Propagation of IEEE802.15.4 in Vegetation

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***Abstract*— Data communications and more specifically wireless data communications have an increasing role in precision agriculture. ZigBee is one of the most widely adopted Wireless Sensor Network (WSN) technology, and it operates on top of IEEE802.15.4 that provides the two lower layers of the OSI model. To optimize the placement of sensors in agricultural explorations (greenhouses, crop fields, ...), besides placing the sensors the nearer as possible to the process to monitor, also the maximum distance between nodes must be taken into account. The maximum distance between wireless nodes depends on the gain of the antennas, output power of the transmitter and attenuation, either in free-space and due to obstacles. Normally propagation models are used to evaluate the values of attenuation. However the traditional propagation models might not be the most adequate for wireless sensors applications. In this paper, a study of the propagation of wireless communications in vegetative environments, using IEEE802.15.4, is presented. Also modifications to the most used propagation models are presented.**

***Index Terms*—IEEE802.15.4, Wireless sensors, Propagation models**

I. Introduction

Precision Agriculture (PA) relies on the use of modern technologies to promote variable management practices within a field, according to site conditions[1]. At the field level information is gathered from sensors, which are distributed along the agricultural explorations. These data are then transmitted to the upper decision making layers of the business model. PA might use different types of communication technologies and protocols, which are distributed according to the layer on which they are needed. For example Ethernet with TCP/IP (Transport Control Protocol / Internet Protocol) on the higher layers, and fieldbuses, such as Controller Area Network, or low cost wireless networks in the lower layers [2].

Wireless sensors have been used for several years in agricultural applications [3], [4], and they have an increasing popularity in the deployment of data acquisition networks in this type of applications. Wireless Sensor Networks (WSN) allow a great flexibility when deploying new systems or when updating previously installed data acquisition systems. However, to correctly place the wireless sensor nodes in the field, it must be taken into account all the parameters that may have influence in the propagation of electromagnetic waves.

A protocol which has a wide adoption by the Wireless Sensor Networks developers community [5] is ZigBee [6]. It is considered one of the most promising standards for wireless sensors [7] for use in agricultural applications. ZigBee implements the upper layer of the OSI (Open Systems Interconnection) reference model for data communications, and it relies on the IEEE802.15.4 [8] protocol for the implementation of the two lower layers, i.e., the Physical Layer and the Data Link Layer.

This paper is focused on the study of the propagation of electromagnetic waves in agricultural and silvopastoral explorations. Considering the above presented information, IEEE802.15.4 is the technology used in all the tests here presented.

Propagation models are used to determine the behaviour of electromagnetic waves, as they travel from the transmitter to the receiver. The models normally used in wireless communication might not be the most adequate for use with wireless sensors [9]. In this paper some of the most used models to determine the excess attenuation due to vegetation are presented. Values of attenuation calculated using those model are then compared with attenuation data acquired in vegetation.

Based on the attenuation measurements, made in vegetation, it was concluded that the traditionally used models can be adapted for use in the target application of this paper. However they cannot be used directly. They must be adapted before use in this type of applications. This adaptation consists in multiplying them by two parameters: one dependent on the type of vegetation and another dependent on the spatial distribution of the vegetation along the propagation path.

II. Propagation of radio waves

Electromagnetic waves suffer changes as they travel from the transmitter to the receiver. Besides the free-space attenuation, also the propagation medium and obstacles in the propagation path cause electromagnetic waves to fade, mainly due to reflections, diffraction and wave scattering. To determine these changes, propagation models are used. They allow to to determine the behaviour of electromagnetic waves as they travel between two wireless nodes. Some of the most used empirical path loss models are [10], [11] the Okmura-Hata model[12], the COST-Walfisch model [13] and the Two-slope model[14].

Although these models are widely used in the conception of wireless communications systems, they might not be

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the most suitable for this type of applications, due to the specific characteristics of the propagation medium and IEEE802.15.4 technology [9]. Normally wireless propagation models consider that the antennas are distant from the ground, the distance between the transmitter and the receiver is in the range of hundreds of meters or even kilometres, and obstacles are trees, mountains, buildings and moving vehicles. On the other hand, in the target application of our work the wireless nodes might be placed on the ground or near it, the distance between the wireless nodes is in the range of a few meters and obstacles are small plants, rocks, shrubs, weeds and crops.

Moreover the wireless radio technologies used in WSN applications have irregular propagation patterns [15], with non-isotropic path loss [16].

A. Total Path Loss

When a wireless signal arrives at the receiver it has suffered attenuation along the propagation path. This attenuation will influence the received power, which can be expressed as a function of the transmitted power, receiving and transmitting antenna gains and the total path loss, as in Eq. 1:

$$P_r = P_t + G_t + G_r - P_L \tag{1}$$

where P_r is the received power, P_t is the transmitted power, G_t and G_r the gains of the transmitting and the receiving antennas and P_L is the total path loss.

The total path loss can be divided into the path loss due to wave spreading, the path loss in free-space, and the losses due to the presence of obstacles in the propagation path (Eq. 2):

$$PL_{tot} = PL_{fs} + A_{env} \tag{2}$$

where PL_{tot} is the total path loss, PL_{fs} the path Loss in free-space and A_{env} the attenuation due to the environment characteristics.

B. Free-Space Path Loss

The free-space path loss term (PL_{fs}) in Eq. 2 can be expressed as a function of the distance between the two wireless nodes [17] (Eq. 3):

$$PL(d) = PL(d_0) + 10Nlog\left(\frac{d}{d_0}\right) + X_\sigma \tag{3}$$

where N represents the path loss exponent, d_0 is an arbitrary distance, X_σ denotes a Gaussian variable with zero mean and standard deviation σ.

In the literature, the values considered for the reference distance (d_0) varies from application to applications. In outdoor applications typically a distance of 1 km for large urban mobile systems, 100m for microcell systems and 1m for indoor propagation [17] are normally used. In this work, since the used technology operates at short range, $d_0 = 1m$ was considered. Parameter d is therefore in meters.

C. Excess Attenuation due to Vegetation

In the agricultural and silvopastoral applications, the obstacles between the wireless nodes are the vegetation and crops. So for the A_{env} term of Eq. 2 only the excess of attenuation due to the presence of vegetation will be considered.

In the literature, several models to evaluate the excess attenuation due to the presence of foliage in the propagation path can be found. Most of these models are represented by the expression of Eq. 4 [18], which expresses the attenuation as a function of the working frequency (f) and the depth of foliage (d):

$$L_{veg} = A \times f^B \times d^C \tag{4}$$

where L_{veg} is the excess attenuation due to the foliage, and the parameters A, B and C are empirically calculated constants, which are dependent on the type of foliage.

One of those models is the Weissberger MED (Modified Exponential Decay) model [19] (Eq. 5). It expresses the excess attenuation due to trees, in dB, at a given working frequency (f), in GHz, with foliage depth of d meters.

$$L = \begin{cases} 1.33f^{0.284}d^{0.588} & 14 \leq d \leq 400 \\ 0.45f^{0.284}d & 0 \leq d < 14 \end{cases} \tag{5}$$

Other propagation models that are in the form of Eq. 4, using the same parameters and units as the Weissberger MED model (losses in dB, for a given frequency,f, in GHz, with a foliage depth of d meters), are: COST235 model, Eq. 6; Fitted ITU-R model, Eq. 7; Early ITU model, Eq. 8.

$$L = 15.6f^{-0.009}d^{0.26} \tag{6}$$

$$L = 0.39f^{0.39}d^{0.25} \tag{7}$$

$$A_{ev} = 0.2f^{0.3}d^{0.6} \tag{8}$$

Another model used to determine the influence of foliage is the Single Vegetative Obstruction Model [20], presented in Eq. 9. Unlike the above presented models, it does not consider the working frequency. It gives the value of the attenuation L in dB as a function of the distance d in m and the specific attenuation for short vegetative paths γ, in dB/m.

$$A_{ev} = d\gamma \tag{9}$$

III. EXPERIMENTAL PROCEDURE

To verify the applicability of the above presented propagation models, in-field data was gathered in the Botanic Garden of the University of Trás-os-Montes and Alto Douro. These data gatherings were made both in free-space and in vegetative medium. All the collected data are presented and analysed in Section IV.

Data gathering was made using the experimental set-up depicted in Fig. 1. Two IEEE802.15.4 transceivers were placed at the same distance to the ground, and since the antennas are not isotropic and consequently do not have an uniform propagation in all directions, the wireless nodes were faced at an angle of 0º relatively to the antenna position.

One of the transceivers (transmitter) continuously sends frames, at a rate of $10 frames/second$, that are received by the other node (Receiver). For every received frame the Receiver transmits, to a laptop running a data acquisition application, the corresponding RSSI (Received Signal Strength Indicator) value.

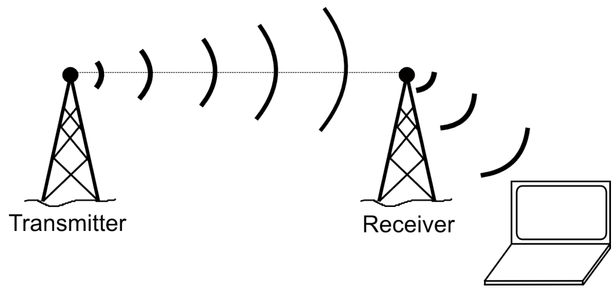

Figure 1. Experimental set-up.

A. Wireless nodes

The wireless nodes, used to acquire the path attenuation data, are based on the XBee IEE802.15.4 transceivers [21] from MaxStream and the low power 8-bit microcontroller PIC18F2620 from Microchip [22]. The output power of the transmitter was set to $1mW$ ($0dBm$), and both the receiver and the transmitter are equipped with a whip antenna with a gain of $-1.41dBi$. Fig. 2 hows the photography of one of the used wireless nodes.

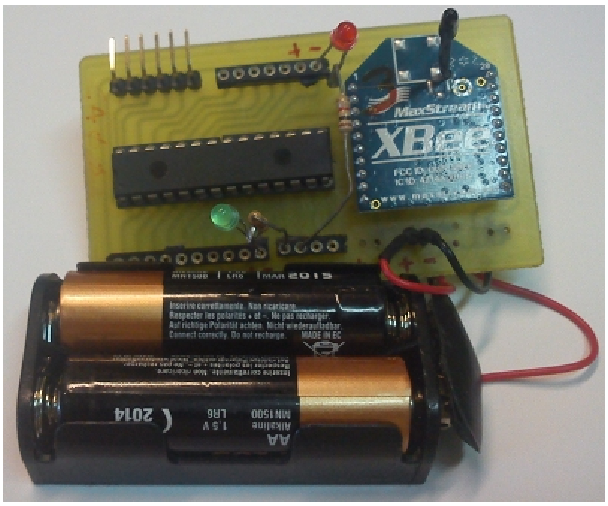

Figure 2. Photography of one of the wireless nodes used to gather the attenuation data.

Considering the gain of the antennas, using Eq. 1, the total path loss in our experimental set-up can be calculated using Eq. 10:

$$PL = -Pr + 2.82 \qquad (10)$$

where PL is the total path loss in dB and P_r the received power in dBm.

B. Data Gathering

An USB (Universal Serial Bus) interface card with an XBee transceiver is connected to the data gathering laptop. This node will ignore the frames coming from the Sender node (Fig. 1) and will only receive and decode the frames sent by the receiver, indicating the RSSI value of the last received frame.

A Java-based device driver, presented in [23], is used to receive and decode the IEEE802.15.4 frames, and send data to a Java applications, that stores it into a file.

For each data gathering:

- Channel C was used;
- Data was collected with the transceivers placed at different distances from each other ($1m$, $2m$, $3m$, $4m$, $5m$, and $10m$);
- The transmitter was programmed to send 10 frames per second;
- The frames where transmitted in unicast;
- Frames had a payload size of 10 bytes;
- For each collection point, a total of 100 samples was taken;

In the free-space attenuation measurements both transceivers were placed at different distances to the ground. When data was gathered in vegetation, both transceivers were placed at one half of the vegetation height.

IV. Tests and Results

In this section are presented the tests, made with the above described wireless modules, in free-space and in vegetation. Besides describing the tests, also the gathered data is presented and analysed. Also a comparison with the normally used propagation models is presented.

A. Free-space propagation

Using the RSSI values collected by the receiver it is possible, using Eq. 10, to determine the total path loss. To evaluate the effect of vegetation in the total path loss, the value of the free-space attenuation must be subtracted to Eq. 2. So the first test consisted in gathering the data about propagation in free-space.

To determine the influence of the distance to the ground in the free-space propagation, in this first test, the transceivers were placed at different distances to the ground. In Fig. 3 are presented the plots corresponding to the various attenuation values, obtained when placing the transceivers at different distances to the ground.

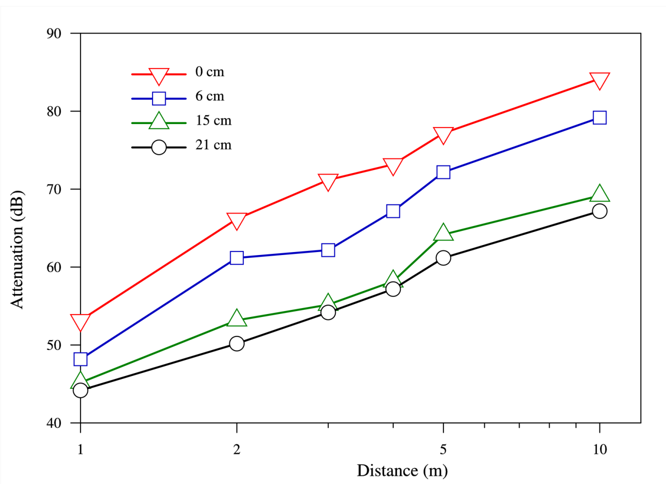

Figure 3. Free-space attenuation.

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Both $PL(d_0)$ and N (Eq. 3) are dependent on the distance to the ground. That dependency is highly noticeable for distances below approximately $15cm$. The different values of $PL(d_0)$ and N for the above data are presented in Table I. N was calculated using the least squares fitting procedure.

Distance to ground (cm)	$PL(d_0)$ (dB)	N
0	53.18	3.33
6	48.18	3.11
15	45.18	2.41
21	44.18	2.28

Table I
$PL(d_0)$ AND N VALUES OBTAINED AT DIFFERENT DISTANCES TO THE GROUND.

B. Propagation in vegetation

Three different plants were chosen for this set of tests in vegetation:

- Rosemary (*Rosmarinus officinalis*);
- Escallonia (*Escallonia laevis*);
- Creeping Juniper (*Juniperus horizontalis*).

These plants were chosen because they are evergreen plants. Choosing these type of plants, allowed to gather attenuation data without having to wait for the plants or the leafs to grow to start the tests, or having to end the tests in Autumn.

Attenuation measurements made in vegetation are presented in Table II. Distance values are in m and attenuation in dB. These attenuation values were obtained subtracting to the total path loss, obtained using Eq. 10, the value of the free-space path loss (presented in Fig. 3). In a) no values are presented because the received signal was too low due to a high attenuation, so it was not possible to read the attenuation value.

	Distance (m)					
Plant	1	2	3	4	5	10
Rosemary	12.33	11.33	11	11	18.78	a)
Escallonia	3.33	1.33	14	7	10.78	2.22
Creeping Juniper	8.33	15.33	15	14	16.78	a)

Table II
ATTENUATION VALUES OBTAINED FOR THE THREE TYPES OF PLANTS.

As it can be observed in Table II, and as it was expected, the attenuation values are different for each type of vegetation. Therefore it is not expected that the above presented models to correctly predict the attenuation values for the vegetation used in the tests.

In Table III are presented the expected values of attenuation, using the various propagation models. None of the models is able to correctly predict the attenuation values. These models were not tuned for the types of vegetation used in this work.

Although the propagation models might give a good approximation when used in traditional wireless communications networks, they ate not suited to be used (directly) in this type of applications. However, they might be used if multiplied by a constant (α), as presented in Eq. 11:

$$PL_{tot} = PL_{fs} + \alpha A_{model} \qquad (11)$$

were PL_{tot} and PL_{fs} are as above, and A_{model} is the attenuation according to each model and α is a specific constant for the vegetation type.

In Table IV are presented the different values for α, obtained from the values presented in Table III. These values were determined using the least squares fitting procedure. Also the correlation factor (C.F.), between the propagation models (considering the values of α) and the acquired values, is presented in the table.

As expected from the previously presented data, the scale factor α will have different values for each one of the propagation models. Also the low values for the correlation factor were expected for Rosemary and Escallonia, because these type of plants do not have a compact and evenly distribution, and there were gaps between the plants. On the other hand, Creeping Juniper had a more evenly distribution therefore the corresponding correlation factor has a better value (91%).

C. Effect of the spatial distribution of plants

The above presented tests dis not take into account the spatial distribution of the plants, i.e., it was only considered the length of the vegetative path and not the percentage of path covered by the vegetation. To evaluate the influence of the space between the plants, in the value of the path attenuation, another test was made, now considering the spatial distribution of the plants.

In this new test, made with Rosemary, consisted in measuring the attenuation values in 6 different scenarios, with different percentage of area covered by vegetation. In Fig. 4 is depicted one of those scenarios (Scenario 3 of table V). In this example the total path length is $280cm$, the length covered by vegetation is $200cm$ therefore the percentage of vegetation in the path is 71.43%.

	Distance (m)					
Prop. Model	1	2	3	4	5	10
Weissberger MED	0.58	1.15	1.73	2.31	2.89	5.77
COST-235 Model	14.54	17.42	19.35	20.86	22.10	26.47
ITU-R(FITU-R)	8.12	9.65	10.68	11.48	12.14	14.43
Early ITU	2.07	3.13	3.99	4.75	5.43	8.22
Sing. Veg. Obstr.	0.5	1	1.5	2	2.5	5

Table III
EXPECTED ATTENUATION VALUES USING THE PROPAGATION MODELS.

	Rosemary		Escallonia		C. Juniper	
Propagation Model	α	C.F.	α	C.F.	α	C.F
Weissberger MED	5.93	0.52	1.04	0.20	6.50	0.91
COST-235 Model	0.61	0.38	4.22	0.33	0.67	0.91
ITU-R(FITU-R)	1.11	0.38	4.30	0.33	1.22	0.91
Early ITU	2.87	0.45	2.42	0.28	3.15	0.91
Sing. Veg. Obstr.	6.84	0.52	1.04	0.20	7.50	0.91

Table IV
CALCULATED α PARAMETER VALUES AND CORRESPONDING CORRELATION FACTOR.

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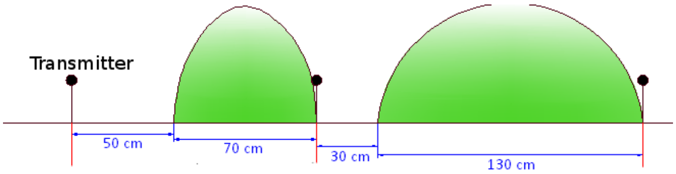

Figure 4. Example of a scenario where measurements in Rosemary were made.

In Table V are presented, for each scenario, the calculated values of the parameter α, the distance at which it was calculated (path length) and the percentage of vegetation in the propagation path.

Scenario Nbr.	% Vegetation in Path	Path Length	α
1	80.00	450	9.13
2	76.47	170	10.37
3	71.43	280	6.99
4	67.05	440	7.45
5	25.93	680	2.54
6	100.00	140	12.45

Table V
VALUES OF α OBTAINED FOR DIFFERENT PERCENTAGES OF VEGETATION BETWEEN THE TRANCEIVERS.

In Fig. 5, a plot of the value of α as a function of the percentage of vegetation is presented. For the gathered data, there is an almost linear relation between the percentage of vegetation in the path and the value α.

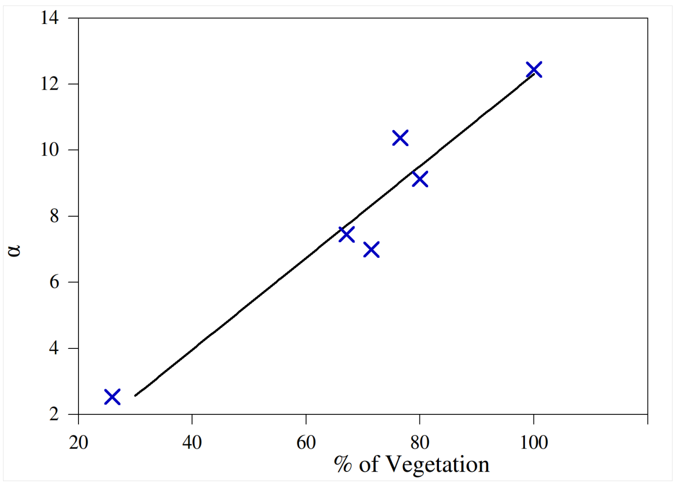

Figure 5. α values as a function of the percentage of vegetation.

From the above presented data, we can then conclude that the multiplicative constant α depends on a factor that is related both with the type of vegetation, and the percentage of vegetation in the path. If we take for example the Weissberger MED, it can then be expressed as:

$$A_{Veg} = \rho\beta 0.45 f^{0.284} d \tag{12}$$

where A_{Veg} is the total attenuation due to the vegetation type, β is a constant dependent on the vegetation and ρ is the density of vegetation in the path ($0 \leq \rho \leq 1$). Note that this formulation can also be made for the other propagation models.

Table VI presents the comparison between the values measured in the various scenarios and the values obtained using Eq. 12. For this comparison it was considered that $\beta = 11.30$, which was obtained using the values of β for each one of the above mentioned scenarios, using Eq. 13:

$$\beta = \frac{1}{n}\sum_{i=1}^{n}\frac{\alpha_i}{\rho_i} \tag{13}$$

Sc. Nbr.	% Veg. in Path	Path Len. (m)	Real P.L. (dB)	Model P.L. (dB)	Error (%)
1	80.00	4.50	82.18	82.06	0.15
2	76.47	1.70	59.18	57.53	2.79
3	71.43	2.80	65.16	66.96	2.77
4	67.05	4.40	77.18	77.58	0.52
5	25.93	6.80	68.18	69.42	1.83
6	100.00	1.40	57.18	56.29	1.55

Table VI
COMPARISON OF THE MEASURED ATTENUATION WITH THE VALUES OBTAINED USING THE MODEL APPROXIMATION.

In the table are presented the length of vegetation in the path, the total length of the path, the real values of the path loss, the path loss calculated using the modified Weissberger model and the absolute value of the relative error.

The relative error was very low for all the scenarios, and its mean value, for the acquired data, is 1.60%. A comparison between the mean absolute percentage errors and β values for the Weissberger MED, COST235, Fitted ITU-R and Early ITU models are presented in Table VII.

Model	β	Error (%)
Weissberger MED	11.35	1.60
COST235	0.99	6.00
Fitted ITU-R	28.24	6.12
Early ITU	35.18	2.81

Table VII
β VALUES AND RELATIVE ERROR FOR EACH PROPAGATION MODEL.

Besides these models, also the Single Vegetative Obstruction Model was presented in section II. This model, unlike the others, considers the type of vegetation (γ). Using the gathered data $\gamma = 4.24dB/m$ was obtained. This value was determined calculating the mean value of γ for each of the above presented scenarios. For each scenario, a γ was calculated using Eq. 14:

$$\gamma = \frac{A_{veg}}{d} \tag{14}$$

were d is the total path length in m.

With this γ value, a mean absolute percentage error of 6.65% was obtained.

On the other hand, if we consider only the length of the path with vegetation in Eq. 14, a new value $\gamma = 6.65dB/m$ is obtained. Unlike the above presented value, this new value considers only the attenuation in vegetation and does not consider the gaps between the vegetation. If we use this new value of γ the result will not reflect the actual value

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of the attenuation. For the gathered data, a mean absolute percentage error of 12.75% is obtained.

However, if we reformulate the the Single Vegetative Obstruction Model to to include the vegetation density, Eq. 15, a mean absolute percentage error of 1.70% is obtained. Which is much better than any of the other values obtained for this model.

$$A_{ev} = \rho d \gamma \tag{15}$$

It can be concluded that all the vegetation propagation models can be used, if we consider the type of vegetation and its distribution along the propagation path.

V. Conclusion and Future Work

The effect of the vegetation in the propagation of electromagnetic waves can be predicted using propagation models. Although there are propagation models which are normally used in the conception and analysis of wireless communications networks, these models cannot be directly used in applications that use wireless sensor networks, based on WPAN (Wireless Personal Area Network) technologies, such as IEEE802.15.4.

In this paper several propagation models, normally used in vegetative propagation paths, were presented and compared with real data acquired in vegetation. These tests allowed to conclude that different types of vegetation have distinct specific attenuation values. Also the distribution of the vegetation along the propagation path must be considered when analysing the attenuation due to the vegetation. So for the presented models to be applied in agricultural environments, they must be adapted, to include the specific effect of each type of vegetation and its density.

The proposed adaptation to the propagation models consists in multiplying them by two new parameters: the percentage of vegetation along the propagation path; a specific attenuation value, dependent on the type of vegetation. In this paper some tests were made in vegetation, and the value of the vegetation specific parameter for Rosemary is determined.

From the analysed propagation models, Weissberger MED and the Single Vegetative Obstruction Model were the models that had better results with mean absolute percentage errors of 1.60% and 1.70%, respectively.

Future developments of this work will include:

- Determine the specific parameters for different types of plants and crops;
- Study the influence of the different stages of the plant development in these values.

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