Wireless Sensor Node Placement Due to Power Loss Effects from Surrounding Vegetation

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Abstract. Wireless communication in an agricultural environment is weakened by surrounding vegetation. The scattering effect on the wireless signal by the foliage surrounding plants means that sensor nodes within the application area have to be placed so that the received signal strength ensures reliable communication. We propose modeling the scattering effect of surrounding foliage with a Gaussian distribution to determine the optimum placement of sensor nodes within the application area. An algorithm to place sensor nodes at optimum positions to ensure reliable communication is presented and analyzed.

Keywords: Wireless sensor networks, signal propagation, path loss, foliage, vegetation, topology.

1 Introduction

Current precision agriculture systems rely on sensors to obtain data about a specific environment. These sensor nodes are standalone devices without access to a non-renewable energy source and are located either within or close to the phenomena they are observing. The nodes communicate with one or more central control point(s), generally called a sink or base station. To collect data from sensors, a precision agriculture application densely deploys multiple wireless sensor nodes within the application area to create a multi-hop wireless sensor network (WSN) that can report real-time operational data to a central sink. The WSN bridges the virtual world of information technology and the real physical world, and is used for information gathering in smart environments [1].

The architecture of a wireless sensor node (as shown in Figure 1), is that of a small electronic device, comprising one or more transducers (for monitoring physical phenomenon), a processing unit to convert the electrical signal received from the transducer into an intelligible message format and to perform simple computations, a communication unit for transmitting and receiving messages and a non-renewable power source to provide energy to the above units [1],[2],[3][4].

Sensors are placed within the application area to ensure adequate coverage of the area. These sensor nodes are designed for unattended operation and are generally

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stationary after deployment. Because of the need to conserve battery lifetime, WSNs have low data rates and the data traffic is discontinuous. In WSNs the flow of data is predominantly unidirectional, from nodes to sink [5]. WSNs operate with a low duty cycle and with low data rates. Communication is initiated when data-specific information about the immediate environment around a node is requested or a specific event that the sensor has been set-up to monitor is triggered.

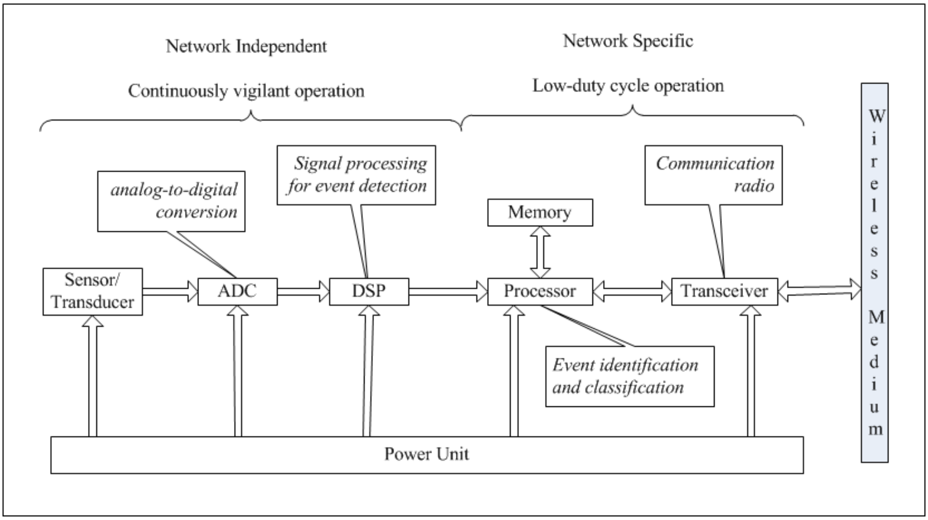

Fig. 1. Wireless sensor node architecture

Precision agriculture applies technological concepts from various sciences, including, agronomy, computer-, communication- and environmental engineering, to optimally manage spatial and temporal variability in soil and crop ecosystems in order to increase long-term quality and yield of farm products while reducing the negative effects on the surrounding flora and fauna [6, 7, 8, 9]. Wireless sensors are used as part of a precision agriculture system to provide localized, real-time data about the current temperature, humidity and soil moisture content of a specific area. Current WSN precision agricultural applications use sensors as yield monitors to support precision harvesting, and for variable rate fertilization and salinity mapping to support precision plant care [10, 11].

To increase the use of WSNs amongst both large and small-scale farmers, the topology design and deployment of sensor nodes should become easily configurable so that a non-technical person could easily deploy a WSN within an agricultural application area. One of the stumbling blocks preventing rapid adoption of WSN technologies in agriculture is that placement of nodes is dependent on experimentation and as signal strength fades, additional nodes are installed.

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 such as the randomly distributed leaves, twigs, branches and tree trunks can cause attenuation, scattering, diffraction, and absorption of the radiated propagating waves [12].

Thus, one of the problems associated with using a WSN application in an agricultural system is that 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. This means that while fewer 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 reliably transmit data to the central sink.

Various attenuation models have focused on trees, and do not consider vegetation density. Examples of current models include Weissberger's modified exponential decay model, ITU Recommendation (ITU-R) and the COST 235 model [13]. Models are required that take into consideration the different types of foliage prevalent in agriculture so that a relatively non-technical person could determine the optimum number and deployment location of nodes within an agricultural area.

In this paper, we develop a model that will optimize the topology and coverage of a WSN application area depending on the scattering of a wireless signal by a mature plant. A theory is presented and a model is developed to predict the effects of foliage on a line-of-sight propagating field.

2 Related Work

In many applications of WSN for precision agriculture, the numbers of sensor nodes are increased to ensure communication reliability as the crop matures. For example, Beckwith et al [14] deployed sensor nodes 20 to 25 meters apart in a dense 65 node, multi-hop WSN over 2 acres, to measure temperature variations over a management block of a wine vineyard. A communication reliability rate of 77% of received messages was achieved.

In the European Lofar Agro project, Baggio [15] created a 150 node WSN to monitor phytophthora, a fungal disease, in a potato field. He noted that the radio range performance of the nodes decreased substantially when the potato crop was flowering. To ensure wireless network connectivity, 30 additional relaying nodes were deployed. These relaying nodes were installed at a height of 75 cm to enhance communication, while the sensing nodes were installed at a height of 20, 40 and 60 cm. In related research, Thelen, Goense and Langendoen [16] 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 dry, fully developed crop canopy limits the distance that wireless signals can cover to around 11 meters when placed near the soil surface.

The propagated radio signals are modified by surrounding vegetation, especially due to the presence of water inside the leaves and stalks, causing delay, deviation (diffraction), or absorption (attenuation) of signal strength [17, 18]. The scattering of the radio signal by surrounding vegetation has been used to determine the growth stage and yield level of a crop. Vegetation scatter models using microwave radar signals to identify moisture in plants and grains have been developed to quantify relations between radiometric observations and vegetation parameters, like leaf area index (LAI), biomass, plant water content, etc. [17].

For example, Fung [18] developed a vegetation scatter model for interpreting scattering from a plane vegetation layer. He demonstrated that layer effects increases with a decrease in volume ratio, depth of layer, plant moisture, and, in general, on the incidence angle of the surrounding foliage. Fung determined that a successful vegetation scatter model could not be established without an adequate permittivity model which properly describes the variations of the permittivity as a function of moisture, frequency and leaf density.

Koay et al. [19] describes 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. The Fung and Koay papers are focused on microwave remote sensing using spaceborne radars and sensors to monitor growth and predict yield with a 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.

Meng, Lee and Ng, in a review of radio wave attenuation in forest environments, argue that the main external factors causing propagation loss variation is antenna height-gain, the plain terrain effect, depolarization, and the humidity effect [12].

Ndzi et al. [20] 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.

Riquelme [21] describes 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.

Liu, Meng, and Wang [22] evaluate radio propagation performance of sensor nodes in a field of wheat at the seedling stage, booting stage and jointing stage. The minimum antenna height for each sensor node to ensure reliable communication during all three growth stages of wheat was determined. The authors found that the radio range width increases with increasing antenna height and that for any antenna height, the radio range decreases as the crop grows.

Thaskani and Rama Murthy [7] propose a WSN topology in which each stationary sensor node is placed at the corner of each grid, and a mobile base station collects data from sensor nodes and processes them. Two models for data collection are considered. In model 1, the base station moves in a horizontal direction forward and backward across the field. The mobile base station collects data from sensor nodes which are near to it at fixed instance of times. In model 2, a mobile base station is placed on mid road of the farm and sensor nodes forward data horizontally towards base station (left to right) using multiple hops. The authors do not consider the power scattering effect of surrounding foliage in determining their topology design.

3 Current Foliage Power Attenuation Models

In The main empirical foliage loss models for the horizontal path on a wireless signal's Line-of-Sight (LoS) propagation path is discussed in this section [12, 23]. Although, these models focus on foliage loss caused by trees and forests for mainly cellular type communication at microwave frequencies there is applicability of the approaches in the WSN field.

1. Weissberger's modified exponential decay model covers a frequency range of 230 MHz to 95 GHz:

$$\begin{aligned} L(dB) &= 1.33F^{0.284}I_f^{0.588}, 14 < I_f < 400m \\ L(dB) &= 0.45F^{0.284}I_f, 0 < I_f < 14m \end{aligned} \tag{1}$$

Where:

L(dB) = Vegetation loss in dB
I_f = Depth of foliage in meters
F = Frequency in GHz.

2. The Early ITU Vegetation Model (ITU-R) was mainly developed from measurements carried out at UHF, and was proposed for cases where either the transmitter or the receiver is near to a small (d < 400 m) grove of trees so that the majority of the signal propagates through the trees.

$$L(dB) = 0.2F^{0.3}I_f^{0.6} \tag{2}$$

Where:

L(dB) = Vegetation loss in dB
I_f=Depth of foliage in meters along line of sight.
F= Frequency in MHz.

3. The COST235 model is based on measurements made in millimeter wave frequencies (9.6 GHz to 57.6 GHz) through a small (d < 200 m) grove of trees. Measurements were performed over two seasons, when the trees are in-leaf and when they are out-of-leaf.

$$\begin{aligned} L(dB) &= 26.6F^{-0.2}I_f^{0.5}, out-of-leaf; \\ L(dB) &= 15.6F^{-0.009}I_f^{0.26}, in-leaf \end{aligned} \tag{3}$$

Where:

L(dB) = Vegetation loss in dB
I_f=Depth of trees in meters.
F= Frequency in MHz.

4. The Fitted ITU-R (FITU-R) model yields the smallest RMS error in vegetation loss for both the in-leaf and the out-of-leaf generic cases with reference to the experimentally measured results.

$$\begin{aligned} L_{FITU-R}(dB) &= 0.37F^{0.18}I_f^{0.59}, out-of-leaf \\ L_{FITU-R}(dB) &= 0.39F^{0.39}I_f^{0.25}, in-leaf \end{aligned} \tag{4}$$

Where:

L_{FITU-R}(dB) = Vegetation loss in dB
I_f=Depth of trees in meters.
F= Frequency in MHz.

4 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 [26].

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 [24]:

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

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.

4.1 Model

In most plantations, for e.g. paddy, maize etc., the plants are planted at equal distances. For a full grown plant there are more leaves and branches near the central stem of the plant than away from it. The surrounding foliage can be modeled as Gaussianly distributed point scatterers around the central stem of the plant.

When 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 equidistant points are initially set over the application area representing the position where the plants are located. Then Gaussianly distributed point scatterers are placed around each plant, thus modeling the surrounding foliage. In previous work [26], the scatterers are generated randomly following a uniform distribution and placed over the application area. Results from randomly generated scatterers indicate that there number of scatterers per square meter is a factor in the calculation to determine if an extra node is required to ensure connectivity and reliable wireless communication in the network. These two models will assist in identifying variables that are important in the development of a foliage attenuation model for WSNs.

The signal received at the destination node may have gone through single or multiple scattering. Multiple scattering has been neglected as the power contributed is less than the power received after single 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 firstly, the transmitter and the scatterer; and secondly between the scatterer and the receiver has been considered the application of the free space model is justified.

5 Algorithm Design

Since sensors may be spread in an arbitrary manner; an important design consideration in a WSN is to ensure sensing coverage and network connectivity. In general, sensing coverage represents how well an area is monitored by sensors. The quality of a WSN can be reflected by the levels of coverage and connectivity that it offers [25]. The key to solving the coverage problem lies in the way the sensors are deployed in the area of concern. Densely covering an area with sensor nodes may not be financially viable. Instead the WSN design should take cognizance of the application requirements and put in place a WSN topology that will ensure sensing coverage and network connectivity.

We propose an algorithm which can satisfy both coverage and connectivity requirements in a WSN deployed in different types of vegetation. In earlier work, we have developed an algorithm using a uniform distribution to determine the effect of surrounding foliage on the optimum placement of the next node in a WSN. In this paper, we describe an algorithm using a Gaussian distribution to approximate the scattering effect of surrounding foliage on the signal strength. Nodes are placed at points within the applications area where the received power is greater than or equal to the experimentally determined optimum power level of **-75** dBm [25]. The algorithm ensures reliable communication between two nodes in the presence of scattering of the radio wave due to surrounding foliage.

In this algorithm, the plants are distributed in a grid a predefined distance apart. A Gaussian scattering of foliage is placed around each plant for a specific radius around each plant. Figure 2 shows the design of the algorithm to optimally place sensor nodes within an application area when a Gaussian distribution is used to approximate foliage around each plant in an application area. In previous experiments, the scatterers were randomly distributed around the sensor nodes [26].

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). It was found that a RSSI of **-75** dBm provided 100% correct received messages per 50 transmitted messages [25].

The initial node is placed within the application area and all scatterers within range of this node are calculated. To guarantee reliable communication between adjacent nodes, a maximum communication range of 25m is used. The next node's position is calculated to be located at a position where the received power due to scattering will not be less than the experimentally determined cutoff value of -75dBm for reliable communications

If there are insufficient scatterers to place a node within the specified 25m range of another node, an additional sensor node to ensure network coverage of the application area is placed at the maximum free space range of 25m from the transmitting node. Obviously, this extra node will only be able to communicate with the next sensor node placed according to a received power of -75 dBm.

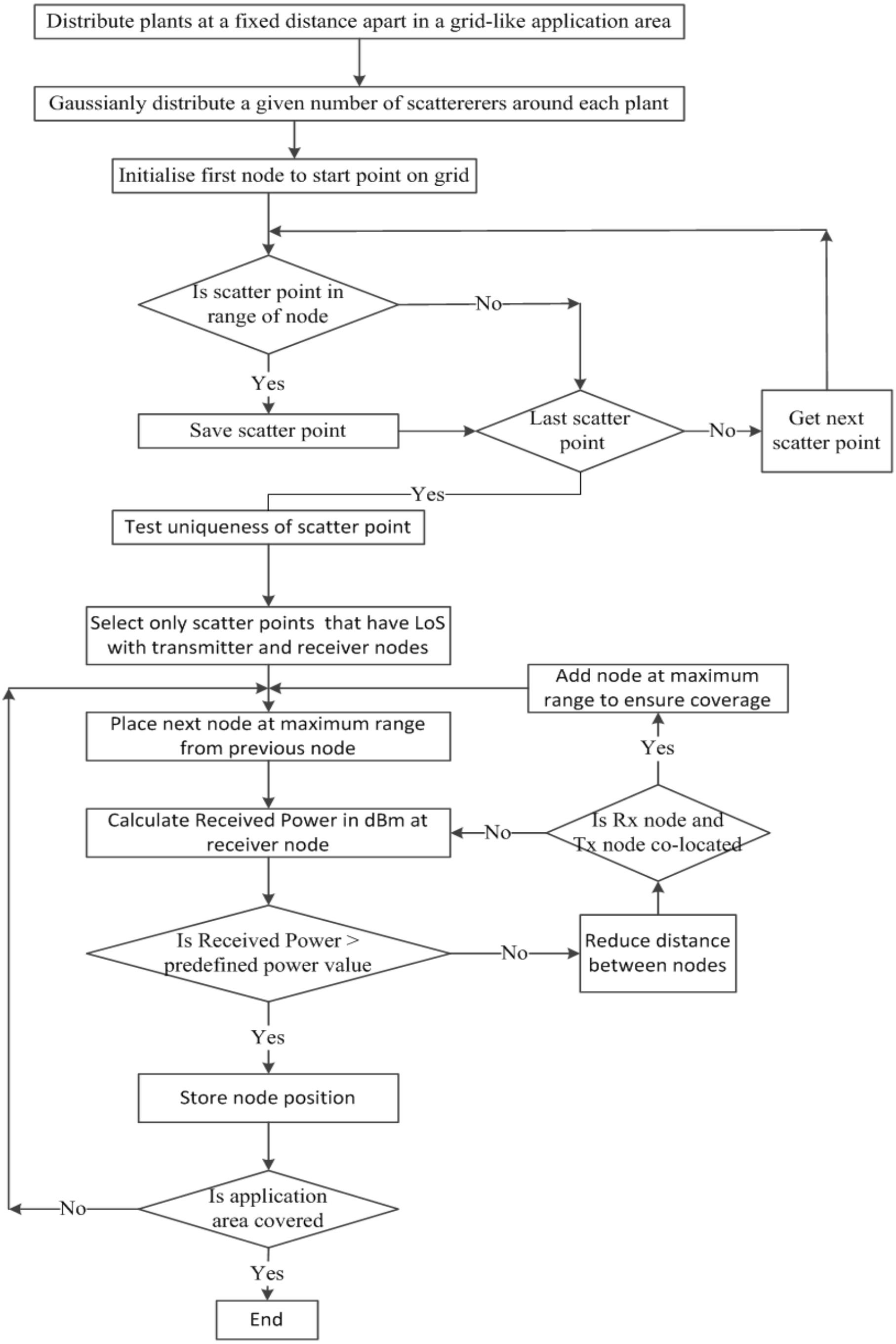

Fig. 2. Algorithm for node placement in presence of scatterers Gaussian distributed around each plant

6 Results and Discussion

A simulation using Matlab was run to determine the optimum node position within a 100m by 100m application area. Two experiments were conducted. One to return a result depicting a uniform placement of sensor nodes around the application area, similar to the case if the sensor nodes were placed in a free space environment. The second experiment was directed to show the placement of sensor nodes and extra nodes when the power loss due to scattering by the surrounding foliage is taken into consideration.

Experiment 1: Plants placed 15m apart with 10 scatterers Gaussianly distributed around each plant

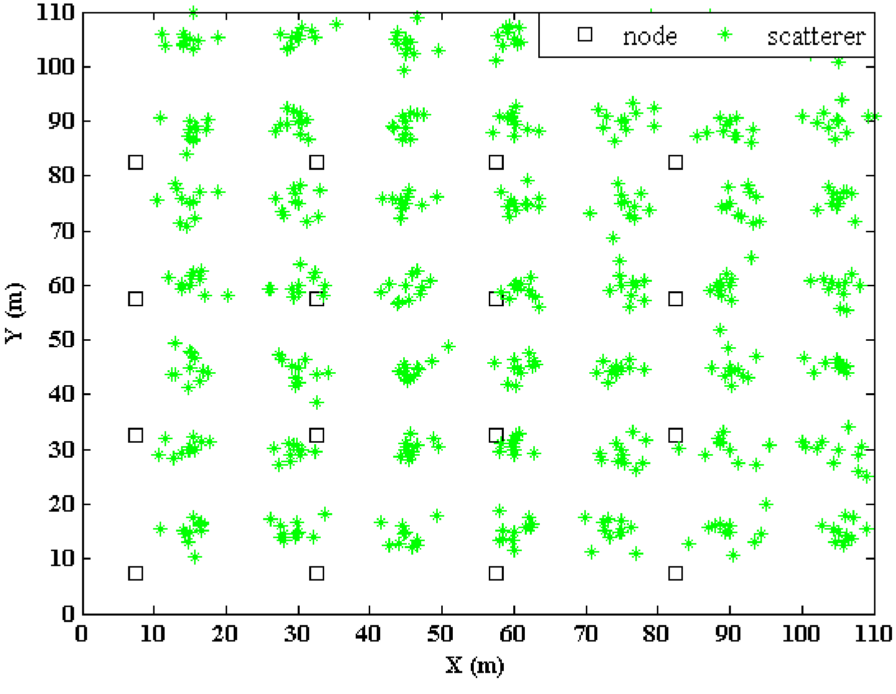

Fig. 3. Plants placed 15m apart with 10 scatterers placed around each plant

In Figure 3, ten scatterers (green asterisk) are Gaussianly distributed around each plant. The initial sensor node (black square) position was placed approximately 5 m (10/2 =5) from the plant position. The next node position to ensure coverage was chosen to be at the maximum range of the initial node position along the y-axis.

The received power level at this position due to all scatterers within range of the initial node is calculated. If the received power is greater than the experimentally determined value of -75 dBm then the position of the next sensor node is determined. If the received power is less than -75 dBm, then the node was gradually shifted closer to the initial transmitting node at a distance of 1m per calculation; and the received power recalculated. This process continues iteratively to ensure complete coverage of the application area.

Experiment 2: Plants placed 25m apart with 10 scatterers Gaussianly distributed around each plant

In Figure 4 the plants were placed 25m apart. The maximum sensor node range to ensure reliable communication is set at 25m. The initial sensor node (black square) position was placed at the same distance from the plant position as in experiment 1. The next node position to ensure coverage was chosen to be at the maximum range of the initial node position along the y-axis.

The received power level at the next node position (located to be at the maximum range of the initial node position along the y-axis position) due to all scatterers within range of the initial node is calculated. If no sensor node (within range of the transmitter node), can receive at the acceptable power level due the scattering effect of the surrounding vegetation, an extra node is placed at the maximum range distance from the transmitter node. This extra node will only be able to communicate with the next sensor node placed according to the algorithm specifications. The scattering effect of surrounding foliage results in a different placement of sensor nodes compared to sensor placement under free space conditions.

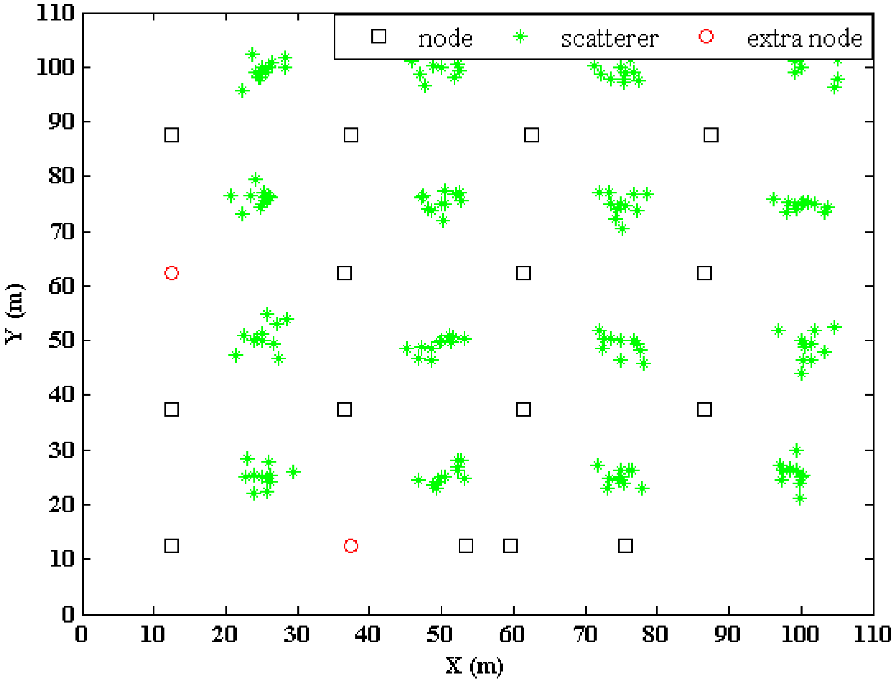

Fig. 4. Plants placed 25m apart with 10 scatterers placed around each plant

7 Conclusion

To guarantee reliable connectivity and adequate coverage of a wireless sensor network application area, sensor nodes have to be placed at positions where the received power is acceptable to ensure reliable communication between nodes. Wireless sensor nodes cannot be placed in similar positions in an agricultural environment as that calculated for a free space environment. The transmitted signal strength is weakened by surrounding vegetation.

The scattering effect on the wireless signal by the foliage surrounding plants means that sensor nodes within the application area have to be placed so that the received signal strength ensures reliable communication. We have proposed modeling the scattering effect of surrounding foliage with a Gaussian distribution to determine to optimum placement of sensor nodes within the application area. We have shown that when nodes are placed at a distance where the effect of the surrounding foliage is minimized than the location of nodes is similar to that of node placement in a free space setting.

When sensor nodes are placed so that the received signal strength is affected by the surrounding foliage, the location of the nodes differs from the free space model. Extra nodes are required to ensure coverage and connectivity within the application area.

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