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CCAJS: A Novel Connect Coverage Algorithm Based on Joint Sensing Model for Wireless Sensor Networks

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Abstract

This paper discusses how to effectively guarantee the coverage and connectivity quality of wireless sensor networks when joint perception model is used for the nodes whose communication ranges are multi-level adjustable in the absence of position information. A Connect Coverage Algorithm Based on Joint Sensing model (CCAJS) is proposed, with which least working nodes are chosen based on probability model ensuring the coverage quality of the network. The algorithm can balance the position distribution of selected working nodes as far as possible, as well as reduce the overall energy consumption of the whole network. The simulation results show that, less working nodes are needed to ensure the coverage quality of networks using joint perception model than using the binary perception model. CCAJS can not only satisfy expected coverage quality and connectivity, but also decrease the energy consumption, thereby prolonging the network lifetime.

Keywords: wireless sensor networks (WSNs), joint perception model, coverage probability, connect coverage, network lifetime

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1. Introduction

The coverage Quality and connectivity are two important measurements of the QoS (Quality of Service, QoS) of the wireless sensor networks (WSNs) [1-2]. States of the node are scheduled with heuristic algorithm by taking advantage of node redundancy [3-5]. The nodes are powered off in turn on the premise of certain QoS, thereby effectively saving the network energy, prolonging the network lifetime. Almost all the existing coverage control strategies without geographic position are based on the binary perception model, namely when an object is located in the perception area of a node, the probability it can be monitored is always 1; whereas when it is outside of the perception area of a node, the probability it can be monitored is always 0. Which means whether an object can be detected is just determined by a single node in the network. However, in the real application scenario, whether an object can be detected is determined by the analysis and fusion of data perceived by multiple adjacent sensor nodes. Therefore, the probability an object can be detected is determined by multiple nodes instead of a single node. The probability an object can be detected is determined by the physical properties of the node and the distance from the node, and so on. Therefore the joint perception model [6-7], also known as the probability perception model, can describe the network coverage more accurately. To prevent the sensor nodes from being isolated，not being able to transmit information monitored to the base station, the network must be fully connected.

Aiming at the characteristics of randomly deployed sensor networks, as well as coverage quality and connectivity of the network, this paper proposes Connect Coverage Algorithm Based on Joint Sensing Model (CCAJS) The position and energy consumption of the nodes selected with this algorithm are both well-distributed, thereby effectively prolonging the network lifetime.

2. Related Works

In recent years, many experts have done a lot of detailed and in-depth research of the features of wireless sensor networks. Literature [8] proposed a *k*-degree discrete barrier coverage algorithm with maximized network lifetime. The algorithm theoretically analyzes the conditions of the upper and lower limits of the coverage of the network model which has concrete barriers, and then effectively covers the concerned moving node; In terms of the network energy consumption, a sensor node scheduling algorithm is proposed, which redeploys the sensor nodes using greedy algorithm and completes sensor nodes state transition with scheduleing mechanism, ultimately achieves the goal of maximizing the network lifetime. When covering the mobile target nodes concerned using this algorithm, the sensor nodes distributed in the monitoring area are always connected or intersected. However, once the target mobile node appears on the coverage "blind area", the mobile target node can no longer be covered effectively, therefore the network model is too idealistic. A heuristic coverage algorithm is proposed in literature [9] by means of mixed integer programming. This algorithm studies heuristic coverage in which sensor nodes intersect and the sensor node perception radius is adjustable. This algorithm requires large amount of calculation with little adjustability. To improve the algorithm presented in literature [9], Yang SH [10] treated the target node coverage area in literature [9] approximately as monitoring area , and then completed the connected coverage over target area by building coverage set using high-density deployed sensor nodes set. On the basis of studies on the above two literatures, Liu H et al. [11] had done a lot of researches on target coverage, and put forward a solving process to find the coverage of the target node at any time in the condition that a sensor node can only cover a single target node. However, this constraint limited the application when covering the monitoring area, and made the solving process unsuitable to real coverage scenario. Literature [12] optimized the scheduling of sensor nodes with artificial colony algorithm and particle swarm algorithm, calculating the best deploy path using heuristic scheduling configuration. It also proposed a theoretical computing process for finding the positions of sensor nodes after the optimal deployment was finished, as well as a method to compute the upper limit of the network lifetime. Literature [13] put forward an Energy-Efficient Coverage and Connectivity Preserving Routing Algorithm(ECCRA) which constructed dual Coverage area using network model and calculated coverage probability and expectations using probability knowledge, then determined the upper limit of coverage expectation, finally achieved effective covering the monitoring area with least sensor nodes. Literature [12] and [13] can complete the effective coverage over the monitoring area to a certain extent, suppressing fast energy consumption of sensor nodes. However, both the two algorithms require large amount of computing and are highly complex, requiring a long time to complete the coverage over monitored area. A work team named after GreenOrbs in the Internet of Things Technology Center in National Laboratory of Information Science and Technology of Tsinghua University has done a lot of experiments on the application of wireless network in engineering and has gotten certain results. Those results are mainly about forestry ecological monitoring, urban environmental monitoring, and so on. The GreenOrbs team initiated a project named CitySee after more than two years of research. In that project, the sensor network is applied to carbon absorption and emission monitoring in cities and communities, providing technology and social security support for government decision making and city development. Meanwhile, the team of the project also published many influential papers. Literature [14] studied the large-scale sensor nodes deployed in forest, and pointed out the subordinate relationships between different levels of the network infrastructure. It studied how the radio signal intensity influenced the physical layer; how the packet loss rate, link quality and transmission rate affected the structure of the whole network in the link layer; the dynamic routing planning, flow control, node grouping, data exchange, topology characteristics and so on in the top layer of the network. In Literature [15], mass sensor nodes are deployed in the city center monitoring various performance indicators of carbon dioxide. this article introduced the function of each layer of the network infrastructure, then analyzed the software and hardware configuration in the network system, finally carried out a lot of experiments verifying the network connectivity and data acquisition, including such hierarchies as visual process of data acquisition, design and management of the wireless sensor network and locating in mobile network. The above large-scale sensor networks feature high applicability in practical. Literature [16] gives a coverage algorithm based on the event-probability-driven mechanism(EPDM), which is mainly driven by events probability-driven nodes to complete effective coverage over monitoring area. In the algorithm, the dependency relationship between the sensor nodes and target nodes is given, then the probability model is calculated, related theorem and reasoning are also proved; the conversions between different node status are also completed using the scheduling mechanism of the node itself. the algorithm can complete effective coverage over different size of networks with relative low cost, prolonging the lifetime of the whole network. Literature[17] presents an coverage algorithm based on energy-efficient multi-objective linear rules (energy-efficient target coverage algorithm, ETCA), which solves the problem of multi-target coverage using cluster structure system. By calculating the coverage ability of the sensors and their residual energy, this algorithm completes the optimal coverage over the target nodes in a linear fashion.

Zuckerman et al. put forward a distributed scheduling algorithm, the off-duty eligibility rule [18]. The node calculates the sponsored area of the neighbors according to the geographical position information, and then computes the coverage relations between nodes. Ye et al. put forward a detection-based node density control protocol, PEAS [19]. Based on the probability, Wu put forward a method to compute the node redundancy [20], with which the node was able to calculate its own redundancy independently. He also proposed a node scheduling protocol, LDAS, which needs no geographical position information. However, this method ignores the two-hop neighbors' perception contribution to the sensing area of the node, Therefore there are still a large number of redundant nodes. Wang et al. studied the coverage problem of sensor networks where the nodes deployed submitted to two-dimensional Gaussian distribution [21].

There is a common problem in the above coverage control algorithms -- the network connectivity is not considered in these algorithms. There are mainly two mechanisms to research on the network connectivity: One is based on the hypothesis that the communication radius of the node is fixed [22]. CDS is built by scheduling the node state, accordingly the backbone nodes are reserved for communication. According to the connectivity between nodes, CPA algorithm [23] divides the nodes into different domains, and the connectivity of the network is guaranteed as long as there is one working node in each domain; the other mechanism is based on the hypothesis that the communication radius of a node is adjustable. The lifetime of the whole network is prolonged by dynamically adjusting the node's transmission power (power control [24-25]) to minimize the energy consumption of the node on the premise of guaranteeing the connectivity of the network. LMST [24] guarantees the network connectivity by constructing a local minimum spanning tree for each node, saving the network energy.

In order to guarantee the coverage quality and connectivity of sensor networks, researchers turn to focus on how to guarantee connective coverage. Liu et al. proposed a joint scheduling algorithm [26] ensuring the connectivity of networks by adding additional communication nodes on the basis of guaranteeing coverage quality. Literature [27] put forward sleep scheduling and topology control. The algorithm divides all the nodes into several subsets, each subset being able to guarantee the coverage quality of specific target and the connectivity of the network [28].

3. Preparation Knowledge

3.1 Node Perception Model and Related Definitions

The analysis in this paper is based on joint perception model [20], namely in the monitoring area M, the perception intensity of the node s to any position q is:

$$I(s,q)=\begin{cases} e^{-\alpha d} & 0<d_{(s,q)}<R_s \\ 0 & R_s<d_{(s,q)} \end{cases} \tag{1}$$

In which $d_{(s,q)}$ stands for the Euclidean distance between s and q, α is a parameter of the equipment reflecting the physical property of the perception module of the node. R_s is the maximum effective perception radius. Assuming node set s contains all the working nodes deployed in monitoring area M, then the intensity of joint perception [20] in point q is:

$$I(q)=1-\prod_{s_j\in S}\left(1-I\left(s_j,q\right)\right) \tag{2}$$

Definition 1: For any point q in the area of M, if the intensity of the joint perception of q satisfies $I(q)\geq I_{th}$, then q is covered (namely, events at q can be detected); otherwise q is not covered. In which, the I_{th} is the threshold of perception intensity (its value is set by the user according to node characteristics and application requirements). Therefore the coverage of q can be expressed as:

$$Cov(q)=\begin{cases}1 & I(q)\geq I_{th}\\ 0 & I(q)<I_{th}\end{cases} \tag{3}$$

In binary perception model, the perception area of a node is a circle centered in s, with radius r_s (the circle is denoted with $C(s,r_s)$, in which $r_s\leq R_s$). All the points in region $C(s,r_s)$ are covered by s, but none of the nodes outside of $C(s,r_s)$ can be covered by s. Therefore, in the binary perception model, r_s satisfies $e^{-\alpha d}=I_{th}$, namely $r_s=-\ln(I_{th})/\alpha$.

Definition 2: The ratio of the covered area of M to the whole area of M is known as the network coverage quality, namely:

$$\eta=\iint_M \frac{Cov(q)}{\text{area}(M)}\mathrm{d}x \tag{4}$$

A sensor network can be abstracted as an undirected graph $G=(V, E)$, in which V and E are the set of nodes and the collection of undirected edges, respectively.

Definition 3: For undirected graph $G=(V, E)$, the connectivity degree of node pair of (u, v) $(u,v\in V)$ is defined as the number of independent paths connecting u and v. Graph Connectivity degree is defined as the minimum connectivity of all the node pairs within V, namely $d_c(G)=\min\forall(u,v)\in V\{d(u,v)\}$. The concept that a graph is interconnected is equivalent to $d_c(G)\geq 1$.

Definition 4: network lifetime refers to the time span from when the network starts up to when one of the target nodes is not able to be covered by any sensor node, or the whole network connectivity can't be guaranteed.

3.2 Network Model

Assume sensor nodes are deployed Randomly and well-distributed in a square region M, the side length being L. Now assume the network has the following properties:

(1) Joint perception model and binary communication model are used for the node.

(2) The network can be homogeneous or heterogeneous, but the perception radius of all the nodes submit to normal distribution $N(R_0,\lambda^2)$, with $R_0\geq 3.3\lambda$ (guaranteeing the perception radius of the node is in$[0,2R_0]$).

(3) $L>>R_{cm}$ and $L>>R_s$, namely the boundary effect of the monitoring area M can be ignored.

(4) The communication equipment of a node can adjust its own transmission power and has m number of different communication range (denoted as $R_{c1}<R_{c2}<R_{c3}\ldots<R_{cm}$).

3.3 Problem Description

Assume large volumes of nodes (the number of nodes is n) are deployed randomly in the monitoring area M. For communication module, presetting the adjustable communication radius level of the nodes to R_{c1}, R_{c2}, $R_{c3},\ldots,R_{cm}$; while for the perception module, presetting the related parameter α of the perception device, threshold of perception intensity $I_{th}(0<I_{th}<1)$,and the maximum perception radius R_s. When calculating characteristic function of random variable x, we uses Fourier transform. To guarantee the quality of network coverage and connectivity, the smallest working node set φ is required to be selected out of n nodes; also, an appropriate communication radius needs to be determined. Therefore an algorithm is needed to schedule the working nodes so that the selected working nodes can be distributed evenly, as well as the energy consumption.

4. Problem Analysis

4.1 Coverage Problem Analysis

By defined 1, the probability of any point q being covered is $P\{I_{th} \le I(q) \le 1\}$ in area M. By definition 2, the expectation value of the coverage quality of the network, denoted by η, is:

$$E(\eta) = E\left(\iint_M Cov(q)\,\mathrm{d}x\right)\mathrm{area}(M)^{-1} = P\left(I_{th} \le I(q) \le 1\right) \tag{5}$$

Demanded coverage quality (η_0) is guaranteed in the monitoring area M as long as $E(\eta) \ge \eta_0$ is guaranteed, namely:

$$P\{I_{th} \le I(q) \le 1\} \ge \eta_0 \tag{6}$$

Let $\ln(1\text{-}I(q))=x$, then $P\{I_{th} \le I(q) \le 1\}=P\{\ln(1\text{-}I_{th}) \ge x > \text{-}\infty\}$, in which $pr(x)$ denotes the probability density function of random variable x, namely:

$$P\left(\ln\left(1-I_{th}\right) \ge x > -\infty\right) = \int_{-\infty}^{\ln(1-I_{th})} pr(x)\,\mathrm{d}x \tag{7}$$

In the monitoring area(M), K_v nodes are randomly selected as working nodes. By formula (2), we have $x = \sum_{i=1}^{K_v} \ln\left(1 - I\left(s_j, q\right)\right)$, Therefore the characteristic function of random variable x is:

$$\varphi_x(t) = E\left[\exp(itx)\right] = E\left[\prod_{j=1}^{K_v} \exp\left(f(t)\cdot\ln\left(1 - I\left(s_j, q\right)\right)\right)\right] \tag{8}$$

In which i is the imaginary unit. Because all the nodes in M obeys uniform random distribution, the probability of the node in any position within M is 1/ area(M). In addition, the position relationships among all the nodes within M are independent of each other, therefore

$$\varphi_x(t) = \left\{\left[\mathrm{area}(M) - \pi R_s^2\right] + \int_0^{R_s} \exp\left(f(t)\cdot\ln\left(1 - \exp(-\alpha r)\right)\right)\cdot 2\pi R_s \mathrm{d}r\right\}^{K_v} \cdot \mathrm{area}(M)^{-K_v} \tag{9}$$

Let $\ln(1\text{-}\exp(\text{-}\alpha r))=l$ then:

$$\begin{aligned}\varphi_x(t) &= \left[\left(\mathrm{area}(M) - \pi R_s^2\right) + \int_{-\infty}^{\ln(1-\exp(-\alpha d))} \left(1 - \left(l - \ln\left(1 - \exp\left(-\alpha R_s\right)\right)\right)\right)\left(\frac{2\pi\ln\left(1 - \exp(l)^2\right)}{-\alpha^2\left(1 - \exp(l)\right)}\mathrm{d}l\right)\right]^{K_v} \cdot \mathrm{area}(M)^{-K_v} \\ &= \left[\left(\mathrm{area}(M) - \pi R_s^2\right) + fourier\left(f(l)\right)\right]^{K_v} \cdot \mathrm{area}(M)^{-K_v}\end{aligned} \tag{10}$$

In which $f(l)=([2\pi\ln(1\text{-}\exp(l)^2)]/\text{-}\alpha^2(1\text{-}\exp(l)))\cdot[1\text{-}(l\text{-}\ln(1\text{-}\exp(\text{-}\alpha R_s)))]$. Thus the probability density function of random variable x can be formulated as:

$$pr(x) = ifourier\left[\varphi_x(t)\right] = ifourier\cdot\left\lfloor\left(\left(\mathrm{area}(M) - \pi R_s^2\right) + fourier\left(f(l)\right)\right)^{K_v} \cdot \mathrm{area}(M)^{-K_v}\right\rfloor \tag{11}$$

By (6), (7) and (11), we get:

$$\int_{-\infty}^{\ln(1-I_{th})} ifourier\left[\left(\left(\mathrm{area}(M) - \pi R_s^2\right) + fourier\left(f(l)\right)\right)^{K_v} \cdot \mathrm{area}(M)^{-K_v}\right]\mathrm{d}x \ge \eta_0 \tag{12}$$

As long as formula (12) works, the randomly selected K_v working nodes are able to guarantee the coverage quality of monitoring area M, meeting the demand for specific coverage quality. The minimum K_v can be calculated using MATLAB to satisfy formula (12). Using binary perception model without considering boundary effect, Literature [29] came up with the relation between the expectation of obtained coverage quality K_u and the number of working nodes, namely $E[\eta]=1-[(1-\pi R^2)/\text{area}(M)]^{Ku}$, where R is calculated from formula $R=-\ln(I_{th})/\alpha$. By $1-[(1-\pi R^2)/\text{area}(M)]^{Ku}\geq\eta_0$, the minimum amount of working nodes K_u necessary to ensure the quality of network coverage can be deduced using binary perception model. **Table 1** shows the amount of working nodes required to ensure the network coverage quality using the joint perception model (R_s=10M) and the binary perception model. As can be seen from **Table 1**, with the requirements of the same coverage quality, the amount of working nodes needed to guarantee the coverage quality in networks is much greater using binary perception model than using the joint perception model. Hence the joint perception model is better than binary perception model in reflecting the combination perception characteristic of sensor networks.

Table 1. Relation-ships between required coverage quality and the amount of working nodes

Variate	**Coverage Quality**					
η_0	0.8	0.83	0.91	0.94	0.96	0.99
α=0.1	87	99	113	126	157	213
I_{th}=0.6	163	196	254	301	378	487
α=0.2	102	119	137	156	175	211
I_{th}=0.4	189	230	273	315	361	406

4.2 Connectivity Problem Analysis

To transmit the data which are monitored by sensors to the base station (Sink node), the network constituted by working nodes must be fully connected. In terms of probability theory, the connectivity of the network can be guaranteed as long as the probability the network is connected is not less than the threshold value τ_1 ($\tau_1$is the threshold for a big probability event, and in this paper, τ_1=0.98), namely $P\{d_c(G)\geq1\}\geq\tau_1$. The mathematical relationship between the number of working nodes and the communication radius of the nodes ensuring the connectivity of the network is analyzed in the following.

Assume n nodes are randomly selected as working nodes in the monitoring area M (denoted as $s_1,s_2,s_3,\ldots s_n$). Using undirected graph G to denote the network consists of $V=\{s_1,s_2,s_3,\ldots s_n\}$. Using $\rho(V,d_n(G)\geq k)$ and $\rho(V,d_c(G)\geq k)$ to denote the minimum communication radius of the node when $d_n(G)\geq k$ and $d_c(G)\geq k$ (where $k\geq1$) are satisfied, respectively:

$$\rho(V,d_n(G)\geq k)\geq\rho(V,d_c(G)\geq k) \tag{13}$$

Literature [13] proves that for $k\geq1$, we have:

$$\lim_{n\to\infty} p\left\{\rho\left(V,d_c(G)\geq k\right)=\rho\left(V,d_n(G)\geq k\right)\right\}=1 \tag{14}$$

Namely when n is large enough, the node degree and the connectivity of graph increase from (k-1) to k, the probability of the connectivity of G increasing from k-1 to k increases with the increase of communication radius of the node approaches 1.when n is large enough, by formula (13) and (14),we get:

$$\rho(V,d_n(G)\geq k)\in(\rho(V,d_c(G)\geq k)-\varepsilon,\ \rho(V,d_c(G)\geq k)) \tag{15}$$

In which $\varepsilon\to0^+$. Therefore, when $\rho(V,d_n(G)\geq k)$ approaches 1, we have:

$$\rho(V,d_n(G)\geq k)\approx\rho(V,d_c(G)\geq k) \tag{16}$$

According to formula (18), when $\rho(V,d_n(G)\geq k)\to1$, the probability the network is interconnected satisfies$\rho(d_n(G)\geq k)\approx\rho(d_c(G)\geq k)$. Because $\rho(d_n(G)\geq1)=P\{\cap(d(s_j)\geq1)\}$, although the event $d(s_j)\geq 1$ and event $d(s_h)\geq 1$ are not independent to each other (for example, if s_j is the neighbor of s_h, then s_h must also be the neighbor of s_h, in which $1\leq j,\ h\leq n,\ j\neq h$, The correlation between them is rather slight, therefore $P\{\cap(d(s_j)\geq 1)\}\approx\Pi P\{d(s_j)\geq 1\}$. Moreover, because the position of all the nodes are independent to each other, so $P\{d(s_j)\geq 1\}=P\{d(s_h)\geq 1\}$ (In which $1\leq j,\ h\leq n,\ j\neq h$). Therefore, when $P\{d_n(G)\geq 1\}\rightarrow 1$, we have:

$$P\{d_c(G)\geq 1\}\approx\{P(d(s_i))\geq 1\}^n \tag{17}$$

Denoting the node communication radius with R_c, we have:

$$P\left\{d\left(s_i\right)\geq 1\right\}=1-\exp\left\{-\pi R_s^2\left(n-1\right)\cdot\text{area}\left(M\right)^{-1}\right\} \tag{18}$$

Substitute the result in formula (18) into formula (17), we get $P\left\{d\left(s_i\right)\geq 1\right\}\approx 1-\exp\left\{-\pi R_s^2\left(n-1\right)\cdot\text{area}\left(M\right)^{-1}\right\}^n$. According to the practical significance of big probability event, as long as the probability a network is interconnected reaches τ_1, it is interconnected from the perspective of probability. So in order to guarantee the connectivity of the network, the amount of working nodes and the communication radius of the node should satisfy:

$$1-exp\left(-\pi R_s^2\left(n-1\right)\cdot\text{area}\left(M\right)^{-1}\right)^n\geq\tau_1 \tag{19}$$

When R_c is set, the minimum n which satisfies formula (19) can be calculated using MATLAB; on the contrary, if n is set, the minimum R_c which satisfies formula (19) can also be figured out.

4.3 Redundancy Node Analysis

Theorem 1: Randomly select k working nodes within M, then the expectation of the coverage quality is:

$$E\left(\eta_k\right)=1-\left\{1-\frac{\pi\left(R_0^2+\lambda^2\right)}{\text{area}\left(M\right)}\right\}^k \tag{20}$$

Proof: In M, the nodes subject to random uniform distribution, so the probability a node is located in any position in M is 1/area(M). If any point q is covered by a sensor node a (the perception radius is denoted with R_a), then sensor node a must be locate in a circle centered in q (the circle is denoted as O(q,R_a) of radius R_a). Therefore, the probability q is covered by sensor node a is:

$$P_a=\text{area}(\text{O}(q,R_a))/\text{area}(M) \tag{21}$$

Because the perception radius of sensor node a conforms to normal distribution and $R_0\geq 3.3\lambda$, the probability that any point is covered by a working node is:

$$P=\int_0^{2R_0}P_a\frac{1}{(2\pi)^{\frac{1}{2}}\lambda}\exp\left(-\frac{\left(R_a-R_0\right)}{2\lambda^2}\right)\mathrm{d}R_0 \tag{22}$$

Let $x=(R_a-R_0)/\lambda$, then:

$$P=\left(\frac{\pi}{2}\right)^{\frac{1}{2}}\frac{1}{\text{area}\left(M\right)}\left(\int_{-\frac{R_0}{\lambda}}^{\frac{R_0}{\lambda}}\lambda^2x^2\exp\left(-\frac{x^2}{2}\right)\mathrm{d}x+\int_{-\frac{R_0}{\lambda}}^{\frac{R_0}{\lambda}}2\lambda xR_0\exp\left(-\frac{x^2}{2}\right)\mathrm{d}x+\int_{-\frac{R_0}{\lambda}}^{\frac{R_0}{\lambda}}R_0^2\exp\left(-\frac{x^2}{2}\right)\mathrm{d}x\right) \tag{23}$$

The calculation is:

$$P=\left(\frac{\pi}{2}\right)^{\frac{1}{2}}\frac{1}{\text{area}\left(M\right)}\left(-\lambda^{2}\exp\left(-\frac{x^{2}}{2}\right)\Bigg|_{-\frac{R_0}{\lambda}}^{\frac{R_0}{\lambda}}+\left(2\pi\right)^{\frac{1}{2}}\lambda+\left(2\pi\right)^{\frac{1}{2}}R_0^{2}\right)\approx\frac{\pi\left(R_0^{2}+\lambda^{2}\right)}{\text{area}\left(M\right)} \tag{24}$$

For all the position of the nodes in *M* are independent of each other, the probability that any node is covered by at least *k* working nodes in *M* is:

$$P_K=\sum_{i=1}^{k}\binom{k}{j}P^{i}\left(1-p\right)^{k-i}=1-\left(1-\frac{\pi\left(R_0^{2}+\lambda^{2}\right)}{\text{area}\left(M\right)}\right)^{k} \tag{25}$$

Assuming the area covered by at least *k* nodes is $M^{'}$, then the expectation of the area for $M^{'}$ is:

$$E(\text{area}(M^{'}))=P_k\text{area}(M) \tag{26}$$

Therefore:

$$E\left(\eta_k\right)=\frac{E\left(\text{area}\left(M^{'}\right)\right)}{\text{area}\left(M^{'}\right)}=1-\left(1-\frac{\pi\left(R_0^{2}+\lambda^{2}\right)}{\text{area}\left(M\right)}\right)^{k} \tag{27}$$

By Theorem 1, we can get the expectation of the minimum number of required working nodes satisfying demanded coverage quality η_d of applications, namely:

$$E\left(k\right)=\frac{\ln\left(1-\eta_d\right)}{\ln\left(1-\frac{\pi\left(R_0^{2}+\lambda^{2}\right)}{\text{area}\left(M\right)}\right)} \tag{28}$$

Theorem 2: After the redundant nodes are powered-off randomly and conflict-freely, if the rest working nodes are able to provide accurate coverage quality η_d demanded by applications, the expectation of the number of covered neighbors of redundant node satisfies:

$$E\left(n\right)>\left(\ln\left(1-\eta_d\right)\Big/\ln\left(\left(1-\frac{\pi\left(R_0^{2}+\lambda^{2}\right)}{\text{area}\left(M\right)}\right)-1\right)\right)\cdot\left(\left(4\pi R_0^{2}+2\pi\lambda^{2}\right)\Big/\text{area}\left(M\right)\right) \tag{29}$$

Proof: Assuming the number of the remaining working nodes is *N* after the redundant nodes are powered off, then the *n* working nodes still follow random and uniform distribution. Because the remaining working nodes can still accurately provide the coverage quality required in applications, so by formula (28), we get:

$$E\left(N\right)=\frac{\ln\left(1-\eta_d\right)}{\ln\left(1-\frac{\pi\left(R_0^{2}+\lambda^{2}\right)}{\text{area}\left(M\right)}\right)} \tag{30}$$

Denote the perception radius of node as R_a, R_b, which represents the perception radius of node *b*. If *b* is the coverage neighbor of *a*, then *b* must be located in a circle centered on a of radius R_a+R_b (denoting the circle as $\text{O}(a,R_a+R_b)$). Therefore, the probability that *b* is a coverage neighbor of *a* is:

$$P_{b-a}=\frac{\text{area}\left(\text{O}\left(a,R_a+R_b\right)\right)}{\text{area}\left(M\right)} \tag{31}$$

Because the perception radius of all nodes obey normal distribution $N(R_0,\lambda^2)$, and $R_0\geq 3.3\lambda$, the probability that a node is the coverage neighbor of another node is：

$$P=\int_0^{2R_0}\int_0^{2R_0}P_{b-a}\frac{1}{2\pi\lambda^2}\exp\left[-\frac{\left(R_a-R_b\right)^2+\left(R_b-R_0\right)^2}{2\lambda^2}\right]\mathrm{d}R_a\mathrm{d}R_b \tag{32}$$

Calculation:

$$\begin{aligned}P=&\frac{1}{\mathrm{area}\left(M\right)}\int_0^{2R_0}\int_0^{2R_0}R_a^2\frac{1}{\lambda^2}\exp\left[-\frac{\left(R_a-R_b\right)^2+\left(R_b-R_0\right)^2}{2\lambda^2}\right]\mathrm{d}R_a\mathrm{d}R_b\\&+\frac{1}{\mathrm{area}\left(M\right)}\int_0^{2R_0}\int_0^{2R_0}R_aR_b\frac{1}{\lambda^2}\exp\left[-\frac{\left(R_a-R_b\right)^2+\left(R_b-R_0\right)^2}{2\lambda^2}\right]\mathrm{d}R_a\mathrm{d}R_b\end{aligned} \tag{33}$$

According to the computation process in formula (33), we have:

$$\int_0^{2R_0}\int_0^{2R_0}R_a^2\frac{1}{\lambda^2}\exp\left[-\frac{\left(R_a-R_b\right)^2+\left(R_b-R_0\right)^2}{2\lambda^2}\right]\mathrm{d}R_a\mathrm{d}R_b\approx\pi\left(R_0^2+\lambda^2\right) \tag{34}$$

Because

$$\int_0^{2R_0}R_a\frac{1}{\left(2\pi\right)^{\frac{1}{2}}\lambda}\exp\left(-\frac{\left(R_0-R_a\right)^2}{2\lambda^2}\right)\mathrm{d}R_a=\int_{-\frac{R_0}{\lambda}}^{\frac{R_0}{\lambda}}\left(R_0+\lambda x\right)\frac{1}{\left(2\pi\right)^{\frac{1}{2}}}\exp\left(-\frac{x}{2}\right)\mathrm{d}x=R_0 \tag{35}$$

So

$$\int_0^{2R_0}\int_0^{2R_0}2\pi R_aR_b\frac{1}{2\pi\lambda^2}\exp\left(-\frac{\left(R_a-R_b\right)^2+\left(R_b-R_0\right)^2}{2\lambda^2}\right)\mathrm{d}R_a\mathrm{d}R_b=2\pi R_0^2 \tag{36}$$

Then we have:

$$P=\frac{4\pi R_0^2+2\pi\lambda^2}{\mathrm{area}\left(M\right)} \tag{37}$$

The expectation of the number of coverage neighbor sensor nodes for each of the remaining N working nodes is:

$$E\left(n\right)=\left(E\left(N\right)-1\right)P=\frac{\ln\left(1-\eta_d\right)}{\ln\left(\left(1-\frac{\pi\left(R_0^2+\lambda^2\right)}{\mathrm{area}\left(M\right)}\right)-1\right)}\cdot\frac{4\pi R_0^2+2\pi\lambda^2}{\mathrm{area}\left(M\right)} \tag{38}$$

Therefore the expectation of the number of redundant coverage neighboring sensor nodes satisfies:

$$E\left(n\right)>\frac{\ln\left(1-\eta_d\right)}{\ln\left(\left(1-\frac{\pi\left(R_0^2+\lambda^2\right)}{\mathrm{area}\left(M\right)}\right)-1\right)}\cdot\frac{4\pi R_0^2+2\pi\lambda^2}{\mathrm{area}\left(M\right)} \tag{39}$$

4.4 CCAJS Protocol Control

By formula (14)，the minimum amount of working nodes K_v ensuring the coverage quality can be calculated. Substitute n with K_v in formula (19), the minimum radius of communication R_c satisfying formula (19) can then be figured out. If $R_c \le R_{cm}$, set the actual communication radius of the node R_{com} to not less than the minimum communication level of R_c, as well as set the actual working node K to K_v; otherwise set the actual communication radius of the node R_{com} to R_{cm}, then substitute R_{cm} with R_c in formula (19), thus find out the minimum number of working node n which satisfies formula (19), and then set the number of the working node k to n. In order that the selected working nodes are well-distributed better in geography, the density control mechanism for working nodes is used locally in the protocol. Namely, the number of the working neighbor of node n satisfies

$$n \geq \frac{K\pi R_{com}^2}{\text{area}(M)} \tag{40}$$

This implies that there are enough working nodes in the communication area, so that the node can be powered off to save the network energy [30-31]. In the CCAJS, each node has three states during its operation: active, back off and asleep. The transformation relationships between the states are as shown in **Fig. 1**. When the network is initialized, the base station figures out K, R_{com} and $K\pi R_{com}^2/\text{area}(M)$ according to the user-defined coverage quality, performance parameters of the sensor nodes and the whole detection area, then sends the information to all the nodes within the area(M). Each node within M sets its own communication radius according to the information coming from the base station. After that, all the nodes broadcast Hello message to obtain the information of the neighboring nodes and then store the information in their neighboring table, then enter active state. When the number of the neighboring nodes which are in active state satisfies formula (40), the node enters back off state, the time the node stays in that state being random. After the back off time span is over, the node once more determines whether the number of its active neighboring nodes satisfies formula (13). If dissatisfied, it returns to working state, otherwise, it broadcasts asleep message informing the other working neighbors to update their neighboring table, then it enters asleep state and stays in that state for a fixed time span before entering active state again. The node broadcasts a Probe message to detect its working neighbors after transforming from sleeping state into active state. Those nodes which are not in asleep state received the probe message will update their neighboring table, and broadcast Hello messages.

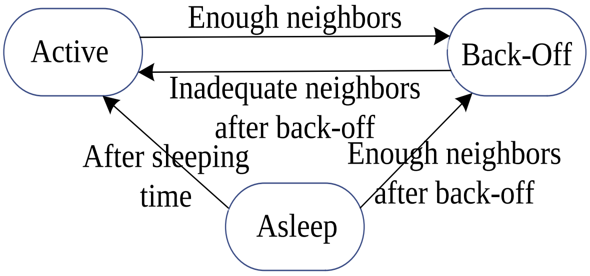

Fig. 1. The node state transition diagram

CCAJS also uses a working node selection mechanism based on residual energy of the node, by which the nodes with less energy have more opportunity to enter asleep state. The retreat time span of a node is randomly generated in [0,T]. The formula to compute T is:

$$T = \left(1 + \frac{W - W_{min}}{W_{th}}\right) \cdot T_0 \tag{41}$$

In which T_0 is a fixed base value of time, w is the residual energy of the node, W_{min} is the minimum value of the residual energy of the node and its neighbors, and W_{th} is the threshold of the energy adjustment. As can be seen from formula (43), the more the remaining energy of the node is greater than that of its coverage neighbors, the greater T would be, and the less chance the node will enters asleep state, thereby realizing the load balancing of energy consumption of the node.

4.5 Complexity Analysis

The three kinds of control message in CCAJS have a uniform format. The operation cycle of each node consists of two parts: work time T_w and sleep time T_s. Initially, the number of nodes deployed in the network is N, and all nodes work in turn. While anytime the actual number of working nodes is K_w. By formula (38), we get $E\left[K_w\right]=K\pi R_{com}^2 \big/ \text{arae}\left(M\right)$. In an operation cycle, $N\cdot E[T_w]=E[K_w]\cdot(E[T_w]+T_s)$. By formula (40), the expectation of the number (denoted with n) of the working neighbors of each node that transforms from sleeping state into work state is $E\left(n\right)=K\pi R_{com}^2 \big/ \text{area}\left(M\right)$, Therefore, a node emitting a Probe message will trigger $E[N]$ nodes to emit Hello messages. Each node will send an asleep message and a Probe message in its life cycle. Therefore, the number of the control messages sent out is $(2+E[n])/(E[T_w]+T_s)$ per unit time.

5. Performance Evaluation

To verify the validity of the effectiveness and performance, we carried out the experiments and analysis using MATLAB as the simulation platform. The energy model and parameters used are of the same as those in literature [14].The wireless communication model for data sending and receiving are as follows, respectively

$$E_{tx}\left(l,d\right)=\begin{cases} lE_{elec}+l\xi_{fs}d^2 & d<d_0 \\ lE_{elec}+l\xi_{mp}d^4 & d\ge d_0 \end{cases} \tag{42}$$

$$E_{rx}\left(l\right)=lE_{elec} \tag{43}$$

Where l represents the number of bits in packets, d is the emission distance, E_{elec} represents the energy dissipation of the radio transceiver circuit, ξ_{fs} and ξ_{mp} represent the energy dissipation of the amplifier using free space model and multiple energy attenuation models, respectively. The experimental parameters are as shown in **Table 2**:

Table 2. Simulation parameter list

Parameter	**Value**	**Parameter**	**Value**
area(M_1)	100*100m^2	I_{th}	0.6
area(M_2)	200*200m^2	E_{elec}	50nJ/b
area(M_3)	300*300m^2	ξ_{fs}	10J/b/m^2
N	400	ξ_{mp}	0.003 J/b/m^2
T_0	5s	Data size	300B
T_s	30s,50s,70s	Packet size	20B
R_s	10m	Nodes energy	5J
α	0.6	Energy limit	0.002J

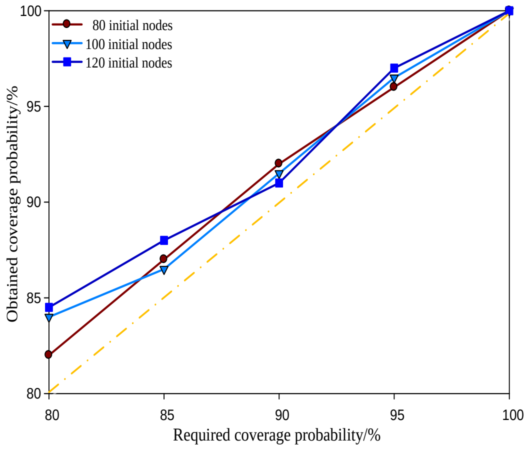

Fig. 2. The relationship between obtained QoC and required QoC

Fig. 2 illustrates the relationship between the quality of obtained coverage and that of the required coverage when different amount of nodes are deployed. As can be seen in this figure, regardless of the initial number of nodes deployed, CCAJS can always guarantee the quality of required coverage and has some coverage redundancy. Small amount of coverage redundancy is essential to enhance the fault tolerance of the network, furthermore, to accurately provide coverage quality is not realistic in the absence of geography information.

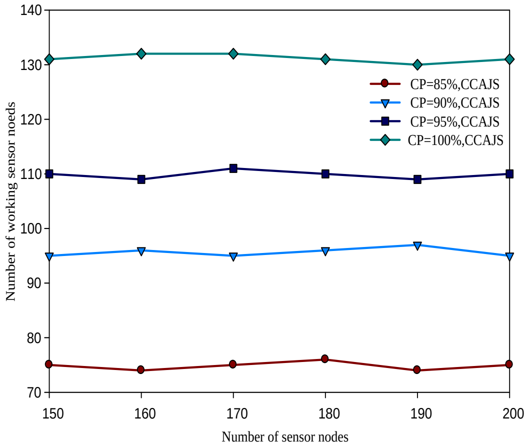

Fig. 3. The relationship between the number of working nodes and the required QOC

Fig. 3 reflects the relationship between the number of working nodes and the number of nodes deployed. As can be seen from **Fig. 3**, regardless of the initial number of node deployed, the number of the working nodes only associated with required coverage quality, which indicates that the protocol is highly extensible. Detailed observation shows that, with the same coverage quality requirements, the actual number of working nodes is greater than that of the theoretical ones. This is because the number of the working neighboring nodes must be integer, so that the number of the actual working nodes is greater than the theoretical calculated values, therefore the coverage quality is slightly higher than the required coverage quality.

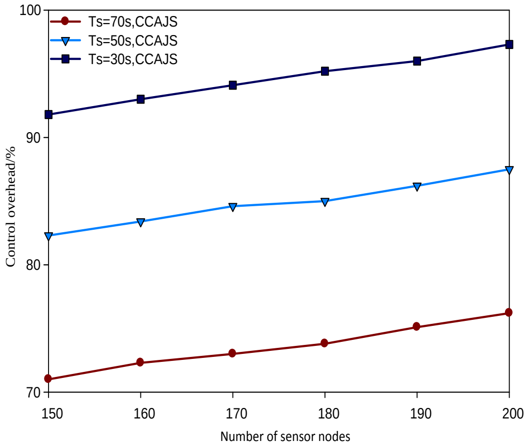

Fig. 4. relationship between control overhead and sleep interval of the node

When selecting working nodes with CCAJS, energy is consumed to receive and transmit control messages, and the working nodes consume large amount of energy when receiving and transmiting perceived data. The ratio of the energy consumption in transmitting or receiving control messages to the overall energy consumption of the network is used to denote control overhead.

Fig. 4 reflects the relationship among the number of deployed nodes, the sleep interval of nodes and the control overhead as the required coverage quality is 95%. As can be seen from **Fig. 4**, the control overhead of the CCAJS algorithm is quite little. On the other hand, the longer the node sleeps, the less the control overhead is. That is because in unit time, the greater T_s is, the less the control messages transmitted or received are. We can also see from **Fig. 4** that with the same T_s, the greater the density of the working node is, the more the control overhead is.

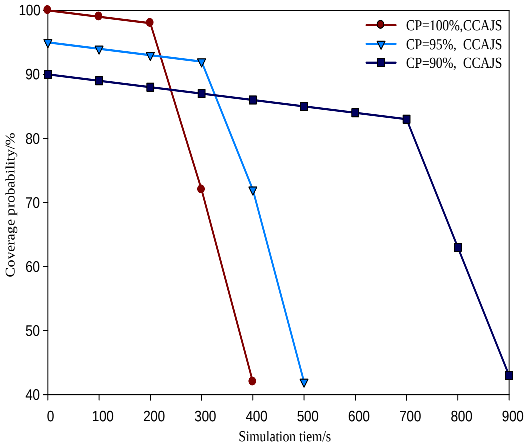

Fig. 5. relationship between obtained QOC and time

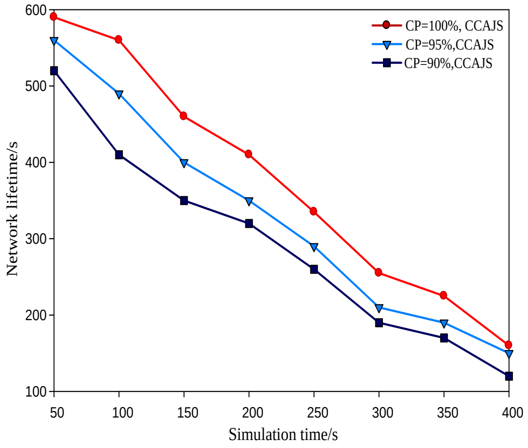

Fig. 6. the proportional relationship of simulation time to the network lifetime

Fig. 5 illustrates the relationship between coverage quality and time when 800 nodes are randomly deployed. **Fig. 6** shows the proportional relationship of simulation time to the network lifetime. Although scheduling the nodes using CCAJS slightly increases control overhead compareding with those algorithms without node scheduling, the network lifetime is greatly prolonged because the nodes works in turn. After the network lifetime is over, the coverage quality declines rapidly from the required coverage quality of applications, which indicates that he overall energy consumption of the network is well-distributed. We can also conclude from **Fig. 5** and **Fig. 6** that CCAJS algorithm has relatively high coverage at the beginning of the network operation, but the coverage drops down as time elapse. The reason for this lies for the dissipation of the node energy, or more nodes are needed to guarantee high coverage. But the higher the network coverage quality is, the more working nodes are needed and more rapidly the energy is consumed, therefore the shorter the network lifetime is, which also reflects the transform relationship between coverage quality and network lifetime.

On simulation platforms of different monitoring area, comparisons of the coverage rate between the number of redundant nodes among CCAJS algorithm for this paper and those for literature [16] and [17] are as shown in **Fig. 7 - 12**.

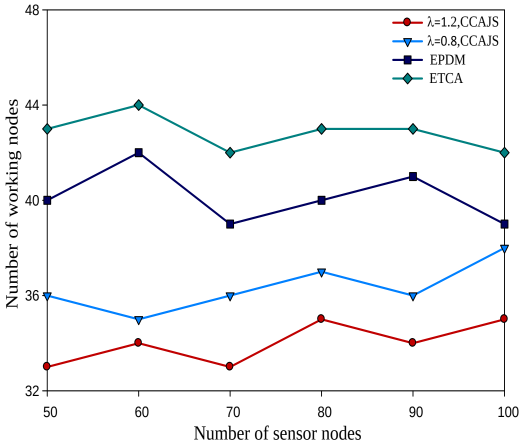

Fig. 7. 100*100m^2, comparison between the number of sensor nodes and the number of working nodes

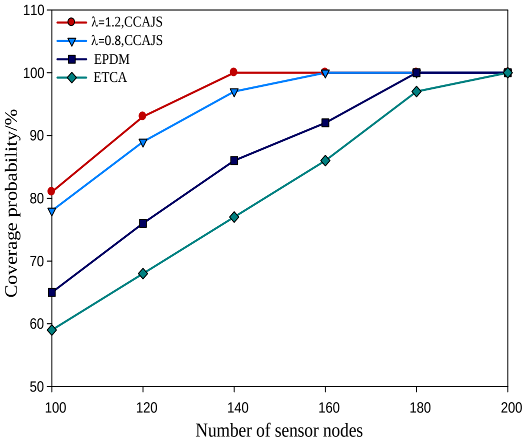

Fig. 8. 200*200m^2, the network coverage change curve

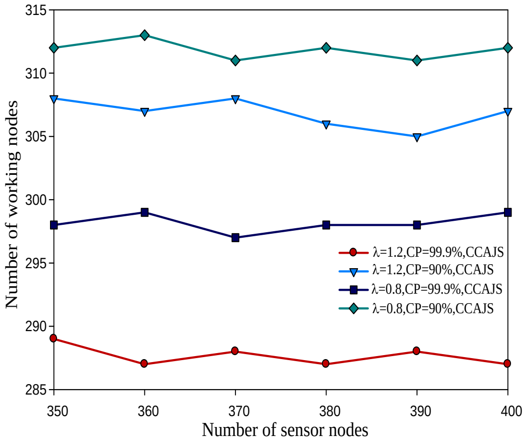

Fig. 9. 300*300m^2, the comparison of CCAJS algorithm with different coverage

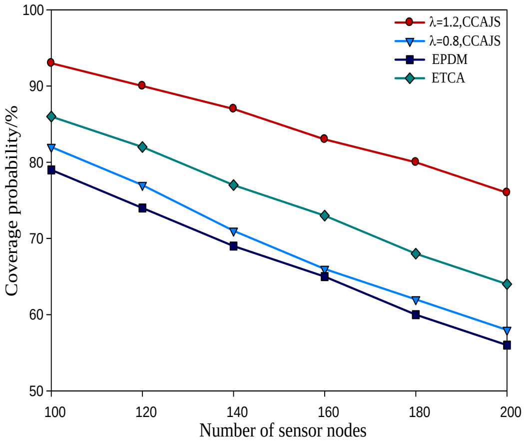

Fig. 10. 300*300m^2, comparison between the number of redundant sensor nodes and network coverage

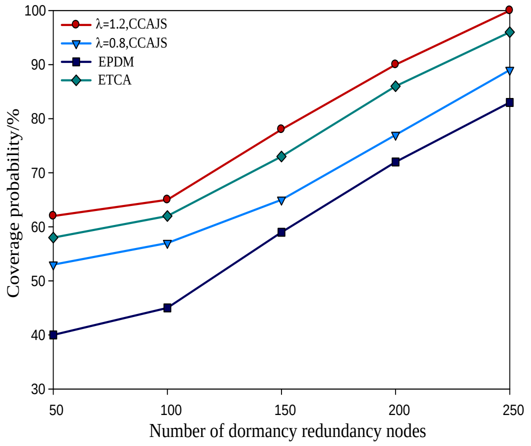

Fig. 11. 300*300m^2, comparison between the number of sleeping redundant nodes and network coverage

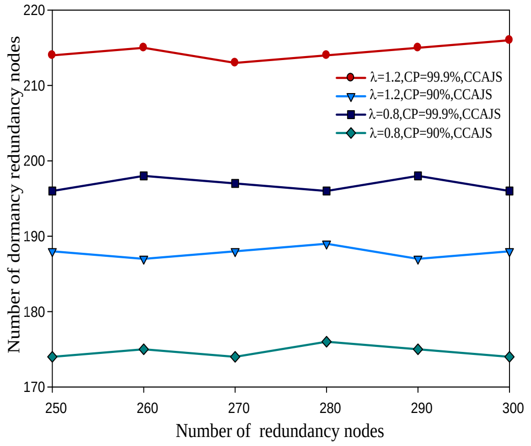

Fig. 12. 300*300m^2, comparison between the number of redundant nodes and sleeping redundant nodes

Fig. 7 to 12 show the changing curve of coverage with different parameters and network scale, as well as the changing curve of the coverage with different number of redundant nodes. **Fig. 7** shows the changing curve of the number of working nodes and the number of sensor nodes of CCAJS algorithm for this paper and SCA algorithm in a simulation area of 100*100m^2. As can be seen from **Fig. 8**, the CCAJS algorithm needs less working nodes with different parameters, while the EPDM needs more sensor nodes. The reason for this is that when λ=1.2, the area covered by the sensor nodes and their neighboring nodes is greater than the coverage area when λ=0.8, while the SCA and EPDM algorithms achieve effective coverage over monitoring area by increasing the number of sensor nodes. **Fig. 8** illustrates the changing curve of the coverage with different number of the working nodes in a simulation area of 200*200m^2. The monitoring area in **Fig. 9** and 10 is 300*300m^2. As can be seen from **Fig. 9** and **Fig. 10**, with the increase of sensor nodes, the coverage of the three algorithms all increases. Because the CCAJS adjusts the coverage with dynamic parameter, the coverage is higher than the other two algorithms at the initial stage. When the number of sensor nodes reaches 137, the algorithm for this paper has completed effective coverage, while the SCA algorithm and EPDM algorithm achieve effective coverage when the numbers are 180 and 199, respectively. The algorithm for this paper improves the average coverage by 11.02% comparing with the other two algorithms. **Fig. 11** shows the proportional relation between the redundant dormancy nodes and the coverage. As can be seen from f **Fig. 11**, with the increase of redundant dormant nodes, the coverage of the three algorithms increases, too. In CCAJS, when redundant nodes increases, the number of working nodes keeps constant while completing effective coverage over monitoring area using conversion scheduling strategy. Whereas the other algorithms adopt uninterrupted continuous coverage methods to complete effective coverage over monitoring area. **Fig. 12** shows the proportional relation between the redundant nodes and the redundant dormant nodes. As can be seen from **Fig. 12**, the redundant nodes and the redundant dormant nodes shows a linear relationship, and the curve amplitude change is relative small, which suggests that under the premise of certain coverage, this kind of network architecture has good scalability.

6. Conclusion

In order to cover the network effectively and connectively in the absence of node location information, this paper discussed the relationships between the coverage quality of networks, network connectivity and the number of working nodes, area of the monitored region, and the performance parameters as the nodes are randomly deployed. We also analyzed the random deployment problem of redundant nodes in the heterogeneous sensor network, as well as presented a decision model of the redundant node. This model needs no geographic location information and is suitable for both homogeneous and heterogeneous network. It should be pointed out that the joint perception model is used for the perception module of the node, because joint perception model can describe the coverage of the network more accurately than the binary perception model. Node scheduling control algorithm is designed to choose least nodes to guarantee the coverage quality and connectivity of networks according to the result of analysis. We also proposed heterogeneous sensor network coverage preserving protocol with maximum network lifetime. The protocol adopts election strategy based on residual energy of the nodes, so that the energy consumption of the nodes can distribute more uniformly. The simulation results show that CCAJS not only effectively provides satisfied QOS and connectivity, but also realizes load balancing of the network energy consumption, thereby achieves saving network energy. The energy equilibrium strategy balances energy consumption, thereby prolonging the network lifetime effectively.

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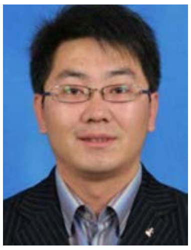

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