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TRANSMISSION POWER CONTROL IN WIRELESS SENSOR NETWORKS UNDER THE MINIMUM CONNECTED AVERAGE NODE DEGREE CONSTRAINT

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Abstract- As a branch of topology control, power control is of great importance to prolong the survival time of the network. A transmission power control algorithm is proposed under the minimum connected average node degree constraint in this paper. Using a Poisson point process in two dimensions, we derive an analytical expression that determines the required transmission range to achieve a specified connectivity probability for a given node density, and then the minimum connected average node degree is obtained. Based on the above results, an algorithm named MCAND is designed to achieve the given connected probability by adjusting the transmission power of each node dynamically, with the node degree equal to the minimum connected average node degree. Simulation results show that the performance of our algorithm is superior to that of the related algorithms based on node degree in terms of coverage and connectivity.

Index terms: Wireless sensor networks, power control, connectivity, coverage, node degree.

I. INTRODUCTION

Wireless sensor networks (WSNs) usually consist of a large number of small nodes that have finite storage, processing, and communication abilities. Once deployed, they are typically self-organized in a multihop fashion to monitor the target field and detect the occurrence of important events. Nowadays, WSN has become a research focus in the information field, attracting the attention of both the academic and the industrial research community [1-4].

It is inconvenient and sometimes even impossible to substitute the node battery. Furthermore, due to node mobility or failure, the network topology is inevitably time-varying and should be controlled as soon as possible. Consequently, the constrained energy supply of nodes, the dynamic change of network topology and other restrictions have brought huge challenges for the design and management of WSN [1, 5]. Topology control, as one of the core techniques in WSN research, is committed to the formation of an optimized network topology with the desired properties such as connectivity and coverage while reducing node energy consumption and increasing network capacity. This technology can enhance the efficiency of routing and MAC protocol, lay a foundation for the data fusion, time synchronization and target localization, and prolong the survival time of the whole network [6-9].

At present, topology control has formed two main research aspects, i.e., sleep scheduling and power control [6, 10]. It is well known that idle listening to the radio channel consumes energy as much as that of data transmission. Thereby it is an efficient approach to switch sensor nodes to the sleep state in order to achieve significant energy conservation. As a consequence, how to set up an optimal working/sleep schedule becomes one issue of topology control [11-14]. In addition, another way to control network topology is to adjust the transmission power of each node in working state, namely power control. With the network connectivity satisfied, power control can balance the number of one-hop reachable neighbor nodes so as to reduce the interference and prolong the network lifetime.

In this paper, a transmission power control algorithm named MCAND is proposed under the minimum connected average node degree constraint. The paper makes the following contributions: (1) using a Poisson point process in two dimensions, we derive an analytical expression that determines the required transmission range to achieve a specified connectivity probability for a given node density, and then the minimum connected average node degree is obtained; (2) based on the above results, MCAND is designed to achieve the given connected probability by adjusting the transmission power of each node dynamically, with the node degree equal to the minimum connected average node degree; (3) simulation comparisons carried out subsequently indicate that the MCAND algorithm is able to configure the network topology flexibly according to the connectivity requirement of practical applications. The results of this paper are of practical value for researchers in this area.

The rest of the paper is organized as follows. We first introduce a literature review of related work in Section 2. In Section 3, the model that is employed in our algorithm is given. The minimum connected average node degree and its related conclusions are presented and proved in Section 4. The transmission power control algorithm of MCAND is designed in Section 5. In Section 6, simulation results are considered. We conclude the paper in Section 7.

II. RELATED WORK

There are extensive research works related to power control. According to the method adopted, they can be divided into three categories, that is, power control algorithms combined with routing protocol, approximation algorithms based on proximity graph, and node degree based algorithms.

Combining power control and routing can be very challenging [15-21]. The defects of these protocols are the overspending of message overhead and the poor scalability. Based on the classical proximity graph model, the literatures [22-25] are focused on the connectivity and bidirectional connectivity of the network. However, these algorithms require accurate location information generally.

The algorithms based on node degree can achieve the optimized topology only with a small amount of local information, and they have few requirements on the nodes and do not need time synchronization. Therefore, they are more convenient for real applications. Two representatives of these algorithms are LMN and LMA [26], whose basic idea is to make the node degree fall between two given thresholds by adjusting the transmission power of each node dynamically. However, they cannot usually guarantee the connectivity of the network, and their performance depends largely on the related parameters. In [27], power control is formulated as a constrained optimization problem, and then the LINT and LILT protocols are presented. Nonetheless, the independent power adaptation decision can introduce additional communication delay. To reduce energy consumption and converge topology rapidly, Zhang et al. [28] propose a transmission power control method based on fuzzy control theory, named FCTP. However, the control action is dependent on the system inputs, for example, the initial transmission power level and the mean degree assuring a good connectivity. Furthermore, coverage and connectivity, as two essential performance metrics of topology control, are not taken into account.

In this context, we put forward a distributed power control algorithm named MCAND. This method can adjust transmission power to achieve the minimum connected average node degree which assures a specified connectivity probability. By analyzing its connectivity, coverage and power consumption performance, we observe that MCAND can adaptively adjust node transmission power in response to topological changes and attempt to maintain a connected topology using the minimum power.

III. ESTABLISHMENT OF ALGORITHM MODEL

3.1 Network model

Suppose N sensor nodes are randomly distributed in a two-dimensional Euclidean region whose area is A. Here the node set is represented as $V = \{1, 2, \cdots, N\}$, where $i(i = 1, 2, \cdots, N)$ denotes a node, and the base station is located in the region. For each node $i \in V$, its sensing and transmission range are denoted as $R_s(i)$ and $R_c(i)$ respectively. The minimum and maximum transmission range of all nodes in the network are $R_{\min}$ and $R_{\max}$ in turn, and node i can take its transmission range value $R_c(i)$ dynamically in the interval of $[R_{\min}, R_{\max}]$.

Definition 1 (Sensing region and direct communication region) the sensing region of node i is the circle of radius $R_s(i)$ centered at node i; the direct communication region of node i is the circle of radius $R_c(i)$ centered at node i.

Definition 2 (Communication graph) the communication graph induced by $R_c(i)$ on V is defined as the directed graph $G_c = (V, E_c)$, where the directed edge $(i, j) \in E_c$ exists if and only if $d(i, j) \le R_c(i)$ in which $d(i, j)$ is the Euclidean distance between node i and j.

Definition 3 (Node degree) the degree of a node i, denoted as $d(i)$, is the number of neighbor nodes within its direct communication region. Then the minimum node degree of a graph G_c is $d_{\min} = \min_{i \in V} \{d(i)\}$, and the average node degree of G_c is $d_{mean} = \frac{1}{N}\sum_{i=1}^{N} d(i)$.

Definition 4 (Node density) the node density is the number of nodes per unit area, denoted as $\rho = N/A$.

Suppose the spatial node distribution is subject to a two-dimensional Poisson point process of density ρ , and the probability for k nodes located in a region whose area is A denoted as

$$p\left(N\left(A\right)=k\right)=\frac{\left(\rho A\right)^{k}}{k!}e^{-\rho A} \qquad k=0,1,2,\cdots. \tag{1}$$

Where the random variable $N\left(A\right)$ denotes the number of nodes located in region A . Therefore, the location of any node is a random variable that is uniformly distributed in the two-dimensional plane.

3.2 Algorithm model

Due to the multi-hop feature of WSN, a node consumes energy not only in its own activities but also in relaying traffic to other nodes. When a node alters its transmission power, its transmission range is adjusted accordingly. As a very complex issue, power control can be simplified to the transmission range assignment (RA) problem [1]. The RA problem can be described as follows: let $V=\left\{1, 2, \cdots, N\right\}$ be a set of nodes in the *d*-dimensional space, with *d*=1, 2, 3. What is the value of $R_c(i)$ for each node i in V such that the corresponding communication graph G_c is connected and the energy consumption is minimum, that is, the range assignment function $f(x)$ is minimum over all the range assignment functions. Formally,

$$\min f(x)=\min\sum_{i\in V}[R_c(i)]^{\alpha} \tag{2}$$

Where $\alpha\geq 2$ is the path loss exponent, depending on the energy consumption model adopted? In fact, the function $f(x)$ mentioned above is the sum of the transmission power levels used by all the nodes in the network. When the nodes are deployed in a two-dimensional or three-dimensional space, power control is an NP-hard problem. Therefore, the approximate algorithm is generally used to solve this problem, which focuses on prolonging the lifetime of the network generally by reducing the transmission power.

For the transmission range $R_c(i)$ of a node to be adjusted dynamically in the interval$[R_{\min}, R_{\max}]$, $R_{\min}$ and $R_{\max}$ should be determined firstly. As we all know, $R_{\max}$ can be determined by the physical properties of the deployed nodes. If each node communicates with $R_{\max}$, the node can reach more neighbor nodes, leading to stronger network connectivity. However, it will increase the communication interference between nodes and degrade the communication efficiency. In contrast, if the transmission range is too small, the network topology is easy to be disconnected. In order to solve this contradiction, the network connectivity should be taken into account when determining $R_{\min}$.

In the related literatures of WSN, $R_{\min}$ usually takes a value not less than the diameter of the network in order to guarantee the connectivity of the network, where the diameter is the maximum distance between any two nodes in the network. This means that the transmission range will cover the whole network. However, it is not necessary for $R_{\min}$ to arrive such a large value only to ensure connectivity in the real scene. On the other hand, it is difficult to do so by technical ways. Therefore, the following discussion will be focused on the minimum transmission range $R_{\min}$ that achieves the specified connectivity probability in an analytical manner. The corresponding average node degree of the network will be obtained subsequently.

IV. MINIMUM CONNECTED AVERAGE NODE DEGREE

Theorem 1 Given a network G containing N nodes, the nodes are distributed according to a two-dimensional Poisson point process of node density ρ. To ensure that $P(G\ is\ connected) \geq p \quad (0 \leq p < 1)$ holds, the minimum node transmission range is

$$R_{\min} = \sqrt{\frac{-\ln(1-p^{1/N})}{\rho\pi}}. \tag{3}$$

Proof. When the network is connected, node i is not an isolated node for each $i \in V$, then we get the node degree $d(i) \geq 1$. So that, the minimum node degree of graph G is $d_{\min} \geq 1$.

As the node distribution is a two-dimensional Poisson point process, we obtain the probability that a node has no neighbor, i.e., it is isolated, is therefore

$$P(d(i)=0) = P(N(\pi R_c^2(i))=0) = \frac{(\rho\pi R_c^2(i))^0}{0!} e^{-\rho\pi R_c^2(i)} = e^{-\rho\pi R_c^2(i)} \tag{4}$$

Thus
$$P(d(i)\geq 1) = 1 - P(d(i)=0) = 1 - e^{-\rho\pi R_c^2(i)} \tag{5}$$

According to the event independence of the Poisson process, we have

$$P(d_{\min} \geq 1) = \binom{N}{N} P(d(i)\geq 1)^N P(d(i)=0)^0 = \left(1 - e^{-\rho\pi R_c^2(i)}\right)^N \tag{6}$$

As a result, according to $P\left(G\ is\ connected\right) \geq p\left(0 \leq p < 1\right)$, $\left(1 - e^{-\rho\pi R_c^2(i)}\right)^N \geq p$ holds, then we get $R_c(i) \geq \sqrt{\dfrac{-\ln(1-p^{1/N})}{\rho\pi}}$. Therefore, it can be obtained that the minimum node transmission range is $R_{\min} = \sqrt{\dfrac{-\ln(1-p^{1/N})}{\rho\pi}}$.

This completes the proof.

By Theorem 1, we can obtain the conclusion that when the network area A and the node number N are known in advance, only by substituting the corresponding parameters into equation (3) can the minimum transmission range $R_{\min}$ be obtained for a given connectivity probability p. Next, a simulation experiment will be carried out firstly for Theorem 1. Suppose the monitor region is a square with a side equal to 100 meters, and the model for the spatial node distribution is described as section 3.1. When the number of nodes N is 20, 30, 40 respectively, $R_{\min}$ and the connectivity probability p are related by the curves shown in Figure 1.

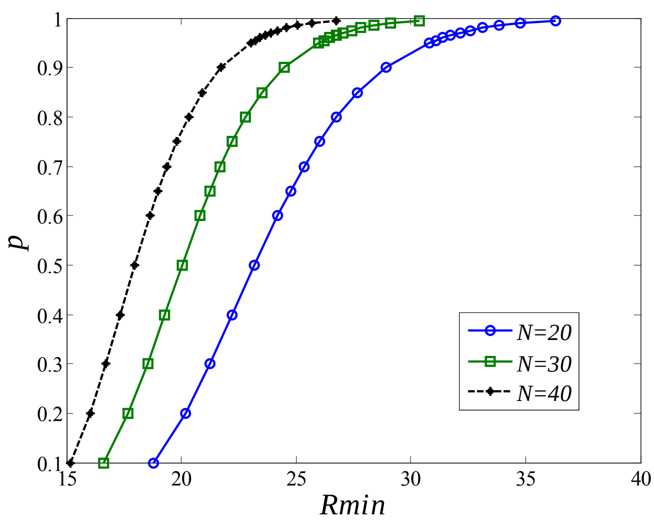


Figure 1. Relationship between $R_{\min}$ and p under different node numbers

Let us observe one of the three curves in Figure 1. As we can see, when the area and the number of nodes are determined, the minimum transmission range needed increases with the increase of the given connectivity probability p. Let us then compare the three curves. When the number of nodes increases gradually along with which the node density increases, the minimum transmission range required decreases for the same requirement of connectivity probability. For example, when the node number is 20, 30, 40, if the connectivity probability is required to be p=0.8, then $R_{\min}$ should be 26.7m, 22.8m, 20.3m respectively; if the connectivity probability is required to be p=0.99, then $R_{\min}$ should be 34.7m, 29.1m, 25.6m respectively. It is easy to understand the phenomenon. High connectivity probability implies that any node can reach more other nodes via a direct link, and this can be accomplished by increasing $R_{\min}$ or the node number. In conclusion, for a deployed WSN, it is easy to obtain the minimum transmission range $R_{\min}$ satisfying a certain connectivity probability by Theorem 1.

For a randomly deployed network, perhaps different nodes have different numbers of neighbor nodes. Given a connectivity requirement, a node should adjust its transmission range according to its node degree. As a result, we must establish the relationship between the transmission range and node degree. Furthermore, when all the nodes communicate with $R_{\min}$, the corresponding average node degree of the network is called the minimum connected average node degree which satisfies the given connectivity probability.

Definition 5 (Minimum connected average node degree) Minimum connected average node degree, represented as $d_{connect}$, is the corresponding average node degree of the network when all the nodes communicate with $R_{\min}$.

Theorem 2 Given a network G containing N nodes, the nodes are distributed according to a two-dimensional Poisson point process of node density ρ. The minimum connected average node degree is

$$d_{connect} = \rho\pi R_{\min}^{2} . \tag{7}$$

Proof. According to the definition of the minimum connected average node degree, when all the nodes communicate with $R_{\min}$, let us build the relationship between the transmission range and the network average node degree, namely $d_{connect}$, we have

$$\begin{aligned} d_{connect} &= \sum_{k=1}^{\infty} kP\left(d\left(i\right)=k\right) = \sum_{k=1}^{\infty} k \frac{\left(\rho\pi R_{\min}^{2}\right)^{k}}{k!} e^{-\rho\pi R_{\min}^{2}} \\ &\rho\pi R_{\min}^{2} \sum_{k=1}^{\infty} \frac{\left(\rho\pi R_{\min}^{2}\right)^{k-1}}{\left(k-1\right)!} e^{-\rho\pi R_{\min}^{2}} = \rho\pi R_{\min}^{2} \end{aligned} \tag{8}$$

The proof is completed.

Since the event $d_{\min} \geq 1$ is only a necessary but not sufficient condition for graph connectivity, the minimum node transmission range $R_{\min}$ obtained can be viewed as a lower bound of the required transmission range. Therefore, the transmission range will be adjusted distributed in the following algorithm to achieve the specific connectivity probability.

V. POWER CONTROL ALGORITHM BASED ON THE MINIMUM CONNECTED AVERAGE NODE DEGREE (MCAND)

Based on the above work, a power control algorithm based on the minimum connected average node degree (MCAND) is proposed, which makes an adjustment dynamically on each node's transmission range in the interval $[R_{\min}, R_{\max}]$ in order to set the node degree equal to the minimum connected average node degree. In this approach, the transmission power of nodes can be reduced with a given connectivity probability satisfied. The specific process of MCAND is listed as follows:

Initialization. For a monitoring area, give the node number N and its area A, set a given connectivity probability p according to the application requirement. Then, calculate the minimum transmission range $R_{\min}$ and the minimum connected average node degree $d_{connect}$ by equation (3) and (7) respectively. For each node $i \in V$, do step1 to step3.

Step1. Broadcast a Hello-1 message containing its ID with the minimum transmission range $R_{\min}$; for each node receiving this message, transmit an Ark response message containing its own ID and ID it received.

Step2. Check the received Ark messages, calculate its neighbor number $d(i)$ and establish its neighbor table $S_{neighbor}(i)$.

Step3. Compare $d(i)$ with $d_{connect}$, do the corresponding operation:

If $d(i) = d_{connect}$, set $R_c(i) = R_{\min}$;

If $d(i) > d_{connect}$, sort $S_{neighbor}(i)$ by distance in ascending order, take the first $d_{connect}$ nodes as its neighbor nodes, and set $R_c(i)$ as the distance from node i to the first $d_{connect}$ node;

If $d(i) < d_{connect}$, increase the transmission range to $R_{\max}$, broadcast a Hello-2 message containing its ID, repeat Step1- Step3. If there is still $d(i) < d_{connect}$, set $R_c(i) = R_{\max}$.

From the algorithm process, we know the communication graph formed finally is a directed graph that may contain unidirectional links, and the transmission power used by each node is not necessarily the same. Some papers have dealt with how to adjust the transmission range and then translate the unidirectional link into a bidirectional link [25], and we will not investigate this question. Analyses on the properties of the algorithm are made as follows.

Algorithm property 1. The algorithm is implemented distributed.

Because the node's transmission range changes in the interval $[R_{\min}, R_{\max}]$ and can be adjusted at most 3 times during the execution process, the Hello message can only be received by the nodes in its direct communication region, namely the message domain is one hop.

Algorithm property 2. The communication complexity of the algorithm is $O(N^2)$, the time complexity is $O(R_{\max})$, and the space complexity is $O(N^2)$.

During the adjustment of the transmission range, each node sends a Hello message no more than 2 times and sends an Ark response message at most $N-1$ times, so that the communication complexity of each node is $O(N)$, and then the communication complexity of the whole network is $O(N^2)$.

Suppose time required to send a Hello message or to receive an Ark response message by unit distance is a unit time, the distance to send or receive a message is at most $R_{\max}$. Consequently the time complexity is $O(R_{\max})$.

The processing of message in our algorithm is mainly reflected in the storage and sorting of the neighbor table. Since the neighbor number of each node is at most $N-1$, the space complexity is $O(N^2)$ .To adapt the dynamic change of network topology caused by the environmental disturbance and node failure, it is necessary for the algorithm to work in a distributed and high efficient way. Adjusting the node transmission range only by local information, the algorithm MCAND proposed in this paper can respond quickly to the network state and adjust the transmission range dynamically according to the periodic changes of network.

VI. SIMULATION AND PERFORMANCE ANALYSIS

The simulation experiment consists of two parts. In the first part, the study of the properties of the MCAND algorithm itself is made, and the performance comparisons among MCAND and other algorithms are made in the second part. Network model used in our simulation is the one as described in section 3. Nodes are deployed in a monitor area of size 100×100, and we set the path loss exponent α=2. The sensing range $R_s(i)$ of each node i is taken a half value of the transmission range $R_c(i)$ [29]. Each result is the average value of 100 simulation experiments.

6.1 Evaluation indexes

The main evaluation indexes include the actual network connectivity rate, the coverage rate, the average coverage degree and the objective function value.

(1) Network connectivity rate

If there exists a communication path from node *i* to node *j*, it is called node *i* is reachable to node *j*. If any two nodes in the communication graph G_c are reachable to each other, it is called the communication graph is connected. The ratio of the number of reachable node pairs to $N \times (N-1)$ is called the network connectivity rate. Only when the network is connected, can the node pairs communicate with each other either directly or over a multihop path, therefore the connectivity is one of the most fundamental and important properties of the network.

(2) Coverage rate

The monitor area is divided into the same cells of square units, and we suppose there is an event occurring at the center of each cell. If the center is within the sensing region of a certain node, the cell is called to be covered. The ratio of the number of covered cells to that of total cells is called the network coverage rate, which is a measurement of the quality of service of the network.

(3) Average coverage degree

If a cell is covered by *k* nodes at the same time, then coverage degree of the cell is called to be *k*. The average coverage degree is the average value of the coverage degrees of all the cells in the network, which is the measurement of the network coverage redundancy. The higher the average coverage degree is, the stronger the fault tolerance of the network is, while the higher the redundancy is.

(4) Objective function value

The objective function is the range assignment function as described in equation (2), that is, the sum of transmission power of all the nodes. This index reflects the energy consumption of the network.

6.2 Property study of MCAND

First, by changing the network node number and the ratio $R_{\max}/R_{\min}$, the property of the MCAND algorithm is evaluated in different environments. When the node number N changes from 1 to 100 and the ratio $R_{\max}/R_{\min}$ changes between 1 and 2, for the given connectivity probability p =0.99, the actual network connectivity rate, the coverage rate and the average coverage degree are shown in Figure 2 to Figure 4 respectively.

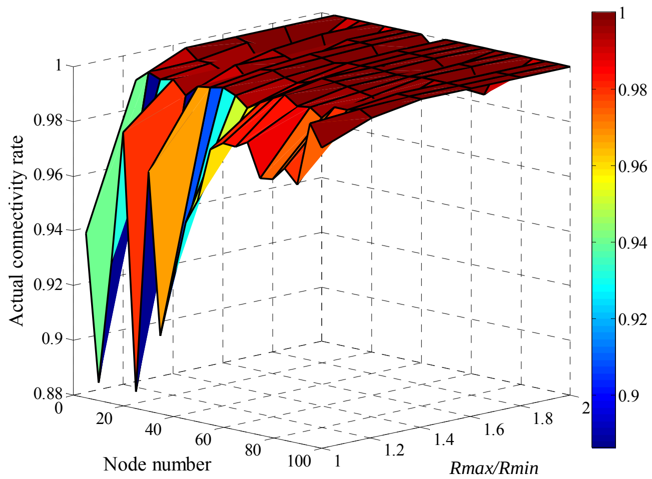


Figure 2. Actual network connectivity rate of MCAND algorithm (p =0.99)

Table 1. Comparison of $d_{connect}$ and the actual average node degree (p =0.99, $R_{\max}/R_{\min}$ =1)

Node number N	5	10	15	20	25
d_{connect}	7	7	8	8	9
Actual average node degree	3	4	5	6	6

As we can see from Figure 2, under the above conditions, all the actual network connectivity rates are above 88.63%. In addition, only when $R_{\max}/R_{\min}$ =1 and the node number is below 90, does the connectivity rate not reach 99%, and it is for the reason that the minimum transmission range $R_{\min}$ obtained by equation (3) is only a lower bound of the transmission range required for the network to reach the specified connectivity probability. According to MCAND algorithm, only when $R_{\max}$ is bigger than $R_{\min}$ can the transmission range be adjusted for the node degree to reach the minimum connected average node degree. However, if $R_{\max}/R_{\min}$ =1, namely $R_{\max} = R_{\min}$, the minimum connected average node degree is difficult to achieve, accordingly the specified connectivity probability cannot be satisfied. In order to verify this, we randomly sample several sets of values of the actual average node degree and the minimum connected average node degree $d_{connect}$ calculated by equation (7) to compare when p =0.99 and $R_{\max}/R_{\min}$ =1, as shown in Table 1. It can be found that the network does not achieve the minimum connected average node degree when $R_{\min}$ is taken as the transmission range of all the nodes and the actual connectivity rate is relatively low. In addition, Figure 2 indicates that the network connectivity can be improved by increasing the number of nodes in the network with the average node degree increased likewise.

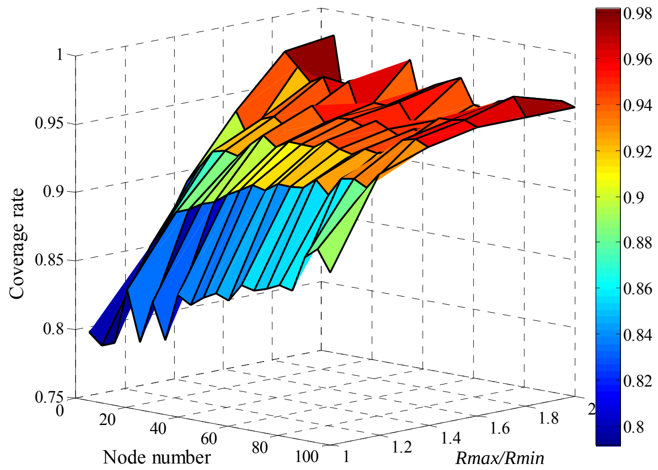


Figure 3. Coverage rate of MCAND algorithm (p =0.99)

As shown in Figure 3, the network coverage rate is between 79.14% and 98.19%. Similar to Figure 2, low coverage rate also appears when the ratio $R_{\max}/R_{\min}$ equals 1 and the node number is small simultaneously. When $R_{\max}/R_{\min}$ >1.2, no matter how many nodes there are, the network coverage rate can be ensured to be more than 90%. For WSN with nodes randomly deployed, it is impractical or unnecessary for the monitor area to be completely covered, in the application of weather forecasting, for example, it is satisfactory to achieve 90% coverage rate. Therefore, when $R_{\max}/R_{\min}$ >1.2, MCAND algorithm can make the network achieve more than 99% connectivity rate by adjusting the transmission range in the interval $[R_{\min}, R_{\max}]$ with a high coverage rate maintained, which can satisfy the need of practical applications.

Figure 4 describes the network average coverage degree. When the ratio $R_{\max}/R_{\min}$ changes between 1 and 2 and the node number varies from 1 to 100, it is easy to see, the network average coverage degree changes between 1.2 and 2.8. Low average coverage degree implies that the number of nodes reporting the same event to the base station is not great, which helps to reduce the network load and wireless communication conflicts, and then saves the energy of nodes. In addition, the coverage degree more than 1 can provide fault tolerance for the network.

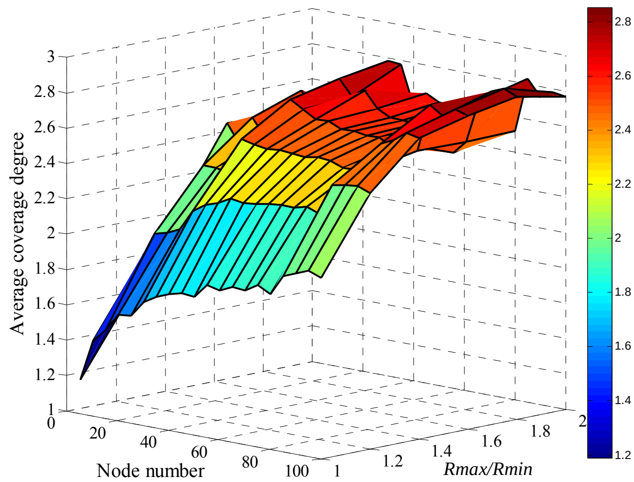


Figure 4. Average coverage degree of MCAND algorithm (p =0.99)

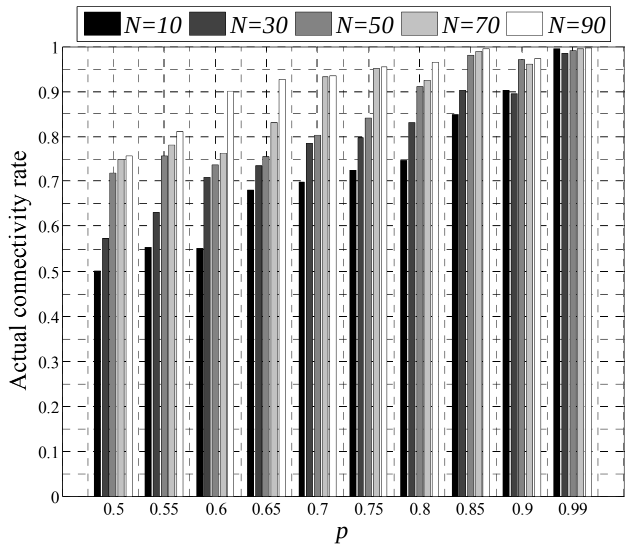
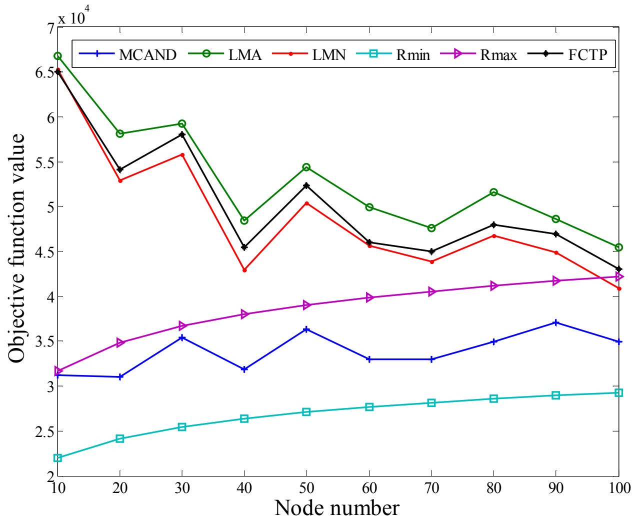


Figure 5. Comparison of p and the actual connectivity rate in MCAND (R_{max}/R_{min} =1.2)

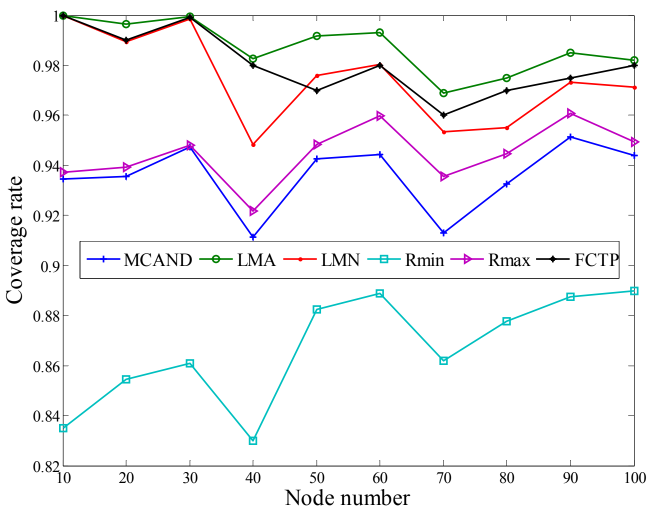
In order to test whether the MCAND algorithm can achieve a specified connectivity probability, we assume R_{max}/R_{min} =1.2, the node number changes between 10 and 90, and the specified connectivity probability varies from 0.5 to 0.99 at the same time. Let us observe whether the actual connectivity rate can reach a specified connectivity probability, and the results are plotted as bar graphs shown in Figure 5. The horizontal coordinate represents the specified connected probability, five vertical stripes from left to right corresponding to each abscissa represent the actual network connectivity rate when node number N =10, 30, 50, 70, 90 respectively. As can be seen, when the number of nodes is 10, only a few cases fail to reach the specified connectivity rate, while the number of nodes reaches more than 30, the actual connectivity rate far exceeds the specified connectivity probability. Furthermore, we also find that in the experiment the specified connectivity probability can be satisfied even with fewer nodes when increasing the ratio R_{max}/R_{min} .

6.3 Comparison with other algorithms

In this section, we compare the performance of six algorithms: MCAND, the algorithms based on node degree such as LMA, LMN and FCTP, the algorithms with all nodes taking R_{min} and R_{max} as the fixed transmission range respectively, represented as R_{min} and R_{max} algorithm correspondingly. Considering the discussion in section 6.2, we set the ratio R_{max}/R_{min} =1.2 and the specified connectivity probability p =0.99 in MCAND algorithm. In the following, the objective function value and the network coverage rate are investigated when the node number increases from 10 to 100.



(a) Objective function value



(b) Coverage rate

Figure 6. Performance comparison under different node numbers (R_{max}/R_{min} =1.2)

Figure 6(a) shows the comparison of objective function value under different node numbers. We find that with the increasing number of nodes, the objective function values of R_{min} and R_{max} rise steadily, while the objective function value of MCAND tends to be stable after a slight oscillation and is more close to that of R_{min}. The curves of LMA, LMN and FCTP tend to be gentle after a sharp decline, and FCTP falls between LMA and LMN. However, the objective function value of MCAND is always less than that of LMA, LMN and FCTP during the increase of the node number, and the less the node number is, the bigger the difference between them will be. This is because the MCAND algorithm adjusts the transmission range to make the node degree equal to the minimum connected average node degree, and this reduces the transmission range of nodes as far as possible so that the node degree decreases. In addition, the larger the node number and the higher the node density, the smaller the transmission range is, and it is closer to R_{min}.

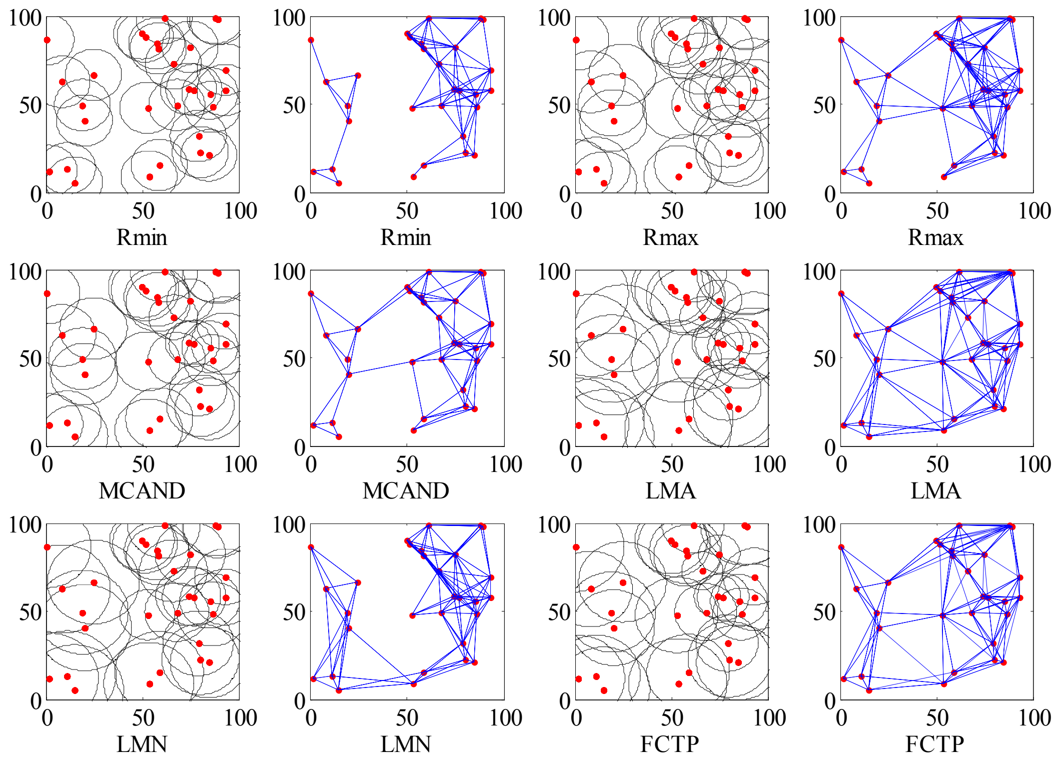


Figure 7. Bidirectional connected graph and coverage graph generated by several algorithms (R_{max}/R_{min} =1.2)

In order to study the coverage quality of the network topology generated by these algorithms, Figure 6(b) describes the coverage rate curves under the same node change process as Figure

6(a). As can be seen, with the increase of the node number, the coverage rates of MCAND, $R_{\min}$ and $R_{\max}$ are rising and finally tend to be stable. The curve of MCAND is closer to that of $R_{\max}$. Comparing Figure 6(a) with Figure 6(b), it can be seen that MCAND is superior to LMA, LMN and FTCP in the objective function value, whereas it is close to LMA, LMN, FCTP and better than LMN ultimately in terms of coverage rate.

For the sake of direct observation, bidirectional connected graph and coverage graph produced by these algorithms are randomly sampled as shown in Figure 7, in which the network node number is 30. We can see that the network topology generated by $R_{\min}$ algorithm is disconnected, and the topologies produced by the other five algorithms are connected. It has to be pointed out that the minimum transmission range $R_{\min}$ we obtain in this paper is used in LMA, LMN and FCTP, otherwise the topologies produced by them will be disconnected. Although the coverage rate of MCAND is slightly lower than that of LMA and FTCP, the topology generated by MCAND is sparser, and the edge number is reduced obviously. This phenomenon is particularly prominent in the dense node distribution, thus the node transmission power is reduced, and the communication interference between nodes decreases at the same time.

VII. CONCLUSION AND FUTURE WORK

In view of the defects of the LMN and LMA algorithms based on node degree, this paper presents a transmission power control algorithm in wireless sensor networks under the minimum connected average node degree constraint. Firstly, we find a convenient and exact mathematical description of the minimum transmission range to achieve a specified connectivity probability under the typical Poisson distribution, and then the minimum connected average node degree is obtained. Based on the above results, MCAND algorithm is designed, which allows the network to satisfy a specified connectivity probability and maintain a certain coverage degree. Simulation results show that our proposed algorithm has a more optimized objective function value with high connectivity rate and coverage rate compared with other related algorithms. Having the advantages of distributed structure, low requirement for nodes and no need for time synchronization, the new algorithm MCAND can quickly adjust the node transmission range according to the requirement of network, so it is more convenient for application in the real network.

There are still some problems remaining to be solved. Because the ultimate goal of topology control is to provide a better basis for routing, meanwhile to prolong the network lifetime, it is quite necessary to consider routing when dealing with the power control problem. Although some researchers try to combine an existing power control and power-aware routing scheme, the impact of power control on routing is not considered. Therefore, the cross-layer power control routing protocols should be designed in the next work. Furthermore, sleep scheduling is especially effective for densely deployed WSN. Since the nodes will exhaust their energy gradually, the dense network will become sparser and sparser. At this time, power control is a feasible way to maintain the Quality of Service. In the future research, we will consider the combination of power control in sparse condition and sleep scheduling in dense condition.

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