Research on Coverage Problems of Wireless Sensor Networks about One-dimensional Region

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Abstract—Monitoring the long-distance pipelines, rivers, roads and boundary lines with wireless sensor networks belongs to one-dimensional region monitoring. This paper primarily studies the coverage problems of the sensor networks in one-dimensional regions. Firstly, the one-dimensional random coverage model is processed for the sensor nodes in one-dimensional monitoring region, and a formula is given to calculate the node covering probability. Secondly, the method of determining the launch radius of sensor nodes is studied, and we prove theoretically that the launch radius of node should be greater than or equal to two times of the sensing radius. Lastly, the calculation of coverage number is discussed. Simulation results show that the sensing radius of the nodes significantly impacts the coverage number and the node coverage probability. The result of the study can be used as the technical reference when designing a WSN in one-dimensional region.

Index Terms—wireless sensor networks, coverage model, node coverage probability, launch radius, coverage number

I. INTRODUCTION

In order to guarantee the performance of sensor networks, many methods for deploying nodes of the wireless sensor networks based on different applications have been proposed. The methods differ from each other in different deployment regions which have different geometrical properties. To make problems easier, we divide the deployment regions of the sensor nodes into one-dimensional, two-dimensional and three-dimensional areas. Coverage, connection and power consumption are the main problems when deploying a sensor network. Currently, the researches connected with coverage of the sensor networks mainly focus on planar areas [1-5]. Also, there are a few researches connected with three-dimensional areas [6-8]. But few researches are connected with coverage of one-dimensional areas. In fact, such problems as the monitoring of the long-distance pipelines, underground tunnels, rivers, roads and boundary lines can be boiled down to the monitoring of one-dimensional regions. It can be an economic and feasible solution using the wireless sensor network (WSN) to monitor the one-dimensional area. Thus, the research on the coverage problems of sensor networks in one-dimensional regions is significant in both theory and reality.

This paper mainly studies the coverage problems of the sensor networks in one-dimensional regions. It is organized as follows. Section 2 reviews the related works. Section 3 provides necessary knowledge for the research. Section 4 proposes the node random coverage model of the wireless sensor networks deployed in one-dimensional regions, and offers the formula for calculating the node coverage probability and discusses the method to determine the launch radius of the sensor node. Section 5 studies the method to calculate the node coverage number based on the coverage model. Section 6 demonstrates the impact that the sensing radius has on the node coverage probability and the coverage number through simulation. Finally, section 7 proposes the conclusion.

II. RELATED RESEARCH WORK

In two-dimensional region coverage, OPIIDZ [9] divided the sensor area into grids and decided in which grid the sensor should be placed through introducing the discovery probability matrix. In order to prolong the system’s life, AKSELA M [10] divided the whole sensor nodes set into some non-intersect subsets. The subsets can cover the whole region and work in turn. The aim of the algorithm is to maximize the number of the subsets. The Computational Geometry method is often used to solve the coverage problems. Meguerdichian [11] firstly applied the Delaunay Voronio method in Computational Geometry to the coverage problems of sensor networks. He also proposed the algorithm within polynomial time and calculated the ways with both the worst and the best coverage. Zhang Honghai, Wang Xiaorui and Di Tian [12-14] proved the relationship between coverage and connection and proposed a node scheduling strategy that could guarantee the coverage and connection of sensor networks. They proved that when the communication radius is greater than twice of the sensing radius the network is connected as if the sensor network covers the whole region.

In the research of coverage of three-dimensional area, using the methods of geometry and graph coloring, Ren Yan [6] et al. built a random coverage model of three-dimensional space and proposed a distributed heuristic algorithm and the low energy consumption path with best coverage. They also designed an optimized routing protocol that could cover the curved surface of WSN best in three-dimensional space. V Ravelomanana and C F
Huang [7-8] studied the curved surface coverage of WSNs in three-dimensional space. They considered the connection of the coverage but they didn’t solve the best random coverage problem.

There are few literatures that study on the problem of one-dimensional coverage. In the study of the incomplete control deployment of wireless sensor networks, Mauro Leoncini etc. [15] proposed that the node coverage follows the standard normal distribution on the line with length $l$. They proved that the network is connected if the node coverage probability $q$, sensing radius $R_s$ and the launch radius $R_c$ follow the formula $R_c \geq 2R_s + (1 - q)l$.

III. PREPARE KNOWLEDGE

A. Assumptions

To make the problem easier, we make the following assumptions:

Assumption 1: The wireless sensor nodes are isomorphic, which means that the sensing radius, the ability to receive the signals, and the launching power of a node is as the same as another’s.

Assumption 2: The nodes’ sensing model and communicating model are disks, which means the nodes sense and spread in circular areas.

Assumption 3: Every node knows its own location.

Assumption 4: The surrounding environment can not influence the sensing and spreading of the nodes.

Assumption 5: The sensor network is deployed in a convex region in which the lines between any two nodes are within the region.

B. Basic Definitions

We define the following definitions in this research.

One-dimensional regions: If the sensor nodes are mainly monitor the areas such as long pipelines, rivers, roads and boundary lines whose width almost can not influence the monitoring quality, we call these areas the one-dimensional monitoring areas, one-dimensional regions in short.

Coverage ratio: It is the ratio of the coverage length of all the nodes to the length of the aim region. The coverage length of the all the node cover is the union of the coverage length of every node.

\[
C = \frac{\bigcup_{i=1}^{n} L_i}{L}.
\]

In the above formula, $C$ is the coverage ratio, $\bigcup_{i=1}^{n} L_i$ is the coverage length of the ith node, $n$ is the number of the nodes and $L$ is the length of the aim region.

Coverage ratio can be divided into region coverage ratio and node coverage ratio. The above definition is about region coverage ratio. The node coverage ratio can be defined in the same way.

The minimum coverage number (coverage number): It is the minimum number of the sensor nodes that can cover the whole aim region.

IV. ANALYSIS OF THE NODE COVERAGE IN ONE-DIMENSIONAL REGION

A. Node Random Coverage Model of One-dimensional Region

According to Assumption 1 and Assumption 2, sensor nodes can only be deployed in four ways as shown in Fig.1. Node B is as same as node C. We can set the coverage of A and D to 0 and 1. Now we only discuss the coverage of node B.

\[
f(r, \theta) = \frac{2}{L} \sin \theta \quad 0 \leq \theta \leq \frac{\pi}{2}, \quad 0 \leq r \leq R_s.
\]

So the node coverage probability is

\[
p(r, \theta) = \int_{0}^{\frac{\pi}{2}} \frac{2\sin \theta}{L} dr d\theta = \frac{2R_s}{L} \cos \theta \quad 0 \leq \theta \leq \frac{\pi}{2}, \quad R_s > 0.
\]

where $R_s$ is the sensing radius of the node.

From (3), we can see that the node coverage probability has something to do not only with the sensing radius, but also with the offset between the node and the long-line. The offset is represented as the angle $\theta$ in Fig.1. The random coverage probability proposed according to the node coverage style in one-dimensional region is called one-dimensional random coverage model. $\theta$ is the coverage probability angle.

B. Launch Radius of the Nodes

In order to guarantee the connection of the nodes in one-dimensional region, we analyze the launch radius as follows. The sensing circles of any two adjacent nodes
can only have three kinds of relationships, which are discrete, intersectant and tangent. When the two adjacent sensing circles are discrete, such as node H and I in Fig.2, they can not cover the whole region because of the loophole between them. When the two circles are tangent, there are neither loophole nor overlap, such as node C and D. The common situation is the two circles are intersectant, such as node E and F.

The distance between E and F is EF. We assume that the launch radius is $R_e$. The launch radius should satisfy the following formula

$$R_e \geq EF = \begin{cases} 
2R_e \cdot \theta = 0 \\
2R_e \cdot \sin \theta , 0 < \theta \leq \pi/2
\end{cases}.$$  \hspace{1cm} (4)

We can see that if the node launch radius is equal or greater than twice of the sensing radius and there are no loopholes, the network is connected.

V. THE COVERAGE NUMBER OF THE ONE-DIMENSIONAL REGION

A. Random Coverage Probability

We assume that every node can work independently and the probability which the node can monitor the whole region is $p$. Then the coverage problem of a WSN can be described as how many nodes are needed to monitor the whole aim region in a certain probability.

Without considering the decrease of the coverage length caused by the possibility that the node might fall into the boundary of the region, the coverage probability of one node can be described below

$$P(A) = p$$

The coverage probability that two nodes can monitor is

$$P(A + A) = 1 - (1 - p)^2$$

Thus, the coverage probability that $n$ nodes can monitor is

$$P(A + A + \cdots + A) = 1 - (1 - p)^n.$$  \hspace{1cm} (5)

To guarantee the coverage probability to be $P$, the sensor nodes that should be deployed in the monitoring region randomly is

$$n = \log_{1-p} (1-P) = \frac{\log(1-P)}{\log(1-p)}.$$  \hspace{1cm} (6)

From the above formula we can see that once determining the region coverage probability needed and the node coverage probability, we can calculate the node number that should be deployed.

B. Calculating the Coverage Number

From the above analysis, we can see that in one-dimensional region the node coverage probability is

$$p(r, \theta) = \frac{2r \cos \theta}{L}, 0 \leq \theta \leq \frac{\pi}{2}, 0 < r < R_s,$$  \hspace{1cm} (7)

where $R_s$ is the sensing radius.

The node average coverage probability is

$$p_{avg}(r, \theta) = \frac{2r \cos \theta}{\pi L}.$$  \hspace{1cm} (8)

The coverage number is

$$n \geq \frac{\log(1-P)}{\log(1-p_{avg}(r, \theta))}.$$  \hspace{1cm} (9)

Formula (9) can be used as the technical reference when designing a WSN in one-dimensional region.

VI. SIMULATION ANALYSIS

The node coverage probability is influenced by the sensing radius and the coverage probability angle. As shown in Fig.3, if the sensing radius and the coverage probability are small, the node coverage probability will be small. The peak of the coverage probability moves to the sensing radius axis apparently. This means that the sensing radius is the significant factor influencing the node coverage probability.

![Node coverage probability](image1)

Figure 3. The node coverage probability of the one-dimensional model

For a line of 1,000 units, if the network is deployed randomly, the sensing radius can affect the coverage probability far more than the coverage probability angle can, as shown in Fig.4.

![Change of number of nodes with probability angle](image2)

Figure 4. The change of the number of nodes with probability angle

VII. CONCLUSION
To solve the coverage problem of WSN in one-dimensional region, we propose a probability model deployed randomly and the relationship between the sensing radius and the communicating radius. We also give the method to calculate the coverage number. The simulation results show that the sensing radius is the main factor that can determine the node coverage probability and the region coverage number. The results can be used as the technical reference when designing a WSN in one-dimensional region.

The topology, routing control and node energy balance of the WSN in one-dimensional region, which are very significant, are the main research areas we will go deep into.

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REFERENCES


