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An Event-Driven Mechanism Coverage Algorithm Based on Sensing-Cloud-Computing in Sensor Networks

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ABSTRACT The structure of network topology in heterogeneous sensor networks changes fast. As a result, the coverage and control ability of sensor nodes will be undermined. In order that we can address this problem, we propose an event-driven mechanism coverage algorithm based on Sensing-cloud-computing in heterogeneous sensor networks (EMC-SC). First, the network coverage model is utilized to compute the boundary relationship between the dual square and the sensor nodes coverage area. Then, the Poisson distribution model is employed to analyze the coverage performance of the randomly deployed sensor nodes and further compute the probability of the coverage which is effective over the monitoring area. Next, the node state mechanism scheduling algorithm is determined according to the amount of exchanged information between the neighbor nodes and the sensor nodes as well as the remaining sensor nodes energy. Finally, the results of the simulation show that, if it is compared with other algorithms which exist, the EMC-SC algorithm which is proposed could improve the network lifetime and the network coverage rate by 12.73% and 16.22%, respectively. Therefore, the effectiveness of the proposed algorithm and the validity of the proposed algorithm are verified.

INDEX TERMS Sensing-cloud-computing, sensor network, coverage rate, network lifetime.

I. INTRODUCTION

The wireless sensor network (WSN) is a type that is new of large-scale self-organized sensor network, which is widely employed in a range which is wide of industry areas [1]–[3]. The behavioral properties of WSN are characterized by its small size, a certain degree of sensing ability, computation ability, storage ability, and communication ability. In addition, the gathered data could be transmitted to the control center (user) or the Sink via the transmission link. The rapid development of WSN has changed the way human sense the physical world and communicates [4]–[6]. However, the disadvantages of the WSN are its vulnerability to the environmental disturbance, the limited manifestations of its behavioral property and capability.

The coverage problem is fundamental to the research of other performances, e.g., location, tracking, and routing of the WSN [7]–[9]. There are different methods of achieving coverage over the monitoring area, e.g., complete coverage, point coverage, and fence coverage. Complete coverage refers to the method where the network composed by the deployed sensor nodes could sense an arbitrary point in the monitoring area. Therefore, no blind spot exists in complete coverage. The research on complete coverage is mainly in view of the nodes' location information, and the complete coverage is achieved by computing the network topology. The complete coverage is applicable to the application scenarios where the requirement on the coverage quality is high. Point coverage

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refers to the method where only a part or a group of points can be covered by the network nodes. Therefore, only a limited amount of nodes are requested to be covered in the monitoring area [10]–[12]. Compared with complete coverage, point coverage is weaker in coverage performance. However, the number of working nodes can be greatly reduced in point coverage. Therefore, the energy efficiency, network lifetime can be greatly improved. Fence coverage refers to the method where sensor nodes are deployed as fences on some important links and these nodes can sense the invasion of targets. The complete coverage and the point coverage methods are mainly employed for the sensing and gathering of the environment information in the monitoring area. By contrast, the fence coverage method is employed for the monitoring and tracking of mobile targets. For some battery-powered WSNs, the sensor nodes are normally randomly deployed in severe conditions. Therefore, it is infeasible to replace batteries for the sensor nodes [13]–[16]. Therefore, the network energy becomes the bottleneck for the lifetime of the WSN [17]–[20]. In order to address the problems above, we propose an Event-driven Mechanism Coverage Algorithm based on Sensing-cloud -computing in Heterogeneous Sensor Networks (EMC-SC). This algorithm first computes the membership among different nodes to determine the joint node coverage association model. The probabilistic theory is used to derive the redundant coverage degree for neighbor nodes and the minimal number of sensor nodes, as well as the expectation of the first coverage over on the node of target. Finally, the results of the simulation show that the EMC-SC algorithm which is proposed could improve the coverage rate of the network and the network lifetime, which verifies the effectiveness and the validity of the algorithm which is proposed.

II. RELATED WORKS

Some researchers, in recent years, have conducted many works on the network coverage and lifetime of the network of the WSN. A geometry-based calculation method was proposed in paper [21]. This algorithm assumes that all of the nodes of sensor share sensing radius which are the same, and a geometry-based calculation method is used calculate the minimal amount of sensor nodes required for the coverage which is complete over the monitoring area. A Data Storage and Retrieval Using Mobile Sinks (SRMSN) algorithm was proposed in paper [22] for WSNs. Two heuristic methods are employed by this algorithm, i.e., virtual grid partitioning technique and multivariate factor analysis. The aim of this algorithm is to guarantee that the mobile Sink is at the optimal location in each time interval, meanwhile the assembly node stays at the location assigned by the Sink. In addition, the self-adaptive function is employed each time to guarantee the optimal distance, which could improve the adaptivity and coverage efficiency of the WSN. A coverage optimization algorithm was proposed for mobile targets in paper [23]. This algorithm considers the direction and velocity of the mobile target in the area which is monitoring. The state transition mechanism of the nodes of the sensor is employed to complete the coverage of the node which is of mobile target. The Poisson model is considered in paper [24] for the random deployment of the nodes to reach the effective coverage for all the nodes in the area of monitoring. Three methods are proposed in paper [24] to compute the maximal area of coverage when the nodes of the sensor perform the seamless coverage. An Optimized Clustering Communication Protocol Based on Intelligent Computing (CCP-IC) was put forward in paper [25], where the intelligent algorithm is used to optimize the clustering in the WSN. In addition, the heuristic function and the function of the adaptation are explained to choose the next hop for the cluster head. The threshold parameter which is controllable and the mutation coefficient are utilized for the optimized choice of the shortest path in the routing of the network. Thus, the consumption of the energy is reduced for the WSN. A time synchronization based k-degree coverage maintenance protocol was proposed in paper [26]. The time sequence decision method is employed for the boundary coverage. The time sequence is utilized to determine the temporal relationship of the nodes at different states and finally achieves the time synchronization. During the coverage process, when the condition for the k-degree coverage is satisfied, this algorithm achieves the consecutive coverage on the node which is the target. Therefore, the coverage, which is effective, of the nodes of the target in the area of monitoring is completed. A network coverage model was proposed for the WSN in paper [27]. According to the scheduling strategy of this coverage model, effective coverage can be achieved for the coverage voids. Therefore, the coverage blind areas are eliminated. The partitioning-based coverage algorithm was proposed in paper [28] and the entire monitoring area is partitioned into several sub-areas. Each sub-area is guaranteed to lie in a cluster. Therefore, the effective coverage for the sub-area is accomplished by the cluster members. In terms of maximizing the network lifetime, a minimal dominant set based algorithm was put forward in paper [29]. In the algorithm, when a certain coverage rate is satisfied, the trimming algorithm is utilized to decrease the amount of nodes on the link. Therefore, the consumption of the energy is reduced and the lifetime of the network is prolonged. A non-linear node state transition mechanism was proposed in paper [30]. In this mechanism, the transition among three different node states is employed to save the energy. Based on the research in paper [30], a further modification was made in paper [31]. In paper [31], within each time intervals, an arbitrary subset of sensor nodes are in work state, while the remaining nodes are in other states. At the end of the interval of time, the subset ID is opened via the time sequence and the operations above are repeated. A single node set coverage algorithm is proposed in paper [32]. In this algorithm, the nodes within the network are divided into several subsets according to the geological location. Then in an arbitrary time, only one subset of nodes is in work state. When the target node leaves the subset, this subset sends the awakening message to the neighboring subset. If the neighboring subset fails to sense the target node within time t, this subset will be closed to save energy. The connected coverage based self-adaptive monitoring sensing algorithm was proposed in paper [33]. In this algorithm, when a certain connection rate is satisfied, the nodes monitor the state of neighbor nodes and adjust its own state accordingly. That is, local nodes in sleep state are awakened in each period to monitor the state of its sensing neighbor. If the state of its sensing neighbor does not change, this node will remain in sleep mode to save energy.

The algorithms described above conducted research on the coverage optimization and network lifetime from different perspectives. However, the shortcomings of the research above are listed as follows. (1) The coverage model is too simple while the analysis, computation and algorithm are too complicated for realization. (2) The membership relationship which is between the target node and the sensor node is not considered for the problem of the coverage problem. (3) During the process of the coverage on the node of the target, the sensor node energy consumption and the network energy are not considered. (4) Resource scheduling is not considered for the problem of the coverage and the problem of the maximization of the network lifetime. So based on the work in paper [22] and paper [25], a related network coverage model is proposed in this work. In addition, the probabilistic theory is used to analyze and compute the rate of the network coverage and the problem of the maximization of the network lifetime. At last, the results of the simulation are provided to verify the effectiveness and the validity of the proposed EMC-SC algorithm.

III. PROBABILISTIC MODEL AND COVERAGE ANALYSIS

A. BASIC ASSUMPTIONS

Since the WSN is seriously affected by the natural environment, e.g., storm and rain. The unpredictability brings challenges to the theoretical analysis of the WSN. For the investigation convenience, we perform our analysis based on the assumptions which are following.

(1) The monitoring are of all the sensor nodes are in the shape of a circle. All the nodes are in isomorphic state at the initial time.

(2) The boundary effect is ignored. The radius of sensing is much smaller than the edge length of the area of monitoring. All the nodes of sensor in the area of monitoring are associated to the network.

(3) The location of the whole sensor nodes can be acquired by the local locating algorithm, e.g., RSSI algorithm and TDOA algorithm. The location of different nodes remains mutually independent [34].

(4) In the area of monitoring, all the nodes of sensor are time synchronized. At the time, which initial is, of the network, all the nodes share the same properties.

(5) The node density is sufficiently large within the monitoring area.

B. BASIC DEFINITIONS

Definition 1: The intersection set between the coverage area of the node of the sensor and the monitoring area is defined as the effective area of coverage.

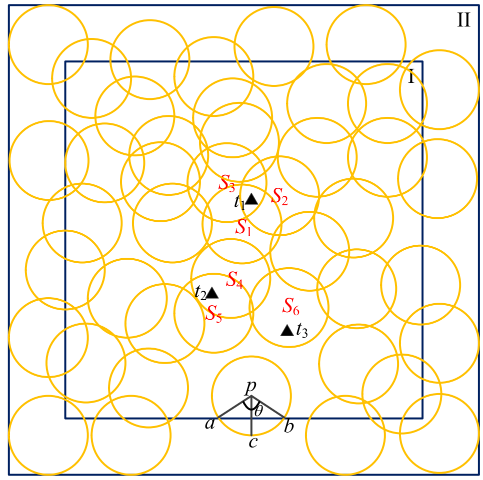

FIGURE 1. The membership relationship between the target node and the sensor nodes.

$$C_1 = \text{area}\,(\cup S_i) \cap \text{area}\,(A) \tag{1}$$

where S_i is the coverage area of an arbitrary node of sensor, area (A) is the size of the area which is monitoring, and C_1 is the effective coverage area.

Definition 2: The ratio of the coverage area which is effective to the monitoring area is defined as the coverage rate which is effective.

$$P = [\text{area}(\cup S_i) \cap \text{area}(A)]/\text{area}\,(A) \tag{2}$$

In which P is the coverage rate which is effective.

Definition 3: The entire network running time is defined as the network lifetime.

Definition 4: If the Euclidean distance which is between two sensor nodes is indeed smaller than the sum of the two sensing radius, as shown in equation (3), then these two nodes are defined as nodes of neighbor. The set of neighbor nodes is defined as the neighbor set.

$$d(i,j) \le R_i + R_j \tag{3}$$

In which $d\ (i, j)$ is the distance of Euclidean between two sensing nodes, R_i and R_j are the sensing radius for the sensor nodes.

C. NETWORK MODEL

In order to better investigate the membership between the target node and the sensor node in the coverage problem, the EMC-SC algorithm is based on the network model in Fig.1. As shown in Fig.1, the orange circle denotes the sensor nodes; the black triangle denotes the target node. The sensor node at the bottom intersects the monitoring area I at point a and b. The arc between a and b lies in monitoring area II. The angle between the lines from a to the circle center and b to the circle center is θ.

It is shown in Fig.1 that t_1 which is a target node is associated with S_1, S_2 and S_3, which are sensor nodes. Thus, the membership relationship is $t_1 \rightarrow \{S_i|S_1, S_2, S_3\}$. Similarly, t_2 follows the membership to S_4 and S_5, t_3 follows the membership to S_6. According to the membership relationship, t_1 is covered by three sensor nodes, i.e., $k = 3$ and t_1 receives 3-degree coverage. When the amount of sensor node increases, the coverage degree of t_1 will increase and t_1 becomes the target node. More redundant data will be generated as the coverage degree for t_1 further increases. In order to have an appropriate coverage degree for t_1, we will verify the expectation on the node coverage in Section IV.

D. COVERAGE ANALYSIS

We take Fig.1 as an example for the analysis. The monitoring area is divided by two squares, while the inner one is denoted by I and the outer one is denoted by II. A finite set is constructed and the nodes of sensor deployed randomly in the monitoring are included in the set which is finite. The area of the node coverage is denoted as $E(C_i)$. Correspondingly, the coverage area which is effective is $E(C_i)/A$. When the sensor nodes set is empty, the rate of the network coverage provided by n randomly deployed sensor nodes is:

$$P(S) = (1 - E(C_i)/A)^n \tag{4}$$

Therefore, while the nodes set of sensor is not empty, the coverage rate of the network is:

$$P(S) = 1 - (1 - E(C_i)/A)^n \tag{5}$$

Theorem 1: In the entire area of monitoring, the coverage expectation of the sensor node is:

$$E(C) = (R_s/l)^2[\pi(l-2R_s)^2 + 2(l - R_s)((2\pi+1)R_s + (\pi/2))]$$

Proof: While the amount of sensor nodes tends to infinity, the whole area of monitoring will be covered, fully. Considering the effect of the boundary, we divide the entire monitoring area by two squares, I and II. The edge length of the outer square is l and that of the inner square is $l - 2R_s$. According to the probabilistic theory, for the area of entire monitoring, the sensor node expectation of the coverage is:

$$E(C) = P(A_{\rm I})\, E(C_{A\rm I}) + P(A_{\rm II})\, E(C_{A\rm II}) \tag{6}$$

where $P(A_{\rm I})$ and $P(A_{\rm II})$ denote the coverage rate in region I and region II, $E(C_{A\rm I})$ and $E(C_{A\rm II})$ denote the coverage expectation in region I and region II, respectively. According to the uniform distribution function, we have:

$$P(A_{\rm I}) = (l - 2R_S)^2/l^2 \tag{7}$$

$$P(A_{\rm II}) = 4R_s(l - R_S)/l^2 \tag{8}$$

When the node of the sensor p is located in the inner monitoring area, the coverage expectation is:

$$E(C_{A\rm I}) = \pi R_s^2 \tag{9}$$

While the node p which is the sensor is located between the inner monitoring area and the outer monitoring area, the area of the coverage which is effective is equal to the size of the differential area between the circle and the arc S_{acb}. With $\theta = 2\arccos(y/R_s)$, the coverage expectation of outer monitoring area is:

$$E(C_{A\rm II}) = \frac{1}{2}\int_0^{l-R_s}\int_0^{R_s} \frac{R_s^2(2\pi - \theta + \sin\theta)}{(l - R_s)R_s} \mathrm{d}x\mathrm{d}y \tag{10}$$

Substituting (7) and (10) into (6), we have:

$$E(C) = \frac{1}{l^2}\left[\pi R_s^2(l - 2R_s)^2\right] + \frac{1}{l^2}\left[2R_s^2\int_0^{l-R_s}\int_0^{R_s}(2\pi - \theta + \sin\theta)\right]\mathrm{d}x\mathrm{d}y \tag{11}$$

After the calculation, we have:

$$E(C) = (R_s/l)^2[\pi(l-2R_s)^2 + 2(l - R_s)((2\pi + 1)R_s + (\pi/2))] \tag{12}$$

The proof is completed.

Corollary 1: The minimal amount of the nodes in the network is: $n = \ln(1-\varepsilon)/\ln(1 - E(C)/A)$, where ε is an arbitrarily small parameter.

Proof: As long as one sensor node exists in the monitoring area, the network coverage must be no smaller than ε. According to (5), we have:

$$P(S) = 1 - (1 - E(C_i)/A)^n \geq \varepsilon \tag{13}$$

Further simplify (13) and take the logarithm operation, we have:

$$\ln(1 - \varepsilon) \geq n\ln(1 - E(C)/A) \tag{14}$$

Then n can be solved as

$$n \leq \ln(1 - \varepsilon)/\ln(1 - E(C)/A) \tag{15}$$

Therefore, the minimal amount of nodes in the network is $n = \ln(1-\varepsilon)/\ln(1 - E(C)/A)$. The proof is completed.

IV. COVERAGE QUALITY

A. REDUNDANT COVERAGE

According to Fig.1, when the amount of sensor nodes increases, the degree of the coverage for the node of target t_1 will also increase. Therefore, the redundant data generated for target node t_1 will increase dramatically. As a result of that, the amount of the data communication in the network will rise and the channel is more congested, which undermines the effective screening and increases the network burden [35]–[39]. Therefore, the maintenance of an appropriate coverage degree for target node t_1 and picking out the redundant data are the key research topics in this Section.

Take Fig.1 as an example. First, we establish the membership relationship between the sensor node and the target node, and calculate the distance of the Euclidean $d_{(i,j)}$ from the sensor node to the target node via the RSSI algorithm or the TDOA algorithm. When the Euclidean distance $d_{(i,j)} \leq R_c$ and the number of nodes with distance from t_1 larger than $d_{(i,j)}$ is over the coverage degree upper bound $k = 3$, we will calculate the coverage expectation for any node according to Theorem 1. All the nodes are ordered according to the coverage expectation, while the nodes with lower expectation will be shut down. The main problem is that the coverage which is over the target node is not completed by a single node. Instead, the coverage is achieved by multiple neighbor nodes. During the redundant coverage process, we need to consider the expected amount of nodes of neighbor when a coverage rate is satisfied. Therefore, Theorem 2 is introduced.

Theorem 2: When the coverage rate on the node of the target is maintained with a certain level, the expected amount of sensor nodes which is neighboring is:

$$E(N) = \frac{4\pi R_0^2 + 2\pi\delta^2}{\text{area}(A)}\left[\ln(1-\varepsilon)/\ln(1-E(C)/A) - 1\right]$$

Proof: According to the known conditions, when the node of the target is covered with a certain level, we switch the conditions for the redundant nodes, e.g., sleep state or the shut-down state. According to (15), the minimal number of working neighbor nodes is:

$$N = \ln(1-\varepsilon)/\ln(1-E(C)/A) \tag{16}$$

If two sensor nodes a and b are neighbor nodes, with sensing radius R_a and R_b, Then according to definition 4, the coverage area for an arbitrary node lies within radius $R_a + R_b$. The coverage rate for neighbor node b is:

$$P_b = \frac{\text{area}(\varphi(a, R_a + R_b))}{\text{area}(A)} \tag{17}$$

where $\phi(a, R_a + R_b)$ denotes a circle centered by node a with radius $R_a + R_b$. Since the sensing radius of a sensor node follows the Gaussian distribution $N(R_0, \delta^2)$ and satisfies $R_0 \geq 3.3\delta$, the coverage rate for the neighbor node is:

$$p = \int_0^{2R_0}\int_0^{2R_0} P_b \frac{1}{2\pi\delta^2}\exp \times \left[-\frac{(R_a - R_0)^2 + (R_b - R_0)^2}{2\delta^2}\right] dR_a dR_b \tag{18}$$

According to the symmetry property of the function, we have:

$$\int_0^{2R_0}\int_0^{2R_0} \frac{R_a^2}{2\delta^2}\exp\left[-\frac{(R_a - R_0)^2 + (R_b - R_0)^2}{2\delta^2}\right] dR_a dR_b \approx \pi\left(R_0^2 + \delta^2\right) \tag{19}$$

Let $x = \frac{R_a - R_0}{\delta}$ and substitute x into (19), we have:

$$\int_{-\frac{R_0}{\delta}}^{\frac{R_0}{\delta}} \left(R_0^2 + \delta x\right)\frac{1}{\sqrt{2\pi}}\exp\left(\frac{x^2}{2}\right) dx = R_0 \tag{20}$$

Therefore,

$$\int_0^{2R_0}\int_0^{2R_0} \frac{R_a R_b}{\delta^2}\exp\left[-\frac{(R_a - R_0)^2 + (R_b - R_0)^2}{2\delta^2}\right] dR_a dR_b = 2\pi R_0^2 \tag{21}$$

Henceforth, in the area of monitoring, the rate of the coverage for the neighbor node is:

$$P = \frac{2\pi\left(R_0^2 + \delta^2\right) + 2\pi R_0^2}{\text{area}(A)} = \frac{4\pi R_0^2 + 2\pi\delta^2}{\text{area}(A)} \tag{22}$$

Among all the N neighbor nodes, the expected coverage rate for an arbitrary neighbor is:

$$E(N) = P(E(n) - 1) \tag{23}$$

Substitute (15) and (22) into (23), we have:

$$E(N) = \frac{4\pi R_0^2 + 2\pi\delta^2}{\text{area}(A)}\left[\ln(1-\varepsilon)/\ln(1-E(C)/A) - 1\right] \tag{24}$$

The proof is completed.

B. K-FOLD COVERAGE RATE

Take Fig. 1 as an example. For a square monitoring area with an edge whose length is L is showed, if the configurations are made manually and the mode radius of the sensing is R, after that $\left\lceil l/\sqrt{2}R \right\rceil^2$ nodes can be covered fully. Denote P_1 as the probability that a node of arbitrary in the area of monitoring is covered by one node of sensor at least. If one node of target is covered by the nodes of sensor, then the distance from at least one node of the sensor to the node of the target is not larger than R. The probability that the distance from N sensor nodes to the target node is no larger than R is:

$$P_1 = 1 - \left(1 - \frac{\pi R^2}{A}\right)^N \tag{25}$$

Denote P_k as the probability that a target node of arbitrary in the area of the monitoring is k-fold covered ($k \geq 2$). If a node of target is k-fold covered, then k sensor nodes are located in the circle centered by this target node with radius R at least. Since the nodes of sensor are deployed uniformly and randomly in the monitoring area and the boundary effect is ignored, the probability that exactly i sensor nodes fall into this circle is:

$$P_k' = C_N^i\left(\frac{\pi R^2}{A}\right)^i\left(1 - \frac{\pi R^2}{A}\right)^{N-i} \tag{26}$$

$$P_k = 1 - \sum_{i=0}^{k-1} C_N^i\left(\frac{\pi R^2}{A}\right)^i\left(1 - \frac{\pi R^2}{A}\right)^{N-i} \tag{27}$$

If $P_k = 99\%$, on average, 99 out of 100 randomly chosen target nodes in the monitoring area is covered by k sensor nodes. Therefore, P_k is also the proportion of the area where the area of monitoring is k-fold covered. $P_k < 1$ indicates that there are coverage blind areas in the area of the monitoring. Since the nodes of sensor are deployed randomly in the area of monitoring, it is possible that an arbitrary node of target which is in the area of the monitoring is covered when the deployment density is high. When an arbitrary node of target in the area of the monitoring is covered, the probability of full coverage is P_{fc}:

$$P_{fc} = \frac{\sum_{i=0}^{k-1} C_N^i f\left(s_i, m, n\right)}{\sum_{i=0}^{k-1}\left(\pi R\left(\frac{\pi R^2}{A}\right)^i\left(1-\frac{\pi R^2}{A}\right)^{N-i}+f\left(s_i, m, n\right)\right)} \tag{28}$$

where $f(s_i, m, n)$ is defined as:

$$f\left(s_i, m, n\right) = \int_0^l u^{m-1}(1-u)^{n-1}\,\mathrm{d}u \tag{29}$$

$$s.t\ \begin{cases} s_i = \pi R_i^2 \\ m = i+1 \\ n = N-i+1 \end{cases} \tag{30}$$

If $P_{fc} = 99\%$, when N nodes are randomly deployed 100 times, an average of 99 times the area of the monitoring achieves k-fold complete coverage.

Theorem 3: When an arbitrary sensor node works with probability η, the probability of k-fold coverage is:

$$P_k(\eta) = 1-\sum_{i=0}^{k-1} C_N^i\left(\eta\frac{\pi R^2}{A}\right)^i\left(1-\eta\frac{\pi R^2}{A}\right)^{N-i}$$

Proof: Since all the sensor nodes are mutually independent, the probability that exactly n sensor nodes are in work state is:

$$P_n = C_N^n \eta^n (1-\eta)^{N-n} \tag{31}$$

Since the sensor nodes are uniformly distributed, the probability that exactly i out of n nodes of sensor fall in the area of size πR^2 is:

$$P_n^{'} = \sum_{n=i}^{n} C_N^n \eta^n (1-\eta)^{N-n} C_n^i\left(\frac{\pi R^2}{A}\right)^i\left(1-\frac{\pi R^2}{A}\right)^{n-i} \tag{32}$$

Further simplify (32), we have:

$$P_n^{'} = \sum_{n=i}^{n} C_N^n C_n^i (1-\eta)^{N-n}\left(\eta\frac{\pi R^2}{A}\right)^i\left(\eta-\eta\frac{\pi R^2}{A}\right)^{n-i} \tag{33}$$

According to the equation $C_N^n C_n^i = C_N^i C_{N-i}^{n-i}$, we further calculate (33) as

$$P_n^{'} = C_N^i\left(\eta\frac{\pi R^2}{A}\right)^i\sum_{i=0}^{N-i} C_{N-i}^{n-i}\left(\eta-\eta\frac{\pi R^2}{A}\right)^{n-i}(1-\eta)^{N-n} \tag{34}$$

Simplify (34) and we have:

$$P_n^{'} = C_N^i\left(\eta\frac{\pi R^2}{A}\right)^i\left(1-\eta\frac{\pi R^2}{A}\right)^{N-i} \tag{35}$$

When the boundary effect is ignored, we have the probability that the area of the monitoring is k-fold covered:

$$P_k(\eta) = 1-\sum_{i=0}^{k-1} C_N^i\left(\eta\frac{\pi R^2}{A}\right)^i\left(1-\eta\frac{\pi R^2}{A}\right)^{N-i} \tag{36}$$

The proof is completed.

C. ANALYSIS FOR THE EMC-SC ALGORITHM

The basic ideology of the EMC-SC algorithm is explained as follows. Firstly, at the network initial time, partial nodes of the sensor are chosen and set in work state, while the other nodes are in listening state or shut-down state. Then, according to Theorem 1, the coverage expectation is calculated for the nodes of sensor within the area of monitoring, and the minimal amount of sensor nodes is determined to complete the full coverage. In the meantime, the link is established to store the coverage degree of the target node. Next, after several rounds, when a node of target has a large amount of data which are redundant, under the condition of maintaining a certain coverage level for the target node, the expectation of the redundant coverage degree is derived according to Theorem 2 and the link is updated. Finally, the nodes which fail to satisfy the expectation of the redundant coverage degree are shut down to save the energy consumption of the network and prolong the lifetime of the network.

Compared with the algorithms in paper [22] and [25], the proposed EMC-SC algorithm could employ the expectation of the sensor node coverage and the amount of neighbor nodes to calculate the redundant coverage degree. Under the condition of maintaining a certain coverage level, the nodes which fail to satisfy the expectation of the redundant coverage degree are shut down. By contrast, the nodes satisfying the condition are switched on in turn to save the network energy. However, the other two algorithms achieve the coverage via the clustering algorithm. In the clustering procedure, the transition of the message between the heads of cluster and the cluster members is employed to switch on or off the nodes. Node energy is consumed in the transmission, forwarding, and reception steps of the message. Therefore, the proposed EMC-SC algorithm is more efficient in terms of the network energy. The EMC-SC algorithm is described as follows.

Step1: Part of the sensor nodes are chosen and switched on randomly. These nodes are set into work state.

Step2: According to the sensor nodes coverage, the membership relationship is utilized to determine the relationship of association between the node of the sensor and the nodes of the target.

Step3: When the amount of nodes of sensor increases, the coverage expectation of the area of the monitoring is calculated by Theorem 1. Then, the minimal amount of sensor nodes is determined.

Step4: While the quantity of redundant coverage nodes reaches the upper bound, under the condition of maintaining coverage rate which is certain, the expected amount of neighbor nodes is calculated via Theorem 2.

Step5: After determining the expected number of neighbor nodes, the mechanism of the energy switching is employed to shut down the nodes of sensor with energy below the expectation.

Step6: When the target node becomes the non-focus node, return to Step 1.

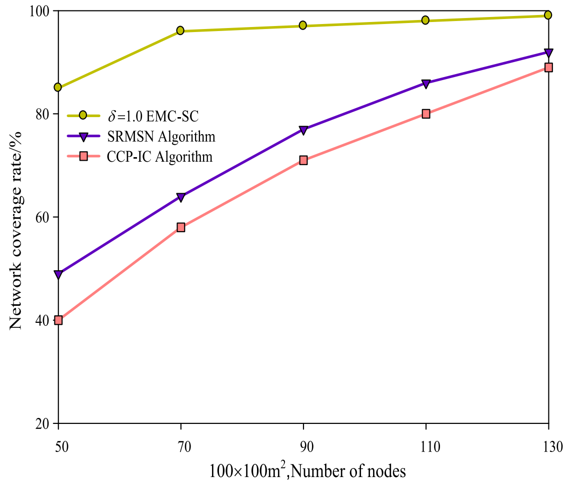

FIGURE 2. Coverage rate with different amount of nodes in area of the monitoring with size $100\times100m^2$.

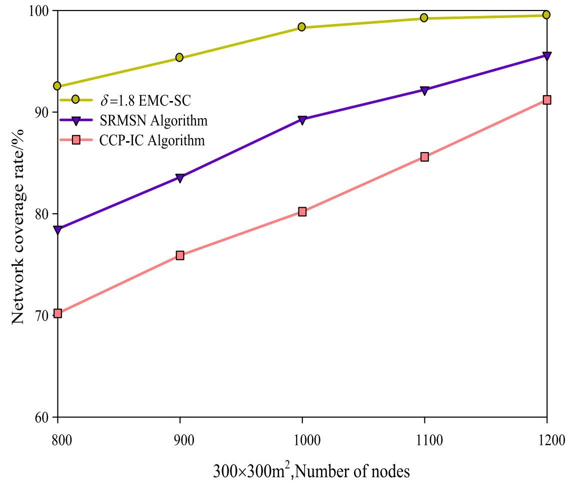

FIGURE 4. Coverage rate with different amount of nodes in area of the monitoring with size $300\times300m^2$.

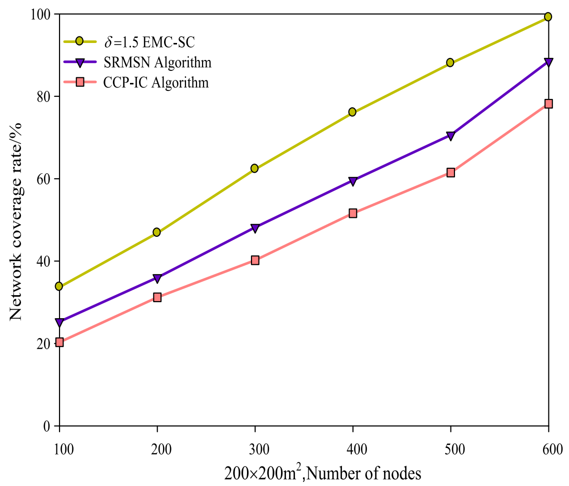

FIGURE 3. Coverage rate with different amount of nodes in area of the monitoring with size $200\times200m^2$.

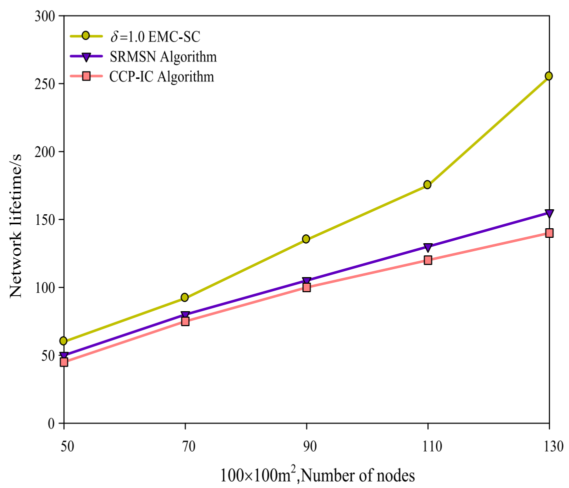

FIGURE 5. Network lifetime with different amount of nodes in area of the monitoring with size $100\times100m^2$.

V. PERFORMANCE EVALUATIONS

In order that we can further verify the validity and effectiveness of the EMC-SC algorithm which is proposed, we consider the coverage rate of the network and the lifetime performances of the network and compare the proposed EMC-SC algorithm with the algorithms in paper [22] and [25]. The MATLAB8.0 platform is employed for the simulations and the node energy is 5J. The sensing radius of the sensor nodes is randomly generated and the radius is larger than 1m. The different sizes of the area of the monitoring are $100\times100m^2$, $200\times200m^2$, $300\times300m^2$. The simulations are repeated 100 times and the boundary effect is ignored.

A. COMPARISON ON NETWORK COVERAGE RATE WITH SINGLE VARIABLE

The network coverage rate performances with different size of monitoring areas are illustrated in Fig. 2 to Fig. 4. Take Fig. 2 as an example. It is shown in Fig. 2 that for all the three algorithms, the rate of network coverage increases with the amount of sensor nodes. The proposed algorithm in this work outperforms the other two algorithms and exhibit faster improvement. When $\delta = 1.0$, $N = 70$, the proposed EMC-SC algorithm tends to be stable. The main reason behind this result is that the association relationship among the sensor nodes is utilized by this algorithm to determine the membership relationship between the target nodes and the sensor node. Then the expectation of the coverage of the neighbor nodes is calculated to shut down the nodes below this expectation. Therefore, the area of the monitoring coverage quality is improved. Because of redundant coverage, that sensing radius of the sensor nodes is randomly generated. Via Theorem 2, we first compute the expectation of the redundant coverage, according to which the nodes are ordered. Then the nodes with lower expected redundant coverage are shut down. According to the start switching mechanism of the nodes of sensor, the sensor nodes are switched among different states. Finally, a certain coverage rate is maintained when the sensor

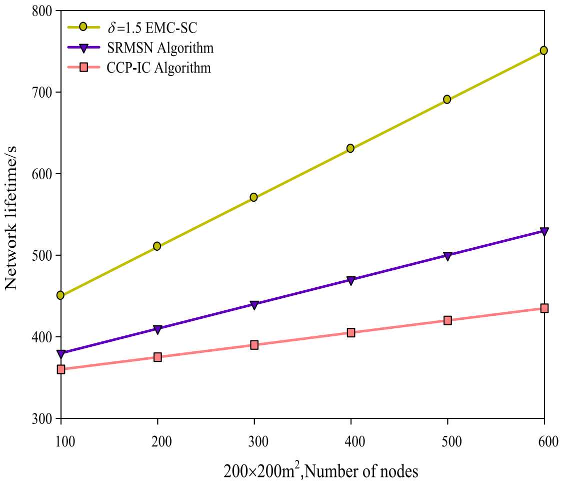

FIGURE 6. **Network lifetime with different amount of nodes in area of the monitoring with size 200×200m^2.**

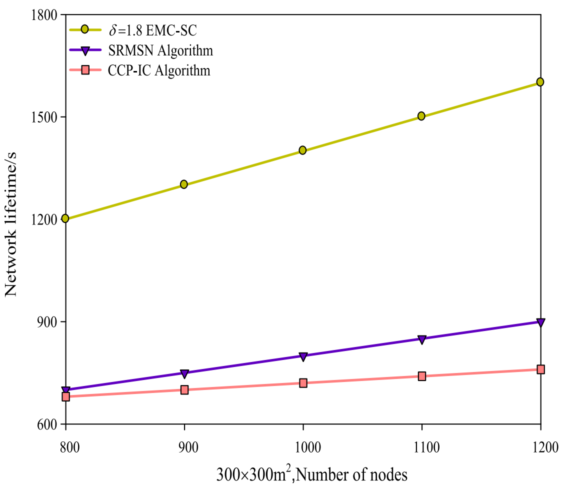

FIGURE 7. **Network lifetime with different amount of nodes in area of the monitoring with size 300×300m^2.**

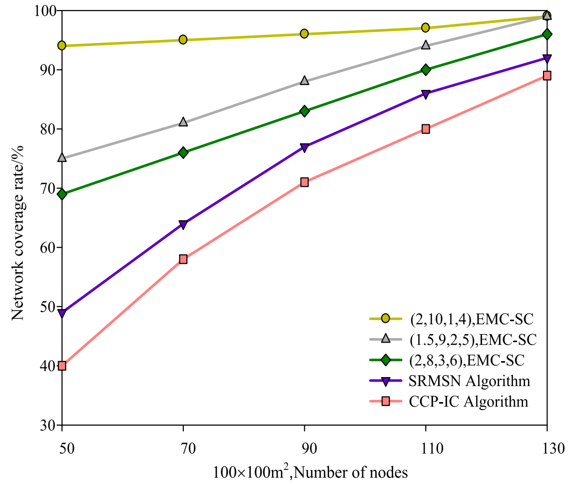

FIGURE 8. **Network coverage rate with different sets of parameters in area of the monitoring with size 100×100m^2.**

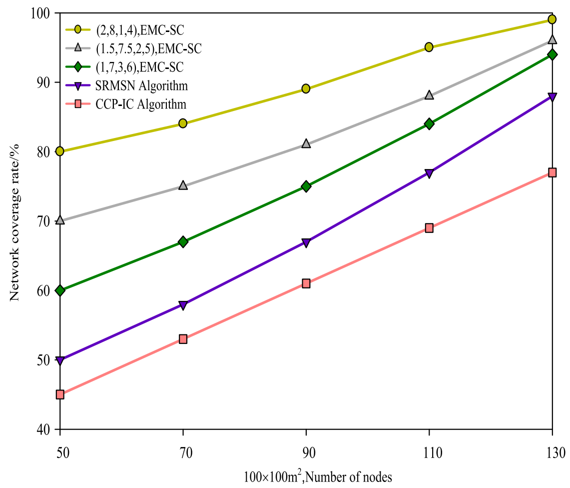

FIGURE 9. **Network coverage rate with different sets of parameters in area of the monitoring with size 100×100m^2.**

nodes cover the target nodes. By contrast, the other two algorithms mainly adopt the consecutive coverage method for the nodes of sensor to complete the coverage which is complete over the area of the monitoring. In addition, the cluster heads in the clustering structure are employed to control the coverage range and achieve the effective coverage. Therefore, if the other two algorithms are compared with this, the algorithm which is proposed could improve the coverage rate of the network by 17.39% on average. Similar observations can be found in Fig. 3 and Fig. 4.

B. COMPARISON ON NETWORK LIFETIME WITH SINGLE VARIABLE

The lifetime performances of the network with distinct size of monitoring areas are illustrated in Fig. 5 to Fig. 7. Take Fig. 5 as a case. The lifetime of the network increases with the amount of sensor nodes for all the three algorithms. The EMC-SC algorithm which is proposed outperforms the other two algorithms and exhibits faster improvement. When $\delta = 1.0$, $N = 110$, the proposed EMC-SC algorithm shows prominent improvement on the network lifetime. The main reason behind this is that the proposed algorithm calculates the expected redundant coverage for the neighbor nodes. Then the expectation of the coverage for any neighbor node in the area of the monitoring can be obtained. The redundant nodes are ordered according to the expected redundant coverage for the neighbor nodes. When the expectation is lower than the calculation result, the corresponding neighbor node is shut down, while the remaining nodes are switched to different states, e.g., sleep, listening or pre-startup states, according to the node state switching mechanism. The aim of this mechanism is to guarantee that the scheduling mechanism at the nodes could effectively curb the consumption of energy at the sensor nodes and prolong the lifetime of the network. By contrast, the other two algorithms accomplish the switching of the node state by the state switching mechanism of the sensor nodes. For an arbitrary sensor node, e.g.,

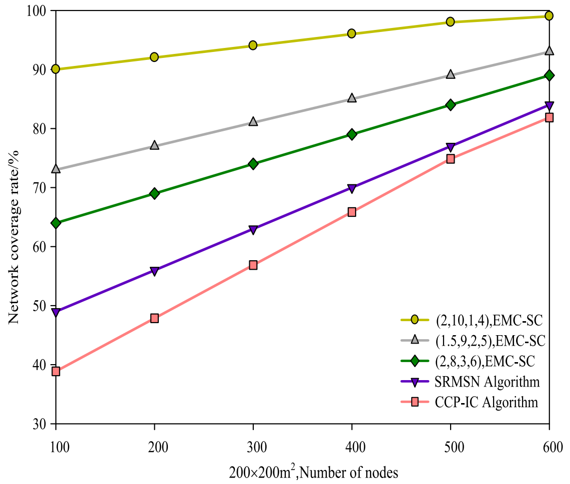

FIGURE 10. Network coverage rate with different sets of parameters in the area of the monitoring with size 200×200m^2.

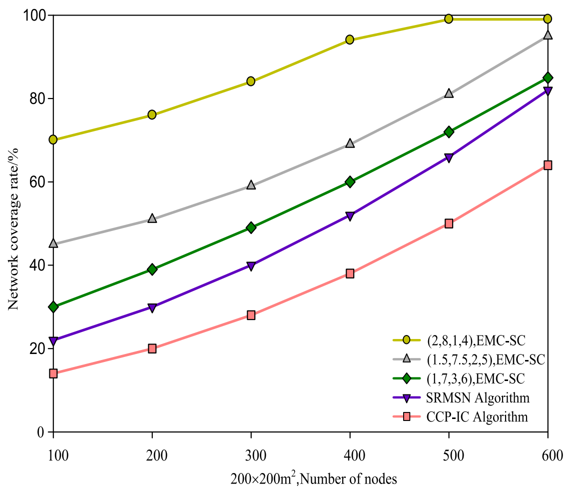

FIGURE 11. Network coverage rate with different sets of parameters in the monitoring area with size 200×200m^2.

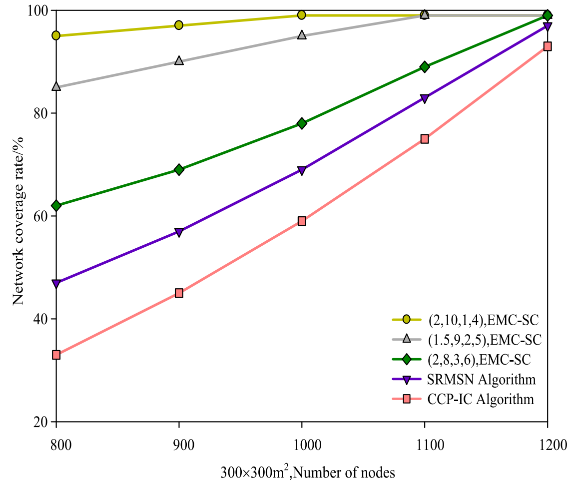

FIGURE 12. Network coverage rate with different sets of parameters in the area of the monitoring with size 300×300m^2.

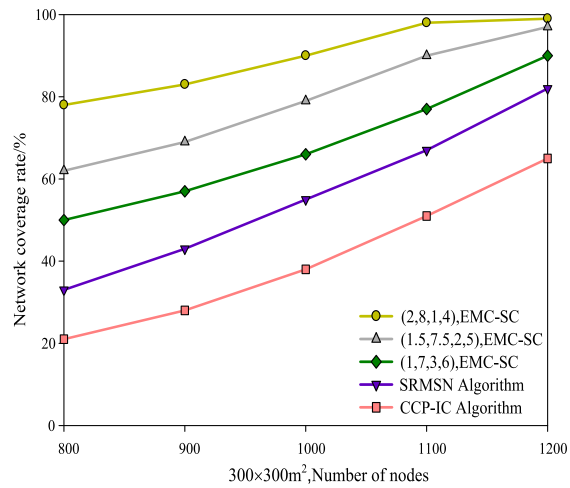

FIGURE 13. Network coverage rate with different sets of parameters in the area of the monitoring with size 300×300m^2.

the cluster head or the cluster members, energy is consumed at the transmission and reception of the messages, which undermines the energy efficiency of the network. On the other hand, neither of these two algorithms fails to consider the constraints on the network energy caused by the redundant nodes. When a large amount of redundant nodes exist in the network and remain in work state, they would exhaust the network energy. Therefore, the proposed EMC-SC algorithm could Outperform the other two algorithms in terms of the network lifetime. According to Fig.5, if the other two algorithms compared with this, the EMC-SC algorithm improves the network lifetime by 15.61%. Similar observations can be found in Fig. 6 and Fig. 7, respectively.

C. COMPARISON ON NETWORK COVERAGE RATE WITH MULTIPLE VARIABLES

The comparisons above are conducted with a single variable. In order that we can further verify the network coverage rate and network lifetime performances of the proposed algorithm with multiple variables, we consider the following parameters $\delta \in [1, 2]$, $R_0 \in [7, 10]$, $R_a \in [1, 3]$, $R_b \in [4, 7]$. The energy of the sensor nodes is 5J. Four different configurations are taken as the multiple of 0.5 and we assume two sets of different parameters, i.e., (δ, R_0, R_a, R_b). The sizes of the area of the monitoring for the simulations are 100×100m^2, 200×200m^2, and 300×300m^2, respectively. Again, MATLAB8.0is adopted as the platform for the simulations and the results are averaged over 100 repetitions.

The network coverage rate performances of the proposed EMC-SC algorithms and the algorithms in [13] and [15] are illustrated in Fig.8 to Fig.13 with two different sets of parameters. Taking Fig.8 and Fig.9 as an example, the size of the area of the monitoring is 100×100m^2. According to the results, when we take different sets of parameters (δ, R_0, R_a, R_b), the proposed EMC-SC algorithm could exhibit improved performances and the improvement speed is higher than that

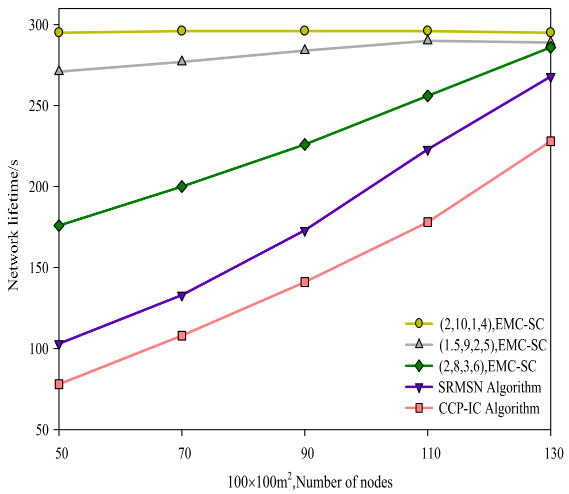

FIGURE 14. Network lifetime with different sets of parameters in the area of the monitoring with size 100×100m^2.

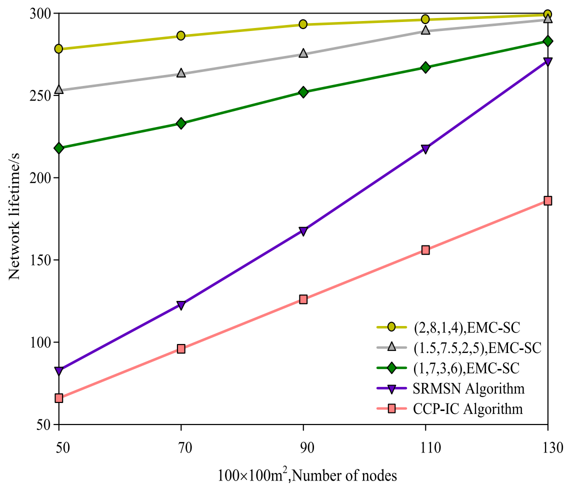

FIGURE 15. Network lifetime with different sets of parameters in the area of the monitoring with size 100×100m^2.

of the other two algorithms. The main reason behind this is that with a larger δ, the sensor nodes are more evenly distributed. Therefore, the coverage area is larger. If the sensing radius $R_a + R_b$ is smaller, the neighbor redundant coverage rate will also become smaller. Therefore, when δ is larger and $R_a + R_b$ is smaller, the effective coverage rate is larger, and vice versa.

By contrast, the algorithms in paper [12] and [15] adopt a linear method, which mainly achieves consecutive coverage over the target node. In addition, the cluster head takes charge of sending and receiving messages and achieves the coverage over the target node within the cluster via the node scheduling mechanism. The two algorithms described above fail to consider the existence of redundant nodes and the influence of the expected redundant coverage on the area of the monitoring. Instead, the cluster head and the cluster members take charge of the complete coverage on the node of target. It is shown that the algorithm which is proposed could improve the network

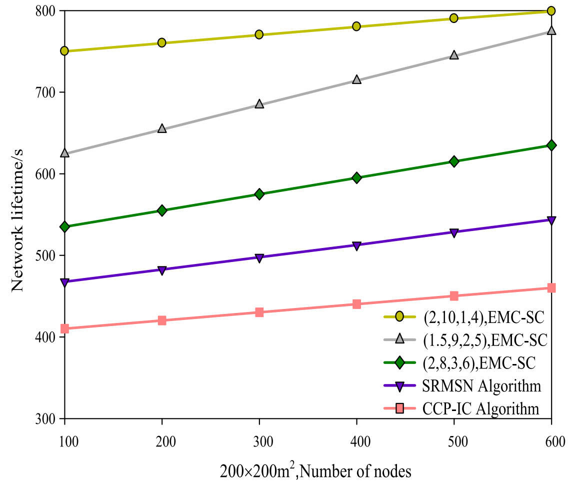

FIGURE 16. Network lifetime with different sets of parameters in the area of the monitoring with size 200×200m^2.

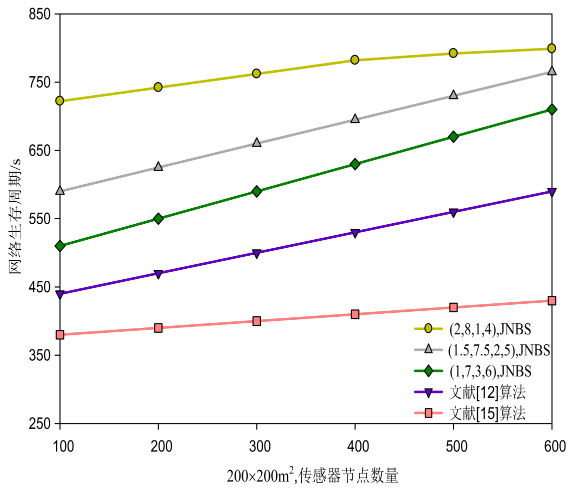

FIGURE 17. Network lifetime with different sets of parameters in the area of the monitoring with size 200×200m^2.

coverage rate by 15.05%. Similar observations can be found in Fig. 10 to Fig. 13.

D. COMPARISON ON NETWORK LIFETIME WITH MULTIPLE VARIABLES

The lifetime of the network performances with different sets of parameters are illustrated in Fig.14 to Fig.19.

The performances of the algorithms in paper [12] and [15] are also included for comparison. Take Fig.14 and Fig.15 as a case. It is shown that with different sets of parameters (2,10,1,4), (1.5,9,2,5), (2,8,1,4), and (1.5,7.5,2,5), the proposed algorithm could always exhibit a stable performance with little fluctuation. In addition, the proposed algorithm outperforms the other two algorithms on the lifetime of the network.

The main reason behind this is that when δ and R_0 increase simultaneously, the sensor nodes in the area of the monitoring are more evenly distributed. Since $R_a + R_b$ are the sens-

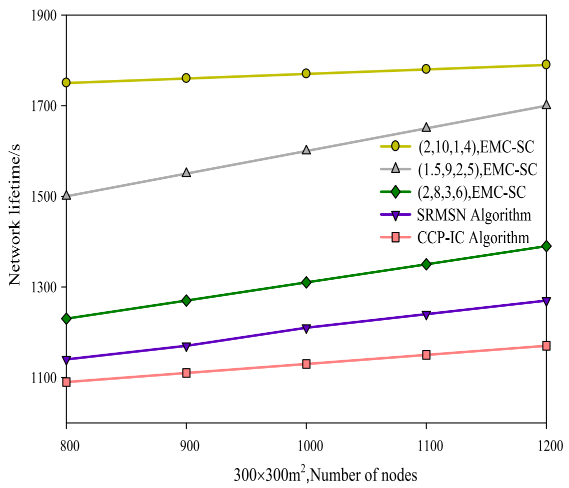

FIGURE 18. Network lifetime with different sets of parameters in the area of the monitoring with size 300×300m².

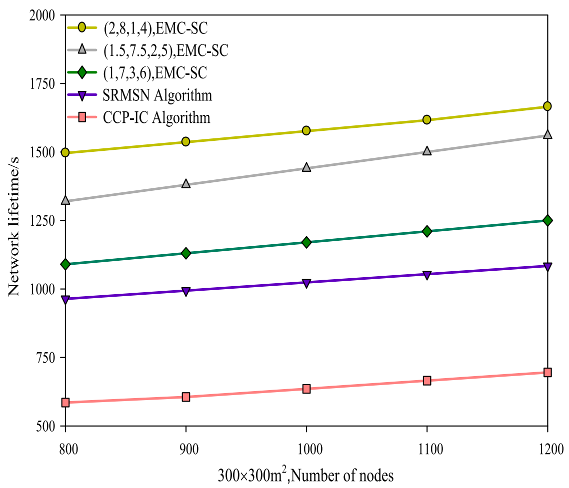

FIGURE 19. Network lifetime with different sets of parameters in the area of the monitoring with size 300×300m².

ing radius, a smaller radius could lead to smaller neighbor redundant coverage rate. Therefore, less network energy is consumed. When the amount of sensor nodes equals 50 and the set of parameters is (2, 8, 3, 6), the proposed EMC-SC algorithm also exhibit higher lifetime of the network than the other 2 algorithms. As the amount of sensor nodes increases, the lifetime of the network also increases for the algorithms in paper [12] and [15]. However, the improvement speed is lower than that of the proposed EMC-SC algorithm. The reason which is main behind this is that these two algorithms employs dynamic clustering to partition the area of the monitoring multiple times so that the sensor nodes which are with higher energy can serve as the cluster head, accomplish the state switching for the cluster members, and further prolong the lifetime of the network. On the other aspect, the other two algorithms fail to consider the influence of redundant nodes on the network lifetime and assume that all the nodes in the cluster are in a certain state. Therefore, the energy consumption caused by the normal working of the nodes is ignored. By contrast, the proposed EMC-SC algorithm could improve the lifetime of the network by 9.83%. Similar observations can be found in Fig. 16 to Fig. 19.

VI. CONCLUSIONS

Based on the analysis on related references, we proposed an EMC-SC algorithm. First, we constructed the network coverage model and provided the association relationship between the sensor node and the nodes of target. Then the membership relationship between the target node and the sensor nodes is determined. Next we used the probabilistic theory to derive the expected the network coverage and the minimal amount of sensor nodes. In addition, we analyzed the coverage expectation for the neighbor nodes. We employed the Gaussian distribution of the sensing radius to derive the coverage expectation for the neighbor nodes. Finally, simulation results verified the network coverage rate and network lifetime performances of the proposed algorithm.

Future work may be focused on the inter-layer coverage in WSNs and the optimization of the network lifetime with intelligent swarm algorithm.

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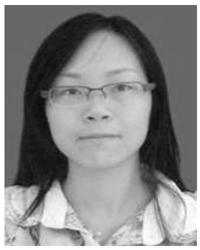

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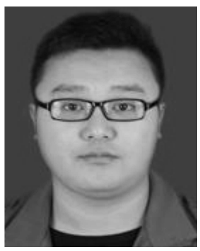

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