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A Foliage Scatter Model to Determine Topology of Wireless Sensor Network

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***Abstract*— Applications of low cost wireless sensor networks (WSN) in precision agriculture is gaining popularity because of the ability of sensors to provide site-specific data over a variable field. Wireless communication between nodes is impeded by the surrounding vegetation of the plants being monitored. To guarantee reliable communication between sensor nodes, the initial node density and topology of a WSN application has to consider the increased foliage of a mature plant. In this paper we propose a model for deployment of wireless nodes based on experimental results that takes into account the scattering effect of surrounding foliage on the wireless signal.**

***Keywords*— wireless sensor network, propagation loss, topology, coverage, scattering.**

I. Introduction

Wireless sensor nodes are used as part of a precision agriculture (PA) system to provide localized, real-time data about the current temperature, humidity and soil moisture content of a specific agricultural field [1]. As the life-cycle of plants progress from a seedling to a young flowering plant and eventual maturation, the surrounding vegetation around the sensor increases. Thus, whilst a few sensors may have been required at the seedling stage to transmit data, as the size and number of leaves of the plant increases, the wireless signal is increasingly scattered, requiring more wireless sensor nodes to be deployed in the application area to adequately transmit data to the central sink. To collect data from sensors, a PA application densely deploys multiple wireless sensor nodes within the application area to create a multi-hop wireless sensor network (WSN) that reports real-time operational data to a central sink. Current applications of WSN in PA systems require a highly skilled workforce and constant human intervention to adapt to the changing foliage conditions of the growing plant.

The propagation of a wireless signal within an agriculture area results in attenuation and variance in the received signal strength due to changes over time in the density of the leaves in the crop. A WSN must be able to operate in a wide range of environments such as bare fields, vineyards, orchards, from flat to complex topography and over a range of weather conditions, all of which affect radio performance [2].

Various outdoor attenuation models for radio propagation through foliage have been developed, including Weissberger's modified exponential decay model, ITU Recommendation (ITU-R) (or Early ITU Vegetation Model), the Updated ITU Vegetation Model, and the COST235 model [3,4,5]. These models tend to focus on scattering of the EM waves by leaves in trees and do not consider the different types of foliage conditions between ground based plants (such as strawberries), medium sized shrubs (such as potatoes and beans), and large vegetation(such as maize and sugarcane).

The commoditization of WSNs within the PA field will not occur unless systems can be put in place to ensure rapid deployment and adequate coverage of the application area. When a WSN is initially deployed within an agricultural field, algorithms to predict the effects of path loss and scattering of the foliage of the mature plant must be considered to determine the optimum placement of nodes to ensure adequate coverage and reliable communication of nodes in the application area. In this paper, a model is presented to predict the effects of scattering by foliage on a wireless signal to determine the optimum placement of sensor nodes within an application area.

The rest of the paper is organized as follows: Section II provides a brief overview of the related works in the field of precision agriculture. The theoretical back ground has been discussed in Section III. Section IV elaborates on the algorithm design. Section V and VI discusses the results and conclusions respectively.

II. Problem Statement

Precision agricultural applications require the placement of wireless sensor nodes at or near the flora being monitored. The appearance of the foliage medium in the path of the communication link has significant effects on the quality of the received signal, because, discrete scatterers in the forest such as the randomly distributed leaves, twigs, branches and tree trunks can cause attenuation, scattering, diffraction, and absorption of the radiated propagating waves [5].

Figure 1 shows the effect of a single scatterer (for example a leaf), on the transmitted wireless signal. Figure 2 shows the effect of multiple scatterers on the wireless

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signal. As the size and number of leaves of the plant increases, the wireless signal is increasingly scattered, requiring more wireless sensor nodes to be deployed in the application area to adequately transmit data to the central sink.

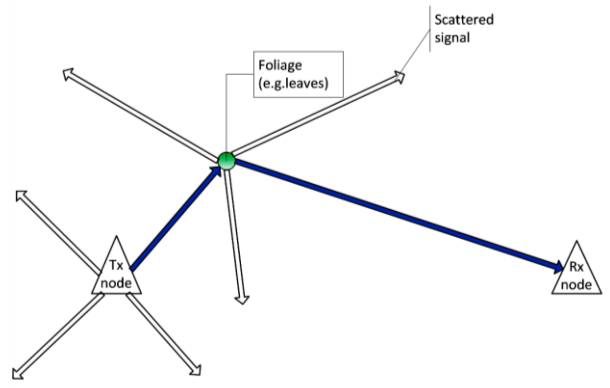

Fig. 1. Effect of a single scatterer on wireless signal.

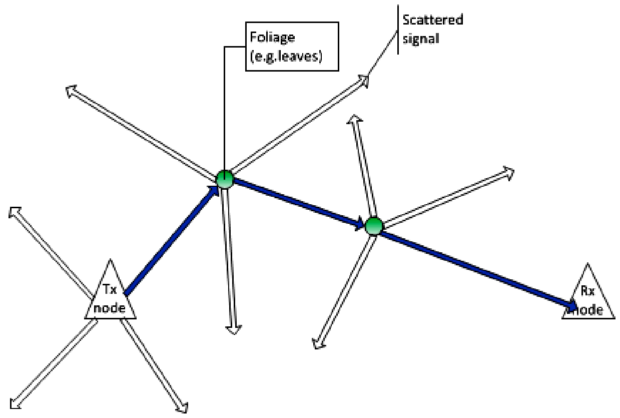

Fig. 2. Effect of multiple scatterers on wireless signal.

Currently the placement of nodes is dependent on experimentation and as signal strength fades, additional nodes are installed. The growth of WSNs in precision agriculture requires that the topology design and deployment of sensor nodes should be easily configurable to enable a non-technical person to easily deploy a WSN within an agricultural application area. Models are required that take into consideration the different types of foliage prevalent in agriculture to determine the optimum number and deployment location of nodes within an agricultural area.

III. Related Work

Many current deployments of WSN in agriculture have focused on testing the systems in a laboratory initially, and then deploying the nodes in the field without considering the effects of foliage on the network topology. For example, Riquelme [6], describe the deployment of a WSN to monitor the water content, temperature and salinity of soil at a cabbage farm located in a semi-arid region of Spain. The topology of the network was not fixed and nodes were deployed arbitrarily and adapted to changing needs. Wireless coverage of the system was assured by fitting a long-range radio module to the sensor to allow direct communication with the base station 5.5km away.

In a WSN application to detect the presence of a fungal disease (phytophtora) in a potato field, it was determined that the wireless signal range decreases when the crop is flowering. Thelen, Goense and Langendoen [7] determined that the reduced range is mainly caused by the foliage of the potato plants. The maximum distance for reliable communication is much shorter than the plane earth propagation equation indicates and that a dry, fully developed crop canopy limits the distance that radios can cover to around 11 meters when placed near the soil surface.

Ndzi et al. [8], evaluated various vegetation attenuation models for frequencies in the range 0.4-7.2 GHz in mango and oil palm plantations. Their observations indicate that greater attenuation is obtained for measurement at canopy height, where there are more branches, twigs and leaves, compared to measurements at trunk heights. The authors suggest placing the nodes above the crop canopy to maximize range. However as the sensors may need to measure soil moisture, humidity and temperature etc., the placement of nodes above the crop canopy may not always be feasible.

Liu, Meng and Wang [9], investigate the effect of height of an antenna on radio propagation loss for three different crop growth stages in wheat, namely; seedling stage, booting stage and jointing stage. Their results indicate that for any crop growth stage, the radio range increases with increasing antenna height, and the radio range decreases as a crop grows for a specific antenna height.

Koay et al. [10] describe a theoretical model developed for paddy fields based on the radiative transfer theory applied to a dense discrete random medium with consideration given to the coherent effects and near-field effects of closely packed scatterers. Koay et. al are focused on microwave remote sensing using spaceborne radars and sensors to monitor growth and predict yield with reasonable accuracy. However, their work can be useful in the WSN application field as there has been a large amount of research done on various scattering models and the effects of soil, moisture and leaf orientation on scattering of electromagnetic waves.

IV. Theoretical Background

The transmission of signals from the source node to the destination node takes place either by line-of-sight or by signals reaching the destination after being scattered by the vegetation. In dense vegetation the probability of having a line-of-sight communication between the nodes is practically impossible. In such scenarios the signal reaches the next node only after being scattered by the leaves and branches. In this paper we model the leaves and branches as point scatterers. These scatterers are distributed in the application area (the area over which the vegetation is present) by some predefined distribution depending on the type of vegetation. Signals reaching the destination node after multiple scattering has been neglected as the power in such signals are very low compared to the signal received after single scattering.

Consider, P_t as the power radiated isotropically by the transmitting node. The flux density crossing the surface of a sphere with radius R meters from the transmitting node is given by,

$$F = \frac{P_t}{4\pi R^2} \; W/m^2 \tag{1}$$

For a transmitter with output power P_t watts driving a lossless antenna with gain G_t, the flux density in the direction of antenna boresight at a distance R meter is,

$$P_r = \frac{P_t G_t}{4\pi R^2} \; W/m^2 \tag{2}$$

If A is the effective aperture area of the antenna at the receiver, the received power is given by,

$$P_r = \frac{P_t G_t A}{4\pi R^2} \; Watts \tag{3}$$

The gain and area of an antenna are related by [11].

$$G = \frac{4\pi A}{\lambda^2} \tag{4}$$

Where G and A are the gain and the effective aperture area of the antenna and λ is the wavelength of operation.

Combining the above equations the received power can be written as

$$P_r = \frac{P_t G_t G_r}{\left(4\pi R/\lambda\right)^2} \; watts \tag{5}$$

where, G_r is the gain of the antenna at the receiver.

In the present case we consider, the gain of the transmitting and the receiving antennas to be unity. The frequency of operation is 2.4 GHz.

A. Model

In most plantations, for e.g. paddy, maize etc., the plants are planted at equal distances, thus resembling a uniform distribution over the application area. While statistically modeling the application area, first its dimension is set. The signal from the transmitter reaches the receiver only after being scattered by the leaves and the branches which are in range of the transmitter. The leaves and the branches are modeled as point scatterers that isotropically scatter the signals incident on it. In the present model the scatterers are generated randomly following a uniform distribution and placed over the application area. The signal received at the destination node may have gone through single or multiple scattering. Multiple scattering takes place when there are other scatterers on the line joining the transmitter and the scatterer under consideration or the receiver and the scatterer under consideration. Thus scatterers that have only line-of-sight communication with the transmitter and the receiver take part in the scattering process. The signal received at the receiver from a particular scatterer is governed by the equation (5). As only line-of-sight communication between the transmitter and the scatterer, scatterer and the receiver has been considered the application of free space model is justified.

V. ALGORITHM DESIGN

An algorithm to determine the effect of surrounding foliage on the optimum placement of the next node in a WSN has been developed. The algorithm ensures reliable communication between two nodes in the presence of scattering of the radio wave due to surrounding foliage. Figure 3 shows the design of the algorithm to optimally place sensor nodes within an application area when scatterers are uniformly distributed around the application area.

Experimental studies were carried out in the field using an Xbee S1 XB24-AWB-001 RF transceiver that operates in the ISM 2.4 GHz frequency band, with a receiver sensitivity of -92 dBm and the transmit power is 1 mW. The Xbee modules where loaded with the function set XBEE 802.15.4 version 10E6. Measurements were taken to determine the effects of different types of foliage on the EM signal. Readings were taken of error-free received messages versus number of messages with errors depending on Received Signal Strength Indicator (RSSI). If was found that a RSSI of **-75** dBm provided 100% correct received messages per 50 transmitted messages [12].

The initial node is placed within the application area and all scatterers within range of this node are calculated. The range is set to be 25m which is a typical range of a wireless sensor node to ensure reliable data communication. The next nodes location is calculated to be placed at a point where the received power due to scattering will not be less than the experimentally determined cutoff value of -75dBm [12].

Because the scatterers were randomly placed within the application area, there were occasional gaps between nodes where there were no scatterers. All sensor nodes have to be within 25m range of another node to maintain reliable communication. Where there are insufficient scatterers to place a node, an additional sensor node is placed at the maximum free space range of 25m from the transmitting node to ensure network coverage of the entire application area.

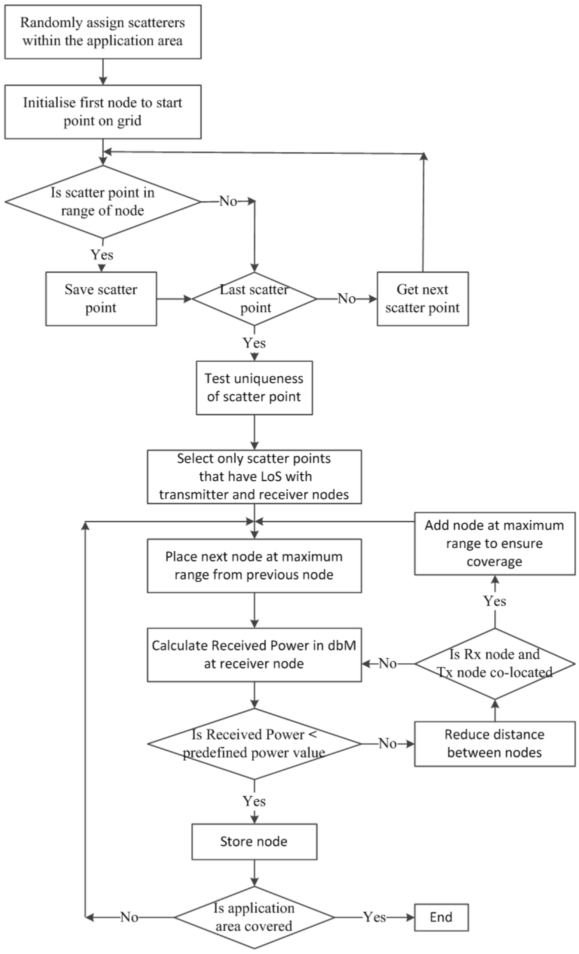

Fig. 3. Node placement in presence of scatterers

VI. Results and Discussion

A. Experiment 1: node placement for uniformly scattered foliage

Figure 4 shows 750 scatterers (green asterisk) uniformly distributed over a 100m by 100m application area. The initial sensor node (square) position was chosen to be at point (17.68, 17.68). This point was chosen to ensure that the distance to the node from the left-corner of the application area is the same as the range of the node (i.e. 25m). The next node was chosen to be at the maximum range of the initial node, i.e. 25m. The received power due to all scatterers within range of the initial node was calculated. If the received power was less than -75 dBm, which was the experimentally calculated minimum acceptable power value for reliable communications, then the node was gradually shifted closer to the initial transmitting node at a distance of 1m per calculation; and the received power recalculated.

Where there are no scatterers present to place a node, such as the top-left corner of the application area, the algorithm to ensure optimum coverage places an extra node (red circle) at the maximum range of the node placed due to scattering of surrounding foliage.

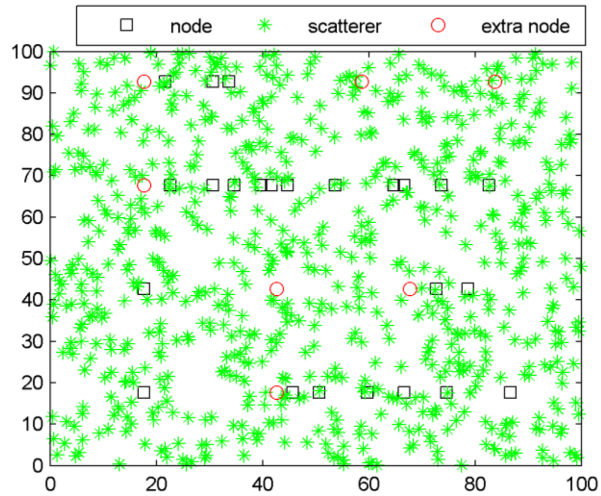

Fig. 4. Node placement for 750 uniformly distributed scatterers over 100mx100m area

B. Experiment 2: minimum number of uniformly distributed scatterers to ensure complete coverage.

The number of scatterers in a 100m by 100m application area was slowly increased to determine the minimum number of scatterers that would not require the placement of an extra node in the application area (refer to Figure 5).

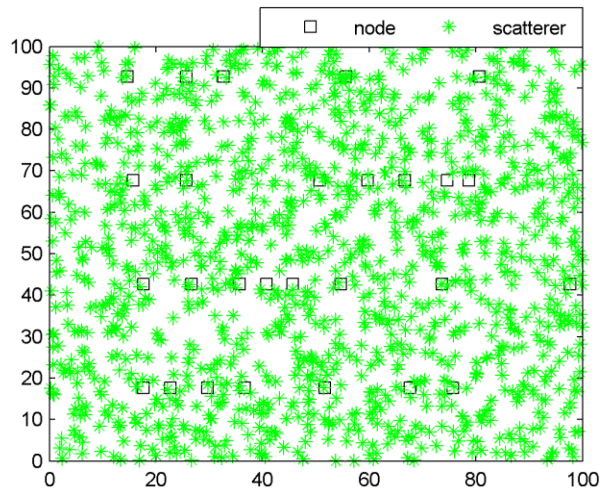

Fig. 5. Minimum number of uniformly distributed scatterers over 100mx100m area

As the density of scatterers in the application area increased, the number of extra nodes that had to be placed between the sensor nodes to ensure reliable communication decreased. At 1300 scatterers, no extra nodes are required in a 100m square area. This indicates that if there are approximately 0.13 scatterers per square metre, then no extra node placements are required.

VII. Conclusion

This paper has presented a technique to optimally place wireless sensor nodes in the presence of vegetation. A model has been developed, based on experimental results and free space modeling, which easily allow the user to determine the number and the position of nodes to be deployed within an agricultural field. Initial results indicate that if the density of surrounding foliage for a mature plant is known, then the number of nodes and the node location to guarantee reliable radio communication in a WSN precision agricultural application can be calculated.

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