraction loss, and attenuation due to gaseous absorption at high frequencies, among others. In addition to this, the amount of vegetation is different according to the zone. In forests, the additional loss due to vegetation can be characterized by the scattering of energy out of the radio path, which limits the performance of the IoT [7]. In agriculture with plants, the randomly distributed leaves and branches can cause attenuation, absorption of the radio-waves, as well as scattering and diffraction [8]. In agriculture with trees, the distance between the bushes, the geometry of the link and the homogeneity of their leafiness result in different effects on radio-waves [9]. For these reasons, it is important to study the performance of WSNs in specific fields to avoid poor Quality of Service (QoS).

This paper attempts to ease data transfer within agricultural operations by measuring the coverage of an access point at different locations of a field. The aim of this study is to determine how leafiness affects signal quality to better positioning sensors within an orange tree plantation. To this end, the Signal to Interference Ratio (SIR), the Received Signal Strength Indicator (RSSI) and the Round-Trip Time (RTT) of a wireless signal have been measured through the foliage. The measurements have been made onto three different scenarios: one without vegetation, and two at an orange tree plantation with different set-ups. In all cases, a single access point and a laptop have been used to take measurements at different distances three times and up to 34 meters.

This paper is structured as follows. The related works are presented in Section II. In Section III, we explain the test bench of the experiment. In Section IV, we perform an analytical study of the losses due to vegetation. The results and

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discussion are described in Section V. Finally, in Section VI, we explain the main conclusions and future work.

II. RELATED WORK

In this section, we analyse several papers related to our proposal. First, we will discuss the existing studies and later we will discuss their flows.

In [8], J. Lloret et al. describe the development of a wireless multisensory network able to detect fires in rural and forest areas. The test bench was carried out in a 2 km circle area environment of an uninhabited rural area with a wide variety of vegetation. Among the different types of plants that can be found in this environment, we find cereal cultivations, vegetables, grapevines, and different types of trees. In order to design the wireless sensor network, the signal loss was taken into account to decide the distance at which the wireless IP cameras can be placed. To do this, vegetation loss was introduced into the power balance formula using an estimation of the amount of vegetation per meter. The result of this study shows a scalable system that can be adapted to any type of environment to detect fires and send a sensor alarm to a central server.

N. A. Binti Masadan et al. conducted in [9] a study to investigate the foliage effect in terms of attenuation and its contribution to path loss. In this case, different empirical methods were used as references to highlight the obtained results. To study the effects that vegetation produce, the RSSI was measured for different path crossings through 5 tropical tree types. The results of this experiment showed that Line of Sight (LOS) links performed better than Non-line of Sight (NLOS) links in vegetation environments. The analysis of the results concluded that the obstructions encountered in NLOS scenarios introduced diffractions, scattering of energy, and reflections that increased attenuation.

J. Lloret et al. present a WSN that uses image processing to discern the status of vineyards in Spain [10]. The proposed solution uses IEEE 802.11 a/b/g/n standard to route alarms to the main node to warn the farmer. To design the WSN the coverage area was studied taking into account that the wireless sensor would be on top of a 6 meters height post. Due to the difference in height of the post and the vines, the vegetation loss was not introduced into the power balance formula. From a theoretical point of view, this solution provides a scalable system with low bandwidth consumption that can detect bad leaves in a 5-stage process.

J. A. Azevedo et al. performed an empirical model to predict attenuation in forest environments that included vegetation parameters such as: tree density, canopy diameter, and foliage density [11]. In this case, foliage density was determined by comparing the background light silhouetted by the canopy. This model was developed with measurements obtained from a campaign carried out in twelve forest environments of Madeira Island with different tree species for frequencies of 870 MHz and 2.4 GHz. Although the performance of this empirical model is better than other well-known models, the difficulty to estimate vegetation parameters prevent making generalizations.

In [12], H. Wu et al. investigated the propagation characteristics of wireless communications in wheat-fields at frequencies of 433 MHz and 2.4 GHz. To study near ground radio link channels, several measurements were made to analyse the impact of plant and antenna heights. Empirical models were compared with a regression analysis in Matlab to obtain an optimal fitting model. Among the conclusions that this research raised, it was determined that the parametric exponential decay (OFPED) model was the most suitable model for this type of environment. However, the collected data demonstrated that RSSI decreased with distance to the transceiver and path loss decreased with the increase of antenna height. Moreover, path loss was higher with higher frequencies.

In 2018, Lopez-Iturri et al. carried out a characterization of 5G and IoT systems working at 2.4 GHz in oak and pine tree fields [7]. The aim of this experiment was to identify the effect that dense forest environments have on signal strength. To do this, measurements and simulations were performed to identify scattering and diffraction zones. The model presented characterizes the attenuation effect between a static transmitter and a mobile user in different positions of these scenarios. However, the lack of air gaps in the model prevented from identifying the diffuse scattering zone. Thus, experimental measurements are needed in order to distinguish it.

Although the system in [8] is able to detect fires and send an alarm to the firefighters, this solution uses an estimation of the vegetation index. The review conducted in [9] shows that the variety of parameters to take into account become prediction models inaccurate. Therefore, mitigation techniques are needed to improve links' reliability. In other cases, such as the one presented in [10], vegetation loss was not introduced into the power balance formula due to design constraints. However, the study carried in [11] shows that the wide variety of vegetation and scenarios make it impossible to estimate all possible vegetation parameters. Moreover, the study conducted in [12] demonstrated that parameters such as antenna height affect the strength of the signal. Finally, the characterizations of 5G and IoT systems presented in [7] raised the inaccuracy of simulation models due to the lack of representation of certain parameters.

It can be inferred that none of the published papers succeed in the characterization of vegetation loss. Although many studies have attempted to evaluate the effect of vegetation on radio wave signals, the lack of collated experimental data has prevented scientist from developing a generalized procedure [13]. The reason behind this is that there is a wide variety of vegetation types and conditions to take into account when designing a generalized model. In this study, we aim to characterize vegetation indexes for orange tree plantations and obtain a signal loss equation to better positioning access points and sensors in agricultural environments in Spain.

III. SCENARIO DESCRIPTION AND TOOLS USED

In this section, the necessary devices to carry the experiment and the set up that has been used are described. The test bench is segmented in four different subdivisions.

A. Place of measurement

Attenuation due to vegetation varies extensively due to the irregularities of the medium and the different types of species, water content and densities. Moreover, attenuation can vary due to the movement of foliage caused by the wind. At frequencies above 1 GHz, the specific attenuation through trees appears to be about 20% greater [13].

Fig. 1. Orange tree plantation where measurements took place.

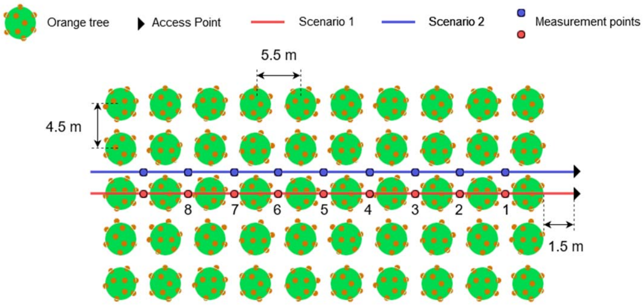

Fig. 2. Measurement points and vegetation geometry.

In order to evaluate the effect of vegetation on radio wave signals, we sought out a wide plantation of orange trees with an area of 1.400 m^2, with a length and a width of 70 m by 20 m. This field is in an open area with no walls, similar to the vast majority of orange tree plantations that can be found in Spain. Fig. 1 shows a satellite image of the chosen land where the experiment took place.

B. Hardware used in the test bench

Radiofrequency (RF) propagation measurements were made at 2.4 GHz using Linksys WRT320N-EZ router as a transmitter (Tx). This device works both in 2.4 GHz and 5 GHz bands simultaneously with the standard IEEE 802.11 b/g/n [14]. Additionally, this router has three internal antennas with an RF power of 17 dBm and 1.5 dBi of antenna gain. As for the receiver (Rx), ASUS Gaming Notebook GL753V was used. This laptop has a 2.8 GHz Intel Core i7-7700 HQ processor, 16 GB of memory and GeForce graphic card 4GB GTX 1050 Ti. Wireless connectivity uses Intel Dual Band Wireless Wifi Bluetooth Card 7265NGW, with IEEE standard 802.11 ac, which is able to work at 867 Mbps. This card has two antennas of 5 dBi of gain.

C. Software used

In all cases, the latest version of the software Vistumbler [15] was used to scan the wireless network and measure the SIR and the RSSI [6]. Moreover, the latency of the connection was measured by sending a ping signal through MS-DOS commands to the gateway to verify the correct reception of the packets.

D. Set-up of the experiment

In order to obtain the SIR and RSSI values, the Tx and the Rx were positioned along the same line, 1 meter above the ground. The evaluation of the effect that vegetation has on RF signals was made by taking measurements in three different scenarios.

- Scenario 1: Measurements were made at an orange tree plantation, with data being collected behind the foliage of each tree.
- Scenario 2: Measurements were made at an orange tree plantation, with data being collected along a row between the trees.
- Scenario 3: Measurements were made on a field with no vegetation, ensuring clear connectivity.

Fig. 2 illustrates the experimental measurement set-up at the orange tree plantation. The measurement points of Scenario 1 were at the same distances as Scenario 2 and Scenario 3 so that comparisons of the signal strength could be made. In all cases, the noise floor of the spectrum analyser was -90 dBm and measurements were taken three times at each point.

IV. ANALYTICAL STUDY

This section presents the analytical study to estimate the signal loss due to the vegetation. From reference [16], the signal loss in rural environments is given by equation (1).

$$L(dB) = L_o - 10 \cdot n \cdot \log(d) - \sum L_{tree\ i} \pm L_{ms} \quad (1)$$

Where:

Lo = Received signal strength (dBm) at a distance of 1 meter, including antenna gains.

n = Attenuation variation index with the distance (n=2)

d = Distance between transmitter and receiver

$L_{tree\ i}$ = Losses due to the *i* tree.

L_{ms} = Propagation losses due to multipath propagation. This interference can be constructive or deconstructive, depending on the phase of the received signal.

The received signal strength 1 meter far from the Tx was measured three times. In order to determine the signal loss due to vegetation, the mean value of the RSSI at 1 meter was performed. The result can be seen in TABLE I.

TABLE I. RSSI VALUES AT 1 METER AND MEAN VALUE.

Number of Measurements	***Measurements***
	RSSI (dBm)
1	-30
2	-30
3	-32
Mean (L_o)	**-30.67**

According to Fig. 2, the transmitter is located at a fixed position, 1.5 meters far from the tree. A series of measures were taken at points 1-2-3-… using a laptop and signal monitoring software. The loss through the first tree can be calculated using equation (2).

$$L_{Tree\ 1} = L_o - 20\log(d) - P_{r1} + L_{ms1} \quad (2)$$

Where Pr_1 is the received signal strength at point '1' and d = 5 meters, the distance from the laptop to the transmitter. The loss through the second tree can be calculated in the same way:

$$L_{Tree\ 2} = L_o - 20\log(d) - P_{r2} - L_{Tree\ 1} + L_{ms2} - L_{ms1} \quad (3)$$

Where L_o = -30.67 dBm and Pr_2 is the received signal strength at point '2' and d = 9.5 meters. As we can see in equation (3), the multipath effect is minimized because sometimes it is added and others it is subtracted. In order to obtain a suitable value without the effect of multipath propagation losses, we computed the mean value. This mean value will be employed as a reference for the losses due to the vegetation. TABLE II shows the values of attenuation obtained at an orange tree plantation. In spite of the fact that all trees are equal, not all of the trees produce the same attenuation. The variation is produced by multipath propagation. This error can be reduced by obtaining a mean value. Since we stablished a threshold signal strength of -90 dBm, the mean value was performed using four measurements instead of six. The reason for this decision was that the signal strength in the fifth measurement was -91 dBm. At this point, some packets were lost.

TABLE II. TREE LOSSES AND MEAN VALUE

Number of Trees	*Measurements*
	Loss (dB)
1	6.69
2	14.76
3	9.30
4	17.17
Mean ($L_{vegetation}$)	**11.98**

Where $L_{vegetation}$ is the mean value of the losses due to a tree. In our case study, we estimated that each tree is around 2 meters long. To estimate the losses due to the vegetation for the studied case, we use the deduced expression for the threshold power:

$$P_{rx} = P_{rx_{1m}} - 20\,log(d) - i \cdot L_{vegetation} \quad (4)$$

Where:

P_{rx1m} = Received signal strength at 1 meter.

d = Distance (in meters) between the transmitter and the receiver.

$L_{vegetation}$ = Propagation losses due to the trees.

i = number of trees.

Equation (5) shows the formula needed to estimate the coverage distance:

$$d = 10^{\frac{P_{rx_{1m}} - i \cdot L_{vegetation} - P_{rx}}{20}} \quad (5)$$

Now, we can calculate the coverage distance, but bearing in mind the vegetation. To do this, we considered a received signal strength of -30.67 dBm for a WLAN device at 1 meter, and a threshold signal strength of -90 dBm to have enough signal quality. Equation (6) shows the formula needed to estimate the coverage distance:

$$d = 10^{\frac{59.33+11.98i}{20}} \quad (6)$$

Fig. 3 shows the relation between the coverage distance and the number of trees. As the figure shows, the maximum number of trees that our connection can support is 4. At this point, the coverage distance is 3.72 meters. Moreover, the number of trees interfering the RF path would cause the interruption of the connection with the wireless network.

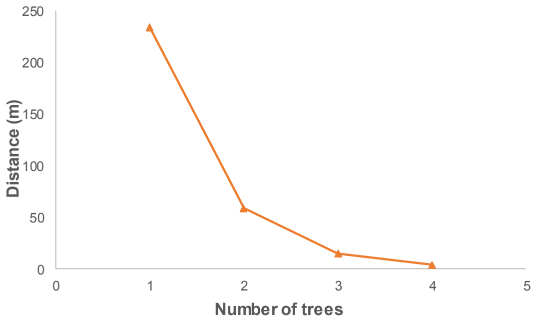

Fig. 3. Coverage distance vs. number of trees.

V. EXPERIMENTAL RESULTS

This section presents the results of the SIR, RSSI and RTT measurements taken at different distances on three scenarios.

Fig. 4 shows the signal strength levels measured at different positions in three scenarios. As the figure shows, the RSSI rapidly drops when measuring the signal strength behind the foliage of the trees (Scenario 1). However, when measuring the RSSI along a row between the trees (Scenario 2), the collected data shows a bigger coverage area. The vegetation effect stands out when comparing the signal strength of both scenarios with the data collected on a field with no vegetation (Scenario 3).

Fig. 5 shows the signal to interference ratio observed in our scenarios. The data collected in Scenario 1 shows that the SIR quickly decreases to 60 % as a response to the leafiness of the trees. Nevertheless, the collected data in Scenario 2 shows that the quality of the signal is less affected by vegetation when placing both Tx and Rx along a row between the trees. However, when comparing the SIR of these scenarios with the SIR from Scenario 3, the effect of vegetation is highlighted.

Fig. 6 shows the RTT measured in all three scenarios. The collected data from Scenario 1 shows a low data rate when increasing the distance between Tx and Rx with the presence of trees between them. This effect cannot be observed in the cases of Scenario 2 and Scenario 3. Nonetheless, when comparing the RTT from Scenario 2 with the RTT from Scenario 3, it can be inferred that the presence of vegetation affects the data rate of the connection.

Fig. 7 shows the packet loss in different scenarios. As the figure shows, the connection between Tx and Rx is interrupted when collecting data behind the foliage of the trees. However, in Scenario 2 and Scenario 3 the connection remains stable, although the presence of trees in Scenario 2 causes some packet loss at high distances.

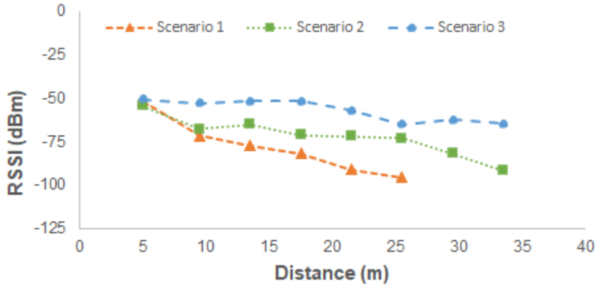

Fig. 4. Received Signal Strength Indicator.

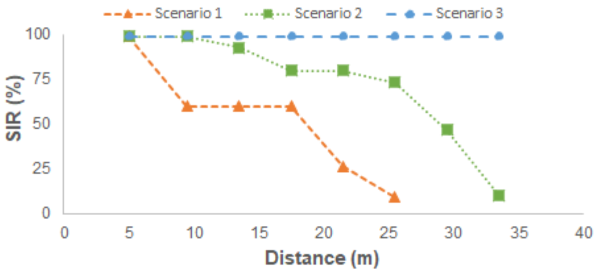

Fig. 5. Signal to Interference Ratio.

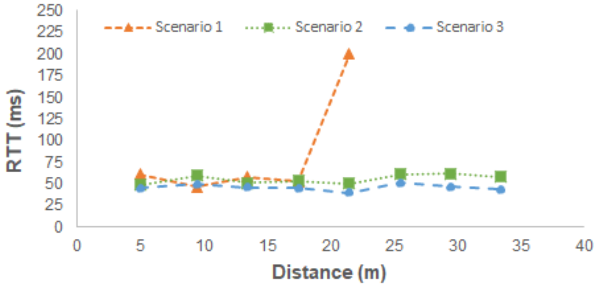

Fig. 6. Round Trip Time.

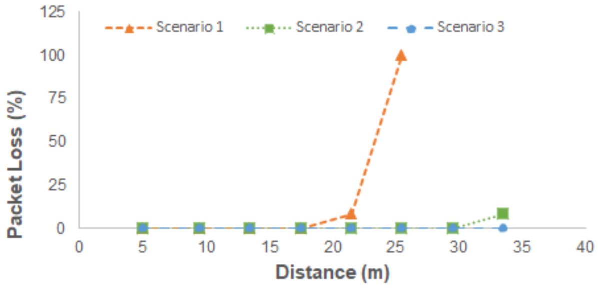

Fig. 7. Packet Loss.

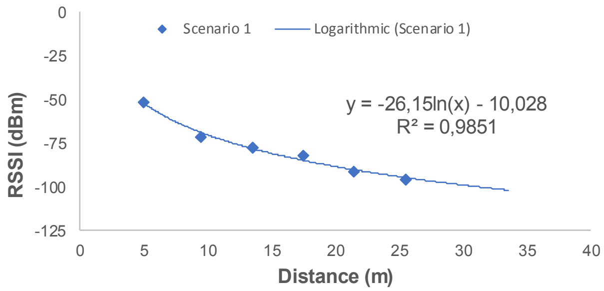

Fig. 8. Trendline of the RSSI in Scenario 1.

We have performed the trendline of the collected data in Scenario 1 and we have estimated the related R-squared value. As Fig. 8 shows, the trendline formula that best fits the data has a logarithmic tendency.

The trendline formula of the data collected in Scenario 1 is presented in equation (7).

$$y = -26.15\ln(x) - 10.03 \tag{7}$$

The estimated R-squared value of the trendline is 0.9851, which means that the equation of the trendline is very accurate.

VI. CONCLUSION

In this paper, we have studied the effect of vegetation in radio coverage signals based on IEEE 802.11 b/g/n standard. As stated before, different types of vegetation result in non-identical effects on radio-waves, such as attenuation, diffraction, refraction and scattering of the signal. This is important when a WSN deployment for agriculture precision is required.

In our case study, the measurements were carried out at an orange tree plantation similar to those that can be found in Spain. In order to study how vegetation affects radio coverage, the experiment was carried through three scenarios: one without vegetation, and two at an orange tree plantation with different set-ups. We have analysed the signal quality by measuring the SIR, the RSSI and the RTT of a wireless signal in all three scenarios.

As the results show, the coverage distance is significantly reduced when measurements were taken behind the foliage of each tree. In this case, not only the signal strength decreased with the number of trees, but also the interference ratio rapidly dropped to 60 %. However, the results from Scenario 2 show that these effects are mitigated when measurements were made along a row between the trees.

Since this type of measurements is needed for designing accurate WSN for real set-ups, as future works, we would like to include in the experimental test different types of plantations and different types of agriculture environments. Additionally, we would compare the results of IEEE 802.11 standard with other technologies such as LoRa, Zigbee and Sigfox whose are currently being used in farming activities.

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