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RADIOMETRIC MEASUREMENT OF CORN CANOPY WATER CONTENT WITH A 916 MHZ WIRELESS SENSOR NETWORK

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Abstract – A wireless sensor network is used as a distributed system for measuring plant water content in crop fields. The WSN works as a radiometric sensor which gets the information about vegetation water content from the RF communication signals. No specific sensor is needed. The equations of the measurement process are developed based on the two ray propagation model. Experimental results obtained in a corn field demonstrate a linear relation between gravimetric moisture of plants and the attenuation of the WSN RF signals.

Keywords: vegetation water content, radio signal attenuation, wireless sensor network

1. INTRODUCTION

Agricultural productivity has been improved with the use of modern techniques of crop management, which demand measurement systems of field variables [1]. Measuring plant water content in crop fields is a difficult task, requiring plant collecting as soon as the method is carried out in laboratory. Radiometric measurement techniques are preferable over others since they are not destructive. Over the past years many research works were addressed to plant and soil moisture estimate employing radar system embedded on satellites [2]-[4]. Remote sensing by satellites is a radiometric method largely used to monitor agricultural fields providing landscape scale information, but its resolutions in time and space are low.

In recent years some researches pointed to the use of wireless sensor networks (WSN) in agricultural monitoring [5]. WSN gives better spatial and temporal resolutions than satellites, besides allowing collection of other soil and plant data. WSN is a fine grained sensor system that employs a great number of small and cheap sensors which data can be aggregate to give high quality information about the environment. This distributed measurement system has applications in many areas: military, scientific, industrial, commercial and others [5]-[8]. This system is composed of a large number of small autonomous devices, denominated sensor nodes, which communicate to each other by radio forming a network. A Sensor node is equipped with a small processor and has restrictions in memory and energy. Its radio range is no more than 100 meters in free space. Some sensors can be attached to the sensor nodes in order to make environmental measurements, which are transmitted to a data base.

In crop fields the RF signals of a WSN are greatly attenuated by plants, mainly due to the presence of bound water [9][10]. This characteristic can be used to measure some variables of the vegetation where the WSN is inserted, eliminating the need of additional instrumentation.

This work presents a method to estimate the water content of a vegetation canopy using the RF communication signals of a wireless sensor network that is present in a crop field in order to monitor environmental variables. It is developed a model of RF attenuation that considers the influence of the soil and the vegetation. A measurement model of vegetation water content is based on the absoption factor (α) of RF signals. A linear relation between them is indicated in the band of 916 MHz. This model demonstrates that longer distances between nodes improve α estimation. A distributed measurement system is needed to compensate the non uniform distribution of plants in the field.

Section 2 presents the model of RF propagation in vegetation medium. Section 3 presents the measuring model and the methodology. The measuring system based on a WSN is in section 4. In section 5 some results obtained in a corn crop field are presented. Conclusions are in section 6.

2. RF ATTENUATION DUE TO CANOPY WATER

Electromagnetic wave that propagates through a vegetated medium can suffer delay, deviation (diffraction), or absorption (attenuation) of its energy. Attenuation stand out in long wavelength RF signals, as L-band radars, which make possible to neglect the others [10][11]. Some models were proposed in the past years for interactions between microwaves and vegetation, as the inhomogeneous half-space model [12] and the water cloud model [13]. Here the vegetation canopy is considered as a continuos dielectric layer, and its dielectric constant (DC) is evaluated as a mean of leaves and air contributions:

$$\varepsilon_c = (\varepsilon_p V_p + V_a) / V \qquad (1)$$

where V_p is the total volume of plants, V_a is the canopy volume occupied by air, and V is canopy total volume, ε_p is the mean dielectric constant of plants and ε_c is a complex value representing the canopy DC ($\varepsilon_c = \varepsilon_c' - j\varepsilon_c''$). ε_c' and ε_c'' are real and imaginary parts of the complex equivalent dielectric constant of vegetation canopy.

The dielectric constant (DC) of water is much greater than the DC of dry mater, resulting that the DC of leaves is governed by its water content.

It is reasonable to suppose a linear relation between vegetation water content (W) and power attenuation in microwaves that propagates through vegetation [14]. According to [9] the transmissivity of a canopy is directly related to vegetation water content. Transmissivity can be also expressed as a function of absorption factor (α) which is a characteristic of the canopy:

$$\gamma = \frac{P_R}{P_T} = e^{-b \cdot W} = e^{-2 \cdot \alpha \cdot d} \quad (2)$$

where parameter b depends on the type of crop and the frequency of the microwaves and W is a linear function of distance (d) of propagation into the medium [15]. P_T is the electromagnetic power leaving the transmitter antenna and P_R is the power that reaches the receiver antenna.

As soon as α is determined, the canopy water content can be calculated:

$$2 \cdot \alpha \cdot d = b \cdot W = b \cdot m_{g(canopy)} \cdot d \quad (3)$$

And the mean value of gravimetric moisture of plants is estimated:

$$m_g = \frac{2 \cdot \alpha}{b \cdot \frac{V_p}{V}} \quad (4)$$

When the propagation of RF is not directional, as in WSN communications, transmission loss is also affected by distance between transmitter (Tx) and receiver (Rx) as stated by Friis transmission formula [16]. If Tx and Rx are close to soil surface, a more complex model is needed. Here a two rays propagation model is used, as represented in fig. 1.

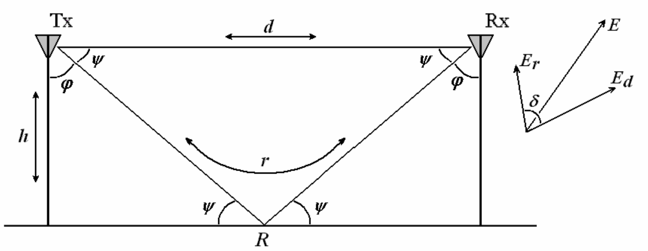

Fig. 1. Two rays propagation model, considering the interaction between two electric fields, the direct field (***E***$_d$) and the field reflected in soil (***E***$_r$).

This model considers the interaction between two electric fields that reach receiver antenna. The first one ($\boldsymbol{E}_d$) is related to the direct propagation (line of sight) signal, and the second one ($\boldsymbol{E}_r$) is related to the signal reflected in soil surface. Transmitter and receiver antenna are placed at same height (h). The total electric field ($\boldsymbol{E}$) results from $\boldsymbol{E}_d$ and $\boldsymbol{E}_r$ interaction. The total received power (P_R) is a square function of ($\boldsymbol{E}$) and can be expressed as:

$$P_R = P_{Rd} + P_{Rr} + 2 \cdot \sqrt{P_{Rd} \cdot P_{Rr}} \cdot \cos(\delta). \quad (5)$$

P_{Rd}, the power of the direct signal, and P_{Rr}, the power of the signal that is reflected in the soil surface, are calculated by (6) and (7):

$$\frac{P_{Rd}}{P_0} = \frac{e^{-2.\alpha.d}}{d^2}, \quad (6)$$

$$\frac{P_{Rr}}{P_0} = \frac{e^{-2 \cdot \alpha . r}}{r^2} \cdot R^2(\psi, \varepsilon_s, p) \cdot D^2(\theta), \quad (7)$$

where P_0 is a reference value, d is the distance between Tx and Rx, R ($-1<R<1$) is the reflection index of the soil surface, which is modeled as a function of the incidence angle (ψ) of the RF wave on the soil and of its dielectric constant (ε_s), and depends on the polarity (p) of the electric field [16]. In vegetation with great contribution of vertical stalks the vertically polarized waves suffer stronger attenuation than horizontally polarized ones [11] [15] [17]. In this work only vertical polarization was used in order to improve the accuracy of water content measurement. D is the antennas directivity ($0 \leq D \leq 1$), which is modeled as a function of the angle φ. The directivities of Tx and Rx are considered equal, as soon as they are symmetrical. δ is the displacement angle between the electric fields $\boldsymbol{E}_d$ and $\boldsymbol{E}_r$, and it is calculated as:

$$\delta = \frac{2 \cdot \pi}{\lambda} \cdot (r - d), \quad (8)$$

where r is the path length of the signal reflected in the soil and d is the path length of the direct signal ($r > d$). r is a function of d and h, as well as ψ and φ.

The total power in Rx antenna can be expressed as a function of five variables:

$$\frac{P_R}{P_0} = \frac{e^{-2 \cdot \alpha \cdot d}}{d^2} \cdot T(d, h, \varepsilon_s, \alpha, \lambda). \quad (9)$$

$$T = 1 + \left(\frac{e^{-\alpha \cdot (r-d)}}{d/r} \right)^2 \cdot D^2(d,h) \cdot R^2(d,h,\varepsilon_s) + 2 \cdot \frac{e^{-\alpha \cdot (r-d)}}{d/r} \cdot D(d,h) \cdot R(d,h,\varepsilon_s) \cdot \cos(\delta) \quad (10)$$

Here, the function T (d, h, λ, α, ϵ_s) is dimensionless. The vegetation influence is represented by the absorption factor (α) that is strongly affected by vegetation water content. If the wavelength (λ) and the reference power (P_0) are known, α can be determined since the variables P_R, ε_s , d and h are measured.

One can see that the larger is the distance d between Tx and Rx the smaller is the sensibility of T function on α and the better is the estimation of the absorption factor.

3. MEASUREMENT SYSTEM

A wireless sensor network is deployed in an agricultural crop field in order to measure environmental variables and transmit them to a data base in a remote station, as outlined in fig. 2. When transmissions are made between sensor nodes, received power is measured in order to calculate attenuation and link quality. Absorption factor (α) is then obtained using (9). Periodically α values are transmitted to the base station in order to calculate an average value which is representative for the agriculturist. Canopy and plant moisture are obtained with (3) and (4) and can be used in the field management decisions.

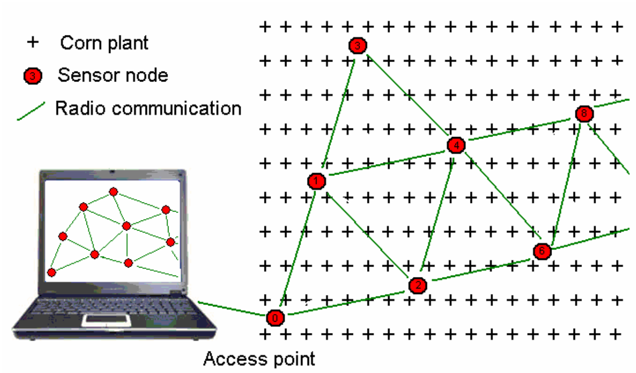

Fig. 2. Outline of a WSN deployment in a corn field.

When the difference between the path lengths r and d of reflected and direct signals, respectively, is small ((r-d) $\rightarrow$ 0), the contribution of the absorption factor on the function T, in (10), can be disregarded. This condition is achieved when relation h/d is close to zero ($h/d \rightarrow 0$). In this way, the absorption factor calculation is simplified, as soon as an iterative method is not required. The factor α can be calculated employing (9):

$$\alpha = \frac{1}{8{,}86 \cdot d}\left[-\frac{P_R}{P_0}[dB] - 20\log(d) + 10\log(T)\right] \tag{11}$$

In order to eliminate P_0, two series of measurements are taken, the first one is made in seeding stage, when there is not any plant in the way of RF propagation ($\alpha = 0$) and the second one is made in growing stage, when plants are in the way of RF. Following this methodology absorption factor can be calculated as a function of the power loss (PL) in the propagation way:

$$\alpha = \frac{PL_v - PL_f}{8{,}86 \cdot d} = \frac{\Delta PL}{8{,}86 \cdot d} \ , \tag{12}$$

where PL_v [dB] is the attenuation perceived when the propagation is performed through vegetation, and PL_f [dB] is perceived when the path is free, when there is no obstacle in the way of propagation:

$$PL_v\ [dB] = P_T - P_{Rv} \ , \tag{13}$$

$$PL_f\ [dB] = P_T - P_{Rf} \ . \tag{14}$$

The positions of the sensor nodes and the transmitted power (P_T) are made constant, and then the difference between the values of received power (P_R) is a function of the absorption factor alone.

One can demonstrate that, when the ratio h/d $\rightarrow$ 0, the contribution of the uncertainty of distance (d) to the uncertainty of absorption factor measurement becomes an inverted function of the square of d:

$$u_\alpha \propto \frac{1}{d^2} \cdot u_d \ . \tag{15}$$

In other words, the longer the distance between sensor nodes, the more accurate the measurement of absoption factor and more accurate the estimation of vegetation gravimetric moisture.

4. EXPERIMENTAL RESULTS

An experiment was conducted in a corn crop field on Fazenda Pinheiro (21°18’45” S; 44°55’25” W), in Lavras town, state of Minas Gerais, Brazil. This experiment aimed to verify the viability in estimating the vegetation water content using the measurement of the signal power from the radios of a WSN. It was employed the sensor nodes Mica2 motes, from Crossbow Technology [18]. The radios work in 916 MHz ISM (license free) band and act as Tx and Rx alternatively. The radio signal strength is measured for all the messages that reach the receptor (Rx). A calibration was processed in anechoic chamber, indicating a ±2dB deviation through out the range – 100 to – 50 dBm.

The experiment was conducted in four distinct times, in order to evaluate different plant conditions in the field. At the first time, the plants was in the end of the vegetative state, denominated VT (vegetative-tasseling) [19], 60 days after seeding, with 2.1 m mean height. The plant rate was 5.6 plants per square meter. The second series of measurements was conducted when plants were in R3 state (reproductive-milk), with 2.3 m mean height. The third series of measurements were made in the R6 state (physiological maturity) of the corn, in harvest period. The plants were 2.3 m high in average. The fourth series of measurements was performed after harvest, when there were no plants in the field (free condition).

The sensor nodes were deployed in a regular fashion performing equal distances from each other. Two series of measurement were conducted, for two different distances: d = 10 m and d = 15 m. All the nodes were placed 1.0 m high form the soil and all antennas in vertical position (vertical polarization). All the transmissions were made with P_T = 5 dBm. It was made 100 measurements of received signal strength (RSS) in communications between each pair of sensor nodes and for each distance. Each series of measurements was conducted in an interval of one hour, making possible to consider constant some variables as vegetation water content, vegetation density and plant height.

For the measurement series 1, 2 and 3, samples of plants were collected and their gravimetric moistures were measured with a gravimetric method, used as reference. The plants were weighted immediately after they have been collected in the field and after they were dried in an oven for three days at 70^{o}C. The difference in weight represents the weight of liquid water that was in the plants.

Comparing the values obtained in the experiments performed in presence of vegetation with those obtained with the measurements in free area it is possible to identify the exclusive influence of the absorption factor on the RF signal attenuation. Then it is possible to estimate absorption factor (α) as indicated in (12).

Table 1 presents the results obtained from the measurements of plants water content and in the absorption factor estimation. α represents the mean value calculated from the results obtained in the measurements made in two different distances (10 m and 15 m). An almost constant ratio α/m_g = 0.205 was achieved with standard deviation SD(α/m_g) = 0.017 (8%). It is in accordance to Schmugge & Jackson [15] proposal.

Table 1. Gravimetric moisture of the corn plant samples and absorption factor estimated with attenuation data (PL).

Series	State	Gravim. moisture (m_g) [g/g]		α	α/m_g
		Mean value	SD		
1	VT	0.856	0.008	0.168	0.196
2	R3	0.803	0.023	0.156	0.194
3	R6	0.535	0.118	0.120	0.225

The graph in fig. 3 shows the mean values of power loss due to plants as a function of plants water content, for two different distances. A nearly linear relation between plants water content (m_g) and the changes in attenuation in the propagation way (ΔPL) can be seeing in both of the graphs.

Fig. 4 presents the mean values and standard deviations obtained in a series of 100 measurements made in the corn crop field, in the first experiment, considering d = 10 m. The values measured in 10 distinct ways of propagation are presented, i. e., ten different links between pairs of nodes. The columns indicate mean values and vertical lines indicate respective standard deviations. The column "Total" indicates the mean value representing all the values measured in the experiment. Its standard deviation is indicated as well.

The data presented in fig. 4 demonstrate that the dispersion of the measured values of the RF signal intensity (RSS) is due mainly to the variability of the observed ways, and the characteristics of the measuring devices is less important. This global dispersion is considered as a consequence of the variations in the characteristics of the vegetation along the field, specially related to the non uniform distribution of the plants, as well as the variations in soil characteristics.

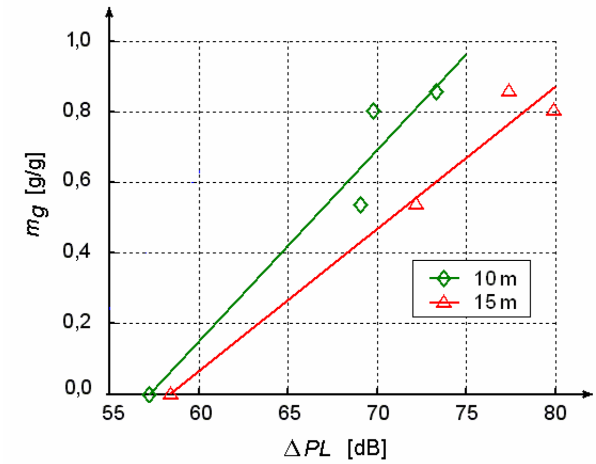

Fig. 3. Linear relation between plants water content and changes in attenuation ($\Delta PL = PL_v - PL_f$). Coefficients of determination: R^2(10 m) = 0.94, R^2(15 m) = 0.97.

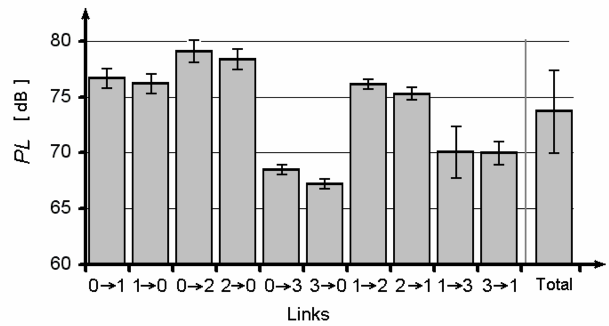

Fig. 4. Measurements of attenuation (PL) in 10 distinct ways – mean values and standard deviations. Growth state VT, d =10m, m_g = 0.856 g/g .

5. CONCLUSIONS

This work demonstrated that measurements of signal strength in the communications of a WSN inserted in an agricultural field can be used to estimate the water content of the plants. The experimental results demonstrated that a linear relation exists between the vegetation water content and the attenuation occurred in the electromagnetic waves of the radios, confirming the proposal of this work. The distance between radios has to be large in order to reduce uncertainties of absorption factor measurements. The results presented in fig. 5 showed that the mean value taken from all measurements is more adequate information for agriculturist decisions if the final objective is irrigation management. Then the proposal of this work is confirmed.

For future works the authors intend to get more accurate measurements of plant gravimetric moisture with the use of a denser network.

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