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Novel node deployment scheme and reliability quantitative analysis for an IoT-based monitoring system

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Abstract: The Internet of things (IoT) is highly suitable for military, environmental, agricultural, and other remote real-time monitoring applications. A reliable topology ensures a stable and dependable monitoring system. Considering the research of an IoT-based air pollution monitoring system for industrial emissions as background, this study proposes a novel dual redundant node deployment scheme. Specifically, hexagonal clustering is proposed for the internal regions. In addition, relationship and quantification formulas for a monitoring area are presented, and the communication range, total number of layers of the topology, and number of cluster headers are determined. Interruptions in a monitoring system may reduce the quality of IoT services. Therefore, sensor nodes are also deployed around the monitoring area (in outer regions). The basic external area is modeled and proposed as a rectangular, 1-covered isosceles triangle deployment plan with the objective of minimizing the number of sensor nodes. A quantitative formula is given using the sensing radius, width of the rectangle, and adjacent distance between nodes. Reliability is a critical index in IoT-based applications. Thus, the reliability of a hexagonal clustering topology is presented using reliability block diagrams. For a reliable remote transmission model, different redundant systems are implemented. Furthermore, the reliability value and mean time to failures are calculated. The results are later compared and analyzed quantitatively. This study presents important theoretical and application-based knowledge that can guarantee reliable service for an IoT-based monitoring system.

Key words: Air pollution monitoring, Internet of things, hexagonal clustering, reliability block diagrams, reliability, mean time to failures

1. Introduction

The Internet of things (IoT) is a new field of information technology. Many IoT applications have been proposed, including those related to the environment, medicine, military, transportation, entertainment, crisis management, homeland security, and smart spaces. An increasing number of industries are using IoT for tasks related to remote monitoring. Figure 1 shows the architecture of an IOT-based monitoring system. These applications may require reliable networks to collect and transmit data without loss. The deployment of sensor nodes plays a major role in prolonging the network lifetime, routing efficiently, ensuring connectivity, and enhancing the reliability of the network. Node deployment is a multiobjective optimization problem. Node deployment strategies were summarized in [1], such as coverage maximization, connectivity enhancement, energy efficiency and lifetime optimization, and multiobjectivity. The reliability of data acquisition is one of the most important factors in an IoT-based air pollution monitoring system. However, due to environmental

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and artificial factors, sensor nodes are likely to report abnormal data that do not reflect the reality at the base station. Sometimes the IoT-based monitoring system is interrupted. Therefore, it is necessary to design a node deployment scheme to ensure the reliability of data acquisition. It is also significant to have a continuous and reliable remote data transmission system. However, in some cases, remote transmission networks without a fixed infrastructure can face different types of problems such as link or path failure and transmission link instability. To improve the reliability of the remote transmission system in an actual application, it is necessary to choose the best redundant structure to ensure the reliability of data transmission.

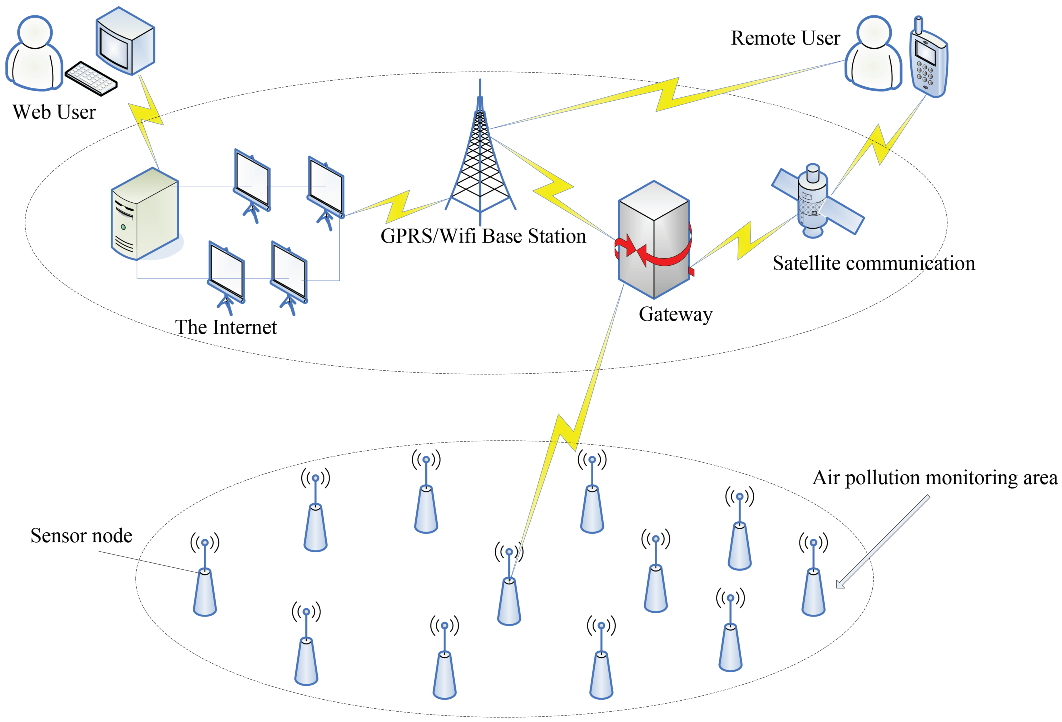

Figure 1. Architecture of an IoT-based monitoring system.

The main contributions of this study are as follows: 1) Considering the research on IoT-based air pollution monitoring systems for industrial emissions as background, the dual redundant node deployment scheme is proposed to improve the reliability of data acquisition. 2) To guarantee coverage, connectivity, reliability, and routing design, a hexagonal clustering structure is presented for node deployment in the internal area. The parameters and relevant quantification formulas are given for the monitoring area, communication range, total number of layers of the topology, and number of clusters. 3) To solve the problem of monitoring system interruptions and abnormal data by inverse analysis, the basic external monitoring area is modeled as a rectangle. Minimizing the cost is considered as the objective, meaning that the fewest nodes are deployed. Thus, a 1-covered isosceles triangle deployment scheme is presented and a quantitative formula is given for the width of the rectangle and the adjacent distance between nodes and the sensing radius. 4) Based on reliability block diagrams (RBDs), a quantitative formula to assess the reliability of the hexagonal clustering structure is presented. 5) To ensure the reliability of a remote transmission system, the quantitative formula of reliability and mean time to failures (MTTF) measures are used under different redundant systems. The characteristics of four redundant systems are compared, providing a theoretical reference for practical applications.

The remainder of this paper is organized as follows. Section 2 summarizes the previous research related to node deployment schemes and the reliability metric used in IoT-based monitoring. The problem formulation is presented in Section 3. The proposed node deployment scheme and theoretical quantitative analysis are explained in Section 4. A quantitative analysis of the reliability of a remote transmission system under different kinds of redundancy is described in Section 5. Results are presented and discussed in Section 6. In Section 7, a conclusion is provided and future work is suggested.

2. Literature review

Several pioneering studies have been conducted on node deployment and reliability metrics in IoT-based monitoring systems. Here, we present a review of some of these studies while focusing on their examination of reliability measurements.

2.1. Node deployment in a traditional IoT-based monitoring system

For node deployment in an IoT-based monitoring system, most previous studies have mainly examined how to design deployment schemes according to actual application requirements. A specific number of nodes must be deployed in appropriate locations of a monitoring area in order to provide full coverage of that monitoring area, meet the required time costs of the network deployed, and offer decent network connectivity, reliability, and energy efficiency. Two common methods of deployment exist: determined and random. The choice of one or the other depends mainly on the type of application, environment, and sensors [1]. A wireless sensor network topology control method based on the average degree constraint was proposed in [2], which reduced the number of working nodes based on guaranteed network connectivity and simplified the complexity of the network communication architecture. In [3], the deployment patterns to achieve full coverage and k-connectivity were studied. The researchers in [4] designed a set of patterns to achieve k-connectivity ($k \leq 4$) and full coverage, which proved optimal under any value of the ratio of the communication range (Rc) to the sensing range (Rs) among regular lattice deployment patterns. A multiobjective wireless sensor network (WSN) planning strategy based on evolutionary algorithms was proposed in [5]. In [6], the authors proposed that a long belt be divided into a few subbelts. Then a string of nodes was placed parallel to the long side of each subbelt in order to cover the subbelt completely. They then determined the optimal distance between two adjacent nodes in a string and the total number of such strings in order to minimize the number of nodes for complete belt coverage. In [7], a parallel deployment of node strips with equal coverage width was proposed. The above research shows that specific node deployment patterns can achieve different goals.

2.2. Reliability measurement

In [8], a study on data transmission reliability, retransmission and redundancy were adopted to ensure reliability. The application of reliability modeling techniques (such as RBDs, fault trees, and Markov chains) and analytical techniques in communication networks was proposed in [9]. Reliability guarantee measures and quantitative analysis of remote transmission backbones based on double redundancy and retransmission were examined for their application in various transmission environments [8]. A methodology based on automatic generation of a fault tree to evaluate both the reliability and availability of wireless sensor networks when permanent faults occur in network devices was presented in [10]. The reliability of chain-topology WSNs using multiple-sending schemes in terms of wireless link reliability and node energy availability was studied in [11].

A dual redundant node deployment scheme is proposed in order to improve the reliability of data acquisition. In our proposed node deployment scheme, different node deployment methods are considered based on different monitoring requirements. A RBD is used to evaluate the reliability of a hexagonal cluster deployment. The reliability of the remote data transmission system is analyzed quantitatively, and the best redundant structure is obtained.

3. Problem formulation

The monitoring area is divided into two regions: internal and external. A deployment diagram of the monitoring area is given as Figure 2. Figure 2a is an abstract diagram of node deployment; Figure 2b presents a top view of node deployment. For the internal region, the objective of the proposed node deployment scheme is to maximize the coverage of the monitoring region by ensuring connectivity. Thus, the main problem is how to choose an optimal sensor node deployment pattern to ensure full coverage and connect to the sink. For the external region to solve the problem of interruptions to the monitoring system and abnormal data, the node deployment method must minimize the deployment cost by minimizing the number of nodes. Here, the problem is how to choose an optimal node method to minimize the total number of nodes. Finally, reliability is one of the most important parameters used in evaluating IoT operational conditions. The final problem is how to represent and evaluate the reliability of a specific network topology and remote transmission system using the RBD model.

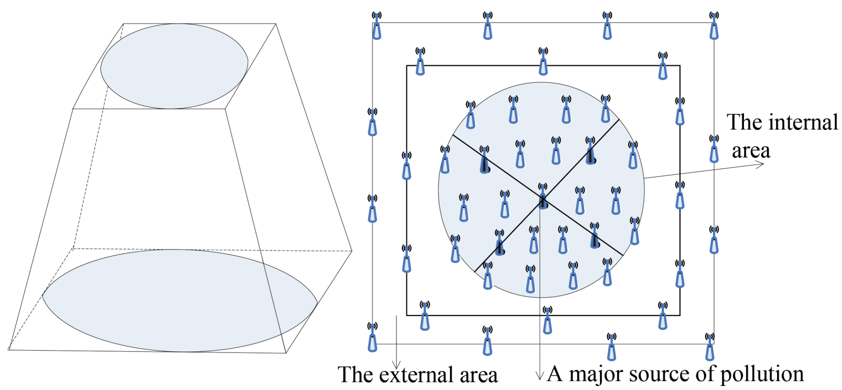

Figure 2. Deployment in a monitoring area: (a) an abstraction of node deployment, (b) top view of node deployment.

4. Proposed node deployment scheme and theoretical quantitative analysis

The proposed node deployment scheme and theoretical quantitative analysis consist of three phases. In the first phase, hexagonal cluster node deployment is determined by considering full coverage and network connectivity. In the second phase, a quantitative analysis of the reliability of the cluster structure in the monitoring area is conducted using RBDs. In the third phase, node deployment is determined by minimizing the number of deployment nodes.

Phase I: In this phase, the hexagonal cluster node deployment schemes are performed by considering the relation between the Rc and the radius (d). Then calculations and analysis of associated parameters of the topology are conducted.

4.1. Analysis and quantization calculation of the hexagonal cluster node deployment scheme

4.1.1. Hexagonal cluster node deployment scheme

One of the main research objectives in a node deployment scheme is to balance the energy consumption of nodes and prolong the lifetime of the network. A modular approach is often adopted for node deployment to ensure the reliability of the network topology.

Definition 1 *The basic area (BA) is a hexagonal monitoring area containing seven nodes, as shown in Figure 3. The six white nodes around the BA are used to monitor data as ordinary sensor nodes (and are not meant for data forwarding) in order to prolong the lifetime of the nodes. The black node in the middle of the BA is equidistant from the six white nodes and performs the function of routing. It not only can monitor data but can also forward them. It acts as the cluster head, receiving and forwarding data from other nodes around it.*

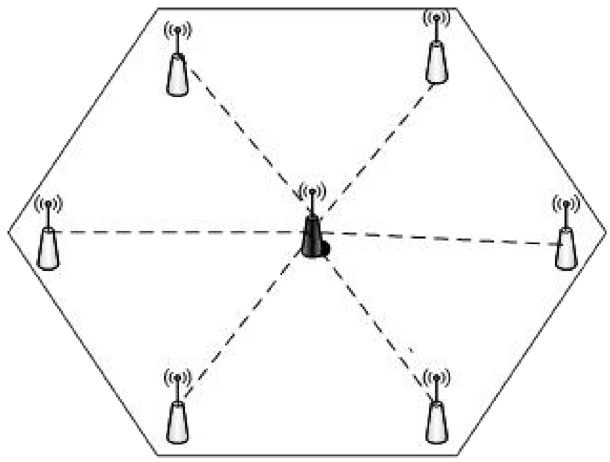

Figure 3. Structure of a BA.

Definition 2 *The general area (GA) is defined as the real monitoring area. If the area of the GA is less than that of the BA, the distance between the center node and surrounding nodes in the BA is adjusted to equal the real monitoring radius. If the area of the GA is more than that of the BA, the BA is designed so that it achieves full monitoring coverage and leaves the topology of the regular hexagon unchanged.*

The node deployment in the monitoring area is chosen to have one sink and a multilevel clustering structure. A coordinator node is configured as the sink node of the entire monitoring area. The sink node is responsible for communication with the monitoring area gateway, which is called the first-level cluster head. The black nodes around the first-level cluster head that perform the function of routing also act as second-level cluster heads. In succession from the inside to the outside, the black nodes are three-level cluster heads, then four-level cluster heads, etc. Thus, there are n-level cluster heads at each turn. Cluster head and sink nodes perform the functions of aggregation and forwarding and are thus more important than normal sensing nodes. They are thus known as key nodes. In an actual monitoring application, the monitoring area involves the tilling of a BA using a hexagon in which the topology remains unchanged. The topology is shown in Figures 4 and 5.

4.1.2. Calculation and analysis of associated parameters of the topology

In an actual application, it is assumed that all sensor nodes are homogeneous and that the sensor's communication range is Rc, which can be determined from specific user manuals. In addition, the radius of the regular hexagon is d and the monitoring area is S.

Theorem 1 *Assume the communication range of the sensor is Rc and the monitoring area is S. Then the total number of layers N that need to be monitored is:*

$$\lceil \frac{\sqrt{3S/\pi}}{2Rc} + 1/2 \rceil.$$

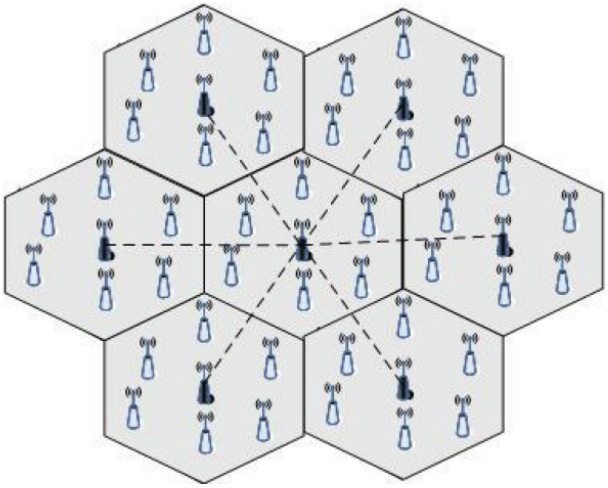

Figure 4. Structure of a two-level cluster head.

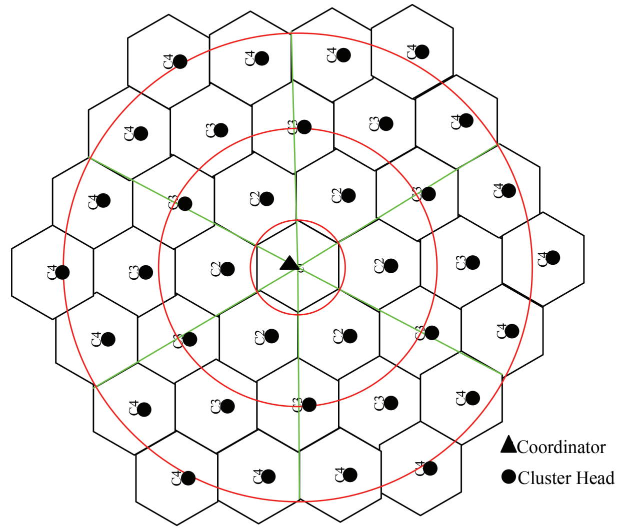

Figure 5. Structure of a multilevel cluster head.

Proof For the topology of a single sink and multilevel cluster, in order to ensure that any two nodes communicate with each other, the sensor nodes in a single cluster first transmit data to the cluster head node. Then data are transmitted from the ith layer cluster head to the (i – 1)th layer cluster head (i = 2, 3, ..., k,). The first layer of the cluster refers to the central hexagonal unit in which the coordinator is deployed.

In the topology of a single sink and multilevel cluster, the distance of adjacent cluster heads is: □

$$2 \times \sqrt{d^2 - (d/2)^2} = \sqrt{3}d.$$

To ensure that the six white nodes around the BA can communicate with the black node in the middle of the BA, Rc$\geq$d. Simultaneously, to ensure connectivity and that the cluster heads from adjacent layers can communicate with each other, Rc$\geq$ $\sqrt{3}$d. Then Rc is set to Max$\{$d,$\sqrt{3}$d$\}$.

Rc = $\sqrt{3}$d.

Therefore, to guarantee network coverage and connectivity, the radius of the hexagon is:

$$d = \frac{\sqrt{3}}{3}Rc. \quad (1)$$

From Figure 5, the relationship between the number of layers and the sampling radius is as shown in the Table.

Table. Relationship between the number of layers and the sampling radius.

Layers (N)	Sampling radius
1	d
2	3d
3	5d
4	7d
...	...
i	(2*i-1)*d

Therefore, the relationship between the number of layers and the monitoring area should satisfy:

$$S = \pi * [(2 * N - 1) * d]^2. \tag{2}$$

From Eq. (2), the number of layers is:

$$N = \lceil \sqrt{S/\pi}/(2 * d) + 1/2 \rceil. \tag{3}$$

Substituting Eq. (1) into Eq. (3), we obtain the following:

$$N = \lceil \frac{\sqrt{3S/\pi}}{2Rc} + 1/2 \rceil. \tag{4}$$

Property 1. Assume N is the number of layers of the topology in the monitoring area. Then the total number of cluster heads N_{key} is:

$$3N(N-1) + 1 \quad (N >= 1).$$

Assume the number of cluster heads in the ith layer is $N_{key(i)}$.

$$\begin{cases} N_{key(i)} = 1, & \text{when} \quad i = 1, \\ N_{key(i)} = (i-1) * 6, & \text{when} \quad i \geq 2. \end{cases}$$

$$N_{key} = 6(N-1) + 3(N-1)(N-2) + 1, (N >= 1). \tag{5}$$

Simplify Eq. (5):

$$N_{key} = 3N(N-1) + 1. \tag{6}$$

Phase II: Reliability is a critical factor in node deployment scheme. Therefore, the entire monitoring area is a multilevel cluster structure. In an effective reliability analysis, a complex system can first be decomposed into subsystems, and then the reliability of each subsystem can be computed and recombined.

4.2. Quantitative analysis of reliability of a cluster structure in a monitoring area

In terms of data aggregation, a multilevel cluster structure can be abstracted to a serial structure consisting of a BA (C_i). The RBD is given as in Figure 6a.

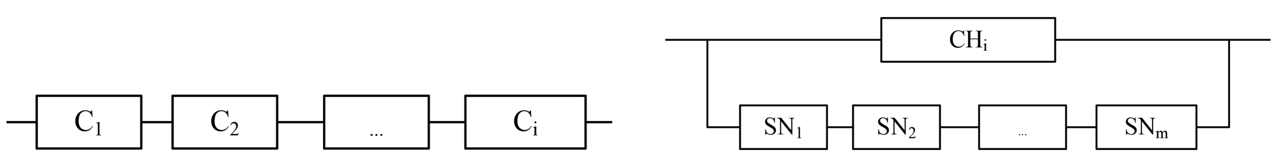

Figure 6. (a) RBD of a multilevel cluster structure. (b) RBD of a single cluster structure.

Each BA(C_i) is a parallel structure composed of one cluster head node CH_i and m sensing nodes such that SN_i ($1 \leq i \leq m$). A RBD is presented as in Figure 6b.

Theorem 2 *Assume the number of BAs is k. The reliability of the cluster head is R, which is the same as the sensor nodes in each BA. If the total number of sensor nodes in each BA is m, the reliability of the multilevel cluster structure is:*

$$(1-(1-R)^{m+1})^k.$$

Proof As shown in Figure 6b, each cluster structure is composed of m sensing nodes and a cluster head in parallel [12]. Therefore, the reliability of the BA is:

$$\begin{aligned} R_{cluster} &= 1-\overline{R_{CH}}\cdot\prod_{i=1}^{m}\overline{R_{SN}} \\ &= 1-(1-R)\cdot\prod_{i=1}^{m}(1-R) \\ &= 1-(1-R)^{m+1}. \end{aligned} \tag{7}$$

The internal area is composed of k basic areas, which must be simultaneously effective in order to ensure the reliability of the internal area. Therefore, the reliability of the multilevel cluster structure is:

$$\begin{aligned} R_{system} &= \prod_{i=1}^{k}R_{cluster} \\ &= (1-(1-R)^{m+1})^k. \end{aligned} \tag{8}$$

Phase III: In order to improve the reliability of a monitoring system, using sensor node characteristics such as wide coverage and low cost, sensor nodes deployed in an external area can be used to monitor the surrounding air quality in real time. Node deployment of the external monitoring area is described in the following subsection. □

4.3. Analysis and calculation of 1-covered isosceles triangle deployment

4.3.1. One-covered isosceles triangle deployment method in the rectangular area

The external monitoring area should first be covered, and then the cost should be minimized. This means that the number of nodes in the external monitoring area should be minimized. The external region is then equivalent to four basic rectangular regions. The model of a basic rectangular region is shown in Figure 7. The length of the rectangular region is L, the width is W, and the area is S such that S = L * W and L$\gg$ W. In addition, the sensor node sensing radius is R_s >W.

Definition 3 *Adjacent distance (D) is defined as the horizontal distance between two adjacent nodes along the length of the rectangular region.*

Definition 4 *Coverage density (ρ) is defined as the ratio of the total area covered by sensor nodes to the actual area:*

$$\rho=\frac{N\pi R_s^2}{S},\rho>1. \tag{9}$$

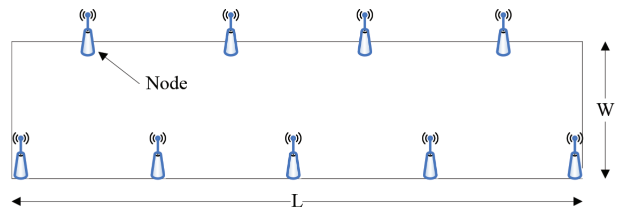

Figure 7. Plan of the rectangular area.

Definition 5 *In a 1-covered isosceles triangle deployment, nodes with a sensing radius of R_s are interlaced along the two sides of the rectangular region. The adjacent three nodes form an isosceles triangle, as shown in Figure 8.*

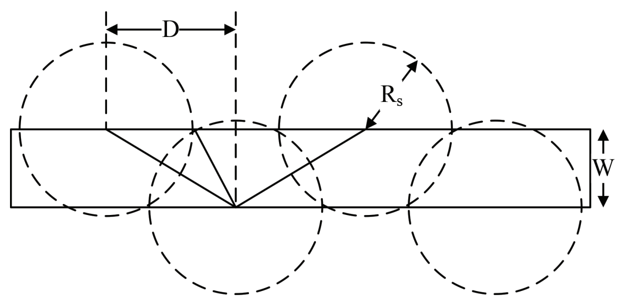

Figure 8. Node deployment for a 1-covered isosceles triangle.

4.3.2. Calculation and analysis of parameters for the topology

Theorem 3 *Set the sensing radius to R_s, the number of nodes to N_{ex}, the length of the rectangle to L, and the width to W. When $D = 1.5\ R_s$ and $R_s/W = 2/\sqrt{3}$, the full coverage of a 1-covered isosceles triangle is obtained and the number of nodes N_{ex} is set to the minimum.*

Proof □

To guarantee the full coverage of a 1-covered isosceles triangle, we calculate the following:

$$D = R_s + \sqrt{R_s^2 - W^2}. \tag{10}$$

The number of nodes required to cover the long-strip rectangular area with length L is:

$$N_{ex} = L/D, \tag{11}$$

$$N_{ex} = L/(R_s + \sqrt{R_s^2 - W^2}). \tag{12}$$

By Definition 4:

$$\rho = \frac{N_{ex}\pi R_s^2}{LW}. \tag{13}$$

By Eq. (13), finding the minimum of N_{ex} is equal to finding the minimum of ρ.

Substituting Eq. (12) into Eq. (13) results in:

$$\begin{aligned}\rho &= \frac{\pi R_s^2}{(W(R_s + \sqrt{R_s^2 - W^2}))} \\ &= \pi(\frac{R_s}{W})^2/(\frac{R_s}{W} + \sqrt{(\frac{R_s}{W})^2 - 1})\end{aligned} \tag{14}$$

$$\begin{cases}\min \rho(\frac{R_s}{W}) = \pi(\frac{R_s}{W})^2/(\frac{R_s}{W} + \sqrt{(\frac{R_s}{W})^2 - 1}), \\ \frac{R_s}{W} > 1.\end{cases}$$

Finding the derivative, ρ gets the minimum:

$$\frac{R_s}{W} = \frac{2}{\sqrt{3}}. \tag{15}$$

Substituting Eq. (15) into Eq. (10) results in:

$$D = 1.5R_s. \tag{16}$$

Property 2. Assume the sensing radius of the sensor is R_s. In order to cover the long-strip rectangular region with length L and width W, the total number of required nodes N_{ex} is *2L/3Rs*.

By Eq. (11):

$$N_{ex} = L/D.$$

Substituting Eq. (16) into Eq. (11) results in:

$$N_{ex} = 2L/3R_s. \tag{17}$$

5. Quantitative analysis of reliability for a remote transmission system under different kinds of redundancy

IoT-based remote communication technologies include the Internet, GPRS, 4G, satellite communication, microwaves, and BeiDou satellite transmission. Based on the actual communication conditions of a monitoring area, different transmission technologies are chosen to improve the reliability of the remote transmission system in an actual application. For example, Internet & BeiDou or GPRS & 4G & satellite also can be used for transmission. The transmission architecture of remote monitoring is shown in Figures 9 and 10, where GW_M is the monitoring regional gateway, GW_C is the monitoring center gateway, and Rs1 and Rs2, ...Rsn are transmission links, which are responsible for dual-direction information transmission between the monitoring-regional and monitoring-center gateways.

5.1. Quantitative analysis of reliability under different kinds of redundancy

1) Reliability of a parallel redundant system

A parallel redundant system is composed of n components in parallel. The system is invalidated only when the n components fail. The RBD of a parallel redundant system is given as Figure 9, where the life of

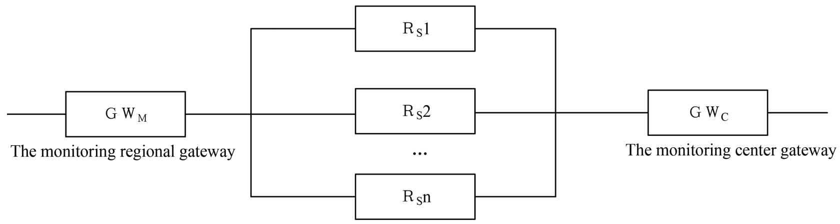

Figure 9. RBD of a parallel redundant system.

the ith component is X_i and the reliability is R_i(t), i = 1, 2,..., n. Assume X_1, X_2, ..., X_n are independent of each other. The reliability of the redundant system is then:

$$R(t) = 1 - \prod_{\mathrm{i}=1}^{\mathrm{n}}[1 - R_{\mathrm{i}}(t)],$$

$$when \quad R_i(t) = e^{-\lambda_i t}, i = 1, 2, \ldots, \mathrm{n},$$

$$R(t) = 1 - \prod_{\mathrm{i}=1}^{\mathrm{n}}[1 - e^{-\lambda_i t}]. \tag{18}$$

The MTTF is defined as the expected (average) time during which a component/system is working properly and is given by:

$$MTTF = \sum_{i=1} \frac{1}{\lambda_i} - \sum_{1\le i\le j\le n} \frac{1}{\lambda_i + \lambda_j} + \ldots + (-1)^{n-1} \frac{1}{\lambda_1 + \lambda_2 + \ldots + \lambda_n}. \tag{19}$$

2) Reliability of a voting redundant system

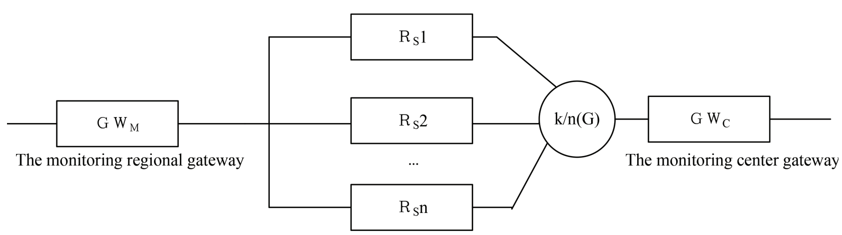

Figure 10. RBD of a voting redundant system.

The voting redundant system k-of-n is composed of n components. The system works normally when k or more than k components work normally. The system fails when the number of failed components is greater than or equal to n-k+1. The RBD of the system is shown in Figure 10. Assume X_1, X_2, ..., X_n is the life of these components, which are independent of each other, and each component has a reliability of R_0(t).

If all components begin to work simultaneously, the reliability of the system is:

$$R(t) = \sum_{j=k}^{n} \binom{n}{j} P\{X_{j+1}, \ldots, X_n \le t < X_1, \ldots, X_j\},$$

$$when \quad R_0(t) = e^{-\lambda t}, ,$$

$$R(t) = \sum_{i=k}^{n} \binom{n}{i} e^{-i\lambda t}(1-e^{-\lambda t})^{n-i}, \tag{20}$$

$$MTTF = \int_0^\infty \sum_{i=k}^{n} \binom{n}{i} e^{-i\lambda t}(1-e^{-\lambda t})^{n-i} dt = \frac{1}{\lambda}\sum_{i=k}^{n}\frac{1}{i}. \tag{21}$$

5.2. Comparisons of properties under different kinds of redundancy

The following four kinds of redundant systems are quantitatively compared: 1) a single system, 2) a dual parallel redundant system, 3) a triple parallel redundant system, and 4) a 2-of-3 redundant system.

1) Single system

$$R(t)_1 = \mathrm{e}^{-\lambda t},$$

$$MTTF_1 = \frac{1}{\lambda}.$$

2) Dual parallel redundant system

When $n = 2$, $R_i(t) = e^{-\lambda t}$ in the dual parallel redundant system, and substituting these values into Eqs. (18) and (19) yields:

$$\begin{cases} R(t)_{dual-Parallel} = 2e^{-\lambda t} - e^{-2\lambda t} \\ MTTF_{dual-Parallel} = \frac{3}{2\lambda}. \end{cases}$$

3) Triple parallel redundant system

When $n = 3$, $R_i(t) = e^{-\lambda t}$ in a triple parallel redundant system, and then:

$$\begin{cases} R(t)_{tri-Parallel} = 3e^{-\lambda t} - 3e^{-2\lambda t} + e^{-3\lambda t} \\ MTTF_{tri-Parallel} = \frac{11}{6\lambda}. \end{cases}$$

4) 2-of-3 redundant system

When $n = 3$, $k = 2$ in a voting redundant system, and substituting these values into Eqs. (20) and (21) yields:

$$\begin{cases} R(t)_{2-of-3} = 3e^{-2\lambda t} - 2e^{-3\lambda t} \\ MTTF_{2-of-3} = \frac{5}{6\lambda}. \end{cases}$$

6. Results and discussion

6.1. Deployment layers and the number of cluster heads under different deployment schemes

We use the simulation tool to verify the theoretical results in this study. The total number of layers and total number of cluster heads were compared in our hexagonal clustering deployment scheme and square clustering deployment scheme in [8]. Eqs. (4) and (6) show that the total number of layers N and total number of cluster heads are correlated with monitoring area S and communication range Rc. The monitoring area S takes values from 0 to 70000 square meters. The communication range Rc is 30 m, the number of layers deployed is given in Figure 11, and the number of cluster heads is given in Figure 12. Changing Rc to 50 m, the number of layers deployed is given in Figure 11 and the number of cluster heads is given in Figure 12. As expected, Figure 11 shows that, based on the same monitoring area, there were fewer layers in the hexagonal clustering deployment scheme compared to the square clustering scheme. Figure 12 shows that a high number of cluster heads was used in the hexagonal clustering deployment scheme when applied to a small monitoring area. However, when the monitoring area increased in size, fewer cluster heads were required with our method than with the square clustering deployment scheme. In a wide-ranging full-coverage application of an IoT-based monitoring system, our hexagonal clustering deployment scheme effectively reduced the cost of deployment and network maintenance.

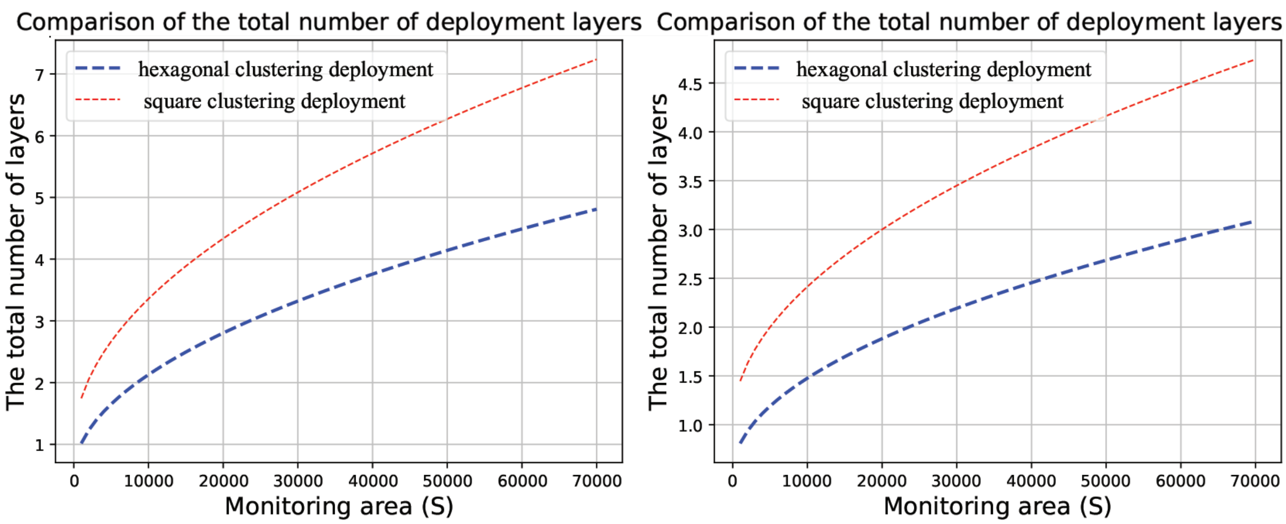

Figure 11. Total number of layers comparison between hexagonal and square clustering deployment scheme: (a)R_c = 30, (b)R_c = 50.

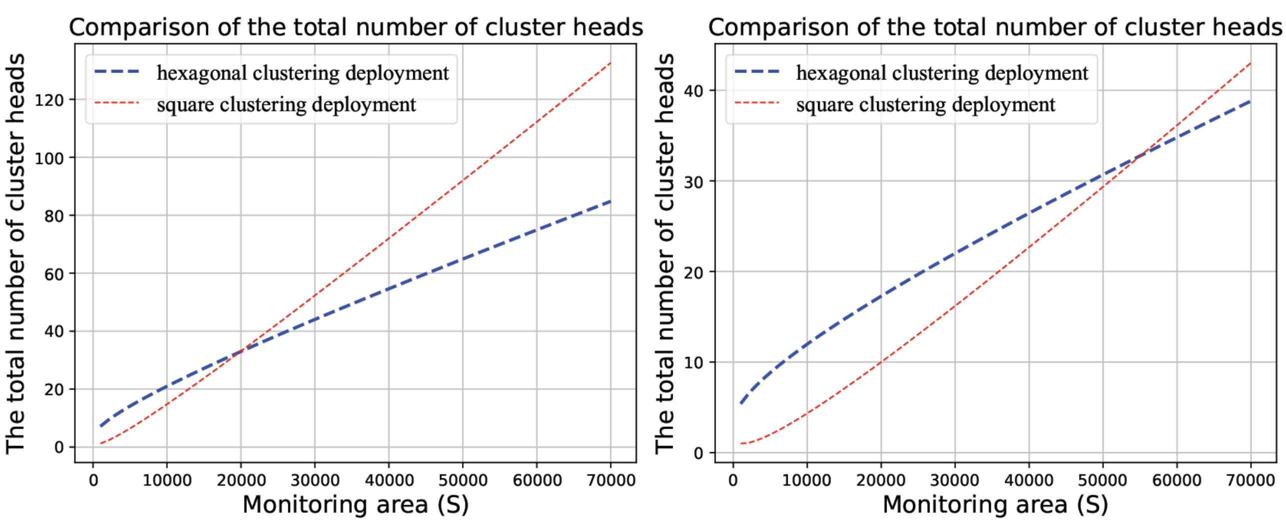

Figure 12. Total number of cluster heads comparison between hexagonal and square clustering deployment scheme: (a)Rc = 30, (b)Rc = 50.

6.2. Relationship between the number of BA k and R_{system}

Eq. (8) demonstrates that R_{system} is correlated with the reliability of the sensor node, the number of BA k, and the total number of sensor nodes m in each BA. m is set to 7. In order to evaluate the number of BA k on the reliability of the system, six different values of k are used: 10, 20, 30, 40, 50, and 60. The results are demonstrated in Figure 13.

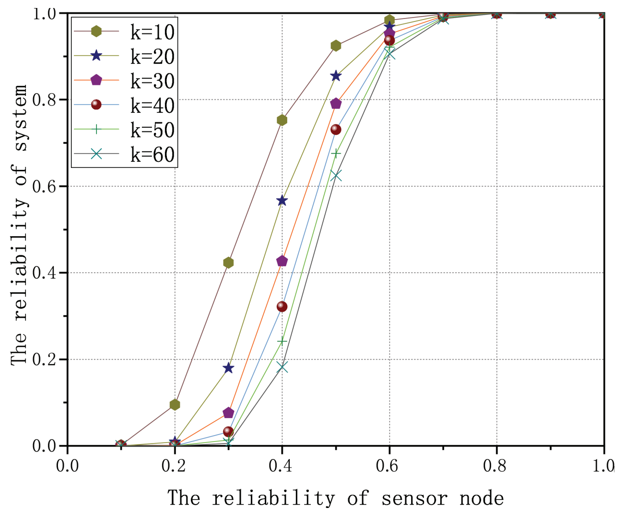

Figure 13. Relationship between the number of BA k and R_{system}.

Figure 13 shows that the reliability of the system decreased with the increase of k when the reliability of the sensor node was fixed, especially when the reliability of the sensor node was low. It indicates that more data aggregation errors occurred as the k value increased.

6.3. Reliability values and MTTF under different redundant systems

The reliability values and MTTF in different redundant systems are related to variations in the failure rate. These relations are presented in Figures 14 and 15.

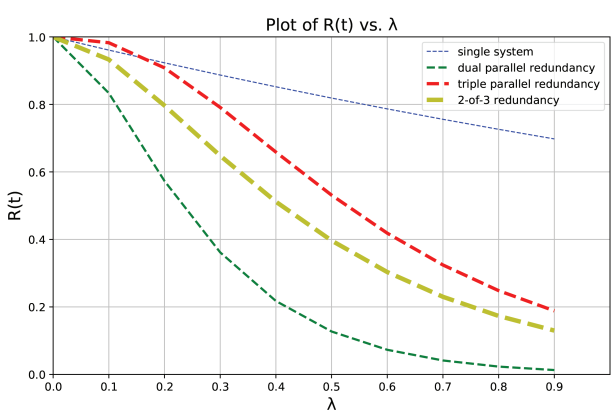

Figure 14. Failure rate versus reliability values.

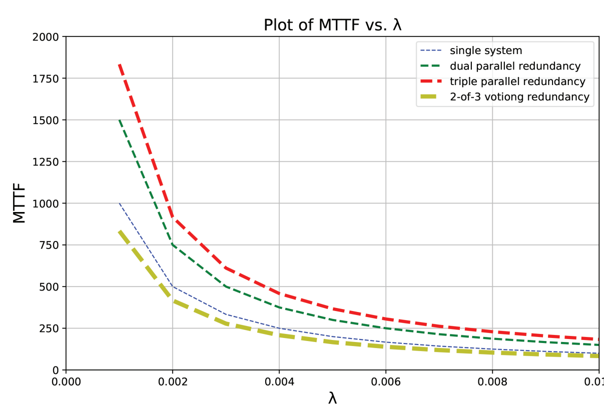

Figure 15. Failure rate versus MTTF.

Figure 14 shows that the reliability of a single system was low in the situation involving a low failure rate. However, with a high failure rate, the reliability of the single system showed the most improvement, followed by the triple parallel redundant, 2-of-3 redundant, and finally dual parallel redundant systems. Figure 15 shows that the MTTF of the triple parallel redundant system was the highest, followed by the dual parallel redundant, single, and finally 2-of-3 redundant systems. The triple parallel redundant system not only prolongs MTTF but also improves the reliability of the remote transmission system of an IoT-based monitoring system.

7. Conclusions

In this study, a novel node deployment method known as a dual redundant node deployment scheme for an IoT-based monitoring system was proposed. A hexagonal clustering strategy was proposed for an internal monitoring area, where the quantitative relations between the layers of the monitoring system, monitoring area, and communication range were determined, as well as those between the layers and the total number of cluster head nodes. A 1-covered isosceles triangle deployment strategy was proposed for an external monitoring area, where the quantitative relations between the sensing radius, width of the rectangular area, and adjacent distance were determined. For the rectangular regions, this method minimizes the number of nodes. Furthermore, a RBD was used to evaluate the reliability of the hexagonal clustering structure. Different kinds of redundant structures for a remote transmission system were compared. Simulation results show that our hexagonal cluster deployment scheme effectively reduced the cost of deployment and network maintenance. The reliability of a multilevel cluster structure decreased with the increases of k, especially when the reliability of the sensor node was low. We obtained the best results using a triple parallel redundant system for a remote transmission system. The findings from this study provide an important theoretical basis for the actual deployment of sensor nodes and can guarantee the reliability of an IoT-based monitoring system. However, our study has not taken into account the optimal number of the BA when the reliability of the sensor node is different. Sensor node deployment is essentially a multiobjective optimization problem. Identifying a trade-off solution for network coverage, network connectivity, reliability, cost, and energy efficiency should be the focus of future research.

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