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ALGORITHM FOR REDUNDANT NODES DEPLOYMENT OF GREENHOUSE WSN MONITORING AND CONTROL SYSTEM

ZHANG LEI

Department of Electrical & Electronic Engineering, Henan University of Urban Construction, Ping Ding Shan, 467036, China

E-mail: 2008_zhang_lei@163.com

ABSTRACT

Specific to the funneling effect of Greenhouse wireless sensor networks (**WSN**) monitoring and control system, redundant nodes deployment algorithm (RNDA) is proposed. RNDA deploys a certain number of redundant nodes based on load of nodes so as to balance energy consumption of network. By means of introducing the next-hop routing probability of node into graph theory as the weight, the probability theorem that source node data arrive at the destination node after making m hop(s), thus providing an effective for researching network data transmission. Theoretical analysis and simulation result show that while remarkably extending network life, RNDA can also effectively balance energy consumption of network nodes.

Keywords: *Wireless Sensor Networks (WSN), Greenhouse Monitoring And Control System, Redundant Nodes Deploy, Funneling Effect, Graph Theory*

1. INTRODUCTION

WSN (wireless sensor networks) boasts low cost, low energy consumption, flexible networking, no need for wiring and other advantages. Combination of WSN and greenhouse monitoring and control system is an urgent need of modern agricultural production. In a greenhouse WSN monitoring and control system, a large number of sensor nodes are deployed in a dense way, featuring a considerable number of redundant nodes. In WSN monitoring and control system based on centralized data acquisition, data are mostly transmitted to base station by way of multi-hop. Nodes close to base station die out too soon due to transmission of large volumes of data, resulting in division or even total paralysis of the network. Such energy consumption phenomenon caused by imbalanced load of nodes is called funneling effect [1-2].

Node redundancy technology is extensively used for improving performance of WSN. Zhang Zhenjiang et al. combine some redundant nodes in WSN into a trunk to serve as an agent for information transmission in the network, thus saving normal nodes and cluster head energy [3]; Chen Feng et al. meet coverage of 3D monitoring area by awakening redundant sleeping nodes by stages [4]. These approaches use existing redundant nodes in the network to extend network life and meet network coverage; but they fail to take into consideration the issue of redundant nodes deployment.

Graph theory is often used for describing relationship and connectivity between nodes, serving as a useful mathematic tool for the research on network structure [5]. Presently, in terms of acquisition shortest network path [6-7], strongest connectivity path, network evaluation/optimization [8] and so on, an array of application researches has been made with graph theory. This article, taking greenhouse WSN as the application background and based on relevant graph theory, proposes the theorem of arrival rate of data following m hop(s) in network, and designs the Redundant Nodes Deployment Algorithm (RNDA) based on balanced load. Theoretical analysis and simulation result show that RNDA remarkably extends network life and also effectively solve funneling effect of greenhouse WSN monitoring and control system.

2. ISSUE DESCRIPTION

In order to solve the issue of funneling effect of multi-hop wireless sensor networks, a certain number of redundant nodes are deployed based on load of nodes in the network so as to balance energy consumption of network and extend its life. WSN features diversified layouts and complicated network routing. The key to redundant nodes

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deployment is acquisition of load of each node against diversified network layout. In this article, the issue is introduced with the example of 2D-layout greenhouse WSN monitoring and control system in greenhouse environment. By way of model building for analysis, eventually a scheme on redundant nodes deployment applicable to any layout is obtained.

Suppose the greenhouse is rectangular, on the condition of meeting area coverage and ensuring connectivity between all adjacent grids, and with sensor node sensing distance and wireless communication distance taken into account, the monitoring area is divided into several virtual grids. At any time, only one node in the grid is active while other nodes are redundant nodes configured according to energy consumption of each grid. The network submits monitoring data to the base station by way of multi-hop. Nodes in the virtual network awake to operate within their own active period as per order specified in advance. With the end of operation in this period, the node will immediately enter sleep status.

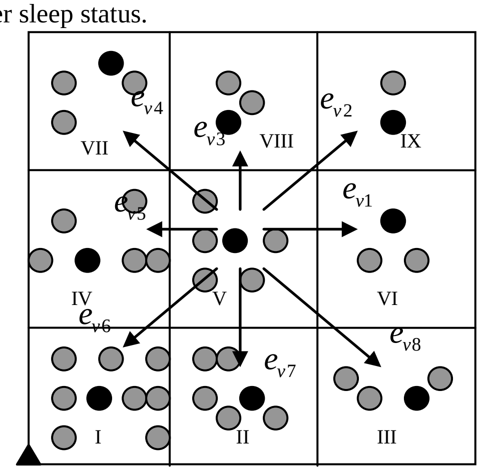

Fig.1 Network Model

Fig. 1 shows the model of greenhouse WSN monitoring and control system network, where the black nodes are active nodes, grey ones are redundant ones, each grid is coded with Roman numerals, and arrows show routing direction of nodes.

Definition 1: The probability in which Node v selects Edge e as the routing of next hop is called Node v's e direction routing probability, expressed as $P_v(e)$. If $P_v(e)$ =0, this direction can not be used for communication.

Definition 2: Node v, in the direction of n presents a routing probability set{ $P_v(e_{v1})$, $P_v(e_{v2})$,…, $P_v(e_{vn})$ }, this set is called routing probability vector of Node v, briefly called probability vector of v, expressed as P_v.

3. RADA

3.1 Calculation of Load Distribution

In the greenhouse, the network topology of active nodes can be expressed as Graph $G=<V,R>$. In the figure, $V=\{v_1,v_2,...,v_n\}$ is the node set of graph, Element v_i is node of graph, $R=\{e_1,e_2,...,e_n\}$ is edge set of the graph, its Element $e_i=\{<v_j,v_k>|1\le j\le n,1\le k\le n\}$ is the edge of the graph, v_j is the starting point of e_i, v_k is the end point of e_i, and routing probability $P_v(e_i)=R(v_j,v_k)=r_{jk}\in[0,1]$ is the weight of Edge e_i. n order square matrix $R_G=(r_{jk})_{n\times n}$ is called as G's adjacency matrix, where $r_{jk}=R(v_j,v_k)$, it is specified that when $j=k$, $r_{jk}=0$.

According to the basic graph theory theorem [9] provided in Bibliography, the following source-node to destination-node m hop(s) data arrival rate theorem can be obtained.

Theorem: Suppose in directed graph $G=<V,R>$, $V=\{v_1,v_2,...,v_n\}$, $R_G=(r_{jk})_{n\times n}$ is adjacency matrix of G, $R_G^m=(r_{jk}^{(m)})_{n\times n}$, so $r_{jk}^{(m)}$ is the probability for Node v_j to make exactly *m* hop(s) to arrive at v_k.

Prove:

（1） When *m=1*, obviously it is tenable.

（2） Suppose when *m=i*, the theorem is tenable.

（3） When *m=i+1*, the theorem is tenable. Proved as follows:

$$(r_{jk}^{(i+1)})_{n\times n}=R_G^{i+1}=R_G\cdot R_G^i=\left(\sum_{p=1}^{n}r_{jp}\cdot r_{pk}^{(i)}\right)_{n\times n}$$

i.e. $r_{jk}^{i+1}=\sum_{p=1}^{n}r_{jp}\cdot r_{pk}^{(i)}$

In this formula, r_{jp} shows the probability for Node v_j to make 1 hop to reach v_p, $r_{pk}^{(i)}$ is the probability for Node v_p to make i hop(s) to reach v_k. So $r_{jp}\cdot r_{pk}^{(i)}$ is the reachable probability for starting from Node v_j, passing v_p and arriving at

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v_k while the total hop number is *i+1*; therefore, $\sum_{p=1}^{n} r_{jp} \cdot r_{pk}^{(i)}$ is the probability for starting from Node v_j and making *i+1* hops to arrive at v_k .Over.

Based on the above-mentioned theorem, it is possible to obtain the data load volume of any Node v_i. Suppose for a pair of nodes in the network, data can go from one to the other node within *m* hop(s), the arrival rate matrix sequence within m hop(s) { R_G^1, R_G^2, ……, R_G^m } is obtained. Sum of Matrix $\sum_{k=1}^{m} R_G^k$'s Column i, $\sum_{j=1}^{n}\sum_{k=1}^{m} r_{ji}^k$, is the probability sum for each node to make 1 to m hop(s) to arrive at v_i . Therefore, v_i receiving and transmission loads are respectively,

$$D_{Rv_i} = l \cdot \sum_{j=1}^{n}\sum_{k=1}^{m} r_{ji}^k \qquad (1)$$

$$D_{Tv_i} = l(\sum_{j=1}^{n}\sum_{k=1}^{m} r_{ji}^k + 1) \qquad (2)$$

In this formula, l is the data volume generated by each node for finishing the monitoring task, and n is the number of nodes.

3.2 Identification of subsections

In a WSN, energy is mainly consumed for wireless communication. Energy consumed for sensing data, processing data and so on can be ignored. During wireless communication, power attenuation of transmission signals presents an exponential decay along with increase in transmission distance. In this article, free space and multi-path attenuation model proposed in Bibliography [10] is used.

$$E_{TX} = \begin{cases} l \times E_{elec} + l \times \varepsilon_{fs} \times d^2 & d < d_0 \\ l \times E_{elec} + l \times \varepsilon_{amp} \times d^4 & d \geq d_0 \end{cases} \qquad (3)$$

$$E_{RX} = l \times E_{elec} \qquad (4)$$

In the formula, d is communication distance; l is transmission or receiving data bit; d_0 is the critical value for switching between the two models; E_{elec} is the energy consumption for transmitting (or receiving) 1 bit data during operation of transmission/receiving circuit; ε_{fs} and ε_{amp} respectively are energy consumption for power amplification under the two models. For easy calculation, it is supposed herein: $d < d_0$.

According to Node i's data receiving volume D_{Rv_i} and data transmission volume D_{Tv_i} obtained based on Formulas (1) and (2), the below periodical energy consumption of Node v_i can be obtained based on Formulas (3) and (4)

$$E_i = (D_{Rv_i} + D_{Tv_i}) \cdot E_{elec} + D_{Tv_i} \cdot \varepsilon_{fs} \cdot d^2 \qquad (5)$$

3.3 Node Deployment

Suppose each node comes with the same initial energy E_{ini} and the node can not work properly if falling below the same energy threshold; in ideal status, it is expected that all virtual grids come with the same life, i.e.:

$$\frac{(1+b_i)E_{ini}}{E_i} = \frac{(1+b_{i+1})E_{ini}}{E_{i+1}} \quad 1 \leq i \leq n-1 \qquad (6)$$

Organized into:

$$b_i = \frac{E_i}{E_{i+1}} \times b_{i+1} + \frac{E_i - E_{i+1}}{E_{i+1}} \qquad (7)$$

This formula is an *n* term linear equation, by selection of specific node to be configured with certain redundant node number as initial condition, the number of redundant nodes needed for other nodes can be obtained. We can configure any number of redundant node(s) for Grid I as the initial condition.

4. SIMULATION ANALYSIS AND RESULT

The analysis shows that the key of the above algorithm lies in determination of probability vector P_v of each node; with this vector, the network topology graph can be built. In an actual WSN, Node v has varied P_v in varied routing algorithm. According to position information of nodes, categorize all nodes in the network; each node uses the same P_v as initial P_v for communication.

Table 1 shows routing probability vector of each category of cluster head. Table 2 shows some parameters needed for the simulation.

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Table 1 Table of Probability Vectors

Cluster head category	Routing Probability Vector p_v	Value range
South border cluster head	$p_v = \{0,0,0, p_{v(e_{v4})}, p_{v(e_{v5})}, 0,0,0\}$	(0,0,0,1/2, 1/2,0,0,0)
West border cluster head	$p_v = \{0,0,0,0,0,0, p_{v(e_{v7})}, p_{v(e_{v8})}$	(0,0,0,0,0, 0,1/2,1/2)
General cluster head	$p_v = \{0,0,0,0, p_{v(e_{v5})}, p_{v(e_{v6})}, p_{v(e_{v7})}, 0$	(0,0,0,0,1/ 3,1/3,1/3,0)
East hot cluster head	$p_v = \{0,0,0,0, p_{v(e_{v5})}, 0,0,0\}$	(0,0,0,0,1, 0,0,0)
North hot cluster head	$p_v = \{0,0,0,0,0,0, p_{v(e_{v7})}, 0\}$	(0,0,0,0,0, 0,1,0)
Northeast hot cluster head	$p_v = \{0,0,0,0,0, p_{v(e_{v6})}, 0,0$	(0,0,0,0,0, 1,0,0)

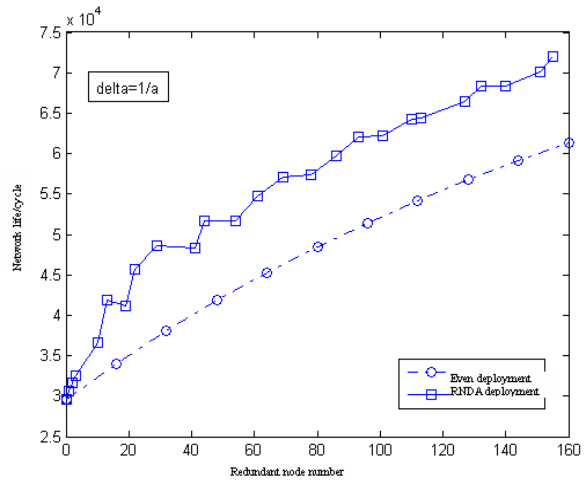
Table 2 Table of Simulation Parameters

Parameter	Value	Parameter	Value
Area	100m × 100m	Active node number a	5
Each node Data volume k	256 *bit*	E_{elec}	50nJ/bit
Node initial Energy E_{init}	2*J*	ε_{fs}	10pJ/bit/m^2
Energy lower limit	$E_{init} \times 1\%$	ε_{amp}	0.0013pJ/bit/m^4
Data fusion Coefficient δ	1/a or 1	d_0	86.2*m*

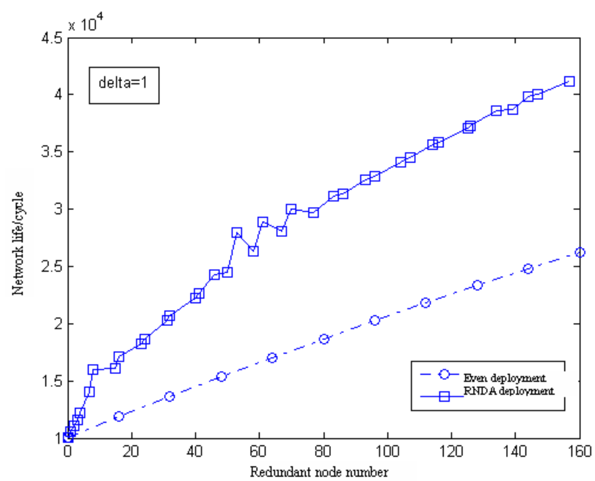
The simulation takes into consideration the influence on network life exerted by cluster head adoption of data fusion strategy and absence of this strategy. WSN data fusion mainly aims to reduce data volume of the network by integrating redundant information of all sensor nodes. In this simulation experiment, data fusion is carried out at cluster heads; when data fusion strategy is not used, data fusion coefficient is set to be $\sigma = 1$; when the strategy is used, different data fusion coefficient can be selected based on varied fusion degree. As sensor nodes here are all isometric sensor nodes, information collected by them is of the same type. According to statistical knowledge, environment parameters in a small scope differ little. Therefore, data of all sub-nodes in a grid can be used into one datum to describe environment information in this grid (such as temperature and humidity). In simulation experiment, data fusion coefficient is set to be $\sigma = 1/a$ when data fusion strategy is adopted, where a is the number of active nodes in the grid. In all the simulation experiments below, it is set as 5.

In MATLAB 7.0, compile M document program to research performance of RNDA, and then make comparison with the pattern of even deployment. In the even deployment pattern, redundant nodes are evenly deployed to each cluster and the network still runs based on 3 task time slots. Below is the comparison of influence on network life exerted by the two patterns with varied grid number and fusion coefficient. Network life is defined as operation cycles when all hot clusters die.

1. 4×4 grids, where grid edge length is $d = 25m$, communication distance inside cluster is $d_{CI} = \sqrt{2}d$, and $d_{CO} = 2d_{CI}$.



(a) Data fusion coefficient $\sigma = 1/a$



(b) Data fusion coefficient

Fig. 2 Influence on Network Life Exerted by Redundant Nodes (4×4 Grids)

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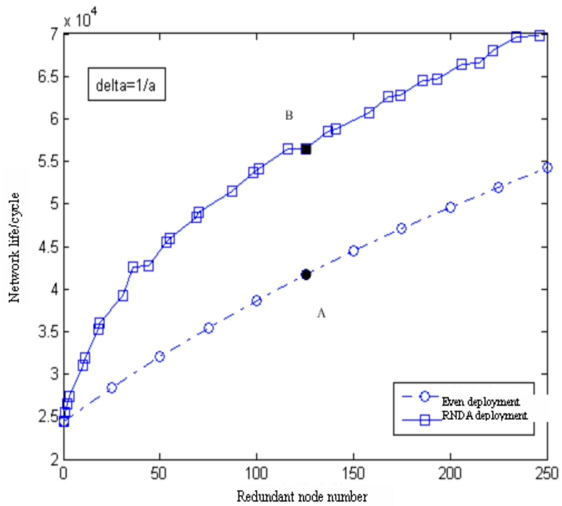
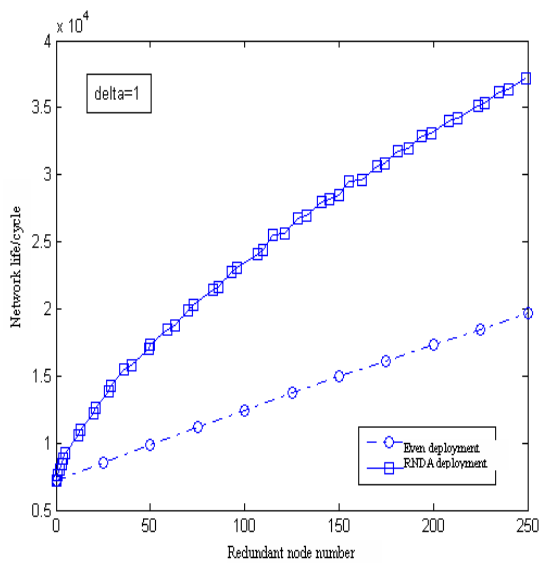
2 . 5×5 grids, grid edge length being $d=20m$.



(a) Data fusion coefficient $\sigma=1/a$



(b) Data fusion coefficient $\sigma=1$

***Fig. 3** Influence on Network Life Exerted by Redundant Nodes (5×5 Grids)*

In Fig. 2 and Fig. 3, each discrete point on the curve stands for one simulation; their horizontal coordinate is the sum of redundant nodes of each cluster in this simulation; in the even deployment pattern, its value equals grid number $\times$ redundant node number which added to each grid; vertical coordinate of each simulation point stands for network life of this simulation.

In the first simulation, both even deployment pattern and RNDA deployment pattern come without redundant nodes; this is the initial status for both patterns, so the two curves meet here. An additional redundant node is added to each grid with every simulation made in the even deployment pattern. On the other hand, in RNDA deployment pattern, as the northeast hot cluster head consumes the most energy, one redundant node is added to this cluster with each simulation. So given this initial condition, the redundant node number of other clusters are obtained according to calculation formula for redundant nodes.

Data fusion coefficient exerts a remarkable influence on network life. This is because when data fusion strategy is not used, network number is 5 times of that used when data fusion strategy is adopted. It can be seen from the figure that when data fusion strategy is adopted, network life is about 2-3 times that of the life when the strategy is not used.

Likewise, virtual grid number influences network life. The more grids divided in the monitoring area and the greater the data volume of the network, the shorter the network life is.

The comparison between the two redundant nodes deployment algorithms shows that when the same redundant nodes are deployed, RNDA enables a longer network life.

In Fig. 3(a), 125 redundant nodes are deployed on Points A and B on the curve. In even deployment pattern (i.e. Point A), 5 redundant nodes are deployed in each grid, while in RNDA deployment pattern, distribution of redundant nodes (i.e. Point B) are shown in Fig. 4.

2 1.2441	2 1.2234	2 1.1613	1 0.9750	1 0.4163
5 4.5139	5 4.7933	4 3.2101	3 2.4651	1 0.9750
9 8.6668	9 8.7771	5 4.6381	4 3.2101	2 1.1613
9 8.7251	19 19.0000	9 8.7771	5 4.7933	2 1.2234
1 0.4163	9 8.7251	9 8.6668	5 4.5139	2 1.2441

Fig. 4 Distribution of 125 Nodes in RNDA Pattern (5×5 Grids, $\sigma=1/a$)

In Fig. 4, there are two rows of data in each grid. The bottom data are the redundant node numbers obtained by calculation based on RNDA. The data on the top are values obtained by rounding of ceil(x) function of MATLAB; this function serves to get the minimum integer greater than x. Rounding of redundant node number is made for the sake of actual deployment, but that brings

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relatively small variation to RNDA deployment curve, i.e. life of network with more nodes may fall shorter than network with less nodes. Such is relatively remarkable in Fig. 2(b). However, such case only occurs between two neighboring simulation points.

Moreover, as symmetrical routing probability vector is used, distribution of redundant nodes is symmetrical to the monitoring area against a 45-degree diagonal. The initial condition is set to be redundant node number of northeast hot cluster as with such a routing strategy, this cluster is the most energy-consuming one among the three hot clusters. At Point B, 19 redundant nodes join this cluster, showing that this is the 19th simulation experiment.

By comparison between network performance at Points A and B in Fig. 3(a), one can see RNDA extends network life by 35.8% in comparison with even deployment pattern. To extend the same network life, RNDA uses much less redundant nodes. When network life is 3.5×10^4 cycles, RNDA only deploys 24% of redundant nodes in the even pattern.

5. EQUATIONS

With greenhouse WSN monitoring and control system as application purpose, this article proposes redundant node deployment algorithm RNDA based on balanced load. This algorithm is closely related to routing; based on routing probability of nodes, this algorithm can be applicable to networks with multi dimensions and multi-path routing. With the next-hop routing probability of the node as edge weight, the theorem of m hop(s) arrival rate is proposed, thus providing a valid approach for researching on network data transmission. The simulation result shows that the algorithm well solves the funneling effect. By deploying of the same redundant nodes, RNDA enables longer network life. Given 125 redundant nodes are deployed, RNDA patterns extends the life by 35.8% in comparison with even pattern. For extension of the same network life, RNDA serve to save a large number of redundant nodes. When network life is 3.5×10^4 cycles, RNDA only deploys 24% of redundant nodes in the even pattern.

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