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WIRELESS SENSOR NETWORK AS A MEASUREMENT TOOL IN PRECISION AGRICULTURE

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Abstract: In this work it is proposed a new tool to measure crop water-content using RF communication signals from nodes of a wireless sensor network. Accurate measurement is obtained combining data from many nodes spread in the crop field. The mathematical model of the measuring process is discussed and experimental data are presented supporting the model.

Keywords: radio signal attenuation, wireless sensor network, precision agriculture, vegetation canopy

1. INTRODUCTION

Precision Agriculture (PA), also denominated Precision Farming, is a method of treatment of large fields, that considers its spatial and temporal variability (soil attributes, plant diseases, yield, etc.), differently of old practices that are conducted in an uniform manner [1,2]. Variations in the order of 1:5 in grain yields, in a same field, have been reported [3], indicating that a site-specific management strategy of agricultural fields is needed. PA benefits from several technologies, including remote sensing, global positioning system (GPS), geographic information system (GIS), microelectronics and wireless communications [1,2].

Remote sensing in agriculture is used to monitor crop growth, retrieve soil and plant moisture, estimate crop area and yield [4-8]. It is a powerful tool to help agriculturists develop PA, taking decisions to manage crop fields in specific sites [1,2]. The satellite monitoring of agriculture has been made for the past decades, employing passive sensors (measurement of reflected solar radiation), and more recently, employing microwave active sensor techniques, with synthetic aperture radars (SAR) [4,5]. SAR is a radar technique that uses signal processing to provide better quality land observation compared old SLAR (Side Looking Airborne Radar), as soon as microcontroller numerical processing provides best resolution for images taken from SAR [5].

Most satellite systems provide images of great areas, in a square shape with 100 km of side or more, where each pixel represents a square of more than 200 m^2, but with a time resolution of more than 10 days (e.g., 16 days for Landsat 7, and 26 days for CBERS) [9,10]. Alternatively wireless sensor networks (WSNs), used for agricultural monitoring, give better spatial and temporal resolutions than satellites, besides allowing collection of others soil and plant data, as temperature, pH, soil electrical conductivity and moisture in several depths [11,12]. WSNs employ a wireless communication medium, distinct from fieldbus systems and other that use wired twisted pair [13]. Besides that, its nodes are equipped with some intelligence and memory, and are powered by small batterys, witch make them autonomous. This characteristics make WSNs indicated for precision agriculture applications. An additional advantage is that although its individual microsensor are not as accurate as macrosensors, the aggregation of many data enables high quality information about the environment.

In crop monitoring, the communication in a WSN is preferably performed by radio signals (RF), in despite of optical means, because line of sight is not guaranteed in the second. The RF signals are greatly attenuated by plants, especially due to the presence of water inside the leaves and stalks [5-7,12], as discussed in the next section. This characteristic can be used to measure variables of the crop where the WSN is inserted, eliminating the need of additional instrumentation.

2. PROPAGATION MODEL

In order to study this problem it is necessary to develop a mathematical model whose variables are the electromagnetic field, crop, soil and air.

Models for microwave propagation are derived from Maxwell equations [6-8,14]. A first choice is to use the Friis transmission formula, which models electromagnetic wave propagation in free space:

$$\frac{P_R}{P_T} = \left(\frac{\lambda}{4\pi d}\right)^2 G_T.G_R = L_{FS}.G_T.G_R \qquad (1)$$

where $\mathbf{P_R}$ and $\mathbf{P_T}$ are received and transmitted power, $\mathbf{G_T}$ and $\mathbf{G_R}$ are transmitter and receiver antenna gains, $\boldsymbol{\lambda}$ is wave length and **d** is the distance between transmitter and receiver. $\mathbf{L_{FS}}$ is said "free space transmission loss".

When transmitter and receiver are placed near the ground, "free space" condition can not be considered anymore. A more accurate model must be used, where another function takes the place of $\mathbf{L_{FS}}$. This function will model the effects of the soil, walls, and other obstacles and factors that influence the wave propagation.

Electromagnetic wave propagation models, like theory of microwave radiometry of vegetation, were developed for vegetal medium. These models consider that any material placed in the path of a electromagnetic wave acts as a dielectric and modifies its propagation, causing delay, deviation (diffraction), or absorption (attenuation) of its energy [14,15]. Many researches applying microwave radar signals have been conducted to identify moisture in plants and grains, for which, models were developed to quantify relations between radiometric observations and vegetation parameters, like leaf area index (LAI), biomass, plant water content, etc. The most popular models are the scatter model for an inhomogeneous half-space, developed by Fung [6], the water cloud model of Attema and Ulaby [7] and MIMICS (Michigan Microwave Canopy Scattering) developed by Ulaby [8]. All these works were devoted to microwave remote sensing, since microwaves have interesting characteristics. Microwave emissivity and absorvity vary strongly with soil and plants water contents and are almost insensitive to clouds [16].

In this work is adopted the Fung's model, where the vegetation canopy is considered as a continuos dielectric layer, and its dielectric constant (DC) is evaluated as a mean of plants and air contributions [6]:

$$\in_c = (\in_p V_p + V_a) / V \qquad (2)$$

where: V_p is the total volume of plants, V_a is the canopy volume occupied by air, and **V** is total volume of vegetation canopy; $\in_p$ is the mean dielectric constant of plants and $\in_c$ is a complex value representing the canopy DC.

Modeling microwave propagation in vegetation medium is a very complex task. For wave lengths in the order of centimeters, a leaf can be modeled as a one layer resistive sheet, as stalks are modeled as long cylinders. Vegetation canopy can be seen as scatterers which extinction and scattering properties are governed by their shape, size, orientation, and dielectric properties [17]. Modeling a canopy as a group of superimposed sheets (scatterers) randomly oriented would be very costly in computational terms. In Fung's model, some assumptions have been made, in order to establish a computational feasible description of the canopy [4]:

• The vegetation canopy is an equivalent medium with homogeneous complex DC ($\in_c = \in_c' - j\in_c''$), where $\in_c'$ and $\in_c''$ are real and imaginary parts of the complex equivalent dielectric constant of vegetation canopy;

• The inclusions are considered very small with respect to the wavelength; thus, scattering loss is minimum, and attenuation only comprises of absorption loss.

Plants are made primarily of water, with 4% to 5% of bulk vegetation, sometimes denominated dry vegetation. Besides this, the dielectric constant (DC) of water is much greater than the DC of dry mater, resulting that the DC of plants is governed by its water content [5,16]. Furthermore, air occupies about 99% of the canopy volume and its DC is much smaller than the water DC in microwaves region. So, one can say that vegetation water content is responsible for microwave absorption and scattering in the canopy.

After Fung [6] and Ulaby [7], Jackson [18,19] proposed a simple model that relates the canopy water content to the attenuation of microwaves propagating throw vegetation. According to Jackson, the optical depth (τ) of vegetation is expressed as a product of a parameter (**b**) by the vegetation water content (**W**) [18,19]:

$$\tau = b \cdot W \qquad (3)$$

W is the canopy water content per unit area (kg/m^2) and is calculated as the product of gravimetric moisture (m_g) of plants, the distance of propagation (**d**) inside the canopy and the fractional volume of plants (V_p/V):

$$W = m_g \cdot d \cdot V_p/V \qquad [kg/m^2] \qquad (4)$$

Optical depth (τ) is the total signal extinction (loss) when it propagates a distance (**d**) throw vegetation. It is related to the extinction coefficient (κ_e) of an homogeneous medium as the product of κ_e and **d**. Then κ_e is a function of **b**, m_g and V_p/V:

$$\kappa_e = b \cdot m_g \cdot V_p/V \qquad (5)$$

and m_g can be estimated by:

$$m_g = (1/b) \cdot \kappa_e \cdot V/V_p \qquad [m^3/m^3] \qquad (6)$$

Parameter **b** depends on the type of crop and the frequency of the microwaves. κ_e is also known as the power attenuation coefficient, and it describes the rate of RF wave power loss per distance when it propagates in a lossy medium. Its unit is nepers per meter (Np/m). Two factors contribute for power loss, absorption and scattering, then κ_e can be expressed as a sum of two terms: $\kappa_e = \kappa_a + \kappa_s$. In vegetal medium, microwave scattering losses are much small if compared to absorption losses, when its wavelength is of the order of centimeters. In this case scattering losses can be neglected ($\kappa_s = 0$), resulting that $\kappa_e = \kappa_a$.

3. PROPOSAL

It is proposed to identify characteristics of crops, like corn and cotton, by the measurement of radio signal power loss in a wireless sensor network, following Jackson's model [18,19]. In previous works, directional sources of electromagnetic waves were employed, performing punctual measurements with accurate equipments [6,7]. The method proposed here utilizes a large number of measuring devices not so accurate that are spread in a crop field. The aggregation of so many measurements gives a better representation of the variable of interest in a region of the crop field [20].

RF propagation occurs in almost all directions due to the employment of ¼ wave length (¼ λ) dipole (or monopole) antennas, resulting in signal attenuation. Path loss (**PL**) is the RF signal loss due to distance and environmental factors. In the environment of a vegetal crop, one can consider the distance between nodes, and the influence of soil and vegetation:

$$PL = P_T - P_R = L_{FS} + L_{soil} + L_v \qquad (7)$$

Transmitter and receiver antenna gains were not considered because they do not account for loss. Soil loss

(L_{soil}) depends on many factors, like its composition, roughness, moisture and temperature. Some authors model it as an increment in free space loss (L_{FS}), changing the exponent, 2, by another greater number, normally between 2 and 4 [14,21,22]:

$$L_{FS} + L_{soil} = (\lambda / 4\pi d)^n ; \qquad 2 < n < 4 \qquad (8)$$

Vegetation loss (L_v) depends primarily on its water content, as stated previously, and it is described by its transmissivity (γ), an exponential function of the optical depth (τ):

$$\gamma = P_R / P_T = e^{-\tau} = e^{-\kappa e.d} \qquad (9)$$

It is expected that all the characteristics but moisture remain unchanged within the period of crop growth. Then variations in path loss (**PL**) will be affected primarily by variations in vegetation loss, and, consequently in optical depth (τ) and vegetation water content (**W**). As soon as the distance **d**, the gains G_T and G_R, the soil roughness, and the transmitted power (P_T) are fixed, **PL** will be a function of **W** only. Thus, plant growing state, its biomass, or even the water stress occurrence, can be estimated by measuring variations in received RF power (P_R). P_R is evaluated as:

$$P_R = P_T - PL = P_T - \kappa_e' \cdot d - PL_0 \qquad [dB] \qquad (10)$$

where $\kappa_e' = 4.34\, \kappa_e$, and PL_0 represents free space loss (L_{FS}) and soil loss (L_{soil}) contributions. κ_e was defined in equation (5)

Vegetation loss (L_v) and consequently extinction factor (κ_e) depends on vegetation water content (**W**) and on the fractional volume of plants (V_p/V). L_v changes across space and time due to variations in **W** and **Vp/V**. The reasons for these variations are changes in plant moisture and in vegetation volume in the way of RF propagation. Biophysical characteristics of plants (height, volume, biomass) varies across the field, as well as its spatial distribution. Furthermore, soil and plants moisture are not the same for all the field, meaning that a number of measurements performed by equipments spread in the crop area will give a more effective information for agriculturists than would be obtained by a single device. Fluctuations also occur in short intervals while plants lean to one or other side, leaving a hole in the foliage or clustering leaves together in some direction [23]. Besides this, the uncertanty of the information is reduced as measurements from a number of devices are taken, as stated by central limit theorem [20].

In order to overcome quick fluctuations in foliage density and RF attenuation, a series of measurements must be made each way of communication, each network connection. Lymberopoulos [21] used a mean of 20 measurements as a representative value for P_R in the communication of a couple of transceptors. Attenuation data from several ways of RF communication have to be taken in each region of the field to obtain a good information about plants in that region. Bulusu [22] pointed that if 6 to 10 measurements from distinct sensor nodes are taken, information uncertanty is reduce to values near the minimum.

In this way, the optical depth (τ) and extinction coefficient (κ_e) of vegetation can be estimated by the measurement of the signal power (or strength) received by the nodes of a wireless sensor network, provided that many communication paths were established and many measurements were performed in each path. So extinction coefficient (κ_e) and vegetation water content (**W**) are estimated by the difference between the mean attenuation occurred before and after plant growth:

$$\Delta PL = PL_v - PL_f = \kappa_e' \cdot d \qquad [dB] \qquad (11)$$

where PL_v is path loss measured when there was vegetation in the way of communication (after growing) and PL_f is path loss measured in free path (without vegetation);

Since nodes are not displaced (fixed **d**), power transmissions (P_T) are unchanged and PL_0 is considered constant, equations (7), (10) and (11) can be used to establish a relation between **W** and P_R (received power):

$$\Delta P_R = P_{Rf} - P_{Rv} = \Delta PL = 4{,}34 \cdot b \cdot W \qquad [dB] \qquad (12)$$

where P_{Rf} is received power when the path is free and P_{Rv} is received power when vegetation is present in the path of RF propagation.

Provided that parameter **b** is almost constant, depending only on vegetation type [18,4], the radio signal attenuation depends linearly on **W** present in the communication path. This signifies a linear variation relative to plant gravimetric moisture (m_g), to foliage density (V_l/V) and to distance between nodes (**d**), as stated in equation (4).

4. MATERIALS AND METHOD

It was used a wireless sensor network (WSN) composed by several nodes placed at regular distances, in order to measure the received power and estimate crop data. In this work, Mica2 (Berkeley) motes, marketed by Crossbow [24], were used as nodes of the network. Mica2 is a small sensor node which is powered by a 3V battery, equipped with a low power embedded microprocessor, a multichannel A/D converter, flash memory, eeprom, and a small radio that operates in the license free 916 MHz ISM band . The nodes have the ability to communicate and cooperate with each other to monitor the environment [21,22].

A/D converter is used, in this case, to measure RSSI value (Received Signal Strength Information) provided by the radio, which is associated to the received RF power as [25]:

$$P_R = -50.0 \cdot V_{RSSI} - 45.5 \qquad [dBm] \qquad (8)$$

where V_{RSSI} is a voltage indicated by the chip radio and is converted for a digital value by the 10 bits A/D converter,

$$V_{RSSI} = RSSI\_DIG \cdot V_{BAT} / 1024 \qquad (9)$$

and **RSSI_DIG** is the value indicated by A/D converter and V_{BAT} is the source voltage (about 3,0 V).

All the nodes were regularly distributed in a triangular pattern at equal distances of 5.0 m. RSSI measurements were taken from the communication paths in a region of a corn field. A hundred measurements were taken by each node for each radio link (communication between nodes). The first measurement set were conducted in the middle of a corn crop (in its second half of growing season, about 100 days after seed), and the second set in a field without vegetation (free path), beside the crop field. All the nodes were placed 1.0 m high, and the antennas in vertical position (vertical polarization), and all transmissions were performed with $\mathbf{P_T}$ **=** 0 dBm = 1 mW. The measurements were taken in a short interval (one hour) so that the temperature, gravimetric moisture, foliage density, growing stage and height of the plants remained constant. Radio received power ($\mathbf{P_R}$) was recorded for three class of links (connections), according to the distance between nodes: the first one for **d** = 5.0 m, the second for **d** = 10.0 m, and the third for **d** = 15.0 m. Results for **d** = 20.0 m was not recorded because the strong attenuation inside vegetation made links very poor and the results were not reliable.

5. RESULTS AND DISCUSSION

Values of all path losses are summarized in table 1. $\mathbf{\Delta P_R}$ and, consequently, $\boldsymbol{\tau}$ and **W,** were identified as linear functions of distance (**d**) between the nodes. These results reveal that, for these distances, and for this crop, the radio signal attenuation does not follow equation (10), but the vegetation influence on signal propagation, equation (12), is confirmed as seen in Figure 1. Variations in values obtained are due to random contributions, like fluctuations in vegetation density. Tavacoli [26] measured propagation of microwave parallel to ground and perpendicularly to seven rows of corn plants. Transmitter and receiver were adjusted to 1.4 GHz and were placed 1.2 m above ground. He obtained a path loss of (17.2 ± 2.9) dB for vertical polarization and (5.5 ± 0.4) dB for horizontal polarization. These results are close to that presented in figure 1.

Table 1 – Path Loss

distance		Free path	Vegetated path
5.0 m	Min.	63.9 dB	66.1 dB
	Mean	67.1 dB	75.9 dB
	Max.	70.1 dB	89.5 dB
10.0 m	Min.	64.3 dB	73.6 dB
	Mean	65.9 dB	81.5 dB
	Max.	67.3 dB	95.6 dB
15.0 m	Min.	68.2 dB	84.6 dB
	Mean	69.0 dB	90.6 dB
	Max.	70.3 dB	97.8 dB

Figure 1 shows that the increase in path loss due to vegetation is linearly dependent to the amount of vegetation in the path, as demonstrated by the straight line **r1**. The three points indicated by circles represents the difference between the mean values ($\mathbf{P_{Rf} - P_{Rv}}$) listed in Table 1. **r1** represents the best linear approximation for the three points, and **r2** is a linear approximation crossing the origin (**r1** : ΔP_R (d) = 1.28.d + 2.53 ; **r2**: ΔP_R (d) = 1.51.d + 0.00). The maximum deviation for **r1** was 1.7%, and for **r2** was 16%. Deviation decreases while distance increases.

6. CONCLUSIONS

It was demonstrated that good information related to growing vegetation can be obtained by measurements of signal strength in the communications of a WSN inserted in an agricultural field. Experimental results supported that the technique proposed here, in which measurements are taken in several paths in a region of the field, using many sensor nodes, provides a more representative value than would be obtained with just one pair of transmitter and receiver. This can be seen if one compares the variations in power loss presented in third and fourth colums of table 1.

It was achieved a linear relation between decrease in signal strength and distance between sensor nodes, which

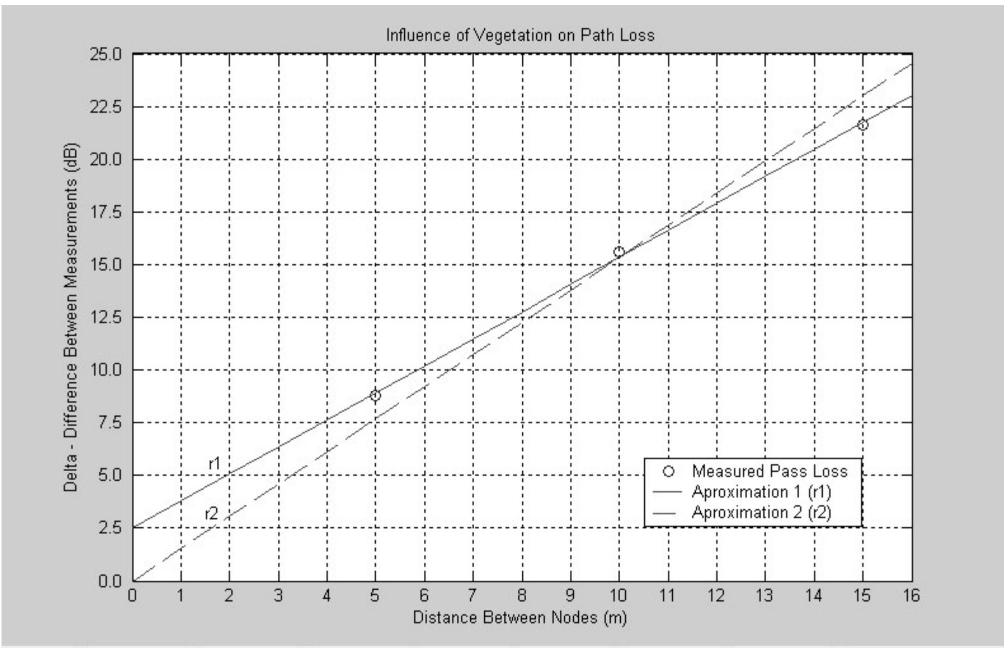

Figure 1 – Influence of vegetation on radio signal attenuation. r1 and r2 are linear approximations for ΔP_R (d), Delta x Distance

indicates that a linear relationship between attenuation and volume vegetation exists. The differences between the measured attenuation in free path and that previewed by equation (10) suggest that a better model have to be developed to describe the influence of soil on microwave propagation. Other experiments have to be conducted in others plant growth stages and under different moistures (m_g), to consolidate the proposal

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