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# Analysis of node deployment in wireless sensor networks in warehouse environment monitoring systems

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## Abstract

This paper mainly studies the deployment of wireless sensor network nodes in the warehouse environment monitoring system, discusses the deployment algorithm of wireless sensor network nodes in the warehouse environment, and finds out the node deployment scheme with better network performance through comparison. Wireless sensor network node deployment is the basis of wireless sensor network application in storage environment monitoring system. It affects the performance of the whole network and is the primary problem to be solved in network application. This paper discusses the advantages of wireless sensor network in the monitoring of storage environment, especially the deployment and simulation analysis of sensor nodes in the warehouse environment. Aiming at the influence of sensor perception model on the effectiveness of the node deployment plan, this paper proposes a node deployment collaborative perception model based on 0-1 perception model and exponential model. The sensor node deployment problem is transformed into a three-dimensional node deployment problem. Finally, the algorithm is applied to tobacco storage environment. In order to verify the effectiveness of the proposed algorithm, the scheme obtained by the proposed algorithm is compared with that obtained by the corresponding deployment algorithm in this paper. The comparison results show that the overall performance of the algorithm is better than that of the usual scheme.

**Keywords:** Warehousing environment, Wireless sensor networks, Node deployment, Detection model

## 1 Foreword

The biggest trend of modern logistics is networking and intelligence. Warehousing is an important part of modern logistics, linking up production and consumption, occupying an important position in the entire logistics system. Through warehouse environment monitoring systems, people get to understand warehousing status quo, make proper regulation of warehousing conditions, and guarantee warehousing quality and security of products. Traditional monitoring methods mostly take remedial measures only after the unforeseen circumstances, and cannot detect the potential safety hazards in the warehouse environment [1]. As people improve service quality requirements, businesses also pay more attention to the storage conditions of warehouse environment. They require that monitoring has strong flexibility, can accurately measure the environment parameters and make trend forecasting to reduce the possibility of disaster events; can ensure warehouse environment security, reduce losses; can ensure the product service quality and enhance customer satisfaction. In recent years, with the development of microelectronics and wireless communications technologies, wireless sensor networks (WSNs) have drawn the world's attention. A WSN contains wireless sensors that have the ability to sense, calculate, communicate, observe, and react to events that occur in a particular area. The application of WSNs technology is a development direction of warehouse environment monitoring systems. Warehousing intelligence is a key research issue of modern logistics [2]. The WSNs technology is in line with the trend of intelligent development. WSNs has the advantages of easy deployment and self-organization that can overcome the weaknesses of the traditional monitoring methods, it has a broad space for development in warehouse environment monitoring and is gradually replacing the traditional monitoring networks.

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## 2 Research status

Scholars have done a lot of research on the node deployment in WSNs. Younis M et al. [3] divided the node deployment in WSNs into two categories: static deployment and dynamic deployment. The classification criterion mainly depends on whether the entire sensor network needs to be operated or the sensor nodes need to be optimized during the deployment of sensor nodes [3]. Based on the deployment method and optimization object, deployment can be divided into two categories.

1. Deployment methods

WSNs nodes will be deployed in varied ways under different application scenarios. Deployment methods are closely related to specific applications. There are two types of deployment: deterministic deployment and random deployment [4]. When the application environment is known, the network operation status is relatively fixed and the sensor nodes are clearly located in space, it is suitable for the deterministic deployment. In order to find a solution, deterministic deployment can abstract the problem into a mathematical model and transform it into a linear programming problem or a static optimization problem. Coskun V (2008) [5] proposed to maximize the network life cycle algorithm, in order to ensure the maximum network coverage based on network connectivity, hexagonal grids are used for node deployment. The proposed algorithm is proved to be effective, scalable, and operable through simulation experiments. Although deterministic deployment can bring some convenience to the problem solution, the model is too idealistic and simplistic. However, it is obvious that random deployment has advantages for scenarios with harsh environment where man-made and large deployment is difficult.

Random deployment is an economical deployment method, but cannot guarantee full coverage. In order to achieve the desired coverage effect, many redundant nodes need to be deployed. This deployment method is applicable when coverage requirements are not strict. However, in some areas where deployment is difficult, it is necessary to increase the coverage effect by investing a large number of sensor nodes to achieve the coverage effect [6]. The traditional random node deployment will form coverage holes in the perceptual area. In response to this, Mohammed Abo-Zahhad et al. 2005 [7] proposed a WSNs deployment approach based on a multi-objective immune algorithm. This method redefines sensor nodes to reduce coverage holes and improve network coverage, saves energy consumption, and guarantees connectivity while limiting sensor mobile costs. By comparing with other deployment methods, it is found that this method can improve network coverage and reduce the mobile costs of WSNs [8].

2. Optimization object

According to the optimization object, node deployment can be divided into coverage-based deployment, network connectivity-based deployment, and energy efficiency-based deployment. The performance of the whole WSN depends on the network coverage. In the node deployment in WSNs, it is highly important to improve the network performance and coverage. Many scholars at home and abroad have done a lot of research on how to improve the network coverage. Hou Y et al. [8] proposed a node optimization algorithm by transforming the node deployment problem into a computational geometry problem]. Fan Zhigang [9] proposed a sensor node deployment algorithm based on cellular grid, which can accurately deploy the monitoring area, not only can achieve complete coverage but also can accurately deploy some redundant nodes to extend network life cycle and can be applied to areas with stringent control for the density of wireless sensor nodes. Fadi M. Al-Turjman et al. (2013) [10] proposed a general method to evaluate the average connectivity based on grid deployment strategy by analyzing the practical problems in deployment. Achieving complete coverage while guaranteeing connectivity is of practical significance in application. S.M. Nazrul Alam et al. (2015) [11] used Voronoi elements to divide the deployment space into several polyhedrons and calculated the furthest distance between any two points in the polyhedron so as to ensure that the wireless sensors communicate with each other and transmit information to the base station. After simulation, the deployment method proposed by S. M. Nazrul Alam et al. was proved to have good connectivity.

Network usage times are crucial for the operation of WSNs. Researchers at home and abroad have studied how to prolong the service life of WSNs. Hashim A. Hashim et al. (2016) [12] proposed an energy-efficient deployment strategy that uses artificial bee colony optimization of network parameters to limit the total number of redundant nodes. To avoid the NP-hard problem, the algorithm uses a two-tier structure based on cost constraints called ILDCC to improve the deployment life cycle. A cubic grid model is proposed in the SP 3D space. Although this deployment strategy is cost-effective and easy to implement, it has several drawbacks, such as the increase in the number of redundant nodes in the network will increase the possibility of collisions and conflicts. With the help of the data link layer protocol, the impact of collisions and collisions can be reduced. D Wang et al. (2008) [13] provided an analytical framework that obeys the coverage and usage cycles under two-dimensional Gaussian distribution. The paper proposes that the algorithm can better meet the coverage and usage requirements. The two algorithms proposed by the analysis framework prove that the network lifetime can be effectively increased, but the boundary problem existing in the deployment is not considered. Fadi M. AL-Turjman et al. (2015) [14] proposed a combined energy-efficient and k-tolerant heterogeneous node deployment WSNs strategy. In order to limit the unlimited search space to a controlled range of numbers, a 3D grid model is adopted. The main goal of the algorithm is to find the $Q_{SN} + Q_{RN}$ optimal node location at the $V^{th}$ grid vertex location so as to maximize the network lifetime. Deployment strategy is mainly divided into two phases, the first phase is to find the optimal location of all nodes to minimize energy consumption, the second phase occurs after each round to improve the connection performance and release overload node pressure. After simulation, compared with several typical methods, the algorithm extends the use of time of node by 40%.

## 3 Problem description

Generally, the environmental parameters that need to be monitored in a warehouse mainly include temperature, humidity, illuminance, and oxygen content. To monitor the environment parameters in warehouse environment, a large number of sensor nodes need to be deployed in the warehouse environment to construct a reasonable node deployment plan to meet the requirements of warehouse parameter monitoring. A reasonable deployment of sensor nodes needs to be technical and economic, therefore, a reasonable node deployment WSN plan is essential for warehouse environment parameter monitoring.

By using the Voronoi diagram partitioning theory, the 3D space can be divided into several small spaces $V_i(i = 1, 2, \cdots n)$. These small spaces are polyhedral cells [15]. Each Voronoi region $VR_{P_i}$ boundary is composed of multiple Voronoi edges, as shown in Fig. 1. Each Voronoi edge is the set of all the points closest to seed $P_i$.

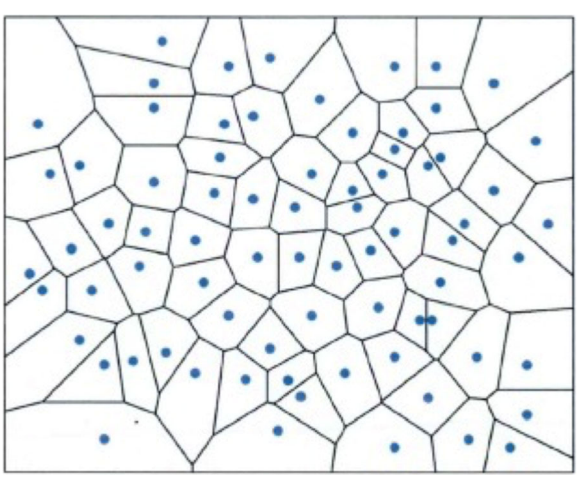

**Fig. 1** Voronoi segmentation

This characteristic naturally divides the space into several regions, each of which is the influence area corresponding to the growing point [16].

Voronoi diagram partition theory can be used to divide the three-dimensional space into several small spaces, and these small spaces are mostly polyhedral elements, and for these polyhedra, can find an outside contact ball with a definite radius. In the space filling, the sensor node can be deployed in the center of the polyhedron, and the radius of the external sphere of the polyhedron is the radius of the unit perception model. Through the deployment of sensor nodes, the three-dimensional space can be fully covered and the whole storage environment can be monitored [17].

### 3.1 Research hypothesis

Through the description of the problem, to achieve node deployment in WSNs under warehouse environment, a suitable space division is the key. Although the best space division plan does not create exactly the same division cells, in order to obtain a suitable plan, it is assumed that all the division cells have the same shape for the following reasons:

(1). With the same shape as cells, one can be more concerned about the shape of the division cell, making the problem easier to handle.
(2). The same cell can provide certain rules. It is possible to deterministically establish the position of any cell by a simple set of equations, use the same cell for spatial division, and also make the deployment method implement distributed computation and make the deployment method have good scalability.
(3). In this paper, we choose the same type of wireless sensor, with the same sensing range and transmission range, so the same cell shape is the best choice.

If the shape of all cells is the same, then the number of cells can be reduced by maximizing the capacity of one cell.

The core of node deployment is to divide the 3D space into a number of small spaces, the sensor nodes are deployed in the center of each small space, so there are the following constraints:

(1). The number of cells divided in the 3D space must be fillable polyhedrons.
(2). The radius of the circumscribed sphere attached to the cell can not be larger than the sensing range $R_s$.
(3). The distance between two farthest points of adjacent cells can not be larger than the transmission distance $R_c$.

Among them, the first constraint limits the number of possible polyhedrons. Because when the 3D space of nodes to be deployed is fixed and when the sensor senses the same radius, the larger the volume of the polyhedron, the fewest number of the polyhedrons required. The second constraint ensures that the entire network covers all the areas to be monitored. The third constraint guarantees the connectivity between sensor nodes [18].

Figure 2 shows the basic structure of using a truncated octahedron to divide and fill a space. If the center $(0, 0, 0)$ of the sized $4 \times 4 \times 4m^3$space is the starting point for truncated octahedral coverage, deploy a truncated octahedron at the geometric center $(0, 0, 0)$, then deploy 8 truncated octahedrons around the truncated octahedron, and the fillable polyhedra are all congruent shapes.

The position of the node can be calculated, that is, by calculating the relative displacement of the two types of nodes in these polyhedrons, the deployment position of the wireless sensor node can be obtained. For the convenience of representation, two types of nodes with different offsets are respectively recorded as class A nodes and class B nodes. Described by offsets$\lambda = (a_1, b_1, c_1)$ and$\gamma = (a_2, b_2, c_2)$, respectively. Therefore, as shown in Fig. 1, the node with $\lambda$is referred to as node A, and the coordinates of the point can be obtained by the formula (1) and represented by $L_A$. The node with $\gamma$ is called node B, and the coordinates of the point can be obtained by formula (2) and represented by $L_B$.

$$L_A^{''} = L_A + \lambda \tag{1}$$

$$L_B = L_A + \gamma \tag{2}$$

Among them, the specific values of λ and γ for different space-fillable polyhedrons are shown in Table 1.

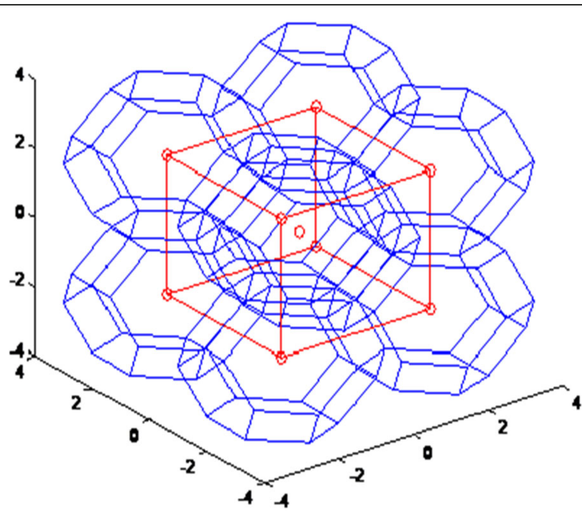

**Fig. 2** Basic structure of the truncated octahedron cover

**Table 1** Offset table

| | Class A node offset | Class B node offset |
|---|---|---|
| Truncated octahedron | $(n \times \frac{4R}{\sqrt{5}}, m \times \frac{4R}{\sqrt{5}}, k \times \frac{4R}{\sqrt{5}})$ | $(\frac{2R}{\sqrt{5}}, \frac{2R}{\sqrt{5}}, \frac{2R}{\sqrt{5}})$ |
| Diamond dodecahedron | $(n \times 2R, m \times 2R, k \times 2R)$ | $\{ (2R, 2R, 0), (2R, 0, 2R), (0, 2R, 2R)$ |
| Optimal hexagonal prism | $(n \times \sqrt{6}R, m \times \sqrt{2}R, k \times \frac{2\sqrt{3}R}{3})$ | $(\frac{\sqrt{6}R}{2}, \frac{\sqrt{2}R}{2}, 0)$ |

### 3.2 Algorithm analysis

The cell perception model is a sphere with an irregular probability range. If we only explore the cell perception model to achieve 100% coverage of 3D space, there must be overlapping coverage. In fact, the Voronoi network division provides a good suggestion to solve the problem of 3D space coverage. It divides the 3D space into multiple spaces and calls them Voronoi cells. If each Voronoi cell is the same, then each Voronoi cell should be a polyhedron that achieves a seamless spatial coverage called a spatially filled polyhedron such as truncated octahedron, rhombic dodecahedron, hexagonal prism, and cube. The geometric center of each refillable polyhedron corresponds to the location of one wireless sensor node in the WSN, and each refillable polyhedron in space should be within the sensing range of the wireless sensor node. In order to maximize the volume of the space-filled polyhedron, the radius of the circumscribed sphere of each refillable polyhedron needs to be equal to the radius R of cell perception model [19]. Therefore, the problem of node deployment is reduced to the issue of space-fillable polyhedron partitioning.

The known fillable polyhedra are a regular prism, a cube, a regular hexagonal prism, a truncated octahedron, and a diamond-shaped dodecahedron. Firstly, through problem description and combined with the relevant theories of Kepler's prediction and Kelvin's prediction, rhomboid dodecahedron and truncated octahedron are selected as spatial fillable polyhedra. Then, through further analysis, it is found that the method to solve the coverage problem in two-dimensional space is to use regular hexagon for two-dimensional coverage. However, a polyhedron with hexagon as its cross-section has no properties of space filling, and a polyhedron with space-filling properties and hexagon as its cross-section is a hexagonal prism. Therefore, the six-prism is included in the comparison. Since the cube is the only regular polyhedron subdivided in three-dimensional space, the cube and the truncated octahedron, the diamond-shaped dodecahedron and the hexagonal prism are selected as fillable polyhedra for spatial subdivision.

For any shape element, the radius of the catch is $R_s$, so the volume of the catch is $\frac{4}{3} * \pi R_s^3$, and the volume of the catch is also the maximum volume of the element. Here we introduce the concept of a V.Q., short for volume quotient, the ratio of the volume of a polyhedron unit to the volume of its external contacts, to compare units of different shapes. If the volume of a polyhedral unit is V, the volume quotient of the polyhedral unit is $\frac{3V}{4\pi R^3}$. V. Q. is always within the range [20]. Our goal is to find a space-filled polyhedron with a maximum volume quotient (i.e., close to 1) to determine a theoretically optimal partitioning solution that minimizes the number of deployed nodes and theoretically optimizes the performance of the deployed solution. During the actual investigation, we found that there are many practical factors affecting the deployment method of wireless sensor network nodes in the storage environment, such as signal conflicts between WSNs and transmitting power between wireless sensors. Therefore, it is very difficult to find an optimal deployment plan in both theory and practice. Therefore, this paper aims to find a deployment method that can achieve better results than common solutions.

Assume that the radius of the external circle of the fillable polyhedron is $R_s$, in the case of space filling with six-prism, the radius of the external contact cannot guarantee the unique six-prism. This is because it is possible to have a number of hexagonal prisms of different heights and sizes on the hexagonal surface and still have the same diameter for their external contacts. Here, the six-prism with the largest V. Q. is selected, V. Q. value is $\frac{3}{2\pi} = 0.477$, and it is called the best six-prism. Similarly, the volume quotient of the cube, the diamond-shaped dodecahedron, and the truncated octahedron can be obtained through calculation. The specific results are shown in Table 2.

By comparing the volume quotients of different fillable polyhedra, it is obvious that if the truncated octahedron is taken as the shape of the fillable polyhedron, the number of active nodes will be the minimum [21].

### 3.3 Algorithm process

Normally, the input of our algorithm is three parameters:

(1) Space restrictions to be monitored.
(2) The radius R of the unit sensing model that affects the offset is different. If the fillable polyhedron selected is different, the corresponding offset is also different.
(3) Coordinate of the initial point, which is directly related to the deployment location of later nodes.

Combined with the content described in Sections 3.1 and 3.2, the detailed algorithm process can be obtained as follows:

(1) Input units perceive the radius $R$ of the model.
(2) Select the starting point, which can be understood as the location where the first wireless sensor node is deployed, and set the coordinates of the starting point to $(x_s, y_s, z_s)$.
(3) To determine whether the coordinates of class A nodes exceed the limited range, which means go to step (8) to end; otherwise, go to step (4), and continue to obtain $L_A$.

The $(x_a, y_a, z_a)$ is the general form of class A node coordinates, class A node coordinates calculation formula as shown in Eq. (1), the size of the offset vector is determined by the structure of space-filling polyhedron, due to the different space-filling polyhedron filling structure is different, the offset vector is different also, and the offset $(a_1, b_1, c_1)$ can be calculated.

(4) By superposing the offset with the coordinates of the class A node obtained in step 3, the coordinates of the class A node are further obtained.
(5) To determine whether the coordinates of class B node exceed the limited range, go to step (8) to end, otherwise go to step (6), and continue to obtain $L_B$.

The $(x_b, y_b, z_b)$ is the general form of class B node coordinates, class B node coordinates calculation formula as shown in Eq. (2), the size of the offset vector is determined by the structure of space-filling polyhedron; due to the different space-filling polyhedron, filling structure is different, the offset vector is different also, and the offset $(a_2, b_2, c_2)$ can be calculated.

(6) By superposing the coordinates of the class B node obtained by offset $\gamma$ and step (3), the coordinates of the class B node are obtained.
(7) Determine whether $L_A''$ exceeds the limit range. If it exceeds the limit, go to step (8) to end; otherwise, go to step (4) and continue to get $L_A$. In which $L_B = L_A + \gamma$.
(8) The end. Output sensor node deployment location coordinates.

**Table 2** Volumetric comparison of fillable polyhedra

| Fillable polyhedra | The cube | Optimal six-prism | Truncated octahedron | Rhombohedral dodecahedron |
|---|---|---|---|---|
| Volume quotient (V. Q.) | $\frac{2}{\sqrt{3}\pi} \approx 0.36755$ | $\frac{3}{2\pi} \approx 0.477$ | $\frac{24}{5\sqrt{5}\pi} \approx 0.68329$ | $\frac{3}{2\pi} \approx 0.477$ |

# 4 Design of node deployment scheme

## 4.1 Analysis of monitoring system requirements

Tobacco warehousing is an important part of tobacco production. The quality of tobacco warehousing affects product quality and production cost. High-quality warehouse environment occupies an important position in the production of enterprises and is conducive to ensure normal production. The application of WSNs to tobacco warehouse environment monitoring systems can make full use of the WSNs self-organizing, easy deployment and real-time advantages, and dispose wireless sensor nodes in the tobacco stacks to realize real-time, fine, and dynamic monitoring of the temperature, relative humidity, and gas concentration of tobacco warehouse environment. The application of WSNs in tobacco warehousing monitoring system is beneficial to promote work efficiency and improve the real-time performance and accuracy of tobacco warehouse environment monitoring, which is conducive to the security of warehousing and the quality of tobacco and tobacco products.

## 4.2 Overall structure of the monitoring system

Through the demand analysis of tobacco, warehouse environment monitoring systems, it is found that the systems need to deploy devices such as temperature and humidity wireless sensors, phosphide detection sensors, dehumidifiers, air conditioners, and cameras, giving full play to the self-organizing, easy deployment and multi-hop transmission advantages of WSNs, building the entire WSNs monitoring system. As shown in Fig. 3.

According to the above analysis of the characteristics of the tobacco warehouse environment requirements, the overall schematic of tobacco warehouse WSN monitoring system is designed, as shown in Fig. 4.

A number of wireless sensor nodes, including temperature sensors, humidity sensors, phosphide detection sensors, etc., are deployed at suitable locations within the tobacco stacks and warehouse. These nodes are utilized for data collection, then the collected data is transmitted to the network base station in real time via multi-hop transmission of WSNs, and the data is summarized, classified, and processed to ensure that monitoring personnel have more accurate and intuitive hold of the warehouse temperature and humidity, phosphine concentration and specific internal warehouse environment. A tobacco warehouse about 105 × 77 × 15 m space size, in which multiple wireless sensor nodes are placed, periodically collecting environmental parameters to detect changes of the parameters of tobacco and warehouse that are to be monitored, so as to ensure warehouse environment and product quality of tobacco and tobacco products. The sensor nodes have a sensing radius of 5 m.

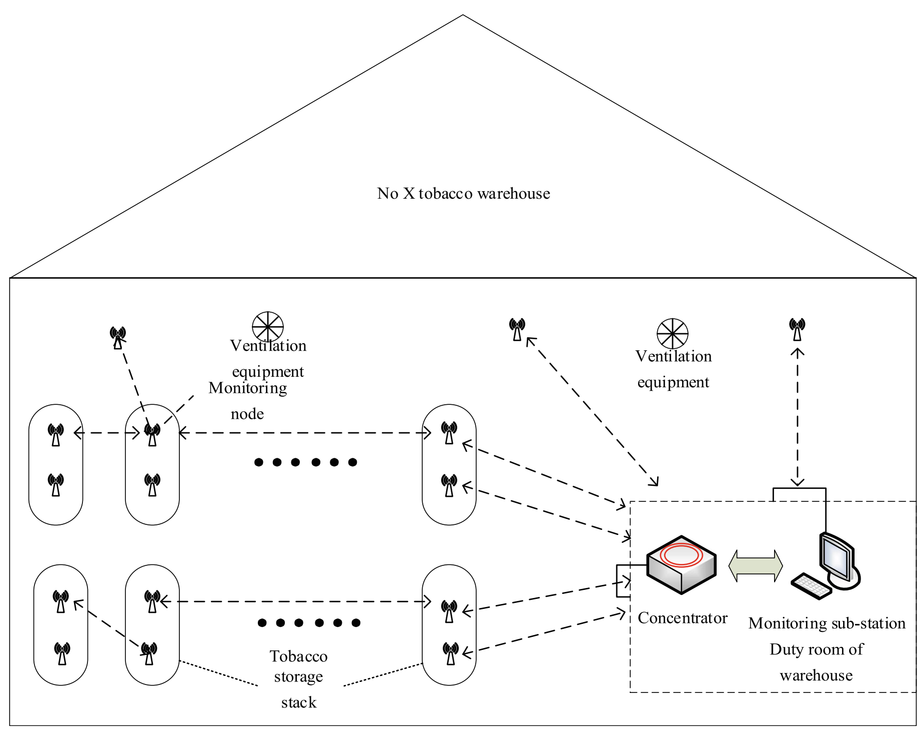


**Fig. 3** Wireless monitoring system diagram of tobacco warehouse environment

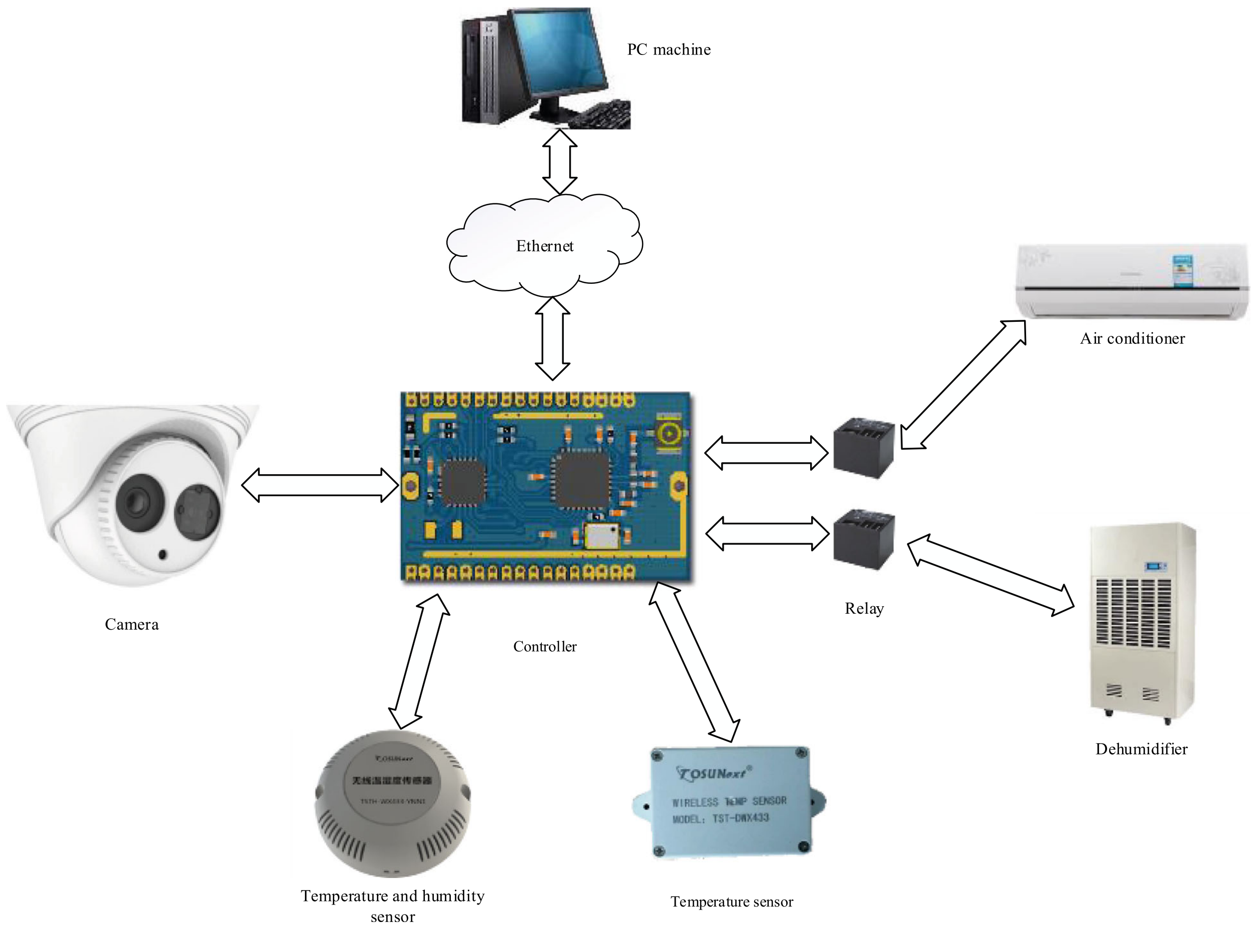


**Fig. 4** Overall system diagrams

### 4.3 Design of node deployment plan

#### *4.3.1 Model establishment and assumptions*

A tobacco leaf warehouse is about 105 m × 77 m × 15 m in size. Multiple wireless sensor nodes are placed in the storage environment, and environmental parameters are periodically or periodically collected to detect changes in the parameters to be monitored in the tobacco leaves and warehouses to ensure the tobacco leaves and tobacco product storage environment and product quality.

In the stage of wireless sensor network node deployment in the tobacco warehouse, the following assumptions are made:

(1) The wireless sensor node can be placed at any position in the tobacco warehouse, and the wireless sensor network node is fixed in position after deployment, and the number of wireless sensor nodes that need to be deployed in the entire tobacco warehouse can be clearly understood through calculation.
Each wireless sensor location has its own identification code, which can clearly know that there is an abnormality in the parameters to be monitored at a certain location; each wireless sensor node has similar processing and communication capabilities and the transmission power can be adjusted.

(2) In the storage wireless sensor network monitoring system, the average distance between two adjacent wireless sensor nodes is smaller than the maximum communication radius between the wireless sensors, which can ensure the information transmission of the entire wireless sensor network, so that the base station can receive the environment. Parameters, and summary processing take appropriate improvement measures.

(3) In the wireless sensor network, each wireless sensor node has its own location without additional hardware such as GPS to help acquire. The transmit power of each wireless sensor node is limited. If the transmit power of the connected sensor node is known, the approximate distance between the wireless sensor nodes can be estimated from the received signal power.

(4) Each wireless sensor network node can guarantee a certain time of work, ensure long-term collection of information, and improve the storage environment.

#### 4.3.2 Node deployment implementation

1. Parameter setting

(1) Determine the storage space to be monitored

The tobacco leaf warehouse to be monitored is about a rectangular parallelepiped space with length, width, and height of 105 m, 77 m, and 15 m respectively.

(2) Defining the perceived radius of the wireless sensor

Defining the perceived radius of the wireless sensor is the basis for solving the problem of node deployment. In the tobacco warehouse, a wireless sensor with a sensing radius of 5 m is selected.

(3) Choice of fillable polyhedron

According to the comprehensive analysis in Section 3.2, the truncated octahedron has the largest volume quotient. The spatial segmentation using the truncated octahedron can use the minimum number of wireless sensor nodes, save costs, and enable wireless under the premise of ensuring connectivity. The use time of the sensor network is maximized, so the warehouse space is three-dimensionally divided by the truncated octahedron in the tobacco warehouse.

When the tobacco warehouse space is three-dimensionally divided by the truncated octahedron, the offset of the coordinate of the class A node is $(n \times 4\sqrt{5}, m \times 4\sqrt{5}, k \times 4\sqrt{5})$, where $n$, $m$, $k$ are integers, and the offset of the coordinates of the class B wireless sensor node is $(2\sqrt{5}, 2\sqrt{5}, 2\sqrt{5})$.

(4) Select the starting point

The first wireless sensor node is deployed starting from a corner of the warehouse, and the coordinates of the point are $(0, 0, 0)$. After the initial node deployment location is determined, the next wireless sensor node is determined until the wireless sensor network node covers the entire warehouse.

2. Algorithm implementation

Typically, the input to this method algorithm is three parameters:

(1) Space area limit to be monitored.
(2) The radius of the unit-aware model affecting the offset, if the selected fillable polyhedron is different, the corresponding offset is also different;
(3) The coordinates of the initial point, which is directly related to the deployment location of the node afterwards.

#### 4.3.3 Simulation environment and simulation results

1. Simulation environment

Tobacco storage is an important link in the production process of tobacco enterprises. The quality of tobacco storage affects the quality of products and the production cost of enterprises. High-quality storage environment is conducive to ensure the normal production and plays an important role in the production of enterprises.

It is an important part of storage work to automatically collect storage environment parameters and transmit them to the control center, analyze timely storage environment, find hidden dangers, and deal with them in time. Humidity, temperature, illumination, gas concentration ($O_2$, $CO_2$, and other gas concentration, etc.), and dust are the main environmental parameters for monitoring.

(1) Air temperature

Air temperature is the air temperature in daily life, used to indicate the degree of cold and hot air. Air temperature has a negative correlation with the distance from the ground, which increases with the decrease of the distance from the ground, and decreases with the increase of the distance from the ground. In the actual storage process, the air temperature in the storage environment must be strictly controlled to ensure the quality of stored goods and reduce the consumption in logistics.

(2) Air humidity

Air humidity is a physical quantity that indicates the moisture content and humidity of the air. Under a certain temperature, air humidity is proportional to the moisture content in the air. If the moisture content in the air is higher, the air humidity will be higher; if the moisture content in the air is lower, the air humidity will be lower.

(3) The light

Illuminance, refers to the luminous flux received on the surface of the subject per unit area. Light has different effects on different items in storage. One is that light can adversely affect many things. The other is that light can protect objects under certain conditions.

The minimum relative humidity for most microbes is 80–90%. At 95%, microbes grow very vigorously, and below 75%, most items are not easily moldy. Most microbes die when the sun shines for 1–4 h and 3–5 m with an ultraviolet lamp. So a certain amount of light can protect stored goods.

(4) Gas concentration

There are various types of gases in the storage environment. When monitoring the concentration of gases, the concentration of gases including oxygen, carbon dioxide, and various harmful gases is mainly monitored.

Most moldy microorganisms, especially molds, grow fast in the environment with high-oxygen concentration, but grow slowly in the environment with high carbon dioxide concentration. It can be found that increasing or decreasing the concentration of carbon dioxide or oxygen can inhibit the life activities of microorganisms or even kill them by controlling the air composition in the storage environment. For example, during the storage process of grain, it is sensitive to the gases contained in the air. In order to ensure the quality of grain to the greatest extent and reduce the damage to grain by microorganisms and pests, it is necessary to control the oxygen concentration in the grain stack. Through a large number of experiments, the results show that the grain storage effect is best when the oxygen concentration in the storage environment is maintained between 2% and 5%.

(5) Dust illumination

Dust refers to the solid particles suspended in the air, and often refers to dust, dust, dust, powder, etc. The precision or sensitivity of precision instruments and electromechanical equipment will be affected by dust or sundries to different degrees. Similarly, corrosion-prone metal products stored in storage environments are prone to corrosion due to dust. For the storage environment where the vulnerable objects are stored, dust concentration detection files in the air should be established to record the results of regular detection. According to the records, appropriate measures should be taken to control dust in a reasonable way, such as installing partial exhaust hood and other improvement measures, so as to effectively control dust.

2. Simulation results

The specific parameters of the simulation scenario are shown in Table 3.

Using the algorithm of this paper in Section 3.2, using the java tool, according to the input parameter settings, the coordinates of the wireless sensor nodes can be obtained, and the coordinates of the deployment positions of some nodes are shown in Fig. 5. Figure 6 is a simplified stereogram of sensor node deployment, where the green area is the warehouse, the white point is the location of sensor node, and each cube vertex is the center point of the octahedron.

## 5 Comparison and analysis of node deployment before and after optimization

### 5.1 Evaluation index of node deployment

To verify the performance of the proposed deployment method based on space-fillable polyhedrons, the optimized deployment method proposed in this paper and the node deployment plan obtained from the pre-optimization deployment method are respectively studied in the same deployment environment, comparison is made from the aspects of coverage performance, connectivity performance, consumption performance, and economic performance.

(1) Coverage performance analysis

To further verify the effectiveness of the deployment method proposed in this paper, we compare the performance of the proposed deployment method with that of the pre-optimization method [22]. Since the truncated octahedron has the largest V.Q., and the required full coverage in the unit space is the minimum, the truncated octahedron is selected as the fillable polyhedron to be filled in the monitored space. Figure 7 shows the comparison of the coverage performance.

As seen from Fig. 7, the target coverage area ratio of WSNs has a positive correlation with the number of network nodes, and the area ratio of the WSNs target covering area increases as the number of WSNs nodes increases. The pre-deployment method simply sets all border nodes to be active, regardless of the target area boundaries, so that the number of active nodes is approximately 1.13 times that of the optimized deployment plan proposed in this paper. Therefore, the rational use of the boundary of the target area can effectively reduce the active nodes near the boundary.

**Table 3** Specific parameters

| Parameter | Value |
|---|---|
| Size of space | 105 m ×7715 m × m |
| Wireless sensor sensing radius | 5 m |
| Initial node coordinates | (0,0,0,) |
| MAC/Route | IEEE802.15.4/AODV |

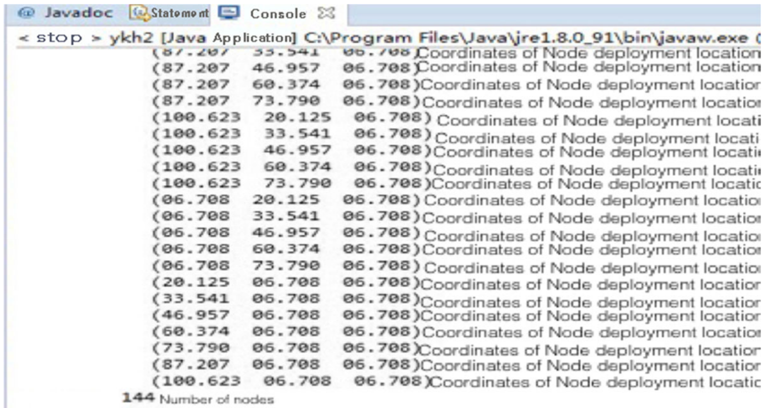


**Fig. 5** Wireless sensor node coordinates

(2) Connectivity performance analysis

To compare the impact of different deployment plans on the connectivity performance of WSNs, the transmission range of the optimized nodes is compared with the node transmission range before optimization [23]. By calculating the distance between the node locations in the adjacent subdivision cells, the comparison results of the minimum required transmission range are shown in Fig. 8.

As can be seen from the analysis of Fig. 8, the minimum transmission range required by the optimized deployment method is 1.7$R_s$, and the minimum transmission range required before optimization is 1.9 $R_s$. In warehouse environment monitoring systems, the deployment of WSNs nodes is limited by the transmission range of each wireless sensor node, and the transmission range required by different deployment plans is different. The greater the required WSNs node transmission range, the greater the probability that the network is not connected, the smaller the required transmission range, the better the connectivity of the entire WSNs. Therefore, the optimized deployment method has slightly better connectivity than the pre-optimization deployment method.

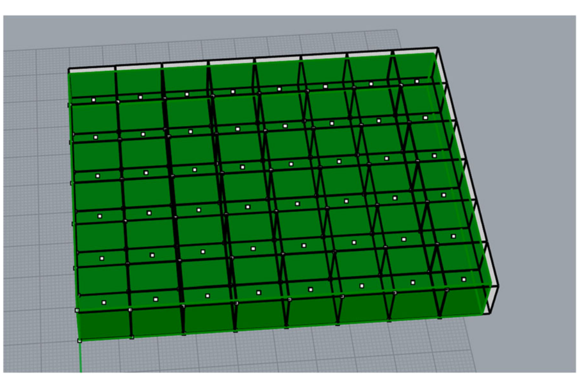

**Fig. 6** Node deployment simplifies stereograms

(3) Consumption performance analysis

The consumption performance affects the performance of the entire WSNs in the warehouse environment, especially on the network usage time, so the energy consumption performance of the node deployment plan is comparatively analyzed. In the tobacco warehouse environment, supposing the number of packets transmitted and forwarded in different deployment methods is the same, then the use of time for deployment depends on the transmission range between the wireless sensor nodes and the number of wireless sensor nodes [24]. Compared with the network life cycle of the deployment method of this paper, the comparison results of different service life cycles are shown in Fig. 9.

It can be seen from Fig. 9 that the deployment of the optimized wireless sensor nodes has a longer life cycle and a better deployment effect.

(4) Analysis of energy consumption performance

Energy consumption performance affects the performance of the entire wireless sensor network in the storage environment, especially the impact of network usage time [25]. Therefore, the energy consumption performance of the node deployment scheme is compared and analyzed here. In order to verify the performance of the space-fillable polyhedron deployment algorithm proposed in this paper, in the same deployment environment, the algorithm proposed in this paper is simulated and compared with the algorithm in literature [26] and literature [27].

In the tobacco storage environment application, the number of data packets transmitted and forwarded in

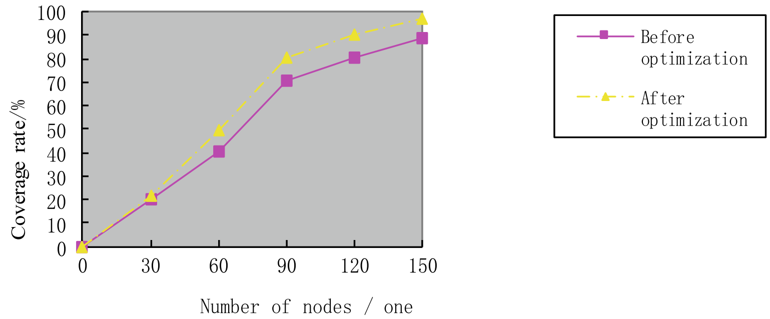


**Fig. 7** The relationship between the coverage rate and number of nodes before and after the optimization

different algorithms is the same, then the deployment time of the deployment scheme depends on the transmission range between the wireless sensor nodes in the scheme and the number of wireless sensor nodes.

It is assumed that in a wireless network, the energy consumption of transmitting a data packet is proportional to the square of the transmission range, and the transmission ranges of the two split units A and B are $\gamma_A$ and $\gamma_B$, respectively. In the split units A and B, the volumes of the individual units are $V^A$ and $V^B$, respectively. If the life cycles of split units A and B are defined as $L^A$ and $L^B$, respectively, then:

$$\frac{L^A}{L^B} = \frac{r_B^2}{r_A^2} \times \frac{V^A}{V^B} \tag{3}$$

It is known that the node deployment scheme in [26] mainly uses the optimal hexagonal prism to cover and fill the entire monitoring space. The literature [27] mainly uses the truncated octahedron to cover the entire monitoring space. In this paper, the tobacco warehouse deployment scheme mainly adopts the interception. The angular octahedron is spatially partitioned and filled. The life cycle of the proposed deployment scheme is used as the benchmark. Using formula (3), the life cycle comparison results of the available schemes are as follows:

$$\frac{L^{[26]}}{L} = \frac{\left(r_s\sqrt{\frac{17}{5}}\right)^2}{\left(r_s\sqrt{\frac{7}{2}}\right)^2} \times \frac{\frac{r_s^3}{4}}{\frac{4r_s^3}{5\sqrt{5}}} = \frac{17\sqrt{5}}{56}$$

Compared with the network life cycle in the scheme obtained by the algorithm, the usage period of different schemes is shown in Fig. 10.

As can be seen from Fig. 10, the wireless sensor node deployment method using the truncated octahedron for spatial segmentation has the longest usage period, is superior to the optimal hexagonal prism and rhombohedral dodecahedron and the cube space splitting mode, and has the best deployment effect

### 5.2 Weight distribution of evaluation indexes

Through the analysis of the principle of AHP, the AHP can be used to determine the weight of the evaluation index of the wireless sensor network node deployment scheme in the storage environment monitoring system, so as to prove the optimal scheme [28]. The specific modeling steps are shown as follows:

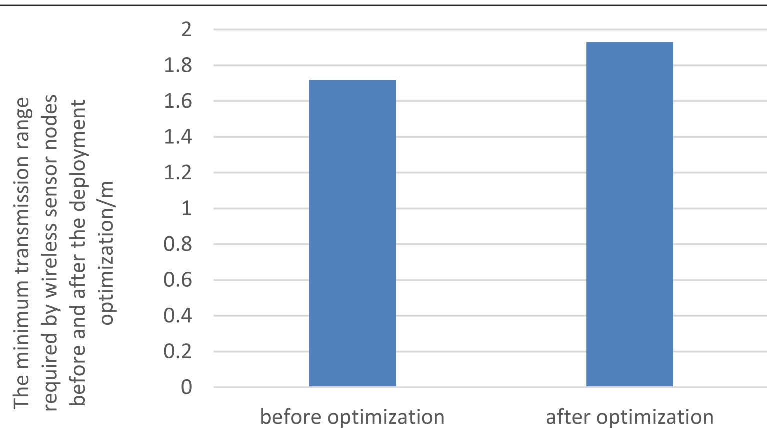


**Fig. 8** The minimum transmission range required by wireless sensor nodes before and after the deployment optimization

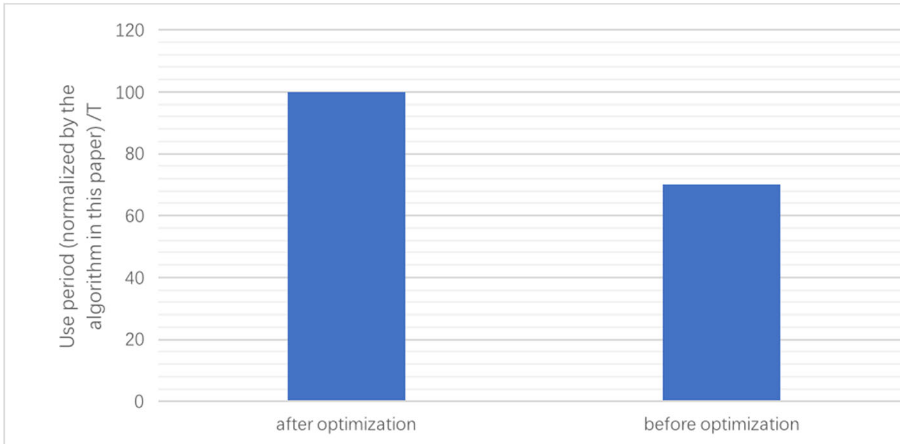


**Fig. 9** Comparison and analysis of life cycle before and after optimization

(1) Establish evaluation index model

Refer to the evaluation index of wireless sensor network node deployment scheme preliminarily established in section 5.1 to draw the hierarchical structure model, as shown in Fig. 11.

The model is mainly composed of three parts, including target layer A, criterion layer B, and scheme layer C.

Target layer: effect of wireless sensor network node deployment scheme in warehouse monitoring system (A)

Criterion layer: covering performance index (B1), connectivity performance index (B2), energy consumption performance index (B3)

Scheme layer: overall network coverage (C1), coverage multiplicity (C2), coverage time (C3), number of active nodes (C4), blind area of connectivity (C5), communication distance of nodes (C6), energy consumption required for network coverage (C7), energy consumption required for connectivity (C8)

(2) Construct judgment matrix

For storage environment monitor system in wireless sensor network node deployment plan effect evaluation hierarchical structure model, based on the structure of judgment matrix, applying YAAHPO. 6.0 software can be calculated by analytic hierarchy process (AHP) judgment matrix the largest eigenvalue of $\lambda_{max}$, the consistency ratio $CR$ and the weight vector of $W$, $RI$, and combined with random consistency index value, calculate the consistency index of $CI = CR \times RI$, YAAHPO. 6.0 AHP software is a relatively advanced and mature analytical tool. Through a large number of empirical studies, it is proved that the results of this software have high reliability and validity. If $CR \leq 0.1$, it is considered that the

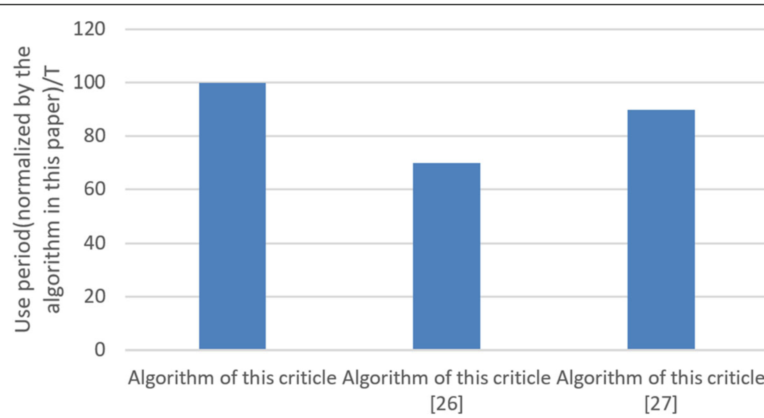


**Fig. 10** Comparison of usage periods

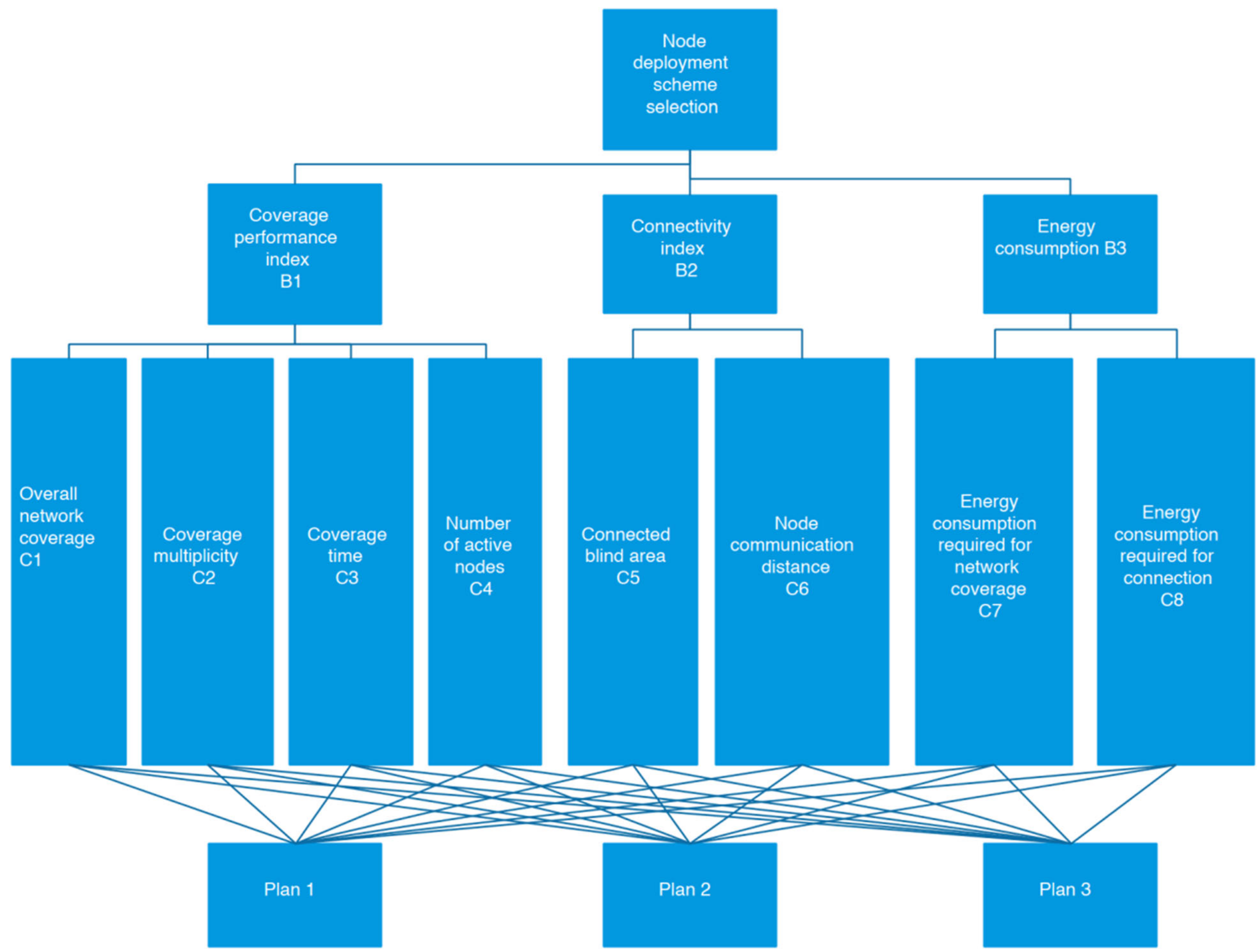


**Fig. 11** Hierarchical model of node deployment scheme selection

judgment matrix conforms to the satisfactory consistency standard and can accept the result of hierarchical single ordering. If $CR > 0.1$, the judgment matrix needs to be reconstructed until it passes the consistency test. Finally, the weight of each index in the evaluation index system of wireless sensor network node deployment scheme in storage environment monitoring system is obtained.

Combined with the AHP, the comprehensive performance of the node deployment schemes obtained by different deployment algorithms is compared. The actual grade scores and comprehensive weights are shown in Table 4.

It can be seen from the Table 4 actual rating score table that the comprehensive weight of the deployment scheme obtained by the algorithm is 4.75, and the combined weights of the literature [26] and the literature [27] are 3.3253 and 3.8987 respectively. The comprehensive weight value of the optimized deployment plan is obviously larger than that of before optimization. The comprehensive weight value of the performance of the deployment scheme obtained in this paper is significantly greater than the other. The comprehensive weight value of the performance of the two schemes, in summary, can be seen that when deploying wireless sensor network nodes in a specific space, the deployment method proposed in this paper has better performance, and the specific spatial partitioning method can be selected according to the actual situation, reducing the number of nodes required for the entire wireless sensor network sensor saves the deployment cost of the wireless sensor network node, improves the coverage of the entire wireless sensor network, and the connectivity between the nodes can be better, and the deployment method can ensure a longer time. The network has a long service life and better comprehensive performance, which satisfies the requirements of wireless sensor network node deployment in the warehouse environment monitoring system.

## 6 Conclusion and discussion

### 6.1 Conclusion

Wireless sensor network node deployment is the basis of wireless sensor network application in the warehouse

**Table 4** The actual rating scale and comprehensive weights

| Level 1 indicator | Level 2 indicator | Level 3 indicator | | Actual rating | | | |
|---|---|---|---|---|---|---|---|
| | | Index | The weight of the elements to the overall system | This article (after optimization) | Literature [26] | Literature [27] | Before optimization |
| | B1 (0.5714) | C1 (0.4763) | 0.2722 | 5 | 4 | 4 | 4 |
| | | C2 (0.2536) | 0.1449 | 5 | 3 | 4 | 3 |
| | | C3 (0.0934) | 0.0534 | 4 | 4 | 4 | 4 |
| | | C4 (0.1766) | 0.1009 | 4 | 3 | 3 | 3 |
| | B2 (0.2857) | C5 (0.3333) | 0.0952 | 4 | 3 | 4 | 4 |
| | | C6 (0.6667) | 0.1905 | 5 | 3 | 4 | 3 |
| | B3 (0.1429) | C7 (0.3333) | 0.0476 | 5 | 3 | 4 | 3 |
| | | C8 (0.6667) | 0.0952 | 5 | 3 | 4 | 3 |
| | | | | 4.75 | 3.3253 | 3.8987 | 3.90 |

environment monitoring system, which affects the performance of the entire network and is the primary problem to be solved when performing network applications. In this paper, the deployment of wireless sensor network sensor nodes in the storage environment is taken as the main line. The theory and algorithm related to the deployment of wireless sensor nodes in the application of storage environment monitoring system are studied. The specific contents are summarized as follows:

(1) Explain the relevant theory based on WSN warehouse environment monitoring system

By introducing the importance of introducing monitoring system in the storage environment, the environmental parameters that need to be monitored in several storage environment monitoring systems such as temperature, humidity, illuminance, gas concentration, and dust are designed.

(2) Building a node deployment algorithm based on space-fillable polyhedron.

Based on the description and analysis of the deployment situation in the warehouse environment monitoring system, a node deployment algorithm based on the space partitioning of the fillable polyhedron is constructed, and the offset of the fillable polyhedron used in the deployment algorithm is calculated, and the algorithm is calculated. Finally, the performance of node deployment scheme is analyzed theoretically.

(3) Node deployment case study

Taking the tobacco storage environment as an example, the effectiveness and dominance of the algorithm based on spatially partitionable polyhedral node deployment is verified. Firstly, according to the characteristics of the tobacco storage environment, the monitoring requirements of the tobacco storage environment are analyzed and the overall architecture of the monitoring system is designed. Secondly, the key design node deployment plan is adopted. Through the analysis of the storage environment structure model, the node deployment algorithm proposed in the paper is used. Deployment: Finally, the performance of the node deployment scheme in the warehouse environment is evaluated. By comparing the schemes obtained by the node deployment algorithm proposed in the literature, the validity and advantages of the proposed algorithm were further proved in the coverage performance analysis, connectivity performance analysis, energy consumption performance analysis and AHP method, and a relatively better scheme was obtained.

### 6.2 Discussion

Influenced by the complexity of warehouse environment, the limitation of the model and the limitation of personal research ability, the node deployment algorithm based on space fillable polyhedron partition proposed in this paper still has many shortcomings in the specific warehouse environment monitoring system. Future research work will focus on the following aspects:

1. In the design of the unit perception model, this paper constructs a unit probability perception model based on the error rate, which meets the coverage requirements of the current warehouse environment. However, the model is also a coverage model similar to the sphere when applied and less consideration is given to the irregular situation of the unit perception model. In the next work, it is necessary to study the unit perception which is more suitable for the warehouse environment application. Model.

2. The deployment strategy proposed in this paper only considers maximizing the space coverage of the storage environment on the premise of maximizing the coverage capacity of each sensor node. It does not consider the adjustable factors such as signal conflict between wireless sensor networks and transmission power between wireless sensors. In the next work, the deployment effectiveness of these factors will be considered comprehensively. The effect of fruit.
3. This paper only considers the deterministic deployment of wireless sensor nodes in the warehouse environment and does not take into account the random deployment of a considerable number of nodes in the actual warehouse environment applications. Therefore, in future research, the deployment of random nodes will be considered, which makes the model of node deployment in the warehouse environment monitoring system more perfect.

#### Abbreviations
AHP: Analytic hierarchy process; V.Q.: Volume quotient; WSNs: Wireless sensor networks

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#### Authors' contributions
JM is the main writer of this paper. He proposed the main idea. XJ and XZ gave some important suggestions for this paper. All authors read and approved the final manuscript.

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#### References
1. S. Khan, *Wireless sensor networks [M]* (CRC Press, Boca Raton, 2016), pp. 10–12
2. O. Atsuyuki, *Spatial tessellations: concepts and applications of Voronoi diagrams* (Wiley, New York, 2010), pp. 32–45
3. M. Younis, K. Akkaya, Strategies and techniques for node placement in wireless sensor networks: A survey. Ad Hoc Networks **6**, 621–655 (2008)
4. J. O'rourke, *Art Gallery. Theorems and algorithms. The International Series of Monographs on Computer Science* (Oxford University Press, New York, 1987)
5. V. Coskun, Relocating sensor nodes to maximize cumulative connected coverage in wireless sensor networks. Sensors **8**, 2792–2817 (2008)
6. S. Tilak, N. Abu-Ghazaleh, W. B Heinzelman, *Proceedings of the First ACM International Workshop on Wireless Sensor Networks and Applications* (ACM, Atlanta, 2002)
7. M. Abo-Zahhad, S.M. Ahmed, N. Sabor, Rearrangement of mobile wireless sensor nodes for coverage maximization based on immune node deployment algorithm. Comput Electrical Eng **43**, 76–89 (2015)
8. Y. Hou, C. Chen, B. Jeng, An optimal new-node placement to enhance the coverage of wireless sensor networks. Wireless Networks **16**, 1033–1043 (2010)
9. F. Zhigang, *Wireless sensor network coverage and node deployment research* (University of Electronic Science and technology, Chengdu, 2008)
10. F.M. Al-Turjman, H.S. Hassanein, M. Ibnkahla, Quantifying connectivity in wireless sensor networks with grid-based deployments. J Network Comput Appl **36**, 368–377 (2013)
11. A. SMN, Z.J. Haas, Coverage and connectivity in three-dimensional networks with random node deployment. Ad Hoc Networks 34, 157–169 (2015)
12. H.A. Hashim, B.O. Ayinde, M.A. Abido, Optimal placement of relay nodes in wireless sensor network using artificial bee colony algorithm. J Network Comput Appl **64**, 239–248 (2016)
13. D. Wang, B. Xie, D.P. Agrawal, Coverage and lifetime optimization of wireless sensor networks with Gaussian distribution. IEEE Trans Mobile Comput **7**, 1444–1458 (2008)
14. F.M. Al-Turjman, H.S. Hassanein, M. Ibnkahla, Towards prolonged lifetime for deployed WSNs in outdoor environment monitoring. Ad Hoc Networks **24**, 172–185 (2015)
15. Y. Chack-shan, Fast 3D k-coverage determination algorithm for sensor networks based on cube partition. Comput Appl **27**, 507–509 (2007)
16. X. Shunping et al., Maximum coverage space optimization based on Voronoi diagram heuristic and group intelligence. J Surveying Mapp **V40**, 778–883 (2011)
17. C. Jun, *Voronoi dynamic spatial data model* (Surveying and mapping press, Beijing, 2002)
18. Li H. Research on the service area division of the regional market town system based on weighted Voronoi diagram and gravitational model. Information Technology and Applications (IFITA), 2010 International Forum on. IEEE, 2010.
19. S.M.N. Alam, Z.J. Haas, Coverage and connectivity in three-dimensional underwater sensor networks. Wireless Commun Mobile Comput **8**, 995–1009 (2008)
20. V.A. Kaseva, Wireless sensor network for hospital security: from user requirements to pilot deployment. EURASIP J Wireless Commun Netw **1**, 1–15 (2011)
21. Z. Chang-Jian, On volume quotient functions. Indagationes Mathematicae **24**, 57–67 (2013)
22. Oktug S, Khalilov A, Tezcan H. 3D coverage analysis under heterogeneous deployment strategies in wireless sensor networks. Fourth Advanced International Conference on. IEEE Computer Society, 2008, 199–204.
23. K.A.M. Almahorg, S. Naik, X. Shen, Efficient localized protocols to compute connected dominating sets for ad hoc networks. Proceedings of the Global Communications Conference, 2010 IEEE Global Telecommunications Conference GLOBECOM 2010 (IEEE, Miami, 2010)
24. N. Javid, M.B. Rasheed, M. Imran, An energy-efficient distributed clustering algorithm for heterogeneous WSNs. EURASIP J Wireless Commun Netw 151 (2015).
25. H. Na, C. Lee, A full-duplex SWIPT system with self-energy recycling to minimize energy consumption. EURASIP J Wireless Commun Netw 2018, 253 (2018)
26. L. Wang, Research on key technologies of warehousing environment monitoring system based on WSN (Beijing Materials College, Beijing, 2011)
27. A. SMN, Z.J. Haas, Coverage and connectivity in three-dimensional networks with random node deployment. Ad Hoc Networks 34, 157–169(2015)
28. S.A. Khan, F. Dweiri, Fuzzy-AHP approach for warehouse performance measurement. IEEE International Conference on Industrial Engineering & Engineering Management (2016)

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