Vegetation Growth Detection Using Wireless Sensor Networks

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***Abstract*—Silvopastoralism is an activity with multiple benefits from both the ecological and economical points of view. Besides the potential cash flow to landowners, it has multiple environmental advantages and it can even help to reduce fire hazard in woodland. This hazard reduction is due to cattle grazing, and for it to become effective, it is needed to move herds to the correct place at the correct time. Only knowing when and where shrubs and sward are ready for grazing it is possible to make an effective management of herd placement. *In loco* inspection of the terrain can be time and resource consuming, as large areas must be verified. An automated system to detect the presence of shrubs and sward can help to improve the management of herds. Since Wireless Sensor Networks (WSN) have spread in the last years and, are becoming very popular in agricultural applications, the objective of this work is to analyse the effect of vegetation in radio-frequency (RF) signals propagation, and use it to detect plants growth. Experiments showed that by measuring and analysing the attenuation in wireless links it is possible to detect plants growth. Besides providing the infrastructure to transmit data from field wireless sensors, the network itself can be used as the sensor.**

***Index Terms*—Wireless Sensor Networks, Propagation models, Propagation in vegetation, Plant growth detection, IEEE802.15.4**

I. INTRODUCTION

Benefits of silvopastoralism can be analysed from the economical and ecological points of view, in both cases it is a practice that has several advantages. As an economic activity it can be seen as an attractive management alternative that has potential to increase landowners cash flow, since it allows the production of timber, forage and livestock in the same place [1]. Besides that, trees can be used to provide other products such as fruits, cork, among others [2], and the shade that trees provide to livestock can enhance their productivity [3], for example in milk production.

From the ecological point of view, silvopastoralism helps to obtain biodiversity, as it enhances the survival of wildlife (providing it food and refuge), helps to reduce soil erosion and avoids landslide by anchoring soils [3]. Since the recycling of nutrients, from animal wastes, occurs, it also helps to reduce the need for artificial fertilization. The need for chemical or mechanical vegetation control is also reduced [1].

Additionally, vegetation under the trees can be used as fodder. Cattle grazing can therefore be used to clean vegetation under the trees, reducing plant fuel. Consequently, it will contribute to reduce the fire hazard [4]. For this plant fuel cleaning to be effective, herds must be sent to the correct place at the right time. This is only possible and profitable if the vegetation height is monitored, allowing the manager to plan the correct movements of herds.

Performing *in loco* terrain inspection, and observe vegetation growth can be time and resource consuming, as large areas must be analysed. An automated system able to detect shrubs and sward growth can improve the management of vegetation height, helping to decide when and where to send herds to clean plant fuel in woodlands.

Instead of using the traditional methods to detect vegetation growth, we propose the use of electromagnetic waves to do it. Electromagnetic waves used by wireless communications systems suffer attenuation due to the presence of vegetation. This attenuation, that usually is considered a disadvantage, is used in this work to detect the presence of vegetation and characterize its growth. The objective of this paper is to show that electromagnetic waves can be used to detect vegetation.

Electromagnetic waves are affected by trees that make part of the forest, however, trees foliage is above the sensors. Sensors will be placed near the ground, where tall trees will not influence. Small trees are part of the vegetation that we want to detect, therefore, if they appear between two wireless nodes, there is no problem.

II. MATERIALS AND METHODS

A. Wireless Sensor Networks

Wireless systems, and Wireless Sensor Networks (WSN) particularly, are becoming widely adopted and are spread in many applications. Due to its flexibility we have been using wireless technologies in agricultural environments for a long time [5], [6]. Nowadays, wireless sensors are becoming more and more used in agricultural applications. We intend to use it in agroforestry environments, not only to transport data from sensors (spread in the field or carried by workers and livestock), but also to detect vegetation growth.

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Nodes that belong to Wireless Networks are not homogeneous, because they can be made by different manufacturers, be based on different hardware platforms and projected by different developers. For all wireless nodes to effectively work in a networked environment, they must be able to communicate with each other, using a common protocol. It is then very important to correctly choose the communications protocol for the WSN. Choosing a widely adopted communications protocol is then advisable.

In the present work an IEEE 802.15.4 [7] based network is used. ZigBee [8], which is one standard with a large adoption by the WSN developers community [9], operates on top of IEEE 802.15.4. Both protocols have in fact an increasing importance in WSN implementation [10], and ZigBee, which adds the upper layers of the protocol stack, is considered the most promising standard for wireless sensors [11].

Besides low resource end-devices, where sensors are connected, IEEE 802.15.4 and ZigBee define the existence of devices with more resources than end-devices, that act as network coordinators (ZigBee and IEEE 802.15.4) or routers (ZigBee). Those devices are the wireless sensor network infrastructure, which allows data to flow between source and destination nodes. This network infrastructure can also be used to act as a sensing element, since they have fixed geographical position, they can be used to measure the vegetation growth between wireless nodes.

B. Vegetation detection using electromagnetic waves

Wireless communication systems use electromagnetic radiation which travels from the transmitter to the receiver. This radiation suffers changes that influences the direction and the way it propagates. Attenuation suffered by electromagnetic waves can be separated into the free-space attenuation and the excess attenuation due to the environment characteristics. Free-space attenuation, due to wave spreading as it gets far from the origin antenna, raises with the square of the distance. This effect is shown in Eq. 1, the Friis free-space equation.

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{1}$$

This equation gives received power, P_r, as a function of the transmitter power, P_t. Parameters G_r and G_t are the gain of the receiving and transmitting antenna respectively, L is the loss factor, λ the wavelength and d the distance.

Besides free-space attenuation, the propagation medium and obstacles cause electromagnetic waves to suffer changes, mainly caused by reflections, diffraction and scattering. This excess attenuation, that usually is considered a disadvantage in communication systems, is used in this work to detect the presence of vegetation.

Let us consider the scenario presented in Fig. 1, constituted by three wireless nodes, using radio-frequency communications, and placed in a field with vegetation. Attenuation suffered by communications between nodes 1 and 2 is different from the attenuation suffered by communication between nodes 2 and 3 – considering the same distance between the nodes. Vegetation found between nodes 2 and 3 covers the Line-of-Sight between those nodes and will cause an excess of attenuation in the path.

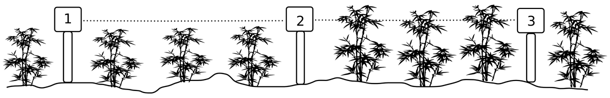

Figure 1. Working principle of the plant growth detection: as plants grow beyond a certain limit, they start cover the Line-of-Sight between nodes, increasing the link Path Loss.

Also the correct placement of nodes and antennas will determine the height of vegetation to be detected by the system.

There are several propagation models, that can help to determine the behaviour of electromagnetic waves, when travelling from the transmitter to the receiver. In a Line-of-Sight configuration if we consider PL_{fs} as the total Path Loss (PL) in free space, and A_{env} the attenuation due to environmental effects (that includes vegetation), the Total Path Loss (PL_{tot}) is given by Eq. 2:

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

where A_{env} represents the excess Path Loss due to environmental characteristics such as the presence of water, logs or leaves on the ground and the presence of vegetation between the two antennas.

C. Propagation Models

As in most wireless sensor applications our system is based on a 8-bit low-cost and low-power microcontroller. In our prototypes we use a nanoWatt Technology microcontroller from Microchip, a PIC18F2620 [12]. So, since the system is composed by low-resource networked nodes, simple and low computational complexity propagation models must be used. The main purpose of the nodes is to acquire data and/or route information, not to solve computation intensive mathematical problems.

Empirical Path Loss prediction models are used, since they are simple. The three main models are [13], [14]: the Okumura-Hata model [15]; the COST-Walfisch model [16]; the Two-slope model [17].

Although those models are intended for use in outdoor propagation, which is the case of the present work, they might not be the most suitable for our work. Typically used propagation models are suitable for wireless networks operating with a coverage area from hundreds of meters to tens of kilometres, the antennas are usually placed in a high place and far from the ground, obstacles to propagation are buildings, mountains, trees and moving vehicles.

Our system, on the other hand, has a small coverage area of a few tens of meters, the antennas are placed very close to the ground and obstacles are rocks, weeds, shrubs and animals.

To analyse the attenuation due to vegetation growth, the first step is to estimate the free-space Path Loss term (PL_{fs}) in Eq. 2. For this parameter we considered Eq. 3 [18], used also by other authors to model propagation [19], and it gives the Path Loss (PL) in dB, as a function of the distance.

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

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In this equation N represents the Path Loss exponent and d_0 is an arbitrary distance. X_σ denotes a Gaussian variable with zero mean and standard deviation σ. The value of the reference distance (d_0) varies from application to application. Typically for outdoor applications it is used a distance of 1 km for large urban mobile systems, $100m$ for microcell systems and $1m$ for indoor propagation [18]. Since our application is intended for short distances, $d_0 = 1m$ was considered, so d is in meters.

Not only the effect of propagation in free-space must be considered. Since we intend to detect vegetation also a propagation model for vegetative environment must be considered. The excess of attenuation due to vegetation can be calculated using the ITU model for attenuation in vegetation in terrestrial path with one terminal in the woodland [20], given by Eq. 4. This equation gives the excess attenuation (A_{ev}), as a function of the length of the path in the woodland (d) in meters, the specific attenuation for very short vegetative paths (γ), expressed in dB/m and the maximum attenuation for one terminal within a specific type and depth of vegetation (A_m), in dB.

$$A_{ev} = A_m \left(1 - e^{-\frac{d\gamma}{A_m}}\right) \quad (4)$$

Excess attenuation due to vegetative medium can also be calculated using the Weissberger MED (Modified Exponential Decay) model [21], Eq. 5. This model gives the losses due to trees, in dB, at a given working frequency (f), in GHz, with foliage depth of $d\ m$.

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

Another way to calculate the excess attenuation due to vegetation is using Eq. 6, the COST235 model, also used by other authors [22] to estimate the effect of vegetation in wave propagation. As the previous model, it gives the losses in dB, for a given frequency (f), in GHz, with foliage depth of $d\ m$.

$$L = 15.6 f^{-0.009} d^{0.26} \quad (6)$$

A simulation that compares the Free-Space attenuation, using Eq. 2, with the attenuation due to vegetation is shown in Fig. 2. In this simulation, values of excess attenuation due to vegetation given by Eq. 4, Eq. 5 and Eq. 6 were added to values obtained for the free-space propagation.

Since IEEE 802.15.4 is used as wireless sensor network technology, in simulations the frequency 2.45 GHz was considered. For the free-space propagation the considered value of N is 3.0 and for $PL(d_0)$ the real value, measured at a distance of 1 m with our equipment was considered, so it was used $PL(d_0) = 52$ dB. For attenuation with the ITU model, we considered the example values presented in the recommendations [20]: $\gamma = 0.45$ and $Am = 0.18 f^{0.752}$.

The simulation of results shows that analysing the Path Loss between two wireless nodes, that increases as the vegetation grows, it is possible to detect the presence of obstacles. In our case these obstacles are shrubs or sward, that progressively and slowly cause the radio frequency signal to fade, as they grow.

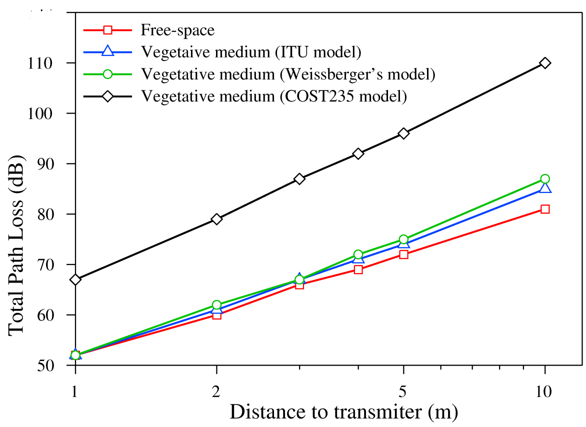

Figure 2. Simulation of electromagnetic waves attenuation in free-space and in vegetative mediums, using the ITU, the Weissberger and COST235 models.

D. In situ measurements

Validation of the proposed method for vegetation detection in silvopastoral environments implies a set of attenuation measurements in free-space and vegetative mediums. Those in-field measurements, whose results are presented in the Results section, were made using the developed 8-bit microcontroller-based prototypes, shown in Fig 3. As radio interface to the microcontroller, XBee IEEE 802.15.4 modules from MaxStream [23] were used. The output power of each transmitter was set to $1mW$ ($0dBm$).

Path attenuation is calculated based on the RSSI (Received Signal Strength Indication) value indicated by the receiving module. Whenever a radio module receives a frame, it indicates to the microcontroller the corresponding RSSI value, in dBm. Since the output power of the transmitter and the antennas gains are known, we can determine the attenuation value using Eq. 7:

$$P_r = P_t - PL + G_t + G_r \quad (7)$$

Where P_r is the received power (in dBm), P_t is the transmission power (in dBm), PL is the total Path Loss (in dB), G_t and G_r are respectively the gain if the transmitting and the receiving antenna. Total Path Loss can be then

Figure 3. Prototype based on a 8-bit microcontroller and XBee module.

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expressed as:

$$PL = P_t - P_r + G_t + G_r \quad (8)$$

The transmitter output power (P_t) is set to $0dBm$, then the Path Loss value (PL), in dB, is $PL = -P_r + G_t + G_r$. Since RSSI indicates the received power, then $PL = -RSSI + G_t + G_r$. All measured values presented in this work are the mean values, as done by other authors [18].

Inside the woodland where the tests were conducted, three different types of propagation micro-environments were chosen to make the measurements presented in the next section. All those areas were chosen to allow Line-of-Sight between the transmitter and the receiver, without any non-vegetative obstacle. The three different chosen areas types were:

- Clear area, without any obstacle between transmitter and receiver (vegetative or non-vegetative), to evaluate the free-space propagation behaviour of the used transceivers;
- Very dense weeds and grass area, where a maximum signal attenuation is expected. The chosen area had plant height varying between 12 and $50cm$ approximately;
- Low-density vegetation area, with small plants, with a height of approximately $10cm$, where plants were randomly placed, by mother nature, and without any human intervention. This area had a plant density of approximately 35 plants (very small oak trees) per square meter.

When deployed in the field, antennas will be placed at a fixed distance to the ground, and, as vegetation grows they are covered by vegetation, as shown in Fig. 4.

To simulate the the different steps of plant growth, attenuation readings, based on the reported RSSI values, were made at different distances to the ground:

- $10cm$ to the ground, to simulate situation (a), where the vegetation does not cover the Line-of-Sight between the antennas;
- $5cm$ to the ground to simulate (b), where the vegetation as grow and starts to cover the antennas;
- At ground level to simulate (c), where the vegetation totally covers the Line-of-Sight between the two nodes.

Distance to the ground will influence the link attenuation, independently of the density of the vegetation. So, to have a reference value, that will allow to determine the excess of attenuation, only due to vegetation, there were also taken measurements in free-space at different distances to the ground.

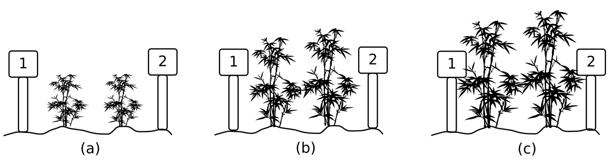

Figure 4. The different stages of the plant growth have different effects on signal attenuation: (a) no attenuation since plants are below the antennas Line-of-Sight; (b) the plants start to cover the path between antennas and its effect starts to be noticed; (c) plants totally cover the path between antennas causing a maximum attenuation.

Since the used transceivers are very low power ($0dBm$), and wireless sensor networks are expected to operate in a very short range area, $10m$ according to the the IEEE 802.15.4 specifications, all the measurements were made up to this distance.

III. Results

As stated in the previous section, to validate the proposed vegetation growth detection method, several measurements were made in a real woodland scenario. Those in-field measurements included the measurement of Path Loss with and without vegetation, with different vegetation densities and at different distances from the ground, simulating plant growth, to evaluate the relation between the plant height and the antenna placement.

The first set of measurements was taken with the transmitter and the receiver at the ground level and it included the measurement of attenuation in the three specified areas types. Results from this set of measurements are shown in Fig. 5, where the lower plot corresponds to measurements in a clear area, where as expected the lower attenuation values were found. The other plots correspond to the attenuation in a low-density vegetation area (middle plot), and in a very dense weeds and grass area (top plot), where the higher attenuation was observed.

Results from the second set of measurements are presented in Fig. 6. Attenuation measurements, were taken in the low-density vegetation area, at different distances from the ground. The two upper plots correspond to the free-space and in vegetation attenuation, at ground level. The middle plots correspond to a distance of $5cm$ and the lower plots to a distance of $10cm$. In all measurements, both nodes were placed at the same distance from the ground.

Values of propagation in free-space are used as a reference, so the excess of attenuation due to the presence of vegetation can be determined by subtracting the values for total Path Loss and path loss in free-space.

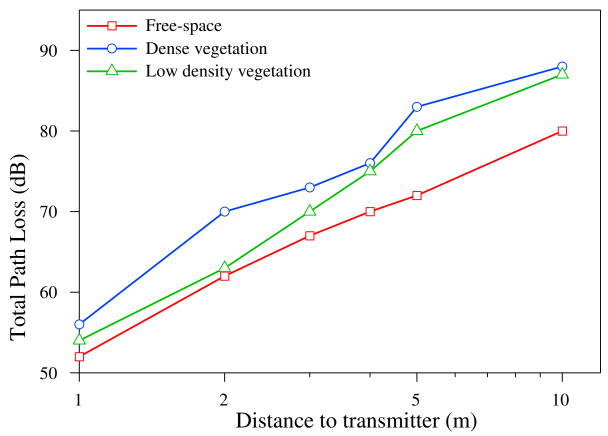

Figure 5. Comparison between the different attenuation values, measured at various distances to the transmitter with different propagation medium: free-air, dense grass/weeds and low-density vegetation at ground level.

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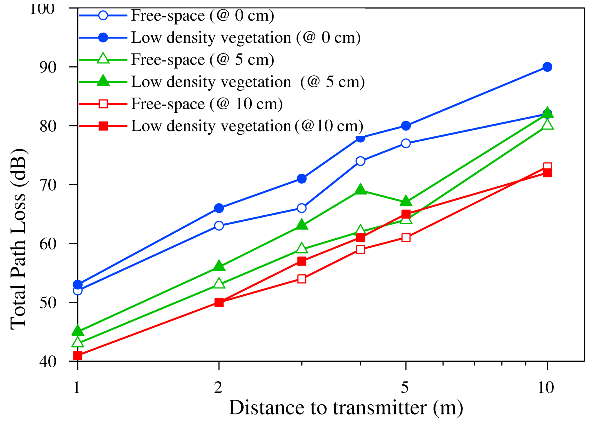

Figure 6. Comparison between the different attenuation values, measured at various distances to the transmitter, at different distances to the ground, in free-space and in low-density vegetation.

IV. Discussion

Observing data from Fig. 5 and Fig. 6, where the attenuation due to vegetation is compared with free-space attenuation, it is clear that vegetation type, density and height will influence the Path Loss in the wireless links. Data from Fig. 6 shows that when the vegetation is below the antenna, propagation is very similar to free-space propagation, and as vegetation grows the attenuation starts to increase.

Differences between the plot for low density vegetation in Fig. 5 and low density vegetation at $0cm$ from the ground, in Fig. 6, are due to the fact that readings where made in the same vegetation area, but not made exactly in the same places. One can observe that even the fact that values are not exactly the same, however they are very similar.

Measured values for free-space attenuation were compared with the considered theoretical model (Eq. 3), and the Path Loss exponent N was calculated based on the measured data using the least squares fitting procedure. The result of this comparison is shown in Fig. 7, where the real results and the simulated values are shown.

Based on the plots from Fig.6, one can conclude that the chosen model can be used, so Eq. 2 becomes:

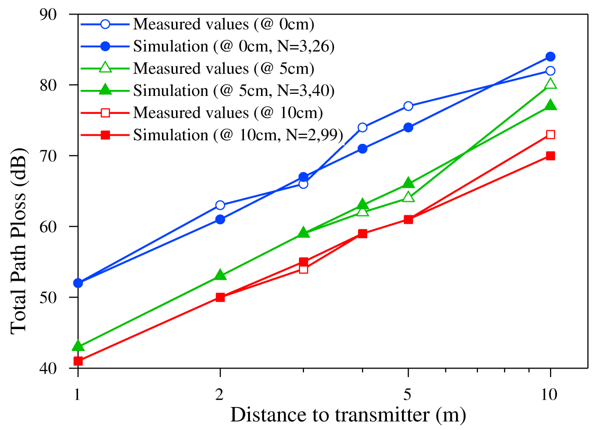

Figure 7. Comparison between the measured and the simulated values for the free-space attenuation, for various distances to the transmitter, at different distances to the ground.

$$PL(d) = PL(d_0) + 10N log\left(\frac{d}{d_0}\right) + PL_{env} \quad (9)$$

where N and $PL(d_0)$ are related with the distance between the transmitting/receiving antenna and the ground.

Analysing acquired data it can be concluded that the attenuation due to vegetation can be expressed as a function of Weissberger's Modified Exponential Decay Model, for distances below 14 m, multiplied by an attenuation constant, K_{aw}. That attenuation constant is dependent on the type, density and geometry of vegetation. The total Path Loss can then be expressed by Eq. 10:

$$PL(d) = PL(d_0) + 10N log\left(\frac{d}{d_0}\right) + K_{aw} 0.45 f^{0.284} d \quad (10)$$

The attenuation constant (K_{aw}) was calculated for each distance to the ground, from the acquired data, using the least squares fitting procedure. In Table I are shown the different values for K_{aw} at different distances from the ground. This table also shows the comparison between the values for two types and densities of vegetation when the antennas are totally covered by vegetation.

Higher values of K_{aw} implies higher attenuation due to vegetative obstacles. So, analysing data one can conclude that the height of the plants to be detected, as expected, influences the distance to the ground at which the antenna should be placed.

Correct values for the constant depend on of the type, density and geometry of vegetation. Savage et al. [24] identified and studied four main geometries, that dictates the dominant modes of propagation through vegetation: line of trees, into vegetation, wedge vegetation and edge of vegetation.

The value for the attenuation constant was calculated for all the measured values, it is then the value that best fits all the samples. A value of $K_{aw} = 0.45$ is obtained when the antenna is placed over the line of vegetation, where influence from vegetation is expected to be residual. Observing Fig. 5 and Fig. 6 it is clear that, for large distances, the excess of attenuation, due to vegetation, is almost null when the top of the vegetation is below the antenna. In this case we can consider that propagation is done as if it were Line-of-Sight.

When the antenna is covered by vegetation, observing Fig. 5 and Fig. 6, excess attenuation varies from $8dB$, when the vegetation fully covers the transmitting and the receiving antennas and $2dB$, when the antennas are partially covered by vegetation.

	Low density vegetation			High density vegetation
	$0cm$	$5cm$	$10cm$	$0cm$
K_{aw}	1.39	1.02	0.45	1.43

Table I
Comparison of different attenuation constants in different types of vegetation

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V. Conclusion

Average attenuation value is affected by the presence of vegetation between two wireless nodes, as it was expected, and can be seen in the presented results. Signal attenuation due to vegetation, which is typically seen as a disadvantage in WSN applications, can be used as a sensing principle to detect the vegetation growth.

So, besides the use to transport data from sensors, Wireless Sensor Networks can also be used to act as the sensor itself. The same electromagnetic waves used by the radio systems to transport data can act as the vegetation sensing element, as they are influenced by the vegetation presence.

As expected from the analysis of the propagation models, electromagnetic waves can then be used in the proposed system to detect the growth of shrubs and sward in silvopastoral environments.

Field measurements confirmed that the height of the plants to be detected is related with the correct installation of the antennas. The distance of the antennas to the ground must then be correctly chosen and adequate for the vegetation height that must be detected.

Since vegetation does not grow very fast, the presence of a new obstacle between the wireless nodes can easily be detected. If an animal passes between the nodes, or a permanent obstacle appears between two nodes it will be easily detected, because it will cause a fast change in the attenuation levels, which is not possible in normal operation. Since this statistical analysis is relatively simple, it can be easily implemented in the autonomous wireless nodes or in a near coordinator system. Obviously that this analysis can also be performed in a remote, and more powerful system where data from all field sensors are analysed.

References

[1] J. Nowak, A. Blount, and S. Workman, "Integrated Timber, Forage and Livestock Production - Benefits of Silvopasture," University of Florida - Institute of Food and Agricultural Sciences Extension, Circular 1430, December 2002. [Online]. Available: http://edis.ifas.ufl.edu/pdffiles/FR/FR13900.pdf

[2] A. S. Miguel-Ayanz, "Mediterranean european silvopastoral systems," in *Proceeding of an Silvopastoralism and Sustainable Land Management*. CABI Publishing, April 2004, pp. 36–40.

[3] S. Pagiola, E. Ramirez, J. Gobbi, C. de Haan, M. Ibrahim, E. Murgueitio, and J. P. Ruiz, "Paying for the environmental services of silvopastoral practices in Nicaragua," *Ecological Economics*, no. In Press, p. Available online 4 June 2007, 2007.

[4] M. R. Mosquera-Losada, E. Fernandez-Nunez, and A. Rigueiro-Rodriguez, "Pasture, tree and soil evolution in silvopastoral systems of Atlantic Europe," *Forest Ecology and Management*, vol. 232, no. 1-3, pp. 135–145, August 2006.

[5] C. A. Serodio, J. Monteiro, and C. Couto, "An integrated network for agricultural management applications," in *Proceedings of 1998 IEEE International Symposium on Industrial Electronics*, vol. 2, 7-10 July 1998, pp. 679–683.

[6] C. Serodio, J. B. Cunha, R. Morais, C. Couto, and J. Monteiro, "A networked platform for agricultural management systems," *Computers and Electronics in Agriculture*, vol. 31, no. 1, pp. 75–90, March 2001.

[7] IEEE, *IEEE standard 802.15.4 – Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)*, IEEE, 2003. [Online]. Available: http://standards.ieee.org/getieee802/download/802.15.4-2003.pdf

[8] ZigBee Alliance, *ZigBee-2007 Specification*, January 2008.

[9] A. Camilli, C. E. Cugnasca, A. M. Saraiva, A. R. Hirakawa, and P. L. Correa, "From wireless sensors to field mapping: Anatomy of an application for precision agriculture," *Computers and Electronics in Agriculture*, vol. 58, no. 1, pp. 25–36, 2007.

[10] P. Baronti, P. Pillai, V. W. Chook, S. Chessa, A. Gotta, and Y. F. Hu, "Wireless sensor networks: A survey on the state of the art and the 802.15.4 and ZigBee standards," *Computer Communications*, vol. 30, no. 7, pp. 1655–1695, 26 May 2007.

[11] N. Wang, N. Zhang, and M. Wang, "Wireless sensors in agriculture and food industry–recent development and future perspective," *Computers and Electronics in Agriculture*, vol. 50, no. 1, pp. 1–14, January 2006.

[12] Microchip Technology Inc., *PIC18F2525/2620/4525/4620 Data Sheet, Enhanced Flash Microcontrollers with 10-Bit A/D and nanoWatt Technology*, 2007.

[13] P. Pajusco, "Propagation channel models for mobile communication," *Comptes Rendus Physique*, vol. 7, no. 7, pp. 703–714, September 2006.

[14] T. Sarkar, J. Zhong, K. Kyungjung, A. Medouri, and M. Salazar-Palma, "A survey of various propagation models for mobile communication," *IEEE Antennas and Propagation Magazine*, vol. 45, no. 2, pp. 51–82, June 2003.

[15] M. Hata, "Empirical formula for propagation loss in land mobile radio services," *IEEE Transactions on Vehicular Technology*, vol. 29, no. 3, pp. 317–325, August 1980.

[16] J. Walfisch and H. Bertoni, "A theoretical model of UHF propagation in urban environments," *IEEE Transactions on Antennas and Propagation*, vol. 36, no. 12, pp. 1788–1796, December 1988.

[17] S. Min and H. Bertoni, "Effect of path loss model on CDMA system design for highway microcells," vol. 2, May 1998, pp. 1009–1013.

[18] J. Andersen, T. Rappaport, and S. Yoshida, "Propagation Measurements and Models for Wireless Communications Channels," *IEEE Communications Magazine*, vol. 33, no. 1, pp. 42–49, January 1995.

[19] P. Pagani and P. Pajusco, "Statistical modeling of the ultra wide band propagation channel through the analysis of experimental measurements," *Comptes Rendus Physique*, vol. 7, no. 7, pp. 762–773, September 2006.

[20] ITU, "Recommendation ITU-R P.833-2, Attenuation in Vegetation," 1999.

[21] M. A. Weissberger, "An Initial Critical Summary of Models for Predicting the Attenuation of Radio Waves by Trees," Electromagnetic Compatibility Analysis Center, Annapolis MD, Final report, July 1982.

[22] E. Tameh and A. Nix, "The use of measurement data to analyse the performance of rooftop diffraction and foliage loss algorithms in a 3-d integrated urban/rural propagation model," in *VTC 98, 48th IEEE Vehicular Technology Conference*, vol. 1, 18-21 May 1998, pp. 303–307.

[23] I. MaxStream, *XBeeTM/XBee-PRO(TM) OEM RF Modules - Product Manual v1.xAx - 802.15.4 Protocol*, 2006.

[24] N. Savage, D. Ndzi, J. Austin, and E. Vilar, "Signal propagation through vegetation: consideration for future broadband communication systems," in *ICAP 2003, Twelfth International Conference on Antennas and Propagation*, vol. 2, 31 March-3 April 2003, pp. 641–645.