Connectivity of wireless sensor networks for plant growth in greenhouse

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Abstract: Wireless sensor networks have been applied in farmland and greenhouse. However, poor connectivity always results in a lot of nodes isolation in the network in a scenario. For this reason, the network connectivity is worth considering to improve its quality, especially when the collected data cannot be sent to the data center because of the obstacles such as the growth of crop plants and weeds. Therefore, how to reduce the effect of crop growth on network connectivity, and enable the reliable transmission of field information, are the key problems to be resolved. To solve these problems, the method which adds long distance routing nodes to the WSN to reduce the deterioration of WSN connectivity during the growth of plants was proposed. To verify this method, the network connectivity of the deployed WSN was represented by the rank of connection matrix based on the graph theory. Consequently, the rank with value of 1 indicates a fully connected network. Moreover, the smaller value of rank means the better connectedness. In addition, the network simulator NS2 simulation results showed that the addition of long-distance backup routing nodes can improve the network connectivity. Furthermore, in experiments, using ZigBee-based wireless sensor network, a remote monitoring system in greenhouse was established, which can obtain environmental information for crops, e.g. temperature, humidity, light intensity and other environmental parameters as well as the wireless link quality especially. Experimental results showed adding of long-distance backup routing nodes can guarantee network connectivity in the region where received signal strength indication (RSSI) was poor, i.e. RSSI value was less than −100 dBm, and the energy was low. In conclusion, this method was essential to improve the connectivity of WSN, and the optimized method still needs further research.

Keywords: wireless sensor network, network connectivity, long-distance route nodes, received signal strength indication (RSSI), greenhouse
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1 Introduction

Wireless sensor networks (WSNs) have been widely used in agricultural applications in recent years, e.g., monitoring environmental factors, growth of vegetables, insect pest and irrigation management[1-4].

For WSN applications, wireless link quality is one of the most important factors which directly impacts on the connectivity of WSN. WSNs in agriculture may run in different environmental conditions, e.g., farmland, greenhouse, flat to complex topography, and over a range of weather conditions, all of these affect radio performance[5]. Furthermore, link power consumption is not only influenced by the distance of nodes and antenna height, but also depends on the growth of crop and terrain around[6].

As we known, there are three factors leading to link

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unreliability including the environment, the interference and hardware transceivers[7]. Thus, the factors, e.g., temperature[10], humidity[8-9], lightning[9] and plant itself, have impacts on wireless link quality which should not be ignored. There was a review of crop canopy influence on the radio, including signal propagation above the cross canopy and near the soil surface results in attenuation[11]. Range of radio transmission was limited to about 10 m when the potato crop is at the flowering period[8]. Li et al.[12] found that the attenuation speed of signal power monotonically decreased in wheat fields, and the signal attenuation at later growth stages was larger than that at earlier stages, when the antenna height was kept unchanged. During the corn tassel and seed-filling periods, Wu et al.[13] found that the RSSI attenuation is most serious and the sensing range reaches the minimum value when antenna height falls in the range of 0.5-1.7 m. The power attenuation was estimated due to the presence of trees and their foliage by measurements of radio propagation within a plum orchard, and compared several radio path loss models[14]. In the present work, we investigated the influence of plant growth on the wireless link in agricultural applications.

In addition, Paul et al. proposed 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. If the density of surrounding foliage for a mature plant is known, the number of nodes and the node location can be calculated to guarantee reliable radio transmission in a WSN precision agricultural application[15].

Obstacles such as crop growth, foliage and weeds have important influence on wireless link, and could directly lead to unreliability of wireless link and even disconnected network. Therefore, it is essential to investigate the problem of how to guarantee connectivity of network as the crop grows up where signal propagation nearing the ground.

There were many references to investigate the connectivity recovery problem in damaged wireless sensor network[16-22], including the single node failure recovery and multiple-node failure restoration. The recovery methods involve adding new relay nodes and using mobile agent nodes to transport data among the disconnected areas. Adding relay nodes is for two purposes. One purpose is to connect a variety of sensor nodes. Another is to enhance the performance or achieve the higher connectivity. Mobile agent nodes can transport data, act as collector that tours the nodes and carries their data, or act as base node that consume the data[16].

Determining the optimal position and number of relay nodes is NP-hard problem during deploying the relay nodes. The established models include Steiner tree[17-20], undirected graph[21-22] and other models[23-24] (such as game-theoretic approach and Coulomb's law). However, these recovery algorithms were designed for redeploying relay nodes or mobile agent nodes to repair remaining network connectivity when nodes failure in harsh environments lead to disconnected network. However, these algorithms do not consider the effect of obstacles, which may indeed have influence on the relay nodes, making the algorithms need further adjustment. Moreover, the approach of deploying redundant nodes generates unnecessary cost in open farmland and greenhouse environments.

Plant growth may result in the network connectivity deterioration. To estimate the deterioration degree of network connectivity, we used graph theory to model the connectivity of network, and obtained the connection matrix of real network. Based on the rank of connection matrix, the monitoring of network connectivity enabled us to find the changes of topology and disconnected network segments. In addition, we identified the signal reduction in disconnected areas by means of measuring the received signal strength indication (RSSI). To improve the connectivity of the wireless sensor networks, we added a long distance routing node to the disconnected area in simulation conditions. Furthermore, we deployed ZigBee-based wireless sensor network in greenhouse where tomato plants were cultivated. Although the connectivity of network may be degraded with the tomato growing, deploying a long distance routing node in disconnected areas improved the network connectivity significantly.

Generally, the aim of this paper was to estimate the network connectivity using rank of connection matrix and to improve the network connectivity by enabling a long distance backup routing node in the disconnected areas.

The paper is organized as follows: Section 2 presents the network connectivity model and triangular lattice deployment model. Section 3.1 simulates the connectivity recovery of ZigBee tree network by NS2. Section 3.2 verifies the connectivity recovery in greenhouse. Finally, Section 4 concludes the article with future research directions. Besides, the appendix describes the derivation process of connection matrix in detail.

2 Materials and methods

The common deployment strategies include random deployment, regular deployment and planned deployment[25]. Furthermore, regular deployment contains triangular lattice, square grid and hexagonal grid[26].

For triangular lattice deployment model, Zhang proved that to cover one crossing point of two disks with the minimum overlap, only one disk should be used and the centers of the three disks should form an equilateral triangle with side length $\sqrt{3}r$, where r is the radius of the disk[27].

For square grid deployment model, the grid side length is $\sqrt{2}r$, where r is the radius of the disks. Square grid deployment model has a larger overlap than triangular lattice, and also need more nodes.

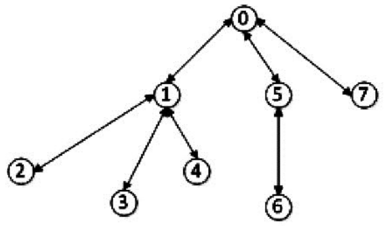
For hexagonal grid deployment model, the grid side length is r, where r is the radius of the disks. So hexagonal grid deployment model has the largest overlap in three models, and also need more nodes.

In fact, the sensor nodes are usually statically deployed in farmland and greenhouse environment. Consequently, in the simulation experiments, in order to achieve full coverage in the destination areas, and make the number of routing nodes least, triangular lattice was chosen to deploy routing nodes.

Based on the definition of full coverage of network, when node communication radius is at least twice of sensing radius, seamless coverage means seamless connectivity[28]. These conditions are essential for obtaining seamless coverage and connectivity in triangular lattice grid. In this study, the network was modeled as undirected graph which derived the adjacent matrix. The adjacent matrix can be simplified based on Warshall's algorithm to get accessibility matrix. At last, connection matrix can be derived from accessibility matrix. The rank of connection matrix can be used to estimate the connectivity of network. It was proved that the rank of connection matrix is equal to the number of connected components by the formula derivation (See appendix). There is a positive correlation between the rank and the number of connected components. The network connectivity of high-rank connection matrix will be worse than that of a low-rank matrix. When the rank is 1, the network connectivity is best. And every node is connected and there only exists one connected components.

As an example of connectivity recovery process, Figure 1 shows three stages of the cluster tree network including: the original cluster tree network, disconnected network under obstacles, and the recovery of connectivity after adding a long distance relay node.

At the first stage, the network was fully connected as shown in Figure 1a, correspondingly, the rank of Figure 1c is 1. As the growth of plant, the obstacles became the main factor that influences the network connectivity. So node 1 and node 5 were disconnected with their child nodes marked with 3, 4, and 6 at the second stage as shown in Figure 1d. Thus the rank of the Figure 1f is 4, meaning that network connectivity has gone bad. So there existed four connected components in Figure 1d. Figure 1g shows the recovered network after adding routing node 8 to the network at the third stage, and the rank of Figure 1i is 2, meaning that the connectivity has gone better. Namely, there existed two connected components in Figure 1g which are {0,1,2,4,5,6,7,8} and {3}. In Figure 1, if the parent node disconnects with its child nodes because of obstacles, their child nodes will become isolated nodes. After adding a long distance routing node to the disconnected area, the connectivity can be improved in theory.



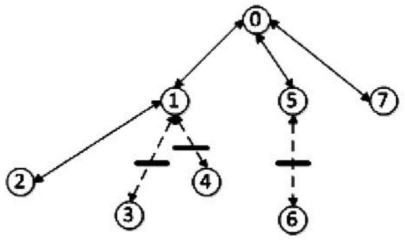
a. The original connected graph

$$\begin{matrix} 1&1&0&0&0&1&0&1\\ 1&1&1&1&1&0&0&0\\ 0&1&1&0&0&0&0&0\\ 0&1&0&1&0&0&0&0\\ 0&1&0&0&1&0&0&0\\ 1&0&0&0&0&1&1&0\\ 0&0&0&0&0&1&1&1\\ 1&0&0&0&0&0&0&1 \end{matrix}$$

b. The adjacent matrix of (a)

$$\begin{matrix} 1&1&1&1&1&1&1&1\\ 1&1&1&1&1&1&1&1\\ 1&1&1&1&1&1&1&1\\ 1&1&1&1&1&1&1&1\\ 1&1&1&1&1&1&1&1\\ 1&1&1&1&1&1&1&1\\ 1&1&1&1&1&1&1&1\\ 1&1&1&1&1&1&1&1 \end{matrix}$$

c. The connection matrix of (a)



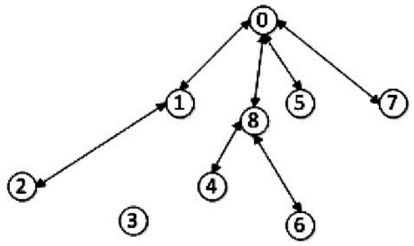
d. The disconnected graph with obstacles

$$\begin{matrix} 1&1&0&0&0&1&0&1\\ 1&1&1&0&0&0&0&0\\ 0&1&1&0&0&0&0&0\\ 0&0&0&1&0&0&0&0\\ 0&0&0&0&1&0&0&0\\ 1&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&1&0\\ 1&0&0&0&0&0&0&1 \end{matrix}$$

e. The adjacent matrix of (d)

$$\begin{matrix} 1&1&1&0&0&1&0&1\\ 1&1&1&0&0&1&0&1\\ 1&1&1&0&0&1&0&1\\ 0&0&0&1&0&0&0&0\\ 0&0&0&0&1&0&0&0\\ 1&1&1&0&0&1&0&1\\ 0&0&0&0&0&0&1&0\\ 1&1&1&0&0&1&0&1 \end{matrix}$$

f. The connection matrix of (d)



g. The improved disconnected graph

$$\begin{matrix} 1&1&0&0&0&1&0&1&1\\ 1&1&1&0&0&0&0&0&0\\ 0&1&1&0&0&0&0&0&0\\ 0&0&0&1&0&0&0&0&0\\ 0&0&0&0&1&0&0&0&1\\ 1&0&0&0&0&1&0&0&0\\ 0&0&0&0&0&0&1&0&1\\ 1&0&0&0&0&0&0&1&0\\ 1&0&0&0&1&0&1&0&1 \end{matrix}$$

h. The adjacent matrix of (g)

$$\begin{matrix} 1&1&1&0&1&1&0&1&1\\ 0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0\\ 0&0&0&1&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0 \end{matrix}$$

i. The connection matrix of (g)

Note: The circle encompassing the number represents the sensor nodes in the WSN. The black cross bar represents obstacles in the WSN. The solid line with two arrows represents the good connectivity between the two sensor nodes. The dotted line represents there is no connectivity between the two sensor nodes.

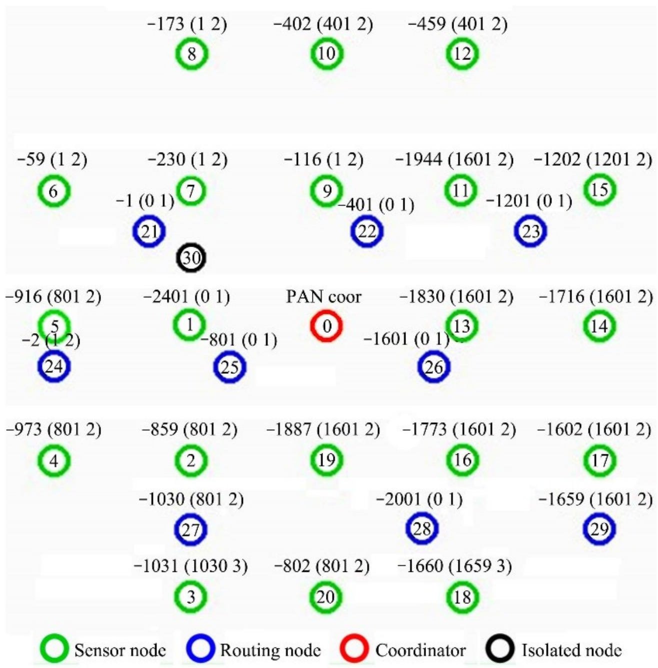
Figure 1 The adjacent matrix of three stages

3 Results and discussion

3.1 Connectivity simulation of ZigBee tree network in NS2

The proposed method was verified by NS2[29] simulations with the IEEE 802.15.4 module developed by Zheng[30]. For the simulations, we considered a beacon-enabled mode cluster tree network of 30 nodes which were placed in a 50 m×50 m square grid, including one coordinator, 9 routing nodes and 20 sensor nodes. The sensor nodes were uniformly deployed in the static area. According to the discussion in section 2, routing nodes were deployed in triangular lattice grid, which can guarantee full coverage among all the sensor nodes. The simulation time was 100 s, and packet length was 127 bytes.

In simulation experiments, three kinds of stages of ZigBee cluster tree network were simulated: fully connected network, disconnected network, and a recovered network. They are shown in Figure 2, 3, 4 respectively.



Note: The circle encompassing the number represents the sensor nodes in the WSN. The number ahead of the "( )" was the network address. And the first number in the "( )" was the parent address, the last number in the "( )" was the depth of network. The same below.

Figure 2 Fully connected network at the first stage

At the initial stage, the color of all nodes was black, meaning that they did not join the network. And when the color of node 0 turns to red, the network is formed. When a routing node turns to blue, it means that it has joined the network. This is also fit for the sensor node when it turns to green. The number ahead of the “( )” was the network address. And the first number in the “( )” was the parent address, the last number in the “( )” was the depth of network.

As shown in the Figure 2, 20 sensor nodes were all joining into the network. Thus, the network was fully connected. The rank of the network was 1. In Figure 2, node 6, 7, 8 and 9 had a common parent node 21. Node 30 was a routing node but not in working.

Figure 3 shows the disconnected network with isolated nodes at the second stage. It was assumed that node 21 disconnected with its child nodes because of obstacles as shown in grey circle in Figure 3. So its child nodes became isolated nodes and disjoined the network as shown in black circle in Figure 3. Thus, the topology of the network had changed, and the rank of connection matrix of network was 6, meant that the network connectivity had gone bad.

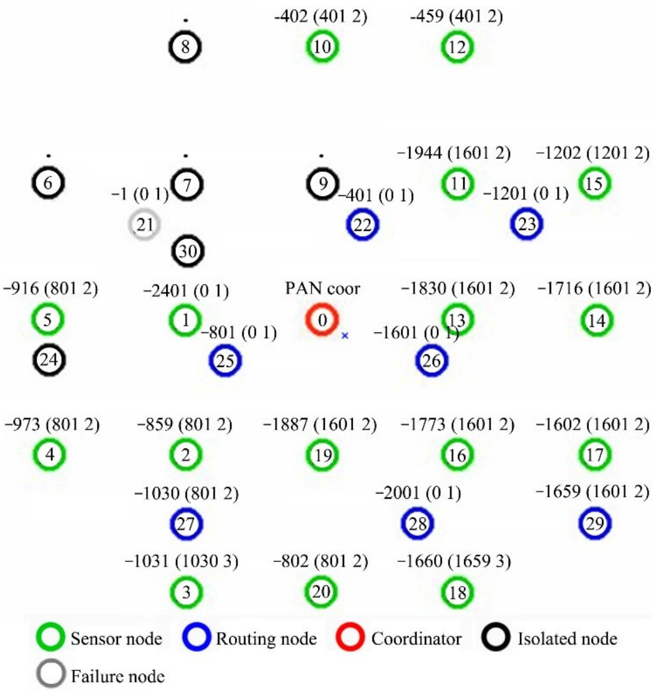


Figure 3 Disconnected network with isolated nodes

When the connectivity became worse, the disconnected area in the network can be represented by analyzing the connected matrix. Then adding a long distance routing node 30 to this area is shown in Figure 4.

As shown in the Figure 4, after node 30 was started, node 6, 7, 8 rejoined the network and acted as child nodes of node 30. The rank of connected matrix was 2 in Figure 4, which showed that the connectivity had recovered.

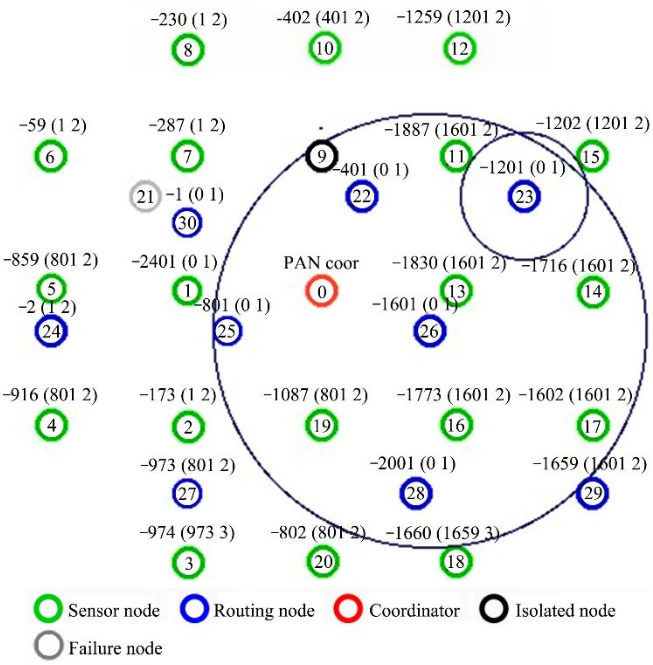


Figure 4 Adding a long distance relay node in network.

3.2 Connection recovery experiments of ZigBee cluster network

In experiments, CC2430 chip based on Z-Stack 2006 from TI was used. The network topology was cluster tree. The coordinator connected with GPRS module through a serial port. GPRS module uploaded the data to the database in remote monitoring system. The sensor module collected a variety of parameters such as temperature, humidity, steam sap flow, plant stem diameter, leaf thickness, leaf wetness as well as RSSI value. The packet size was 21 bytes. The network was deployed in greenhouse with sensor nodes deployed among the tomato stalks. Figure 5 displays the deployment environment and equipment in experiment.

The experiments in greenhouse went through three stages. The first stage was at the seedling stage of tomato which average height was 15 cm, and the number of leaves in lateral branches was 3-5. The second stage was the growing stage when the average height of tomato grew to 1 m. The number of leaves in lateral branches was 7-9. The third stage was the mature period when tomato became mature. The plant height was 2 m, and the number of leaves in lateral branches was 13-17. The

RSSI value variation with distance between the coordinator and sensor node in three stages was shown in Figure 6.

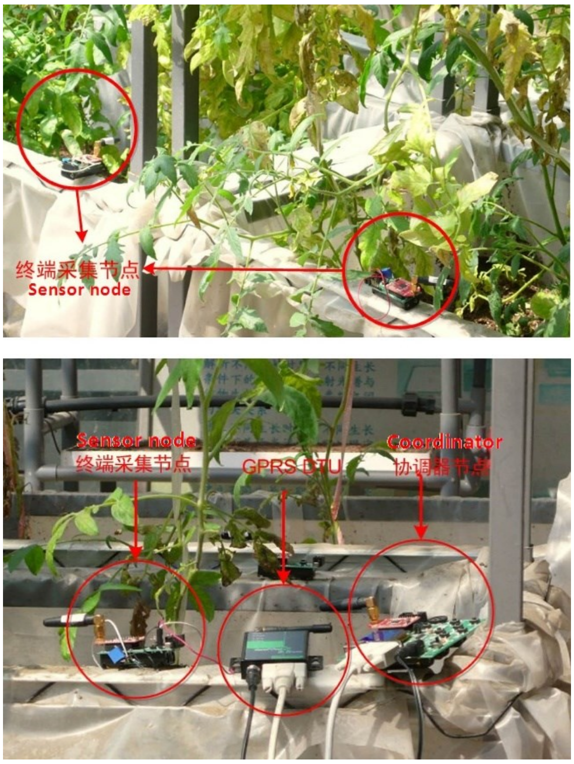


Figure 5 Deployment environment and equipment in experiment

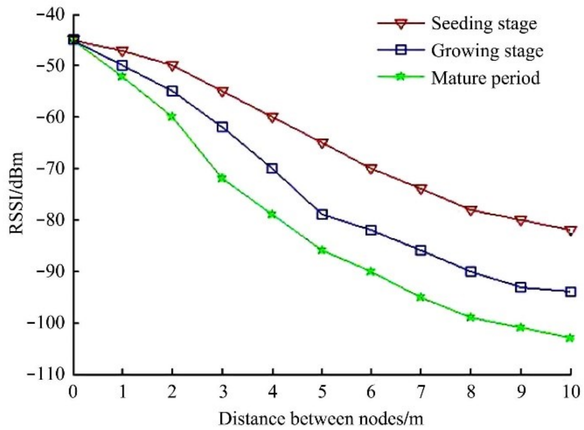


Figure 6 Variation of RSSI with distance

Figure 7 shows a floor plan of measured RSSI value distribution in greenhouse under the plant whose average height was 2 m. Space between rows was 45 cm, and space between columns was 35 cm. In Figure 7, for the reason of varying growing status of plant, plant coverage density was varying. As the increasing distance between the coordinator and sensor node, the RSSI value of sensor node declined gradually. And the greater of the plant coverage density around the sensor node was, the smaller of the RSSI value would be.

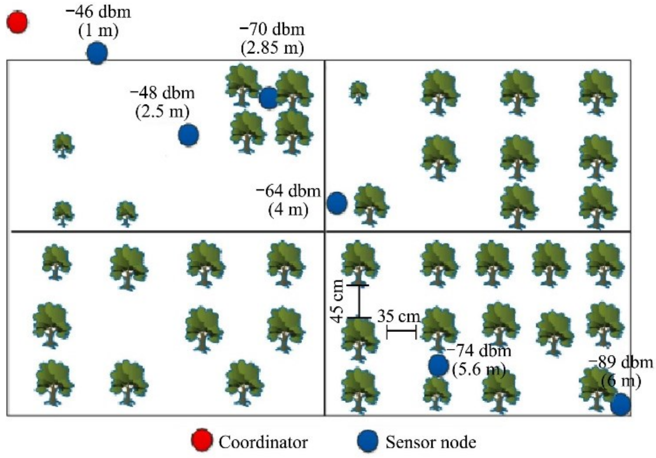


Figure 7 A floor plan of measured RSSI value distribution in greenhouse under the plant

After querying the database for nodes deployment and the RSSI value which were obtained by multiple measurements, the received signal strength contour maps are shown in Figure 8-10 at different stages of tomato growth.

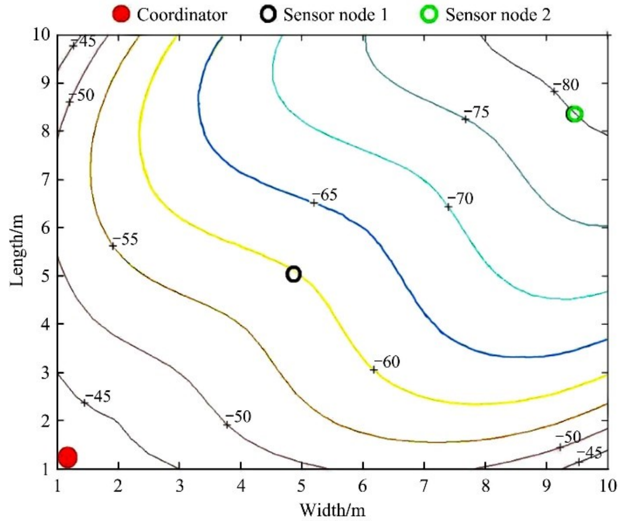


Figure 8 RSSI value contour without obstacles

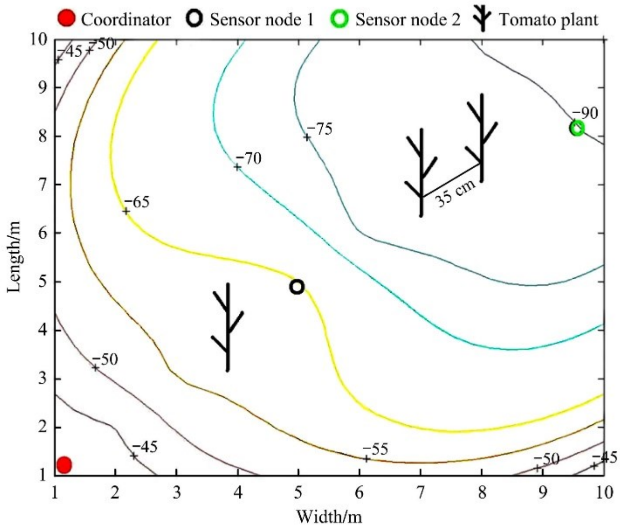


Figure 9 RSSI value contour with obstacles

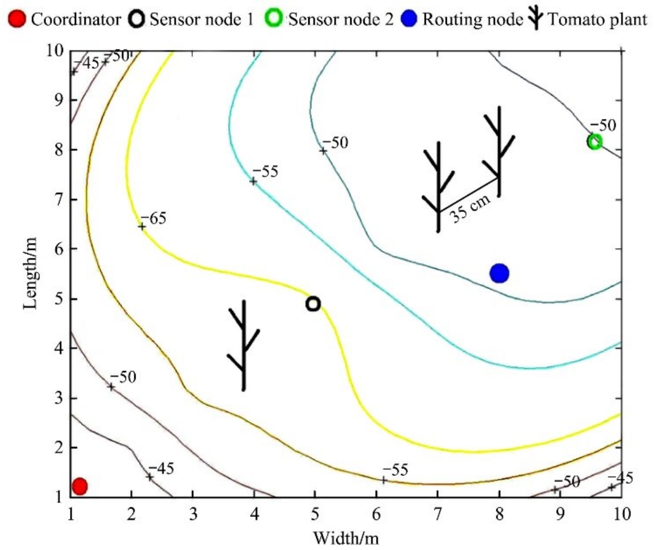


Figure 10 RSSI value contour after adding a long distance relay node

In Figure 8, when at the first stage, there were not existing obstacles between nodes, so the RSSI value was relatively equal around every sensor node and the corresponding contour line was round smooth. As the increasing distance between the coordinator and sensor nodes, the corresponding RSSI value was getting small gradually. In Figure 9, when going into the third stage, the plant had become the obstacles between nodes. The corresponding RSSI value declined because of obstacles.

Figure 10 shows the RSSI value contour map after adding a long distance routing node to the area where RSSI value declined most. In Figure 10, after adding a long distance routing node, RSSI values of sensor nodes around the long distance routing node had grown. So adding a long distance routing node will help the isolated nodes to rejoin the routing node and raise their RSSI value. In addition, the network connectivity can be better.

4 Conclusions

This work has reported the connectivity problems of WSN in greenhouse. We estimated the connectivity of WSN by connection matrix, and investigated the disconnected area by RSSI in greenhouse. The theory analysis, simulation and experiments in greenhouse showed that connection matrix can be used to estimate the network connectivity. In addition, when RSSI value was below -100 dBm, it is essential to start the long distance routing node with high transmit power. Thus, adding long distance routing nodes with high transmit power and receiving sensitivity to the disconnected area can improve the connectivity of network effectively.

In the present work, we investigated the influence of plant growth on the wireless link in agricultural applications. Future work will consider how to find the optimal position of relay nodes under the obstacles. On the other hand, connection matrix can well estimate the disconnected network, but it still need other methods to estimate the k-vertex connectivity (k>1).

Acknowledgment

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Appendix

Network connectivity can be analyzed by graph theory. The undirected graph G and its adjacent matrix represent the adjacent relation between nodes, and connection matrix represents the connectivity of overall network.

Assuming that G=(V, E) is a graph with n vertex, then the adjacent matrix of G has the property as following:

$$A[i,j]=\begin{cases}1 & \text{if } (v_i,v_j) \text{ or } \langle v_i,v_j\rangle \text{ is the edge of } E(G)\\ 0 & \text{if } (v_i,v_j) \text{ or } \langle v_i,v_j\rangle \text{ is not the edge of } E(G)\end{cases} \quad (1)$$

The connection matrix is n-order matrix with the property as follow:

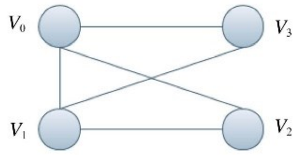
$$P[i,j]=\begin{cases}1 & \text{if } v_i \text{ and } v_j \text{ is } \textit{connected}\\ 0 & \text{if } v_i \text{ and } v_j \text{ is } \textit{not connected}\end{cases} \quad (2)$$

Assuming A is the n-order adjacent matrix, B is the accessibility matrix with n order, and C is the connection matrix. B can be expressed with: $B = A + A^2 + A^3 + A^4 + \ldots\ldots A^n$. Then C is obtained from B based on Equation (3):

$$C[i,j]=\begin{cases}1 & \text{if } B[i,j]\geq 1\\ 0 & \text{if } B[i,j]=0\end{cases} \quad (3)$$

Figure 11 shows an example of connection matrix. However, the method above is complex in computing. So connection matrix can be obtained by the Warshall's algorithms. Figure 12 shows the connection matrix.

$$A=\begin{bmatrix}0&1&1&1\\1&0&1&1\\1&1&0&0\\1&1&0&0\end{bmatrix}$$



$$B=A^1+A^2+A^3+A^4=\begin{bmatrix}22&22&16&16\\22&22&16&16\\16&16&14&14\\16&16&14&14\end{bmatrix}\qquad C=\begin{bmatrix}1&1&1&1\\1&1&1&1\\1&1&1&1\\1&1&1&1\end{bmatrix}$$

Figure 11 Example of connection matrix

$$\begin{bmatrix}1&1&1&0&0&0\\1&1&1&0&0&0\\1&1&1&0&0&0\\0&0&0&1&1&0\\0&0&0&1&1&0\\0&0&0&0&0&1\end{bmatrix}$$

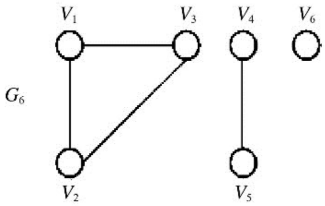


Figure 12 Connection matrix of undirected graph

In wireless sensor network, if the node can communicate with other nodes within its communication radius, then the node is adjacent with other nodes (i.e. they are connected in single hop). Therefore, adjacent matrix can show the connection of nodes in single hop. In the paper, we assume that the node is also connected with itself, i.e. $A[i, i]=1$. So the adjacent matrix is expressed with $A=\{A[i, j]\}_{n\times n}$, where n is the number of nodes in network. The element $A[i, j]$ in A satisfies the Equation (4).

$$A[i,j]=\begin{cases}1 & \text{if } v_i \text{ and } v_j \text{ is } \textit{adjacent}\\ 0 & \text{if } v_i \text{ and } v_j \text{ is } \textit{not adjacent}\end{cases} \tag{4}$$

The connection matrix can be derived based on the above explanation. And it was proved that the rank of connection matrix is equal to the number of connected components.

First, according to the definition of connected graph, if graph G is connected, then every node is connected with the other. So every element value in connection matrix is 1, then the rank of connection matrix is 1.

Assume undirected graph $G<V, E>$. If there exists k connected components in G, which can be expressed as $G(V_1),\ldots,G(V_k)$, and the connection matrix of $G(V_i)$ is expressed as $P(V_i)$ (where $i = 1,\ldots,k$). Then every element value in $P(V_i)$ is 1 as well as the rank of $P(V_i)$. Figure 13 shows the connection matrix P.

Hence, it is obtained the Equation (4) as follow.

$$\begin{aligned}rank(P)&=rank(P(V_1))+rank(P(V_2))+\ldots\\&+rank(P(V_k))=k\end{aligned} \tag{5}$$

From Equation (5), if undirected graph $G<V, E>$ has k connected components, then the rank of P is k, ie $rank(P)=k$, (Suppose P is the connection matrix of G).

In turn, suppose the rank of P is k. Then P must be symmetric matrix, which can be expressed as the expressions in Figure 13 or Figure 14-15.

$$P=\begin{bmatrix}P(V_1)&0&0&0\\0&P(V_2)&0&0\\\cdots&\cdots&\cdots&\cdots\\0&0&0&P(V_k)\end{bmatrix}\qquad P(V_i)=\begin{bmatrix}1&\cdots\cdots&1\\1&\cdots\cdots&1\\\cdots&\cdots&\cdots\\1&\cdots\cdots&1\end{bmatrix}$$

Figure 13 Connection matrix P

$$P=\begin{array}{c}\begin{array}{cccccc}v_1\ldots v_{n_1}&\ldots&v_{n_{i-1}+1}\ldots v_{n_i}&v_{n_i+1}&\ldots&v_{n_{k-1}+1}\ldots v_{n_k}\end{array}\\ \begin{bmatrix}P(V_1)&\ldots&Q_{n_1\cdot(n_i-n_{i-1})}&E_{n_1\cdot 1}&\ldots&Q_{n_1\cdot(n_k-n_{k-1})}\\ &&\cdots\cdots\cdots\cdots&&&\\ Q_{(n_i-n_{i-1})\cdot n_1}&\ldots&P(V_i)&Q_{(n_i-n_{i-1})\cdot 1}&\ldots&Q_{(n_i-n_{i-1})\cdot(n_k-n_{k-1})}\\ E_{1\cdot n_1}&\ldots&Q_{1\cdot(n_i-n_{i-1})}&1&\ldots&Q_{1\cdot(n_k-n_{k-1})}\\ &&\cdots\cdots\cdots\cdots&&&\\ Q_{(n_k-n_{k-1})\cdot n_1}&\ldots&Q_{(n_k-n_{k-1})\cdot(n_i-n_{i-1})}&Q_{(n_k-n_{k-1})\cdot 1}&\ldots&P(V_k)\end{bmatrix}\end{array}\begin{array}{c}v_1\ldots v_{n_1}\\ \ldots\\ v_{n_{i-1}+1}\ldots v_{n_i}\\ v_{n_i+1}\\ \ldots\\ v_{n_{k-1}+1}\ldots v_{n_k}\end{array}$$

$$E_{m\cdot n}=\begin{bmatrix}1&1\cdots\\&\cdots\cdots\\1&1\cdots\\1&1\cdots\end{bmatrix}_{m\times n}\qquad Q_{m\cdot n}=\begin{bmatrix}0&(\cdots\\&\cdots\cdots\\0&(\cdots\\0&(\cdots\end{bmatrix}_{m\times n}$$

Figure 14 Another formula of P

$$P=\begin{array}{c}\begin{array}{cccccc}v_1\ldots v_{n_1}&v_{n_i+1}&\ldots&v_{n_{i-1}+1}\ldots v_{n_i}&\ldots&v_{n_{k-1}+1}\ldots v_{n_k}\end{array}\\ \begin{bmatrix}P(V_1)&E_{n_1\cdot 1}&\ldots&Q_{n_1\cdot(n_i-n_{i-1})}&\ldots&Q_{n_1\cdot(n_k-n_{k-1})}\\ E_{1\cdot n_1}&1&\ldots&Q_{1\cdot(n_i-n_{i-1})}&\ldots&Q_{1\cdot(n_k-n_{k-1})}\\ &&\cdots\cdots\cdots\cdots&&&\\ Q_{(n_i-n_{i-1})\cdot n_1}&Q_{(n_i-n_{i-1})\cdot 1}&\ldots&P(V_i)&\ldots&Q_{(n_i-n_{i-1})\cdot(n_k-n_{k-1})}\\ &&\cdots\cdots\cdots\cdots&&&\\ Q_{(n_k-n_{k-1})\cdot n_1}&Q_{(n_k-n_{k-1})\cdot 1}&\ldots&Q_{(n_k-n_{k-1})\cdot(n_i-n_{i-1})}&\ldots&P(V_k)\end{bmatrix}\end{array}\begin{array}{c}v_1\ldots v_{n_1}\\ v_{n_i+1}\\ \ldots\\ v_{n_{i-1}+1}\ldots v_{n_i}\\ \ldots\\ v_{n_{k-1}+1}\ldots v_{n_k}\end{array}$$

Figure 15 Transformation matrix of P

For Figure 13, symbol “0” means disconnected link between nodes, and $P(V_i)$ is fully connected. So the rank of $P(V_i)$ is 1, and the rank of P is k just as described in Equation (5).

Also, P can be expressed as the formulas in Figure 14-15. Through the elementary transformation of rows and columns of P in Figure 14, the transformed matrix P is shown in Figure 15, which was just like the formula in Figure 13. Then computing the rank of P like Equation (5).

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