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Wireless sensor network coverage measurement and planning in mixed crop farming

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ABSTRACT

Wireless sensor network technology holds great promise for application in agriculture to improve crop yield, improve quality, and reduce costs. This paper presents wireless sensor network coverage measurements in a mixed crop farmland. As one of its key contributions, this study shows that general vegetation attenuation models do not apply to low power wireless sensor networks. A log-linear model is proposed in this paper and validated for application in mixed crop environment. Unlike in mono-crop environment, this study shows that the network coverage is heterogeneous with asymmetric channel between communicating node pair. Crop specific parameters of the log-linear model are derived and used to simulate network coverage in a 7 acre test-bed farm. An adaptive energy consumption model for each sensor node is proposed and used to compute energy consumption in the network. A cluster head and two antenna heights deployment model is also proposed and simulated to alleviate short network lifetime due to vegetation attenuation of signals. The results show that this network deployment model extends the lifetime of the network by a factor of more than 20 compare to a deployment where cluster heads are not used.

1. Introduction

Advancements in electronics and communication have made possible the development of small sensors that can be integrated with miniature communication modules to make up wireless sensor nodes. Short range communication technologies include WIFI, Bluetooth, ultra-wideband and ZigBee. Amongst these technologies, ZigBee is more suitable for wireless sensor network because of its low energy requirements. Studies in (Petrova et al., 2006) show that the IEEE802.15.4 (ZigBee) modulation scheme enables a range extension of up to 8 times for the same amount of energy compared to IEEE802.15.1 (Bluetooth). Although a general purpose technology, one of the areas where wireless sensor network (WSN) is expected to make a global impact is in agriculture (López Riquelme et al., 2009). Food security, urbanization, population growth and climate change have attracted attention not just to food production, but also to food management, transportation, traceability and the need to reduce food wastage. These can be accomplished with the use of wireless systems provided appropriate sensors and controls are implemented.

In crop farming, WSN can be used to monitor and control factors that influence crop growing conditions and yields. They can also be used to determine the optimum time to harvest, which cultivar is more suitable for what condition, detect disease, control machinery, etc. (Camilli et al., 2007; López Riquelme et al., 2009; Abbasi et al., 2011; Díaz et al., 2011; Yu et al., 2013). In animal farming, wireless sensors can be used to monitor animal movement, activities, health condition, numbers, disease, interaction and diversity (Nadimi et al., 2008a,b; Huircán et al., 2010; Zerger et al., 2010; Nadimi et al., 2012). However the biggest impact of WSN in agriculture is expected to be the implementation of semi-autonomous and autonomous controls in farming. They can be used to optimize resources, mitigate the impact of climate change, and reduce cost, labor, and increase productivity.

A good number of studies have been carried out on WSN architecture in agriculture (Díaz et al., 2011). Limited studies have been reported on the models that could be used to deploy these

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networks (Mao et al., 2007; Ndzi et al., 2012a,b; Vougioukas et al., 2012). One of the reasons for the lack of appropriate models is because most crops and environments vary. In addition, the ad-hoc mode of operation of most of these nodes means that researchers have paid very little attention to individual nodes but mainly to the whole network. For precision farming in mixed crop agriculture the performance and reliability of each node is important. This is because different plants have different requirements, root zones/depths, and tolerant periods to adverse conditions before lasting damage occurs or yields are affected. To implement an autonomous system with context-aware sensor fusion and control, network reliability is required. Therefore this paper reports on measurements in a 12 acre farm used as a test-bed for WSN deployment.

Vegetation attenuation models (Qinetiq, 2002) reported in open literature make a number of assumptions. These include the assumptions that the communication system set-up uses the classical master–slave configuration and that one of the antennas is at a higher height or located outside the vegetation. In WSN where nodes operate in a peer-to-peer configuration and sometimes in an ad-hoc manner, very little studies have been carried out to develop appropriate models for network planning. Therefore, this paper evaluates a generic form of one of the vegetation attenuation models (Weissberger, 1982), validates path loss models and proposes appropriate parameters that could be used in the implementation of the models.

This paper is organized as follows; Section 2 describes the WSN device that was used, the measurement set-up and the layout of the agro–farm. Details of the various types of plant are also provided. Section 3 presents the measurement results of signal propagation in the different types of crops. Section 4 presents the path loss models that can be used for wireless network planning. Section 5 describes the node connectivity, network planning and possible performance indicators. It also presents energy consumption modeling in the network and the results from the proposed network deployment topology. Conclusions are drawn in Section 6.

2. System description and measurements

2.1. Measurement system

This study was conducted using wireless sensor devices (motes) from MEMSIC which are equipped with Atmel RF230 radio chip that implements the IEEE802.15.4 standard. In the 2.4–2.5 GHz band there are 16 channels with each channel having a bandwidth of 3 MHz separated by 5 MHz. It is designed to support an effective data rate of 256 kbps. The devices were configured to transmit a total power of 3.2 dBm. The receiver sensitivity is rated as −91 dBm. Omni-directional antennas with gains of 4.3 dBi were used to ensure greater coverage and each mote was powered by 2 AA size batteries (Huircán et al., 2010). Although other systems could have been used, the authors elected to use samples of commercially available WSN devices to ensure that a derived deployment plan is not only feasible but also implementable within a short timescale.

Link estimation is an essential part of network planning, prediction and network protocols development and evaluation. A number of quality measures were specified and are implemented in most of the devices that support the IEEE802.15.4 standard. These include Relative Signal Strength Indicator (RSSI) and Link Quality Indicator (LQI). RSSI gives an estimate of the signal power received and LQI is based on chip error. Studies based on devices that implemented the IEEE802.15.4 reported that RSSI was only reliable for detecting good links and is unreliable at signal values that are close to the limits of the receiver sensitivity (Atmel, 2003). However, Srinivasan and Levis (2006)), used 30 wireless sensor nodes to show that RSSI, for a given link, has very small variation over time and the packet reception rate is at least 85% for signals above the sensitivity threshold of −85 dBm. At smaller signal strengths no correlation between packet reception rate and RSSI which, may be more strongly influenced by system noise, was found. Comparison of LQI and RSSI showed that LQI only offers a better correlation with packet reception rate when averaged over a large number of packets. The study also showed that over a small number of packets, LQI varied over a wide range making it an unreliable parameter for short term measurements.

In general, for communication between two nodes there are three states in wireless links: connected, transitional and disconnected states (Zuniga and Krishnamachari, 2004). In the transitional state, communication links are unreliable and are characterized by large variations in the link quality parameters, such as RSSI.

Based on the studies into the reliability of RSSI and the need for measurements at many positions, measurements reported in this paper use RSSI as a measure of the link quality. The RSSI value of the Atmel RF230 radio device in the IRIS motes is saved as a 5-bit value indicating the receive power from −91 dBm to −10 dBm. RSSI computation in the device does not distinguish between IEEE 802.15.4 signal and other signal sources (Atmel-AT86RF230, 2011). Therefore it is critical to conduct the studies where there are no IEEE802.11 devices. Using the Basic Operating Mode, the relationship between RSSI values, which is updated every 2 μs, and the received signal is given by

$$P_{RF} = RSSI_{Base} + RSSI \quad (1)$$

where $RSSI_{Base}$ is equal to −91 dBm.

2.2. Measurement environment and set-up

These studies were carried out to understand network coverage in areas cover by the following crops: corn, herbs (Misai Kuching), cashew nut, mango and guava trees. In addition, studies were conducted in open fields in areas with soil and grass covering to establish connection between sensor network cluster heads. Images of some of the areas where measurements were conducted are shown in Fig. 1. Also shown is the partitioning of the crops growing area. The whole 12 acres is not illustrated as part is covered by greenhouses and other buildings.

These areas were selected to provide the generic network coverage models and represent samples of the crops in the farm. Although the WSN deployment will focus on this part in the initial phase, network coverage is planned for the complete 250 acre site. The site includes rubber plantation and natural tropical forest. The study reported in this paper were conducted with the sensor nodes positioned closed to the ground, 15 cm above ground, and at 1 m heights. Whilst WSN coverage can benefit from the nodes being positioned at heights that are above the surrounding vegetation, this will either be cost inefficient or require constant repositioning due to the time variant nature of plant heights.

Different types of plants require different sets of growing conditions. This study is a small part of a bigger research program to better understand plant growth, impact of climate change, productivity and biodiversity. The conditions that will be monitored and controlled require some of the sensors to be placed in the soil. Others sensors will be placed at the base of the crops on the ground and also at trunk and branch heights. The distances between the sensor(s) and the wireless module, and the wireless module and the antenna need to be small to reduce signal losses in the units.

All trees or crops were planted in rows with regular spacing between plants and rows. The number of crop rows per bed

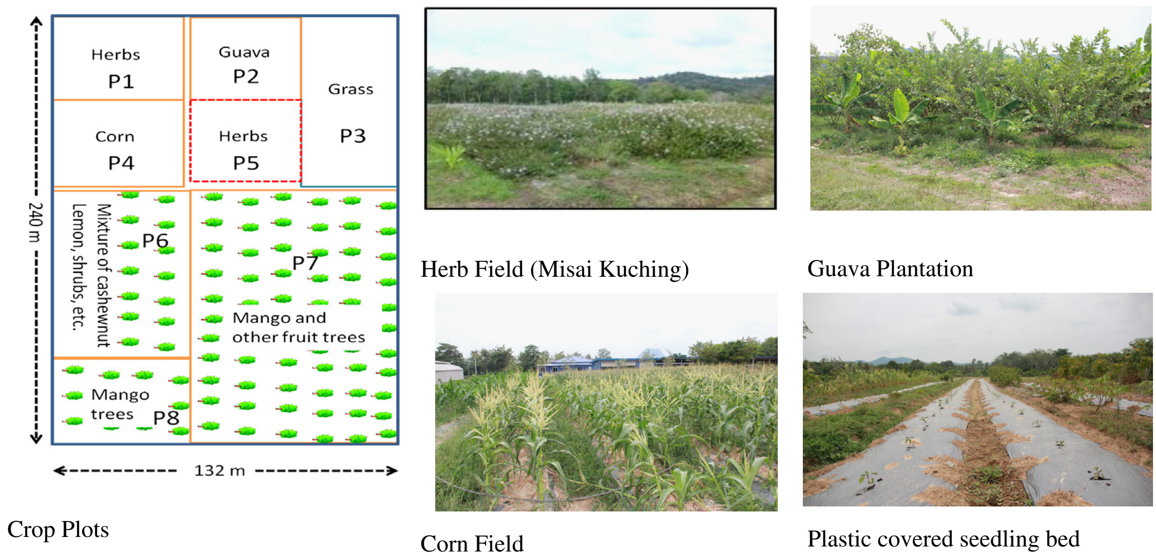

Fig. 1. Measurement environments.

depends on the type of crop. The planting configurations are illustrated in Fig. 2. The specifications for each type of crop, including the dimensions, are given in Table 1. Two rows of the guava trees are inter-spaced with banana plants. However the link set-up was such that the banana plants had very little or no influence on the results obtained.

3. Measurement results

This study was conducted at 15 cm and 1 m antenna heights to assess system coverage at these heights. Since one of the important cost factors in WSN deployment is power consumption, the WSN nodes can be configured to transmit different power levels. Doubling the transmit power level only extends the range by a factor of $\sqrt[n]{2}$, where n is the power decay exponent which may not be commensurate to the increase in energy depletion rate. In free space, the range will be increased by a factor of 0.414. Therefore the rate of radio wave attenuation is not only critical for network coverage but also for network planning and power optimization.

Fig. 3 shows the signal variation with range over grass and soil covered surfaces at the two antenna heights. One interesting observation is that on grass, the range is at least 10 m longer at 15 cm antenna height than on the soil. At 77 m, for 1 m antenna height, the signal over the grass field is also 8 dB stronger compared to the same distance over the soil. This can be attributed to surface roughness with the grass having a smoother surface than soil.

Fig. 4 shows the trend of signal power with distance in herbs and in the corn field. At 15 cm height, the range of the wireless sensor nodes with −91 dBm noise floor is limited to a maximum of 25 m. At 1 m height, the antenna is higher than the herbs and the range increases significantly with a 22 dB margin above the receiver noise floor at 28 m. Measurements were not conducted beyond 28 m because of the limited range of the plot. Compared to measurements over the grass field and soil covered ground, at 28 m the signal strength in the herbs at 1 m antenna height is 4 dB weaker. At 1 m the antenna was below the height of the corn. Fig. 4(b) shows that there is very little difference in signal strength between the two antenna heights. It is interesting to note that at ranges less than 8 m, attenuation is higher at 1 m antenna height compared to 15 cm. This can be explained by the fact that the foliage is thicker at 1 m height thereby attenuating the coherent

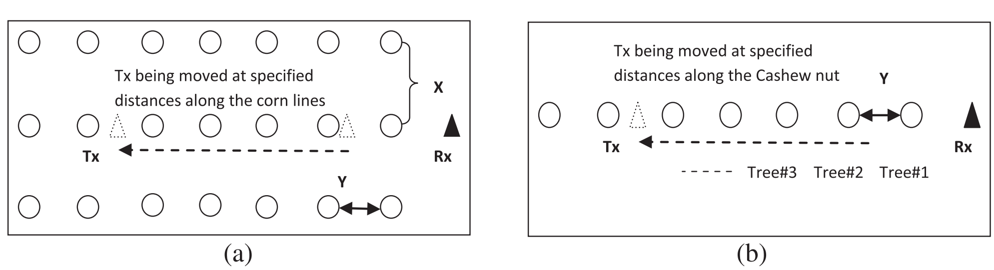

Fig. 2. Crops planting pattern; (a) two or more rows of plants per bed and, (b) one row of plants per bed.

Table 1
Crop specification and planting geometry.

Crop	Row spacing *X* (cm)	Plant spacing *Y* (cm)	Average plant height (cm)	Average stem diameter (cm)	Planting – rows per bed
Corn	40	30	210	3.5	2
Cashew nut	200	200	150	6	1
Herb -Misai Kuching	30	30	50	0.6	2
Guava	180	180	240	6	1

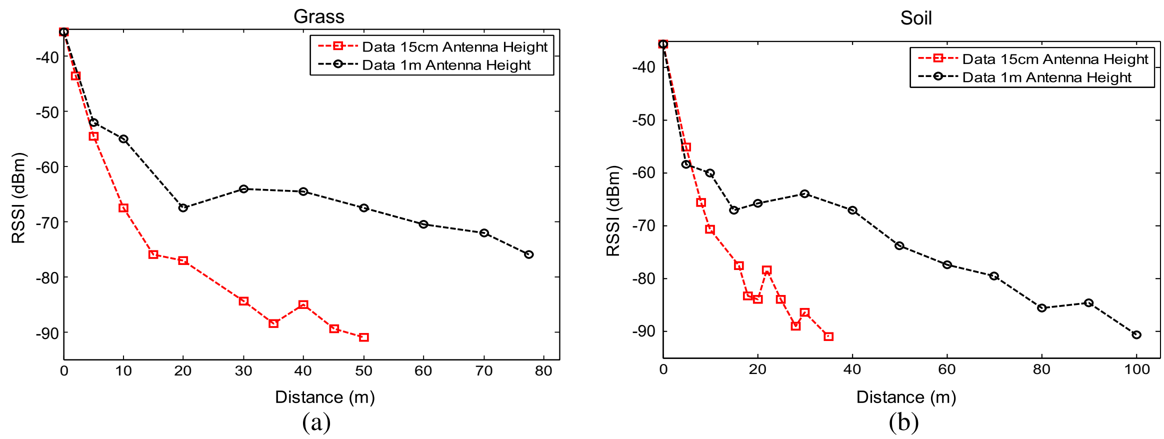

Fig. 3. Signal variation with range, (a) over grassfield and, (b) over soil covered grounds.

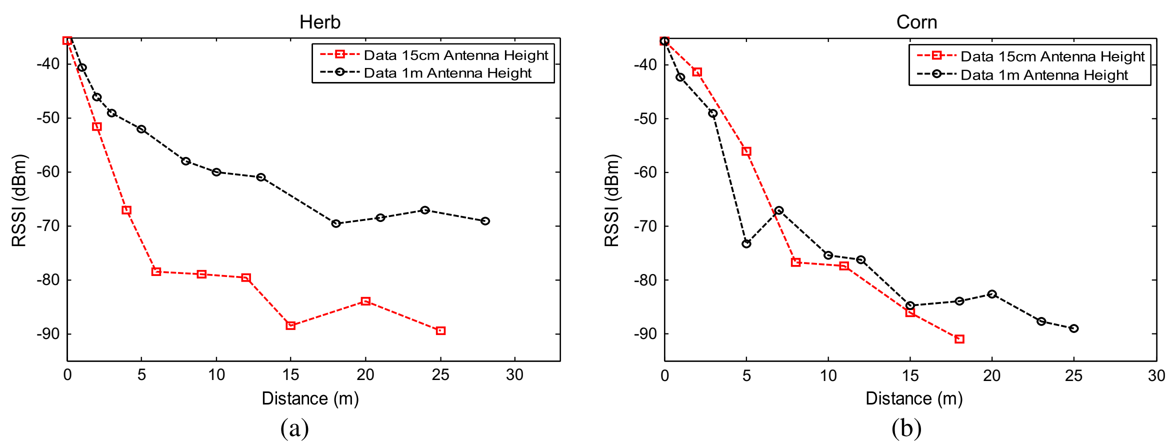

Fig. 4. Signal varation with range in (a) Herb and, (b) corn.

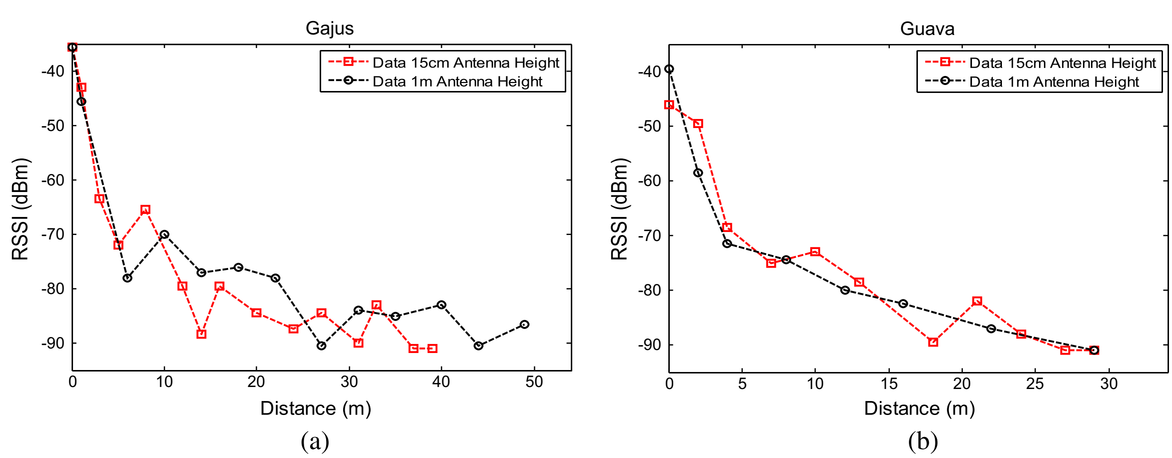

Fig. 5. Signal variation with range in (a) cashew nut and (b) guava plantation.

components much more than at 15 cm height which is dominated by corn stocks. At higher vegetation (corn) depths, there are more diffused signal components at higher heights than at the base and this may account for the lower attenuation observed at 1 m antenna height in Fig. 4(b).

Fig. 5 shows the results obtained from measurements conducted on cashew nut trees and guava. It should be noted that none of the antenna heights were above the tree canopy. The figure shows that there is very little or no difference in signal attenuation at the two antenna heights, except that there is significantly more signal variation at 15 cm antenna height.

4. Modeling of wireless signal coverage

Results in Section 3 show that wireless sensor node range can only be extended if the antenna is position above the vegetation canopy. Signal propagation involves the interaction between the direct, scattered and reflected components. Severely scattered signal would results in dropped packets, increase in the number of retransmissions, energy consumption and hence, shorter battery life.

The models that are widely used in wireless sensor networks in the presence of vegetation include the two-ray ground reflection model and the Weissberger vegetation attenuation models (Weissberger, 1982). All the vegetation attenuation models that have been developed are for wide area communication networks where one antenna is located at a significant height or outside the vegetation. In addition, communication devices transmit higher power levels than wireless sensor nodes. Examples of vegetation attenuation models include those recommended by the International Telecommunication Union (ITU-R Rec-833-6, 2007). A good survey of vegetation attenuation models is given in (Savage, 2003; Meng and Lee, 2010).

In a transmission medium, the received power, P_r, at the transmitter is given by Eq. (2).

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^n \quad (2)$$

where P_t is the transmitted power, G_t and G_r are the transmitter and receiver antenna gains, respectively; λ is the wavelength of the radio waves; d is the distance between the transmitter and receiver antennas; and n is the rate at which power decays with distance. In free space n is equal to 2. This equation assumes a homogeneous medium where the rate of signal attenuation is constant. However in the presence of vegetation the transmission medium is not homogeneous neither in density, orientation nor dimension of the vegetation components. For normalized signal power, Eq. (2) can be simplified to Eq. (3). This can be converted into a linear equation using logarithm as in Eq. (4)

$$P_r = P_0 d^{-n} \quad (3)$$

$$P_r(dB) = P_0(dB) - 10 * n * \log_{10}(d) \quad (4)$$

In Eq. (4), d is the normalized distance. Compared to published vegetation attenuation models such as the Modified Exponential Decay (MED) model and the Non-zero Gradient model, this is a simplified model (Meng and Lee, 2010; Ndzi et al., 2012a,b). From a propagation mechanisms perspective, at very shallow vegetation depths, signal propagation is dominated by coherent components which decrease rapidly with distance. Beyond this point propagation is mainly due to forward scattering and the signal is dominated by diffuse components. However, because of the small transmitted power from wireless sensor nodes, most scattered or diffused components are very weak. Nonetheless, their presence is illustrated by the reduction in the signal decay gradient at distances further from the transmitter.

The generalized form of the MED vegetation attenuation model is given by

$$P_r(dB) = X f^Y d^Z \quad (5)$$

where f is the frequency in megahertz (MHz), d is the vegetation depth in meters and, X, Y and Z are the model parameters. Different values have been proposed in literature for this model under a variety of names e.g. COST 235, ITUR, FITUR and Weissberger (Weissberger, 1982; ITU-R Rec-833-6, 2007; Meng and Lee, 2010). To assess the application of this model in wireless sensor networks, the generalized form of the MED model has been fitted to the measured data in the presence of vegetation.

Linear regression technique has been used to estimate the value of n in Eq. (4). The MED model and the Free Space Loss (FSL) model have also been fitted to the data. Fig. 6 shows examples of fittings to the measured data, n estimates and the root mean square errors (given in brackets) between the models and the measured data. The figures show that the log-linear model, Eq. (4), generates the smallest root mean square error (RMSE). The advantage of the log-linear and FSL models is that they apply to cases with or without vegetation in the propagation paths.

The values of the parameters of the models together with the RMSE between the models and the measured data are given in Table 2. The results show that the log-linear model offers the highest accuracy. The simplicity of the model and the limited transmission range of wireless sensor nodes mean that there is no strong reason to use complex vegetation attenuation models WSN planning. Some of the fitted parameter values give very optimistic network coverage predictions at 1 m antenna height and pessimistic estimates at 0.15 m antenna height. For example, the network coverage at 1 m antenna height is estimated to be approximately 180 m on the soil covered surface. For reliable communication, the maximum range of the node should be assumed to be limited to 80 m.

To assess the impact of antenna height gain on wireless node coverage, additional studies were conducted in an open grass field. Fig. 7 shows the signal variation with distance for 0.15, 0.5 and 1 m antenna heights. The results show that up to approximately 31 m, the received signal power for 0.5 m antenna height is either equal to or greater than the received signal power at the antenna height

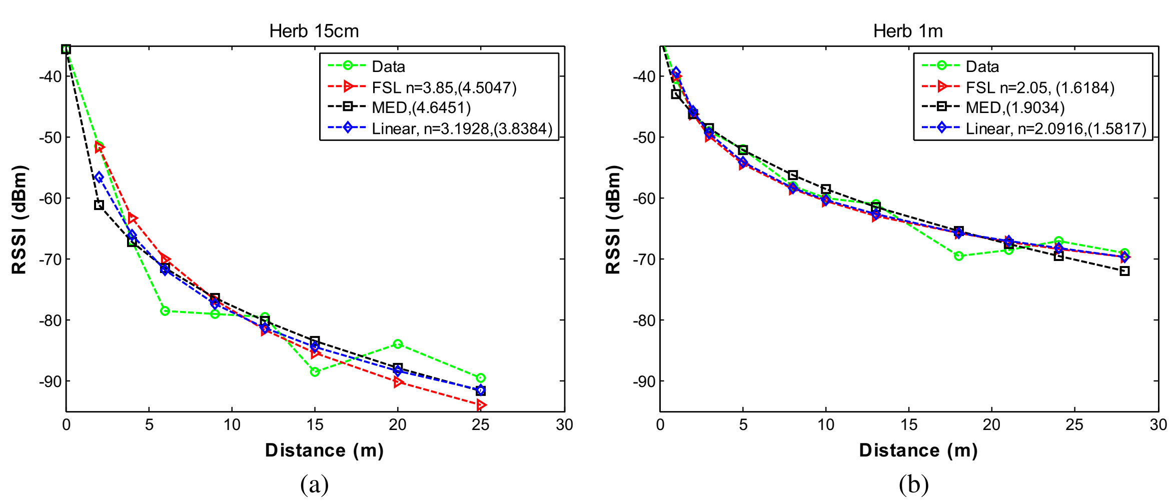

Fig. 6. Modelling of signal power variation with distance in herb plantation at (a) 15 cm and, (b) 1 m antenna heights.

Table 2
Parameters of fitted models and the root mean square errors between the model and the data.

	Antenna height (m)	Linear model			FSL model		MED model			RMSE
		n	Po	RMSE	*n*	RMSE	*x*	*y*	*z*	
Soil	1	2.34	−36.86	4.33	2.14	4.40	–	–	–	–
	0.15	4.04	−28.75	2.32	3.16	3.24	–	–	–	–
Cashew Nut	1	2.34	−49.53	4.41	3.01	5.49	19.91	0.00	0.26	5.05
	0.15	2.77	−47.50	4.23	3.34	5.04	18.51	0.00	0.31	5.16
Corn	1	3.45	−40.48	3.95	3.49	3.95	27.81	−0.10	0.46	4.75
	0.15	5.30	−23.88	3.00	3.70	6.24	11.01	−0.05	0.71	4.29
Herb	1	2.09	−39.41	1.58	2.03	1.61	–	–	–	–
	0.15	3.19	−46.90	3.84	3.83	4.50	14.01	0.05	0.31	4.65
Grass Field	1	1.79	−39.02	2.52	1.72	2.53	–	–	–	–
	0.15	3.46	−32.59	1.72	2.93	3.01	25.31	−0.10	0.41	3.49
Plastic covered bed	1	1.73	−43.43	1.91	1.99	2.25	–	–	–	–
	0.15	2.82	−38.94	2.49	2.74	2.50	–	–	–	–
Guava	1	2.58	−52.41	1.63	3.67	4.77	5.71	0.15	0.31	1.93
	0.15	3.23	−44.03	3.43	3.56	3.67	1.41	0.25	0.46	4.25

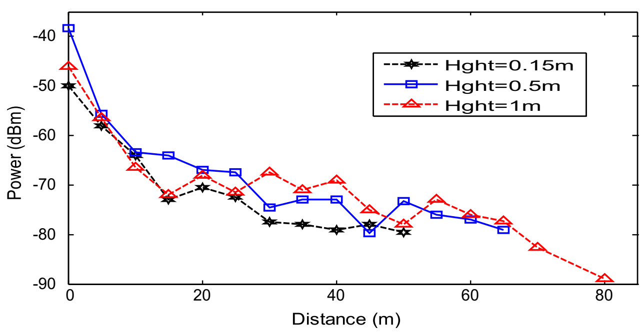

Fig. 7. Received signal variation with distance for 0.15 m, 0.5 m and 1 m antenna heights.

of 1 m. Ground reflected paths will exist when the boundary of the first Fresnel Zone, h_0 in Eq. (6) is equal to or greater than, the antenna height (Ndzi et al., 2012a,b).

$$h_0 = \sqrt{\lambda d} \tag{6}$$

where d is the antenna separation and λ is the wavelength. For 2.4 GHz h_0 is 0.5 m at a distance of 8 m and 1.0 m at a distance of 32 m. Contributions from ground reflected signal components therefore can significantly influence the received signal power. Although the difference in the averaged received power is only 1 dB at 65 m, the packet loss for 0.5 m antenna height increased to 100% beyond this point due to the poor quality of the received signal. This study shows that the range increases by 15 m when the antenna height is increased from 15 cm to 0.5 m and a further 15 m when the height is increased to 1 m.

5. WSN modeling and planning

In mixed crop farming, sensor node deployment and density is determined by the number of environmental factors to be monitored and their spatial variations. The determining factors include: crops types, plant root zones/depths, soil type, yield cycle, water/nutrient requirements at different stages in the yield cycle, meteorological conditions and topography. In mono-crop farming node density is mainly influenced by soil type, crop type, spatial variation and topography of the farm land. Different crops have different tolerances to drought, temperature, humidity and nutrient deficiency. These different requirements imply that, in addition to ensuring optimum spatial condition sampling with sensors in autonomous systems, temporal context-aware fertigation must be implemented. In this study the envisaged network objectives are to monitor air temperature, humidity, soil moisture, soil water potential, soil nutrients, fruit maturity and ripeness, and other environmental parameters. The investigated antenna height of 1 m is low enough to allow sensors deployed underground, on the surface and on crop branches to be connected to the wireless module without compromising data integrity. In this study the field is divided based on the types of crops.

Significant research has been carried out into network deployment patterns to determine the optimal number of sensor nodes required to achieve network coverage and connectivity. Distinctions are made between node coverage, which is for information collection, and node connectivity which is for information transmission. Fig. 8 illustrates some of the simple geometries often used in the simulation of node deployment and the number of connections between the nodes (Bai et al., 2006, 2011).

Network coverage enables communication between nodes whilst connectivity provides fault tolerance. Connectivity can only

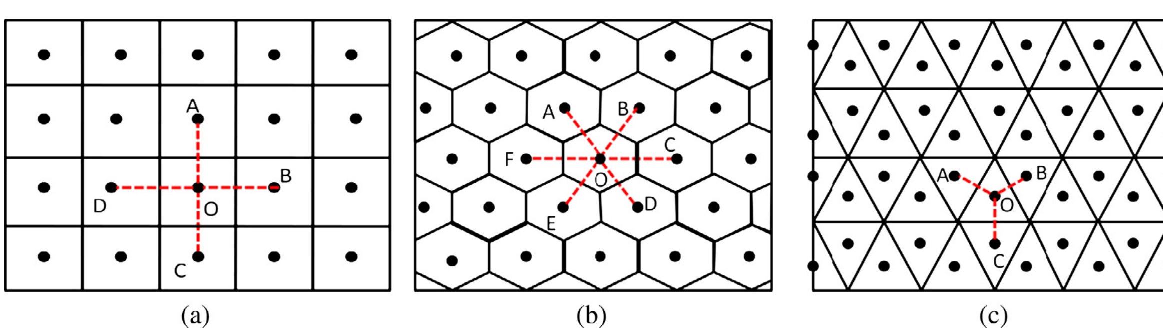

Fig. 8. WSN node deployment geometries and connectivity (a) square grid, (b) sexagone, and (c) triangle.

exist if two nodes are within each other's communication range. A network with a high number of connectivity is resilient to fault but this must be balanced against costs. In order to model network coverage and connectivity, the following notations will be used:

- r_c denotes the communication range of a node.
- r_s is the spatial sampling resolution required.
- A_s is the area covered by a node.
- N is the number of nodes in the network.
- C_i is the ith network cluster head.

5.1. Coverage and connectivity modeling

Because of different plant root zones, spatial sampling and node deployment is determined by the different crops and their locations within the farm. In order to plan the network adequately, the following criteria has been used:

- For each plot, P_i a minimum of 2 sensor nodes will be used.
- If there are only 2 nodes within a crops plot, $r_s < \frac{\sqrt{(X^2+Y^2)}}{2}$, where X and Y are the dimensions of a rectangular plot. In this case, $r_c \geqslant r_s$.
- A maximum node range ($R_{\max}$) is used irrespective of the vegetation type to mitigate network partitioning due to time variant vegetation density.

For most network modeling, environmental homogeneity or randomly generated heterogeneous model parameters are often used to compute the path loss. As a result most of the nodes in the network end up having the same range or unrealistic ranges. For these systems, deployment can be easily modeled and connectivity pattern accurately controlled. For mixed crops the node coverage range is not uniform. The range has to be calculated across crop plot boundaries. In Fig. 9 assume that for plots 1 and 2 signal propagation are characterized by $\{P_{01}, n_1\}$ and $\{P_{02}, n_2\}$, where P_0 and n are the values given in Table 2 for different crop types.

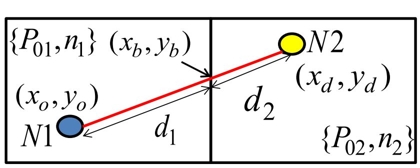

Fig. 9. Cross-crop plot node coverage.

The path length between nodes $N1$ and $N2$ is $R = \sqrt{(x_d - x_0)^2 + (y_d - y_0)^2} = d_1 + d_2$. If a receiver node sensitivity is $P_{r\,\min}$ the maximum range of $N1$ is given by

$$R_{N1} = \sqrt{(x_d - x_0)^2 + (y_d - y_0)^2} + 10^{\left(\frac{P_{r\min} - P_{r1} + P_{01}}{-10n_2}\right)} \tag{7}$$

where P_{r1} is the signal strength at (x_b, y_b) For this to be valid $P_{r1} \geqslant P_{r\min}$ condition must be satisfied at (x_b, y_b). The use of this environment aware model allows the link margin and also power level of each node to be individually modeled. Adaptive power control can be built into the system to allow different nodes to transmit different power levels depending on their locations and path losses.

For the mixed crop area, using a uniform coverage model produces a network connectivity as illustrated in Fig. 10a. All the nodes achieve the 2-connectivity required for basic network fault tolerance but the network performance is over-optimistic. Setting a larger value for uniform node range will also produce over-optimistic or over-pessimistic results. Fig. 10b shows the network connectivity when the network is adapted to the type of vegetation, using results in Table 2. The network connectivity adapts to the prevailing environment and the node deployment can be optimized to meet specific spatial sampling and connectivity requirements.

Network deployment shown in Fig. 10 has a high nodes density and may have a high redundancy. Nonetheless some applications of WSN, especially in intensive agriculture such as in aquaculture, may demand such a high node density. The costs of the network include the initial cost of the motes and the running cost.

Most simulation studies use the two-ray model which often incorporates the direct ray and the reflected ray. At sufficiently long distances, the model simplifies to the Plane Earth model for which doubling the antenna height is equivalent to increasing the transmit power by 6 dBm. This model, when it has been used in network simulation studies, assumes surface homogeneity which will not be valid in most agricultural environments.

5.2. Reciprocal connectivity

In wireless network modeling, channel symmetry is often widely assumed. In some networks where adaptive power control is used; a receiving node (D) collects information about the signal level and quality (signal-to-noise/interference level) from transmitting node (T). Then it uses this information to select the transmit power level that it needs to communicate with the original

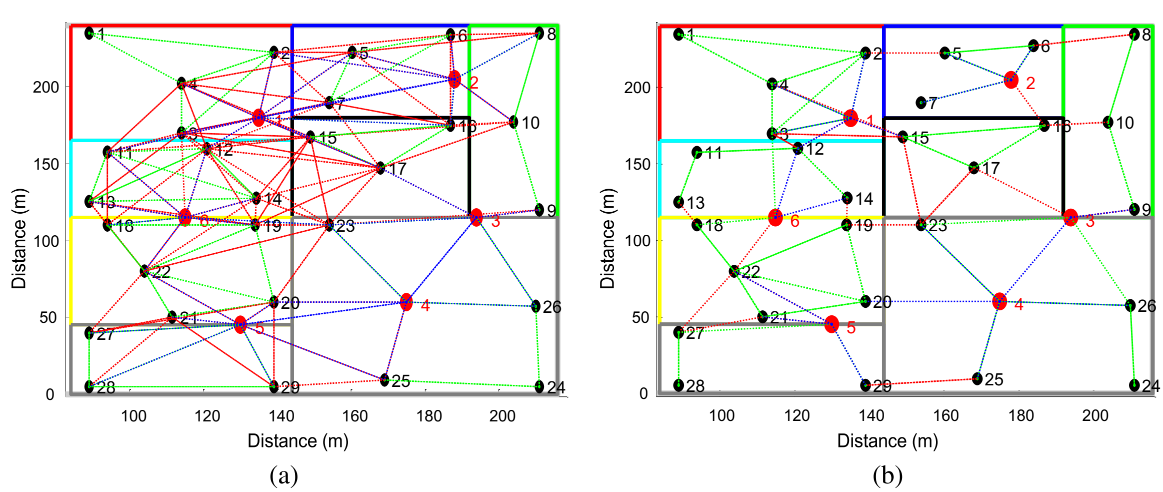

Fig. 10. Wireless sensor node coverage and connectivity (a) uniform node coverage range, and (b) using vegetation specific network coverage.

sender (T). This makes two fundamental assumptions about the wireless channel:

- the receiving node is experiencing the same interference level as the transmitting node;
- the channel is homogeneous between the transmitter and the receiver.

This can lead to an excessive transmit power settings if the receiving node experiences interference from nodes that may be close to it but not to the destination node.

In signal propagation, especially in the presence of vegetation, there are three regions (depending on the vegetation depth) that are dominated by different propagation characteristics: coherent, forward scatter and diffused regions. This forms the basis of the Radiative Energy transport theory that has been applied to vegetation in (Johnson and Schwering, 1985) and represented by a 3 gradient model in (Qinetiq, 2002). Figs. 3–5 show that the rate of signal decay in the first 5–10 m is much higher than subsequently and the gradient depends on the type of vegetation and its density. This is followed by the forward scatter region which contains a mixture of coherent and scattered components and the gradient is smaller than in the coherent region. The multiple components in the diffused region combine to represent a small decay gradient with distance. However, communication in this region is characterized by multiple retransmissions due to high packet error ratio which reduces the battery lifetime of the node. Nodes that are located in high vegetation density plots, such as in the corn fields, may be able to receive transmissions from nodes located in other plots. However they may be unable to relay their own data because of the high extinction rate of the coherent signal in the first few meters from the node. This creates an asymmetry in communication between two nodes located in different plots with different crop types or densities. Mandke et al. (2007) have argued that ambient interference, hardware impairments and fading properties of wireless channels must be fully evaluated due to potential cross-layer consequences for communications between two entities on an asymmetric link. This asymmetry in communication can be built into the network simulation model.

5.3. Network energy consumption modeling

Base on the network connectivity, the power consumed in the network can be computed. WSN nodes have three energy consumptions states: sleep, transmit and receive. Using the energy model presented in (Kamarudin et al., 2012), the energy consumption during transmission, when receiving and in the sleep state can be represented by

$$E_{Tx} = P_{Tx} * t_{Tx} \tag{8}$$

$$E_{Rx} = P_{Rx} * t_{Rx} \tag{9}$$

$$E_{sleep} = P_{slp} * t_{slp} \tag{10}$$

where P_{Tx}, P_{Rx} and P_{slp} are the power settings used when transmitting, receiving and in the sleep state. The parameters t_{Tx}, t_{Rx} and t_{slp} are the time duration when the mote is transmitting, receiving and sleeping, respectively. The time duration depends on the amount of data to transmit and the data transmission rate. The time period when the motes are in the transmission and reception states increases with increase in interference level, path loss and packet collision when automatic retransmission is used.

The transmit power of each node can be adjusted based on its distance from neighboring nodes, its connectivity and the received signal to noise ratio. The flow diagram of the simulation implemented is shown in Fig. 11. The initial battery voltage is 3.0 V.

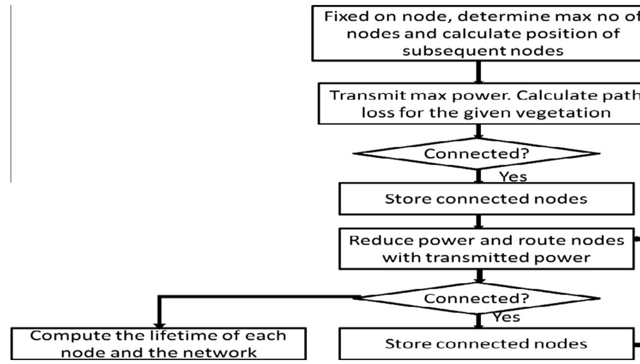

Fig. 11. Flow diagram of network simulation to compute node placement and network life time.

In an ideal system, all nodes must achieve a minimum of 2-connectivity for fault tolerance. However, this can be achieved at the expense of cost. Self-organizing and ad-hoc properties of the network allow nodes to join and leave the network with little or no disruption to normal operations. Therefore the simulation set-up was for a minimum number of nodes to be deployed. The interest is in node connectivity and complete network connectivity. Fig. 12 shows the minimum node deployment that provides one redundancy (back-up) for each plot, except in plots P1 and P7 where there are more than two nodes. The log-linear model parameters for cashew nut plot have been used to simulate network performance in the mango plot because the trees have similar characteristics. Fig. 12a(i) shows a possible placement of nodes that achieves 59% 2-connectivity. Fig. 12a(ii) shows that more nodes (76%) achieve 2-connectivity but at the expense of network partitioning. An optimum network is one whose connectivity remains stable over a wide range of signal level conditions. As shown in Fig. 12b(i), only one node losses 2-connectivity over a 7 dB received signal range. This reduces the possibility of network partition and provides flexibility for the implementation of transmission power control. Spatial sensing coverage and network connectivity are opposing requirements that must be optimized to eliminate network partition whilst providing fault tolerance. Fig. 13 presents an alternative to Fig. 12a(i). Although three nodes lose 2-connectivity over an 8 dB range, it offers better connectivity than Fig. 12a(i).

Fig. 14 shows a network with node 12 acting as a sink node. The base station (node 12) is assumed to have unlimited power supply. Fig. 14b can be used to select the transmit power level for each node. From the node deployment diagram, only node 1 is shown to have only one connection but Fig. 14b shows that there are 4 nodes with only a single connectivity. This discrepancy is due to non-reciprocity or asymmetry of the channel between some node pairs. Networks operating in this environment must be configured to broadcast without handshaking to circumvent problems associated with asymmetric channels.

Using minimum power routing for data transmission in the network in Fig. 14, the energy consumption profile of the network and the number of nodes alive is shown in Fig. 15. The energy consumption in the network has been computed based on the parameters given in Table 3. The data transmission interval for each node is 3 min. Based on each data packet size of 100 bytes, $t_{Tx} = t_{Rx} = 32ms$. This assumes that there are no overheads. Each node transmits at least once in each 3 min interval. Intermediary nodes will receive data from other nodes and forward it to other nodes or to the sink node. A node that only transmits its own data and is not an intermediary node is assumed to sleep for the remainder of the interval. The transmitted power of each node is

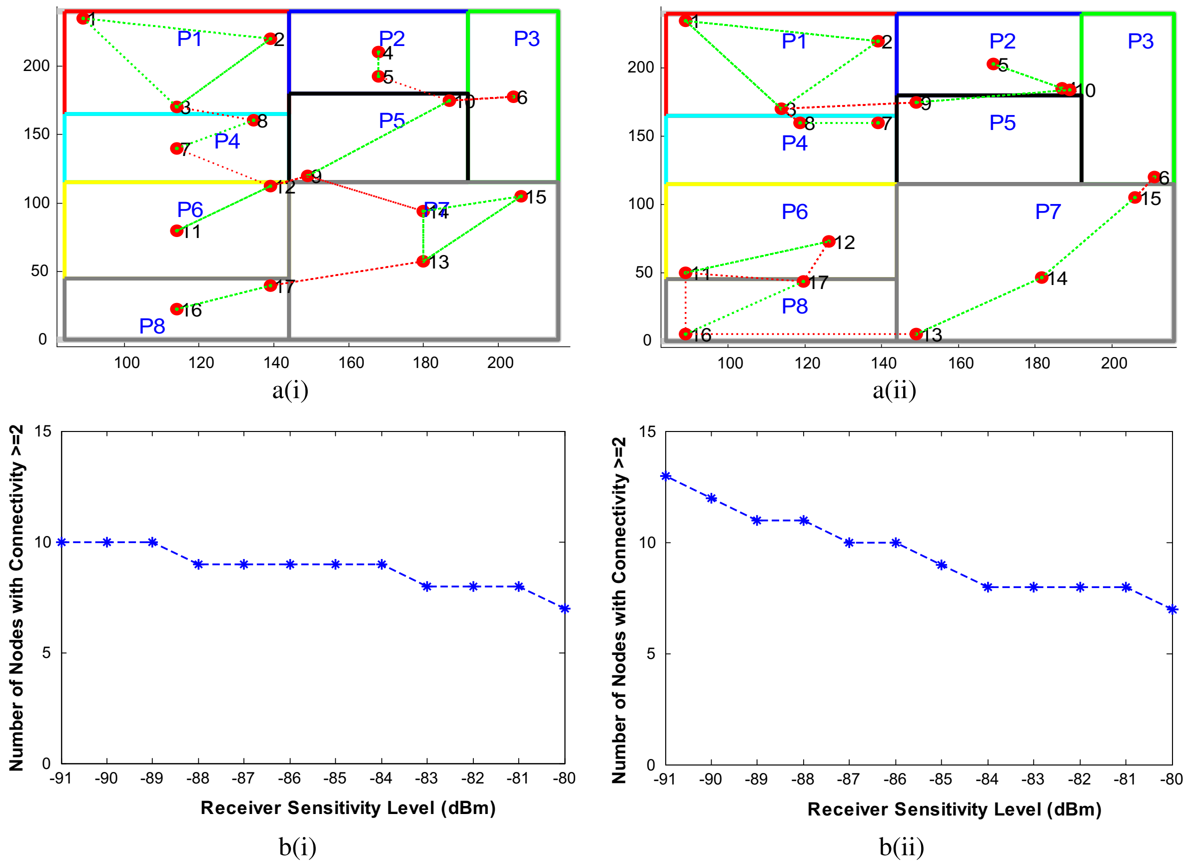

Fig. 12. Simulated network, (a) node placement and, (b) number of nodes with 2 or more connectivity.

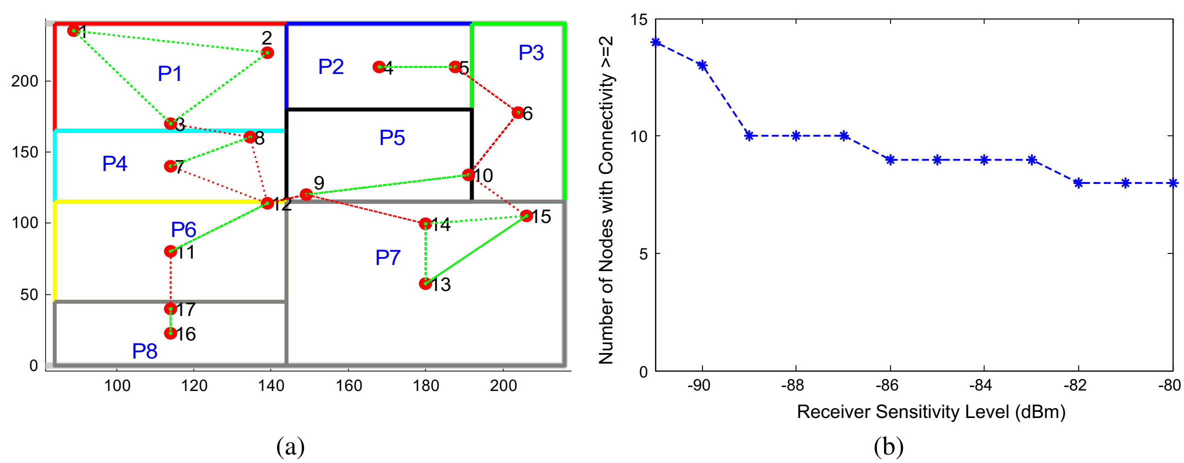

Fig. 13. Simulated network (a) node positions and, (b) number of nodes with 2 or more connectivity.

also set to the minimum level that is necessary for it to transmit to the next hop or data sink. This adaptive approach implies that nodes in the network will consume energy at rates that are dictated by their surrounding i.e. crop type and path length to the next hop. The use of minimum nodes deployment strategy means that when the number of nodes alive drops to 6, the network is partitioned. This problem can be alleviated by using multi-height deployment with coordinating nodes that are deployed above vegetation heights to act as cluster heads. Research on antenna height optimization and diversity reception in wireless sensor networks has been reported in Kwong et al. (2012) and Sasloglou (2009), respectively. The approach proposed by Kwong et al. can be used to select the cluster head height at each location. The use of above vegetation antenna height would allow a uniform deployment topology to be used for cluster head network. In this case the network is decomposed into heterogeneous and homogeneous topologies.

Applying this scheme, the network can be planned in 3-dimension allowing connectivity between nodes, nodes to cluster head and cluster heads to cluster head. This approach has two main advantages; it allows for the number of nodes to be reduced and can also allow for greater spatial sampling. This is possible when there is line of sight between connecting cluster heads. Optimization of spatial coverage and network lifetime could be achieved using one-hop configuration. If the cluster heads are assumed to have unlimited battery power (e.g. using solar power source),

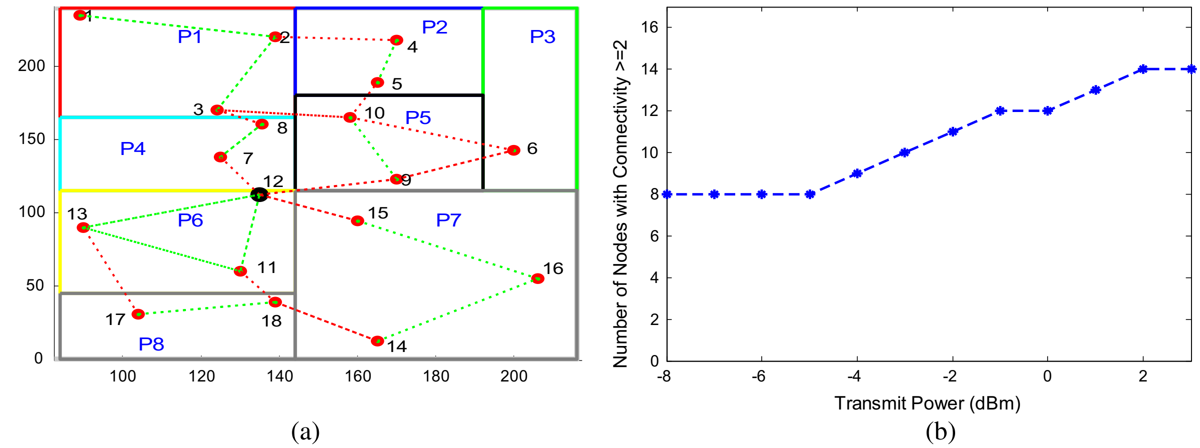

Fig. 14. One network deployment optimized solution (a) node position and, (b) number of nodes with 2 or more connections.

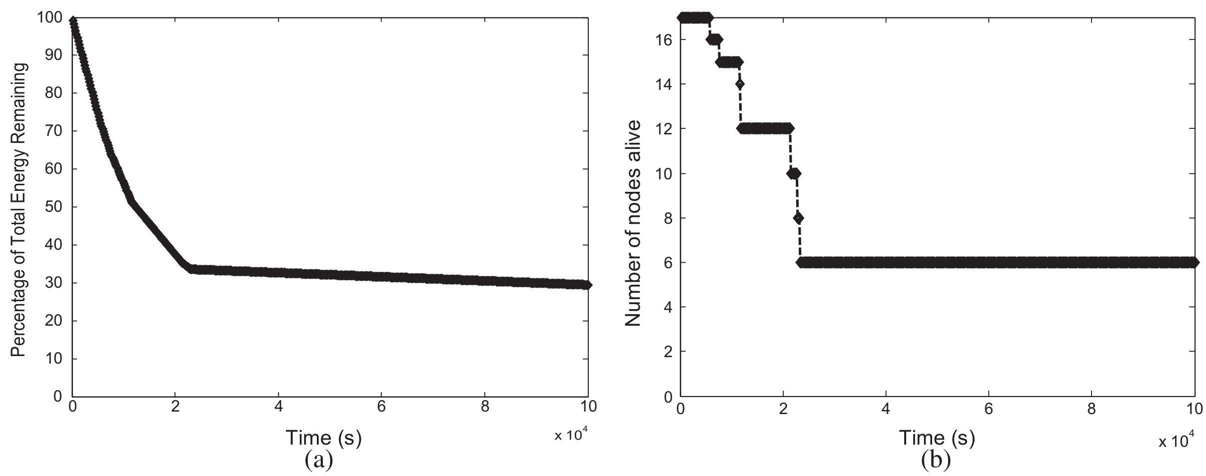

Fig. 15. (a) Percentage of total energy remaining in the network and, (b) the number of nodes alive in the network.

Table 3
WSN simulation parameter based on Atmel ZigBee chip specification.

Parameter	Value
Number of nodes per plot	1 ⩽ number of nodes ⩽ diagonal distance/node range in plot
Data packet size	100 bytes
Transmission interval	3 min
Required battery voltage	1.8 V
Transmit power levels	−10 dBm to 3 dBm (steps of 1 dBm)
Receiver sensitivity level	−91 dBm
Data rate	250 Kb/s
E_{Rx}	0.113 mJ (I_{Rx} = 19.7 mA)
E_{Sleep}	144 nJ (I_{Sleep} = 80 nA)

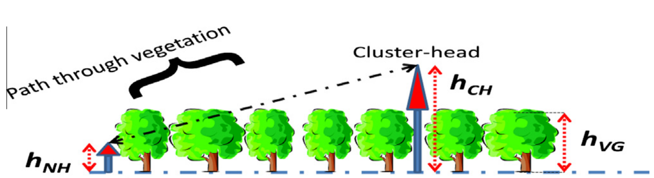

Fig. 16. Illustration of cluster-head based heterogeneous height deployment system.

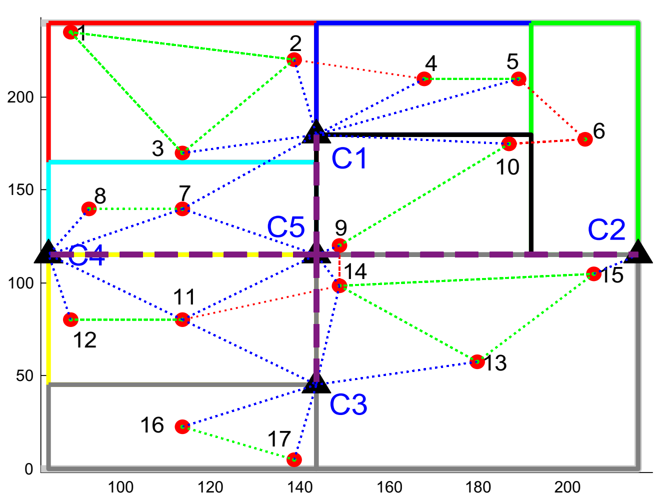

Fig. 17. Cluster-head based network deployment.

greater efficiency can be achieved with cluster heads providing the network backbone.

Assume that a cluster head mounted at a height of h_{CH} is located at position (x_{CH}, y_{CH}) in a plot with vegetation height h_{VG} Also assume that a node is located at position (x, y) at a height of h_{NH}

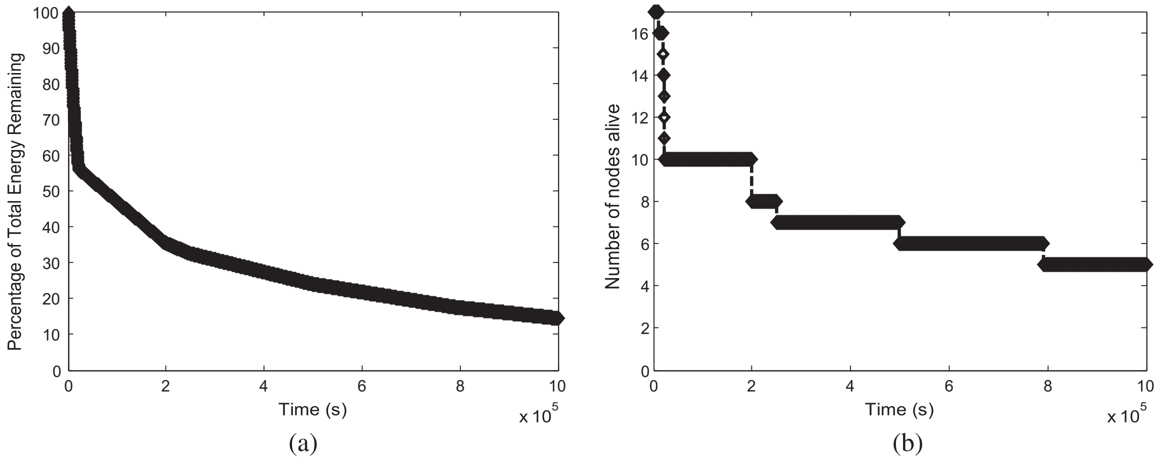

Fig. 18. (a) Percentage of total energy remaining in the network and, (b) the number of nodes alive in a cluster head based network.

in a vegetation whose log-linear parameters are n and P_0. The path loss for transmission from the node to the cluster head is given by Eq. (11). This is illustrated in Fig. 16.

$$PL = 10\log\left(\frac{(h_{VB}-h_{NH})\sqrt{(x-x_{CH})^2+(y-y_{CH})^2}}{(h_{CH}-h_{VG})}\right) - P_0 + FSL\left(\sqrt{(x-x_{CH})^2+(y-y_{CH})^2}\left[1-\frac{(h_{VB}-h_{NH})}{(h_{CH}-h_{VG})}\right]\right) - L \tag{11}$$

where $FSL(d)$ is Free Space Loss over a distance d. After propagating through the vegetation, the signal would have already experienced the initial steep attenuation associated with the coherent signal. Therefore a factor L is added to the equation to account for reduced losses from the air/vegetation interface when the signal has already gone through the vegetation.

An example of the network deployment using this scheme is shown in Fig. 17. Using the cluster heads C1 to C5, with C5 acting as the data sink, all nodes in the network are within one hop from a cluster head. The connections between the nodes and cluster heads are shown in blue color. The impact of the use of cluster heads is a reduction in the transmission power required by each node to transmit data to the sink. In this configuration, the stringent rule of a minimum of 2-connectivity can be relaxed, especially for nodes that connect directly to cluster heads.

Fig. 18 illustrates the energy consumption profile of the network and the number of nodes alive as a function of operation time. In computing the number of nodes alive, only the maximum available power path at the beginning of operation is used. However where a node has more than one path or connectivity, the node can change the next hop node based on available power. Therefore some nodes will operate for longer periods than shown in Fig. 18b. Using cluster heads and considering only the energy of the sensor nodes, the total remaining energy in the network after 100,000 s of continual operations is 46.95% of the initial total energy compared to 29% in Fig. 15. The network also operates for a time duration that is a factor 25 times longer compared to the network in Fig. 14 before the number of nodes alive in the network reduces to 6.

6. Conclusions

Ad hoc wireless sensor network deployment in a heterogeneous environment presents unique challenges. For the purpose of network simulations and planning, the environment can be quantized into homogeneous units that can be described using channel propagation models for each specific channel. In this paper, detailed measurements studies have been carried out in a mixed crop environment with different signal attenuation characteristics. Analysis showed that the best model that describes low power signal propagation in mixed crop environment is the log-linear model. Two important factors have been considered in the planning of the network: the number of nodes and the node connectivity. A minimum of 2 nodes have been used in each crop plot to provide redundancy. In some instances more nodes can be deployed per plot depending on the coverage required and the tolerance of the system/crops being monitored to changing conditions. The study shows that node pairs deployed in different crop plots have asymmetric channels. In this case, network protocols that use broadcast routing mechanism would be more efficient for information transmission. This study has also shown that two or more network height layers can lead to network energy conservation (up to 17% in the simulated network) and a potential reduction in the number of nodes required to provide network coverage. In addition, it also increases the robustness of the network as nodes do not have to rely on multiple hops to transmit data to the sink. This network structure can allow easy integration of different network standards e.g. ZigBee and WIFI with the cluster heads acting as gateways between the different standards.

References

Abbasi, A.Z., Islam, N., Shaikh, Z.A., 2011. A review of wireless sensors and networks' applications in agriculture. Comput. Stand. Interfaces, 1–8.

Atmel, 2003. Understanding packet delivery performance in dense wireless sensor networks. In: Proceedings of the first international conference on Embedded networked sensor systems – SenSys '03. ACM Press, New York, New York, USA.

Atmel-AT86RF230, 2011. Low Power 2.4 GHz Transceiver for ZigBee, IEEE 802.15.4.

Bai, X., Yun, Z., Xuan, D., Lai, T.H., Jia, W., 2006. Deploying Four-Connectivity And Full-Coverage Wireless Sensor Networks.

Bai, X., Yun, Z., Xuan, D., Chen, B., Zhao, W., Motivation, A., 2011. Optimal multiple-coverage of sensor. Networks, 2498–2506.

Camilli, A., Cugnasca, C.E., Saraiva, A.M., Hirakawa, A.R., Corrêa, P.L.P., 2007. From wireless sensors to field mapping: Anatomy of an application for precision agriculture. Comput. Electron. Agric. 58, 25–36.

Díaz, S.E., Pérez, J.C., Mateos, A.C., Marinescu, M.-C., Guerra, B.B., 2011. A novel methodology for the monitoring of the agricultural production process based on wireless sensor networks. Comput. Electron. Agric. 76, 252–265.

Huircán, J.I., Muñoz, C., Young, H., Von Dossow, L., Bustos, J., Vivallo, G., Toneatti, M., 2010. ZigBee-based wireless sensor network localization for cattle monitoring in grazing fields. Comput. Electron. Agric. 74, 258–264.

ITU-R Rec-833-6, 2007. Attenuation in vegetation.

Johnson, R.A., Schwering, F., 1985. A transport theory of millimeter wave propagation in wood and forest. New Jersey.

Kamarudin, L.M., Ahmad, R.B., Ndzi, D., Zakaria, A., Ong, B.L., Kamarudin, K., Harun, A., Mamduh, S.M., 2012. Modeling and Simulation of WSNs for Agriculture Applications Using Dynamic Transmit Power Control Algorithm. In: 2012 Third International Conference on Intelligent Systems Modelling and Simulation, pp. 616–621.

Kwong, K.H., Wu, T.-T., Goh, H.G., Sasloglou, K., Stephen, B., Glover, I., Shen, C., Du, W., Michie, C., Andonovic, I., 2012. Practical considerations for wireless sensor networks in cattle monitoring applications. Comput. Electron. Agric. 81, 33–44.

López Riquelme, J.A., Soto, F., Suardíaz, J., Sánchez, P., Iborra, A., Vera, J.A., 2009. Wireless Sensor Networks for precision horticulture in Southern Spain. Comput. Electron. Agric. 68, 25–35.

Mandke, K., Daniels, R.C., Choi, S.-H., Nettles, S.M., Heath, R.W., 2007. Physical Concerns for Cross-layer Prototyping and Wireless Network Experimentation. In: Proceedings of the the second ACM international workshop on Wireless network testbeds, experimental evaluation and characterization – WinTECH '07 11.

Mao, G., Anderson, B.D.O., Fidan, B., 2007. Path loss exponent estimation for wireless sensor network localization. Comput. Netw. 51, 2467–2483.

Meng, Y.S., Lee, Y.H., 2010. Investigations of foliage effect on modern wireless communication systems: a review. Prog. Electromagn. Res. 105, 313–332.

Nadimi, E.S., Søgaard, H.T., Bak, T., 2008a. ZigBee-based wireless sensor networks for classifying the behaviour of a herd of animals using classification trees. Biosyst. Eng. 100, 167–176.

Nadimi, E.S., Søgaard, H.T., Bak, T., Oudshoorn, F.W., 2008b. ZigBee-based wireless sensor networks for monitoring animal presence and pasture time in a strip of new grass. Comput. Electron. Agric. 61, 79–87.

Nadimi, E.S., Jørgensen, R.N., Blanes-Vidal, V., Christensen, S., 2012. Monitoring and classifying animal behavior using ZigBee-based mobile ad hoc wireless sensor networks and artificial neural networks. Comput. Electron. Agric. 82, 44–54.

Ndzi, D.L., Arif, M.A.M., Shakaff, A.Y., Ahmad, M.N., Harun, A., Kamarudin, L.M., Zakaria, A., Ramli, M.F., Razalli, M.S., 2012a. Signal propagation in aquaculture environment for wireless sensor network applications. Prog. Electromagn. Res. 125, 1–19.

Ndzi, D.L., Kamarudin, L.M., Mohammad, E.A.A., Zakaria, A., Ahmad, R.B., Fareq, M.M.A., Shakaff, A.Y., Jafaar, M.N., 2012b. Vegetation attenuation measurements and modeling in plantations for wireless sensor network planning. Prog. Electromagn. Res. B 36, 283–301.

Petrova, M., Riihij, J., Petri, M., 2006. Performance Study of IEEE 802. 15. 4 Using Measurements and Simulations. In: IEEE Proceedings on Wireless Communications and Networking Conference, WCNC 2006. pp. 487–492.

Qinetiq, 2002. A Generic Model of 1–60 GHz Radio Propagation through Vegetation – Final Report.

Sasloglou, K., 2009. Antenna and base-station diversity for WSN livestock monitoring. Wireless Sensor Network 01, 383–396.

Savage, N., 2003. Radio wave propagation through vegetation: factors influencing signal attenuation. Radio Sci. 38, 1088.

Srinivasan, K., Levis, P., 2006. RSSI is Under Appreciated. In: Third Workshop on Embedded Networked Sensors.

Vougioukas, S., Anastassiu, H.T., Regen, C., Zude, M., 2012. Influence of foliage on radio path losses (PLs) for wireless sensor network (WSN) planning in orchards. Biosyst. Eng., 1–12.

Weissberger, M.A., 1982. An initial summary of models for predicting the attenuation of radio waves by trees.

Yu, X., Wu, P., Han, W., Zhang, Z., 2013. A survey on wireless sensor network infrastructure for agriculture. Comput. Stand. Interfaces 35, 59–64.

Zerger, A., Viscarra Rossel, R.A., Swain, D.L., Wark, T., Handcock, R.N., Doerr, V.A.J., Bishop-Hurley, G.J., Doerr, E.D., Gibbons, P.G., Lobsey, C., 2010. Environmental sensor networks for vegetation, animal and soil sciences. Int. J. Appl. Earth Obs. Geoinf. 12, 303–316.

Zuniga, M., Krishnamachari, B., 2004. Analyzing the Transitional Region in Low Power Wireless Links. In: IEEE Comms. Soc. Intl. Conf. on Sensor and Ad Hoc Communications and Networks (SECON). pp. 517–526.