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A Novel Mobile-Coverage Scheme for Hybrid Sensor Networks

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ABSTRACT In this paper, a novel Mobile-Coverage scheme is proposed to improve the coverage and lifetime of hybrid sensor networks, and thus the target region can be completely covered with minimum number of *mobile* sensor nodes and the energy consumption can be reduced in hybrid sensor networks at the same time. Our scheme is applied to a hybrid network comprising of both static and *mobile* sensor nodes, which are randomly deployed in a rectangle area. We derived the minimum number of sensor nodes as well as the *mobile* nodes required to cover the target region completely. Compared to the existing works, the minimum number of *mobile* sensor nodes required in this paper is significantly smaller, which implies that the movement distance and energy consumption of *mobile* nodes in our scheme is reduced. Moreover, we proved that the construction of our scheme based on the Virtual Force and Voronoi Graph (VFVG) is correct, and then derived the optimal trade-off between the coverage of the target region and energy consumption of *mobile* nodes. Our scheme can achieve the maximum coverage which is 98.7% by minimum number of *mobile* sensor nodes. Meanwhile, a connectivity rate of 76.84% can also be achieved by our connectivity evaluation method. Finally, a new topology construction algorithm-Topology Construction and Maintenance based on Trust (TCMT) is created to further increase the lifetime of the sensor network. We also evaluated the performance of our scheme in terms of coverage and lifetime, and carried out extensive experiments to compare the coverage and energy consumption in our scheme and several previous schemes. The experimental results showed that our scheme is more efficient than the previous schemes simulated.

INDEX TERMS Topology construction and maintain, minimum numbers of *mobile* sensor, voronoi graph, virtual force, TCMT.

I. INTRODUCTION

Over the past decades, with the rapid development of wireless sensor technologies and embedded systems, WSNs (Wireless Sensor Networks) [1], [2] have become one of the most important technologies in the IOT (Internet of Things) industry [3] to meet the requirements on mobility, self-organization, as well as scalability of wireless communications. Therefore, WSNs have been widely implemented in the fields of agriculture [4], medicine [5], industry [6], and military [7]. Recently, it has also been applied to the fields of intelligent communication, intelligent home and smart city.

However, with the widespread implementation of WSNs, various issues have been gradually exposed which are urgent to be solved. In some extreme environments like the underwater scenario [8] or desert [9], deploying nodes massively are technically challenging and economically expensive, and sensor nodes are usually left unattended. Therefore, it is essential to propose a random deployment [10] scheme, such as the airdrop scheme [11], to obtain sufficient information from the target area with as few sensor nodes as possible.

Recently, various schemes to address the random deployment problem under the situation of two-dimensional plane have been proposed. It has been substantially shown in [12] that the regular hexagonal deployment is optimal in two-dimensional network. However, this particular deployment method is impractical. Furthermore, in *mobile* sensor networks, sensor nodes moving to a hexagonal target will greatly increase energy consumption and degrade the

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performance of sensor networks. In this paper, we mainly focus on the coverage strategy in two-dimensional hybrid WSNs, in which the coverage and lifetime have been significantly improved. At present, random deployment methods can be classified into three categories, namely, the virtual force model [13], the computational geometry model [14], and the bio-geography model [15]. The virtual force model treats each sensor node as a virtual electron, which moves due to the gravity or repulsion. This kind of methods is usually utilized to derive the optimal node locations for networks with high node density in the center area. The positions of sensor nodes can also be adjusted via priori calculation which satisfies a certain geometric condition. Regarding the bio-geography model, previous researchers gave some cases, such as GA (Genetic Algorithm) [16], and ACA (Ant Colony Algorithm) [17], which allowed sensor nodes to adjust their positions by simulating biological habits.

However, the mode of sensor nodes is usually single in previous algorithm, which means that all sensor nodes are *mobile* in WSNs and move according to algorithmic iterations without energy constraints. However, in reality, sensor nodes are usually energy-limited, long-distance movement can fleetly consume the energy of sensor nodes and shorten the lifetime of WSNs. Therefore, the research on deployment of hybrid sensor nodes with limited energy has attracted tremendous attention in recent years. Wang *et al.* [18] gave a survey in which various random deployment algorithms for static and *mobile* sensor nodes as well as hybrid WSNs were discussed and compared.

In this paper, we aim at ascertaining the minimum number of sensor nodes to cover the target area completely, and obtaining the optimal ratio of *mobile* sensor nodes to static nodes under the optimal coverage. Normally, the smaller proportion of *mobile* nodes, the less energy consumption due to moving in WSNs. Meanwhile, the energy is also consumed by data transmission. After a while, some nodes run out of their energy and a new topology of sensor network needs to be established. A suitable topology can further improve the lifetime of WSNs.

The main contributions of this paper can be summarized as follows:

- A novel Mobile-Coverage scheme for random deployment to strike a balance between coverage and lifetime of WSNs is proposed. The novelty of our scheme is embodied in 1) the minimum number of sensor nodes required to completely cover the target area is derived mathematically, and the maximum coverage by the minimum number of sensor nodes is derived as well; 2) the optimal proportion of *mobile* nodes to balance the energy consumption and coverage of WSNs is calculated; 3) a new designed algorithm named virtual force and voronoi graph (VFVG) of *mobile* scheme is proposed to improve the coverage and reduce the moving distance; 4) a novel topology construction and maintenance algorithm (TCMT) is proposed to further extend the lifetime of WSNs.
- We show the correctness of the construction of our scheme. The optimal proportion of *mobile* nodes via calculating the relationship between the number of *mobile* nodes and the coverage in our scheme is proved, and the relationship between the number of *mobile* nodes and the moving distance is acquired under virtual force.
- We compare our scheme with some existing schemes via carrying out extensive experiments. The experimental results show that compared to the existing schemes, our scheme outperforms in efficiency.

The remainder of this paper is organized as follows. In Section II, some related works are surveyed. In Section III, the network model utilizing minimum number of nodes to cover the target region completely is demonstrated. In Section IV, the complete construction of our scheme is presented, followed with a VFVG algorithm increasing the coverage and reducing the energy consumption of WSNs. Additionally, a novel topology scheme TCMT (including the topology construction and maintenance) is proposed to further extends the lifetime of WSNs. In Section V, the performance of our scheme in terms of coverage and lifetime is evaluated. In addition, the comparison of coverage and lifetime in different procedures between our scheme and several previous schemes is conducted. In Section VI, some conclusions are drawn.

II. RELATED WORKS

In wireless sensor networks, the coverage, lifetime and topology construction of random-deployment of WSNs have aroused extensive concern in recent years. In this section, we survey the existing schemes which aim to increase the coverage and improve the lifetime via topology construction and maintenance in random-deployment of WSNs.

A. COVERAGE OF WSNs

The coverage of WSN has been studied in a number of literature survey papers from different perspectives. Aiming to different types of sensor nodes, corresponding algorithms were proposed. The types of sensor nodes mainly include: static, *mobile* [19], hybrid [20], and *mobile* robot [21]. In static wireless sensor networks, all randomly deployed sensor nodes are static [22], while *mobile* wireless sensor networks [23] need movable platform so as to move after initial deployment.

Ren C. Luo *et al.* proposed an efficient *mobile* sensor node deployment method [24] called ‘‘grid deployment’’, where the map is divided into multiple individual grids and the weight of each grid is determined by environmental factors such as pre-deployed nodes, boundaries, and obstacles. In their method, the energy consumption of sensor nodes can be reduced via calculating the minimum values of grid to determine the moving target after random deployment. Deng *et al.* proved that a hexagonal structure [25] is the best topology in two-dimensional networks, which can provide the maximum coverage area with the minimum number of sensor nodes and minimum energy consumption. In their scheme, the external force will be added to the most peripheral nodes to promote the formation of hexagonal topology and avoid covering holes or unusual structure at the early stage. The result of their scheme presents that it is stable and can be used in a large-scale WSN.

The schemes mentioned above only consider the networks with just one kind of sensor nodes-either static or *mobile*. However, in reality, it is more desirable to consider a hybrid network with both kinds of nodes. To this end, Vecchio *et al.* proposed a distributed technique for iteratively computing the trajectories of the *mobile* nodes in a greedy fashion [26]. The static sensor nodes actively assist the *mobile* nodes in this task via a bidding protocol, and thus achieve the goal of maximizing the area coverage of the interested region. Zhang *et al.* investigated how to redeploy *mobile* sensor nodes to improve network coverage in hybrid wireless sensor networks [27], and proposed a two-phase coverage-enhancing algorithm. In hybrid sensor networks, *mobile* sensor nodes are also utilized to strengthen the coverage capability of static nodes. Xu *et al.* solved a problem about the intrusion detection in barrier-coverage [28] by using a single variable first-order gray model GM(1,1), via which the part of more vulnerable barriers can be determined based on the intruder detection history from sensor nodes. Then, they relocated the available *mobile* sensor nodes to the identified vulnerable parts of the barriers in a timely manner.

Recently, Zygowski *et al.* presented their research on the maximum area coverage of hybrid sensor networks [29]. In their work, regions of the sensing area that are not within the sensing range of any sensor node will constitute coverage holes. Aiming at this problem, a mixed integer linear program (MILP) formulation that calculates the optimal path to be taken by the *mobile* node is proposed, which maximizes the combined total area covered by the static and *mobile* nodes.

With the rapid development of robot technology, it is applied to wireless sensor networks as an auxiliary technology nowadays. Beneficial from that, instead of using *mobile* nodes, an alternative way is to use *mobile* robots to carry static sensor nodes, so as to enable all static sensor nodes to move. Meanwhile, robots may carry static sensors as payloads and deploy them at proper positions. In that case, we often optimize the robot network via a path planning algorithm in the deterministic deployment modes. Khoufi *et al.* studied the deployment of static sensor nodes in an area containing obstacles with two *mobile* robots [30]. In their study, the time needed for the two robots to deploy all sensor nodes and return to their starting positions is minimized by game theory. Moreover, Tuna *et al.* proposed a novel approach [31] of using autonomous *mobile* robots to deploy a WSN for human existence detection in case of disasters. In their scheme, during the WSN deployment, *mobile* robots perform cooperatively via the Simultaneous Localization and Mapping (SLAM) and communicate with each other over the WSN.

Sensor nodes can either be randomly [32] or deterministically [33] deployed in the interested area depending on the requirements. In some environments, such as disaster regions, random deployment is more feasible than deterministic deployment. Farsi *et al.* proposed a detailed survey [34] of coverage in wireless sensor networks, emphasizing the importance of minimum number that maintain full coverage and connectivity in randomly deployed wireless sensor network.

B. LIFETIME OF WSNs

Dhami *et al.* proposed an energy-efficient genetic algorithm [35] based approach with the concept of Virtual Grid based Dynamic Routes Adjustment (VGDRA) to improve the energy conservation and enhance the lifetime of wireless sensor networks. In [36], an enhanced clustering hierarchy (ECH) approach was proposed to improve the energy efficiency in WSNs by utilizing sleep mechanism for overlapping and neighboring nodes.

Quoc *et al.* designed the sensor nodes connection model [37] based on the Gaussian network connection model, in which interested area was divided into some virtual square grids as a node. Based on the above model, a novel routing method was proposed, which combines the shortest path routing protocol to improve the routing efficiency of the wireless sensor network, as well as the lifetime.

Dezfuli *et al.* proposed a method [38] where the network area is divided into multiple square grids on a geographical basis, and an evolutionary firefly algorithm to improve the lifetime and coverage of WSNs. The sensor nodes with the highest energy in each grid was selected as a cluster head. After that, the remaining energy of the covered area can be calculated.

Xiang *et al.* proposed a cuckoo search (CS) algorithm [39] to optimize the sensor node deployment strategy in a hybrid sensor network. The candidate target positions of *mobile* sensor nodes are determined by the CS algorithm, and then the position optimization scheme is used to reduce the number of *mobile* nodes and the average moving distance. It improves the coverage of the interested area, and reduce the energy consumption of WSNs.

Xiao *et al.* focused on analysing the target discovery ability of static sensor networks [40], and investigating the target discovery probability and discovery delay with different nodes density, sensing range and duty cycle. Based on that, they gave a coverage adaptive optimization algorithm that can significantly improve the lifetime of WSNs.

In addition, some schemes utilized reducing communication cost to extend the lifetime of WSNs. For instance, a distributed energy-efficient resource allocation algorithm [41] was proposed to prolong the lifetime of Device-to-Device (D2D) communications by exploiting the properties of nonlinear fractional programming. Liangrui Tang *et al.* proposed a joint energy supply and routing path selection algorithm [42] to extend the network lifetime based on an initiative power supply. An enhanced routing-Gi protocol [43] for a mobile sink in WSNs was proposed to not only enhance energy efficiency, but also minimise the packet loss rate. Additionally, An improved low-energy adaptive

TABLE 1. Table of comparison.

Techniques	Nodes Type	Advantages	Disadvantages	Complexity
VF [13]	Mobile	-Provides maximized coverage while keeping network connectivity -Ability to deal with obstacles	-High computational capability -Use mobile nodes only	High
GA [16]	Hybrid	-Achieve full area coverage with minimum number of sensor nodes	-Did not consider network connectivity -Did not consider power consumption	Low
ACA [26]	Mobile	-Achieve full coverage and connectivity -Minimize power consumption	-High computational capability -Use mobile nodes only	Normal
Grid Deployment [24], [35], [37]	Mobile	-Provides ideal deployment of WSNs with the shortest moving path -Ability to keep network connectivity	-Did not deal with obstacles -Reduces network efficiency in case of nodes failure	Low
Topology [25], [45], [47], [48]	Static	-Provides maximized network connectivity -Ability to prolong network lifetime	-High processing time -Use static nodes only	Normal

clustering hierarchy protocol [44] for MSNs was proposed to not only prolong the network lifetime, but also reduce the packet loss using fuzzy inference systems. An enhanced clustering hierarchy (ECH) approach [36] was proposed to achieve energy efficiency in WSNs by using sleeping-waking mechanism for overlapping and neighboring nodes. Thus, the data redundancy is minimized and then network lifetime is maximized.

The research of topology in WSNs is usually conducted to reduce the energy consumption and improve the lifetime of WSNs. Nguyen *et al.* provided a fuzzy clustering topology [45] to prolong the lifetime of WSNs, where the residual energy of sensor nodes, the distances from sensor nodes to the base station, and influence of neighboring parameters of the sensor nodes, as well as the cluster-head radius are adjusted by fuzzy clustering topology. Through the comparison of experiments, the clustering algorithm can be applied to any real-world WSNs. Aziz *et al.* gave a survey about the significant topology control algorithms [46] to provide insights into how energy efficiency was enhanced by designing and defining the lifetime of sensor network. Yi *et al.* proposed an algorithm [47] based on the initiative to balance the nodes energy consumption according to the current classic topology control algorithm. In [48], a topology control algorithm with double cluster heads based on affinity propagation clustering (APDC-M) was proposed. The simulation results showed that APDC-M can make the cluster head election more reasonable and the cluster head distribution more uniform, and effectively reduce the energy consumption of the cluster heads at the same time. Table 1 provides a comparison among the previously mentioned improving coverage and lifetime techniques.

III. PROBLEM STATEMENT

In this section, we introduce the main system modeling assumptions, including network model as well as the model analysis. Furthermore, the main problems including maximum coverage and lifetime in the model of WSNs are introduced. We devote to utilizing fewer hybrid sensor nodes to achieve the maximum coverage. Meanwhile, the lifetime of WSNs can be prolonged through an available topology optimization algorithm. We define a number of nations to more accurately describe our network model and Mobile-Coverage scheme. The notations and their definitions which will be used throughout this paper are listed in Table 2.

TABLE 2. Table of notations.

Notation	Definition
F	the virtual force applied to each *mobile* node
P	the interested area of WSN
r_s	the sensing radius of each sensor node
r_c	the communication radius of each sensor node
N	the number of all sensor nodes
M	the maximum displacement distance of single iteration
m	the iterations of algorithm
d	the length of grid
E_s	the residual energy of network
E_t	the total energy of network
E_c	the energy consumption
N_t	the number of all sensor nodes
N_j	the number of static sensor nodes
f	coverage of sensor network
f_0	the initial coverage
C_i	the trust degree
$f_e(i)$	the probability of energy exhaustion
$f_d(i)$	the probability of data-congestion
k_i	the degree of sensor nodes
$\mathbb{S}$	sensor nodes set
$\mathbb{Q}$	grid nodes set
$\mathbb{W}$	derived nodes set
k	the number of derived nodes set

A. NETWORK MODEL

In this paper, we consider a hybrid WSN consisting of two types of sensor nodes, namely, static nodes and *mobile* nodes. The static nodes cannot move once being deployed, while the *mobile* nodes move according to the Mobile-Coverage scheme. In practical WSN applications, how to cover the target area completely with minimum number of sensor nodes is an essential problem. Meanwhile, the static sensor nodes commonly cannot be deployed in hazardous or abominably area under the pre-configured location, and the density of sensor nodes is uncontrollable. Therefore, it is necessary to deploy a fraction of sensor nodes as *mobile* nodes. Fig. 1 gives the initial deployment including static and *mobile* sensor nodes.

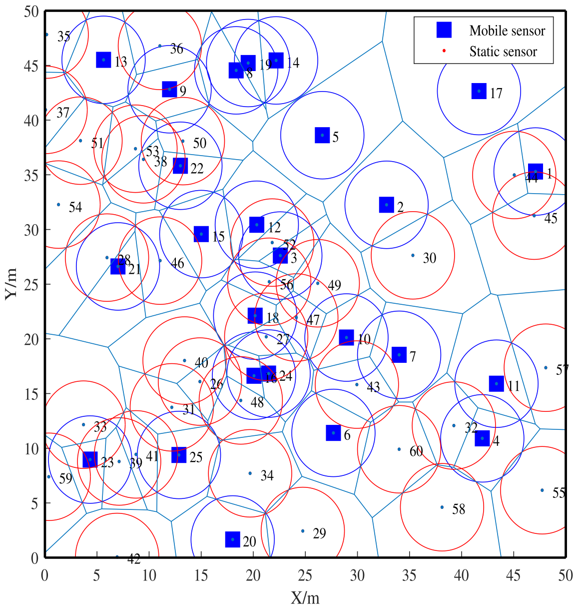

FIGURE 1. **Sensor nodes are randomly deployed in a rectangular region, including *mobile* and static sensor nodes. Note that circles are signed as perceived region of sensor nodes, both *mobile* and static sensor nodes have the same perceived radius. The blue circles represent the *mobile* sensor nodes, and the red circles are static sensor nodes.**

1) MINIMUM NUMBER OF SENSOR NODES

Given that massive wireless sensor networks are economically expensive, the ability of fewer nodes to get more perceptual information becomes one of the focuses of our research. In order to get the minimum number of nodes, we transform the problem into figuring out how many circles can completely cover the target area in a fixed region, with the radius of circles being r and the fixed region being $L \times W$. Accordingly, we first present the following theorem.

Theorem 1: Let A denote a rectangle in two-dimensional plane with area P, and $N(r)$ denote the minimum number of circles with radius r which can cover A completely, then it can be derived that

$$N(r) > \left(2\sqrt{3}/9r^2\right)\left(P - 2\pi r^2\right) \tag{1}$$

Proof: Let a_i be the N_i-th circle with radius r, and C_i denote the center of a_i, such that $i \in \{1, \cdots, N(r)\}$. If any two circles a_i and a_j where $i \neq j$ are overlapping, then let $c_{i,j}$ be the common chord of them.

Let b_i be defined as the set of points H in region A, then those points should satisfy the following condition:

$$d\left(Q, C_i\right) \leqq d\left(Q, C_j\right) \quad (j \neq i) \tag{2}$$

where $d(O, Q)$ is the distance between O and Q. The set b_i is proved by the above formula, and clearly a closed subset of a_i. In other words, b_i is not empty. In any case there must exist a point Q in region A which does not belong to a_j while C_i is also in region A, otherwise the $N(r) - 1$ circles a_j can cover A. Furthermore, we assume that $N(r)$ is the minimum number of circles which can cover A completely.

Let B denote a boundary point of b_i. Then B is also a boundary point of A or

$$d\left(B, C_i\right) = d\left(B, C_j\right) \quad (j \neq i) \tag{3}$$

Then B is either on the boundary of A or on some $c_{i,j}$, so that b_i is a polygon bounded by subsegments of the $c_{i,j}$ and subsegments of boundary of A.

The set of b_i form a non-overlapping collection of polygons which exactly cover A. In particular, if the four vertices of A are "straightened out", we have a total area $> R - 2\pi r^2$. According to the corollary of Kershner [49], we can get the following theorem.

Theorem 2: Let σ be a fixed circle and let A_k denote the area of a regular polygon of k sides inscribed in σ. Then

$$0 < A_{k+1} - A_k < A_k - A_{k-1} \quad (k \geqq 3) \tag{4}$$

when $k > j \geqq 3$, further theorem are given

$$\begin{aligned} (k-j)\left(A_k - A_{k-1}\right) &\leqq A_k - A_j \\ A_k - A_j &\leqq (k-j)\left(A_{j+1} - A_j\right) \end{aligned} \tag{5}$$

Finally, he provided the the relationship between the regular hexagon and the circle in a rectangle. Let τ denote a bounded plane network consisting of F finite polygons. Suppose that each vertex of τ is on at least three edges. Supposed that each polygon of τ can be covered by a circle σ of fixed radius r. Then the total area of $\tau < F * A_6$, where $A_6 = (3\sqrt{3}/2)\, r^2$ is the area of a regular hexagon inscribed in σ.

Then the minimum number of circles can cover the region A can be given by

$$R - 2\pi r^2 < N(r)(3\sqrt{3}/2)\, r^2 \tag{6}$$

This completes the proof.

■

2) MINIMUM NUMBER OF *MOBILE* SENSOR NODES

For the random deployment in WSNs, upon getting the minimum number of sensor nodes, it is desired that the Mobile-Coverage scheme moves as few sensor nodes as possible. Fewer *mobile* sensor nodes means less energy consumption. Here, we borrow the idea of the virtual force scheme, and assume that each *mobile* sensor node is subjected to forces on other nodes and boundaries. Let Fx_i denote the force of a *mobile* sensor i on the X-axis, and Fx_j is on the Y-axis. In order to achieve the balance of force in the senor network, the *mobile* sensor nodes move under the influence of joint forces. Hence the energy consumption model of WSNs is given by

$$E_s = E_t - 2d \sum_{i=0}^{N_t - N_j} \sqrt{F_{x_i^2} + F_{y_i^2}} \tag{7}$$

where E_s is the residual energy of WSNs after executing the Mobile-Coverage adjustment scheme, N_t is the total number of sensor nodes including both static and *mobile* sensor nodes, N_j is the number of static sensor nodes, and d is defined as the length of grid divided on the target region.

To get the appropriate number of *mobile* sensor nodes, we also need to consider the coverage of WSNs. It is evident that decreasing the number of *mobile* sensor nodes will reduce the coverage. According to the grid scheme, the coverage of WSNs is given by

$$f = \frac{d^2 m(N_t - N_j)}{P(A)} + f_0 \tag{8}$$

where f_0 is the initial coverage which can be obtained before executing our scheme, and m represents the iterations of algorithm.

3) TOPOLOGY OF SENSOR NETWORK

After obtaining the minimum number of total and *mobile* sensor nodes, the WSNs will be deployed randomly and adjusted by our scheme. As the WSNs keep running, some sensor nodes will stop working due to energy exhaustion. While the sensor nodes are close to the BS (Base station), energy of the sensor nodes will be consumed fleetly. Effective topology adjustment scheme can further extend the lifetime of WSNs.

As shown in Figure 2, according yo different performance requirements of wireless sensor networks, the topology of wireless sensor network consists of two parts, namely, topology construction and topology maintenance, in which topology construction can be applied to energy, coverage and connectivity. In this paper, a novel scheme of topology control based on energy is proposed. Firstly, a node reliability model is built based on the probability of nodes energy exhaustion, and the value of the optimal trust degree is obtained under the constraint conditions of the maximum nodes reliability and the longest network lifetime. Finally, sensor nodes with the optimal trust degree are selected as the key nodes in sensor networks. Under the novel topology algorithm, the performance of the whole sensor network can be effectively optimized and the network lifetime also can be extended.

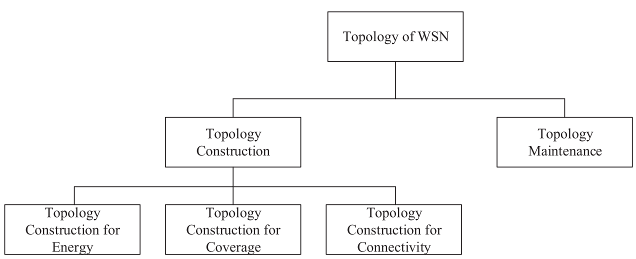

FIGURE 2. The main components of wireless sensor network topology.

B. MODEL ANALYSIS

There are two important problems in wireless sensor networks listed as follows.

- **Coverage of sensor network:** The wireless sensor networks cannot cover the interested region completely due to the low coverage rate, and thereby the resources are wasted.
- **Lifetime of sensor network:** Due to the heavy energy consumption of node movement, the network lifetime is significantly shortened.

According to Section III-A, it is easy to observe that we can get the minimum number of sensor nodes to fully cover the interested region, as well as the minimum number of *mobile* sensor nodes to reduce the energy consumption. In addition, we can also obtain the trust degree of sensor nodes to construct and maintain the topology of sensor networks. Accordingly, the coverage of the target region can be enhanced and the lifetime of sensor networks can be further prolonged.

IV. THE MOBILE-COVERAGE ADJUSTMENT SCHEME

A. VIRTUAL FORCE

In this subsection, we first present some preliminary knowledge about the virtual force algorithm and the voronoi graph, which are the foundations of our proposed scheme.

The virtual force algorithm [13] is introduced by interaction force in physics to resolve the problem of coverage, which assumes that there are interactions between different nodes within the interested region.

In the optimization of wireless sensor networks coverage algorithm, the joint force moving model is adopted until the mutual force balance between the regional nodes is reached. Let F_i is force around wireless node s_i, the force of node s_j on s_i is F_{ij}, the euclidean distance of adjacent nodes is d. F_{iR} is defined as the joint force of grid nodes that are not covered in target region to sensor node s_i. If there are a large number of nodes at the boundary of the region, strong repulsion force will exist according to the above rules. Meanwhile, coverage capability of some sensor nodes will be wasted, F_b is defined as force of boundary binding. The joint force on the sensor node s_i is given by

$$F_i = \sum_{j=1, j\neq i}^{k} F_{ij} + F_{iR} + F_b \tag{9}$$

where F_{ij} has two parts-gravity and repulsion. When the sensor nodes in a target region are densely packed, the repulsion is stronger than the gravity. The moving distance and position are determined according to the final joint forces, each sensor node changes the original position according to the virtual force. Therefore, we have

$$x_{new} = \begin{cases} x_{old} & (F_{xy} = 0) \\ x_{old} + \frac{F_x}{F_{xy}} \times M \times e^{-\frac{1}{F_{xy}}} & (0 \leqslant d \leqslant 1.4r) \end{cases}$$
$$y_{new} = \begin{cases} y_{old} & (F_{xy} = 0) \\ [5pt] y_{old} + \frac{F_y}{F_{xy}} \times M \times e^{\frac{-1}{F_{xy}}} & (0 \leqslant d \leqslant 1.4r) \end{cases} \tag{10}$$

where M is the maximum displacement distance of sensor nodes in the single iteration of the algorithm, F_{xy} is the joint force of all sensors, F_x and F_y are the two-dimensional component of the joint force, and represents the force exerted by the sensor node on the X-axis and Y-axis respectively.

The virtual force scheme can effectively diffuse the sensor nodes in the interested region and make them in a relatively balanced position.

B. VORONOI GRAPH

Voronoi graph [50] is a domain partition diagram based on Delaunay triangle, which is composed of sensor nodes connected by perpendicular lines in a limited area. The Euclidean distance is used as the standard to divide the plane. Voronoi graph has the properties of proximate adjacency and perfect theoretical system, so it is often applied to solve the problems of nearest neighbor, the largest empty circle and Delaunay triangle dual. How to build a Voronoi for all sensor nodes? Firstly, a midperpendicular line is drawn for adjacent nodes in a random discrete node set in a bounded plane region. Secondly, the redundant line segments are connected by multiple midperpendicular lines to form multiple polygons of different shapes, and each polygon contains a unique corresponding node. Finally, the nearest two-dimensional plane region is formed for a node, and all point sets in the formed two-dimensional region are the closest to the point in the region relative to the point in the adjacent region. At this time, the scope of effect on the nodes is called the Voronoi graph (as shown in Fig. 1). If any derived points are deleted, the corresponding influence area will disappear and can only affect the Voronoi polygon region adjacent to it.

C. TOPOLOGY OF WSNs

In recent years, topology control has become an important research area. It is applied to the energy consumption, maintaining coverage and connectivity of WSN. In this paper, a novel topology construction scheme based on the energy consumption is proposed. The topology of wireless sensor networks is determined by the trust degree of each sensor nodes. For any generic node i, its trust value is given by

$$C(i) = 1 - f_{\mathrm{e}}(i) f_{\mathrm{d}}(i) \tag{11}$$

where $f_{\mathrm{e}}(i)$ is the probability of energy exhaustion, $f_{\mathrm{d}}(i)$ presents the probability of data-congestion. The probability of energy exhaustion is dependent on the initial energy of each sensor $E_t(i)$, energy consumption $E_c(i)$ and the running time t, and can be given by

$$f_{\mathrm{e}}(i) = 1 - \mathrm{e}^{-\frac{1}{E_t(i)/E_{\mathrm{c}}(i)} t} \tag{12}$$

where the energy consumption model gives the energy consumed E_{tc} in data transmission

$$E_{\mathrm{tc}} = E_{\mathrm{elec}} l + \varepsilon_{\mathrm{amp}} l d^2 \tag{13}$$

where l is the bits in data transmission, d represents the distance of two nodes, E_{elec} denote the parameter of radio frequency transmission, and $\varepsilon_{\mathrm{amp}}$ is the parameter of amplification, we denote E_{x} as the energy consumption for each sensor node receive l bits. Hence

$$E_{\mathrm{x}} = E_{\mathrm{elec}} l \tag{14}$$

Therefore, total energy consumption $E_c(i)$ per unit time is given by

$$E_{\mathrm{c}}(i) = E_{\mathrm{tc}} + E_{\mathrm{x}} = 2\, E_{\mathrm{elec}} l + \varepsilon_{\mathrm{amp}} l d^2 \tag{15}$$

In the interested region A with area P, probability density function of each nodes is given by

$$g(x, y) = \begin{cases} 1/A, & (x, y) \in A \\ 0, & \end{cases} \tag{16}$$

Then the probability that a sensor node is in the communication radius r_c is given by

$$ff = \iint_{\pi r_s^2} g(x, y) \mathrm{d}x \mathrm{d}y = \frac{\pi r_c^2}{P} \tag{17}$$

Hence the relationship d and degree of sensor node is written as

$$k = N ff = N \frac{\pi d^2}{P} \tag{18}$$

Furthermore, according to 15 and 18, the relationship $E_{\mathrm{c}}(i)$ and k can be written as

$$E_{\mathrm{c}}(i) = E_{\mathrm{tc}} + E_{\mathrm{x}} = 2\, E_{\mathrm{elec}} l + \frac{\varepsilon_{\mathrm{amp}} l P}{N\pi} k \tag{19}$$

Then, 19 combines with 12, the probability $f_{\mathrm{e}}(i)$ is redefine as

$$f_{\mathrm{e}}(i) = 1 - \mathrm{e}^{-(a+bk)t} \tag{20}$$

where $a = \frac{2\, E_{\mathrm{elec}}\, l}{E_t(i)}$; $b = \frac{\varepsilon_{\mathrm{amp}}\, l P}{N \pi E_t(i)}$ In this paper, the energy consumption caused by data transmission is not considered, $f_{\mathrm{d}}(i)$ can be viewed as a constant.

D. NETWORK CONNECTIVITY EVALUATION METHOD

While the Mobile-Coverage Adjustment Scheme including considerations about WSNs connectivity, it is still necessary to give a detailed evaluation method of connectivity. To this end, this subsection presents a method for evaluating WSNs connectivity, which can not only test the performance of the proposed scheme in maintaining connectivity, but also provides a simple simulation evaluation method for checking the connectivity of other coverage algorithms. The evaluation method is given.

Firstly, any pair of working nodes with a distance within r_c can communicate with each other. The nodes are associated with other nodes within single-hop, and the nodes can also determine which working nodes are associated with themselves by receiving messages containing identities from neighbor nodes. Then, we can write the adjacency matrix of the working nodes as $\boldsymbol{G} = \{g_{ij}\}_{n\times n}$, where n is the total number of the working nodes, and each element in $\boldsymbol{G}$ satisfies

$$g_{ij} = \begin{cases} 1 & S_j \rightarrow S_i \\ 0 & S_j \nrightarrow S_i \end{cases} \tag{21}$$

Therefore, it is obvious that if $g_{i,j} = 1$, the node v_j is associated with v_i, and otherwise not.

In this paper, each working node is considered to be associated with itself, hence $\forall i \in \{1, \cdots, n\}$, $g_{i,i} = 1$ always holds. Let $\boldsymbol{G} = (a_1, a_2, \cdots, a_n)^T$, where $a_i (i = 1, 2, \cdots, n)$ represents the i-th row vector of $\boldsymbol{G}$, then $\boldsymbol{G}$ can be transformed as

$$\boldsymbol{G} = (a_1, a_2, \cdots, a_n)^{\mathrm{T}} \xrightarrow[a_i' = a_i \vee a_j \ and \ a_j' = 0]{\|a_i\|, \|a_j\| > 1 \ and \ a_i \wedge a_j \neq 1}$$
$$\boldsymbol{G}' = \left(a_1', a_2', \cdots, a_n'\right)^{\mathrm{T}} (i, j = 1, 2, \cdots, n \ and \ i \neq j) \quad (22)$$

The new matrix $\boldsymbol{G}'$ transformed from $\boldsymbol{G}$ is defined as the connected matrix, where the working nodes corresponding to the columns of non-zero elements in each row vector with a modulus value greater than 1 are connected. If the WSNs are fully connected, then there must be a row vector in $\boldsymbol{G}'$ that has all elements in it and all other row vectors are zero vectors. At this time, the rank of $\boldsymbol{G}'$ is 1. If the WSNs are not fully connected, there will be more than one non-zero vector in $\boldsymbol{G}'$. If there are more isolated and dispersed partial connected regions formed by the working nodes, the more non-zero vectors will be. An example of fully connected matrix transform is presented in Table 3, in which the number of non-zero vectors in $\boldsymbol{G}$ can effectively express the network connectivity rate. The formula of network connectivity rate is given by

$$P_c = 2 * N_{\boldsymbol{G},1} / N_{\boldsymbol{G},0,1} \quad (23)$$

TABLE 3. An example of matrix transform.

	S_1	S_2	S_3	S_4	S_5	S_6
S_1	1	0	1	0	1	0
S_2	0	1	0	0	0	0
S_3	1	0	1	1	0	1
S_4	0	1	1	1	0	1
S_5	1	0	0	0	1	0
S_6	0	1	1	0	0	1

where P_c is the connectivity rate of a WSN, $N_{\boldsymbol{G},1}$ is the number of non-zero vectors in $\boldsymbol{G}$, and $N_{\boldsymbol{G},0,1}$ is the number of all vectors in $\boldsymbol{G}$.

$$\rightarrow \boldsymbol{G} = \begin{bmatrix} 1\,0\,1\,0\,1\,0 \\ 0\,1\,0\,1\,0\,1 \\ 1\,0\,1\,1\,0\,1 \\ 0\,0\,1\,1\,0\,0 \\ 1\,0\,0\,0\,1\,0 \\ 0\,0\,1\,1\,0\,1 \end{bmatrix} \rightarrow \boldsymbol{G}' = \begin{bmatrix} 1\,1\,1\,1\,1\,1 \\ 0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0 \end{bmatrix}$$

E. SYSTEM MODEL

Suppose that there are N nodes, each of which has a perceived radius of R_s. The set of network nodes $\mathbb{S}$ are randomly deployed in a two-dimensional region A, and each node has autonomous mobility and a communication radius of R_c, such that $R_c \geqslant 2 R_s$. For each node $S_i \in \mathbb{S}$, it can be regarded as the center of a circle with radius of R_s. It is assumed that each node has the following properties:

1) Every *mobile* sensor node knows its own position via a mounted GPS unit or a localization service in the network. We also assume that there is a control center (e.g., the base station), which collects location information of sensor nodes and broadcasts movement orders to *mobile* sensor nodes.
2) The communication radius of the sensor nodes is $R_c = 2R_s$.
3) The interested region A with area P is rectangle, and the hybrid sensor network includes static and *mobile* sensor nodes. The static sensor nodes cannot move after random-deployment, while the *mobile* sensor nodes can adjust their positions.

The monitoring area was divided into squares, and the number of lattice points within the sensing radius of sensor nodes was calculated, as well as the coverage rate. In what follows, we introduce the definition and the coverage calculation of the system. The system comprises three components, which are defined as follows.

- **Node-set**: The set of network nodes $\boldsymbol{S}$ are randomly deployed in in monitoring region A. Accordingly, A is divided into different Voronoi polygon regions, $S_i \in \boldsymbol{V}_i (\boldsymbol{S}, R_s, \boldsymbol{V})$, where $\boldsymbol{V}_i$ is the Voronoi polygon region of S_i, $\boldsymbol{S} \subset \boldsymbol{V}$.
- **Derived node-set**: The monitoring region A is divided into multiple Voronoi irregular polygon according to the positions of all nodes. Since the polygon region is divided according to the randomly deployed node-set, each irregular polygon contains a sensor node S_i, and each vertex set of the polygon is the derived node-set $\boldsymbol{W}$.
- **Centroid node-set**: The derived node-set is calculated by centroid to get the centroid node-set $\boldsymbol{N}$. Therefore, we have

$$N_{ix} = \frac{\sum_{i=0}^{k} x_i}{k}$$
$$N_{iy} = \frac{\sum_{i=0}^{k} y_i}{k} \quad (24)$$

Where k is the number of derived node-set $\boldsymbol{W}$. Discrete node coverage is calculated in the two-dimensional region A, and A is divided into $m \times n$ grid nodes, where the coordinate of grid nodes is $Q = (x_i, y_i)$, and sensor node $S_i = \{x_i, y_i, R_S\}$. The distance between point Q and node S_i is $d(S_i, Q)$. The Probability model of sensor node S_i and grid nodes Q are derived from the Boolean model, where

$$P(S_i, Q) = \begin{cases} 1 & d(S_i, Q) < R_S \\ 0 & d(S_i, Q) \geqslant R_S \end{cases} \quad (25)$$

Due to the noise in the actual environment and other factors of interference, the measurement model shows a particular probability distribution. Therefore, we have

$$P(S_i, Q) = \begin{cases} 0 & d(S_i, Q) \geqslant R_S + r_e \\ e^{(-\alpha_1 \lambda_1 \beta_1 / \lambda_2 \beta_2 + a_2)} & R_S - r_e < d(S_i, Q) \\ & d(S_i, Q) < R_S + r_e \\ 1 & d(S_i, Q) \leqslant R_S - r_e \end{cases} \quad (26)$$

where r_e $(0 < r_e < R_S)$ represents the validity parameter of sensor nodes measurement, α_1, β_1, β_2 represent monitoring probability measurement parameters respectively, α_2 is the interference factor. Meanwhile, let $\lambda_1 = r_e - R_S + d(S_i, Q)$, $\lambda_2 = r_e + R_S + d(S_i, Q)$. According to the probability distribution model, the monitoring probability of the point may be less than 1. Hence, the multi-point linkage scheme of sensor node is usually used, and the probability distribution formula is given by

$$P(S, Q) = 1 - \prod_{1}^{N} (1 - P(S_i, Q)) \quad (27)$$

In grid generation, the criteria for grid nodes Q can be effectively covered by sensor nodes as follows

$$P(S, Q) \geqslant H_{th} \quad (28)$$

where H_{th} represents the threshold to determine whether the grid node is effectively covered or not. The coverage in the interested region is expressed as the ratio between the sensing range of sensor nodes and the area of monitoring region A. After discrete segmentation of A, the coverage is expressed as

$$P_A(S) = \frac{count}{m \times n} \quad (29)$$

where *count* is the number of effective coverage grids.

F. SCHEME CONSTRUCTION

In this subsection we present the complete construction of our scheme. The proposed Mobile-Coverage adjustment Scheme can be formulated as a tuple of three components (**Setup**, **VFVG**, **TCMT**) with the following functionalities:

- **Setup**. A sensor network is randomly deployed on the interested region A with area P. do:
  1) Compute the minimum number of sensor nodes with which the interested region A can be covered.
  2) Randomly deploy these sensor nodes in the region A.
  3) Establish communications between neighbor nodes within the communication radius r_c, and divide the region A into grids.
- **VFVG**. Compute the virtual force of each *mobile* sensor node, and move their positions in each iteration. The moving range d is the length of a grid. Each node is divided by voronoi in the region area A, and the regular hexagon shape is taken as the target for node movement. We proposed a novel algorithm (VFVG) to solve the problem of how to move the *mobile* sensor nodes. In our algorithm, we first move the *mobile* sensor nodes in the region with the largest density, then compute the voronoi set of each *mobile* sensor node, where each *mobile* node can be surrounded by some voronoi grid points. When the voronoi grid points of each sensor node, denoted as derived node-set, are known, we calculate the center node-set by the centroid algorithm. Finally, we move the *mobile* sensor nodes to the center of voronoi by the fine adjustment. The VFVG algorithm is given by Algorithm 1.

Algorithm 1 VFVG Algorithm

Input: Wireless sensor nodes set $\boldsymbol{S_t} = \{s_{t_1}, s_{t_2}, \ldots, s_{t_n}\}$ and static sensor nodes set $\boldsymbol{S_j} = \{s_{j_1}, s_{j_2}, \ldots, s_{j_m}\}$, and interested area P including L, W, sensing radius r_s, communication radius r_c, iterations T, total energy of sensor network E_t.
Output:The coverage and energy consumption of wireless sensor network
Initialization:The static and *mobile* sensor nodes are randomly deployed on the interested area P
1. **for** $t = 0, 1, \ldots, T$ **do**
2. Compute the resultant force on each *mobile* node set $\boldsymbol{F_s} = \{\boldsymbol{F_{s_1}}, \boldsymbol{F_{s_2}}, \ldots, \boldsymbol{F_{s_{n-m}}}\}$ via algorithm of virtual force.
3. **if** $\boldsymbol{F_s} = \emptyset$, stop iterating.
4. **else** compute direction θ and distance d of movement, get the energy consumption of each *mobile* sensor node.
5. Build the voronoi graph set $\boldsymbol{W_s} = \{\boldsymbol{W_{s_1}}, \boldsymbol{W_{s_2}}, \ldots, \boldsymbol{W_{s_{n-j}}}\}$, compute the centroid node set $\boldsymbol{N_w} = \{\boldsymbol{N_{w_1}}, \boldsymbol{N_{w_2}}, \ldots, \boldsymbol{N_{w_{n-j}}}\}$ and precise adjustment of distance.
6. Compute coverage p of the sensor network and energy consumption E_c
7. **end for**
8. output $\boldsymbol{p}$ and $E_s = E_t - E_c$.

- **TCMT**. We get the final positions of *mobile* sensor nodes through the above VFVG algorithm. At this very moment, the remaining energy of each static sensor node is identical, while the remaining energy of *mobile* sensor nodes is different. So we need a topology algorithm to reduce the energy consumption of *mobile* sensor nodes and prolong the lifetime of WSN. Here, the TCMT algorithm aimming to topology construction and maintenance is proposed, where the trust model of sensor nodes is introduced to select the topology key nodes. Each sensor node has a trust degree via calculating C_i, and the number of neighbor nodes is k. We rank the trust degree of each node, and then select largest trust degree as the topology key nodes orderly until the network is fully connected. The TCMT algorithm is given by Algorithm 2.

The VFVG algorithm increases the coverage of WSNs and reduces the moving distance of *mobile* sensor nodes. As a result, the lifetime of WSNs is also improved. The TCMT algorithm is based on the adjusted position via VFVG algorithm, and further reduces the energy consumption due to the data transmission, and prolongs the lifetime of WSNs.

G. COMPUTATIONAL COMPLEXITY

In this subsection, we evaluate the computational complexity of our Mobile-Coverage scheme and compare it with several existing schems. $O(In(n-1)m + Tnk)$ is the overall complexity of our mobile scheme, I is the number of iterations of the

Algorithm 2 TCMT Algorithm

Input: Trust degrees of sensor nodes set $\boldsymbol{T_s} = \{\boldsymbol{T_{s_1}}, \boldsymbol{T_{s_2}}, \ldots, \boldsymbol{T_{s_n}}\}$, the remaining energy of sensor nodes set $\boldsymbol{E_s} = \{\boldsymbol{E_{s_1}}, \boldsymbol{E_{s_2}}, \ldots, \boldsymbol{E_{s_n}}\}$, and trust degree C_{s_i} including $f_e(i)L$, $f_d(i)$, $E_{t,c}$, communication radius r_c, degree of sensor node k, the distance d, the number n, scanning time M, sensor nodes set $\boldsymbol{S_n}$.
Output:Topology of WSNs
Initialization: The position of each sensor node is adjusted by our VFVG algorithm.
1. **for** $t = 0, 1, \ldots, M$ **do**
2. **for** $i = 0, 1, \ldots, N$ **do**
3. Compute the number of neighbor each sensor node. **if** $\boldsymbol{d} <= r_c$, $k_{s_i} = k_{s_i} + 1$.
4. $C_{s_i} = 1 - f_e(i)f_d(i)$
5. $Max(T_{s_i})$
6. Draw the topology of the node and its neighbors.
7. **end for**
8. Update $\boldsymbol{E_s}$ by $\boldsymbol{E_{s_i}} = \boldsymbol{E_{si}} - \boldsymbol{E_{t,c}}$
9. **end for**
10. output topology of S_i.

VFVG algorithm, m is the number of *mobile* sensor nodes, T is the execution interval of TCMT algorithm, and k is the times of trust evaluation. Table 4 gives the computational complex of relevant algorithms.

TABLE 4. Computational complexity.

Mobile scheme	Complex	Topology algorithm	Complex
VFVG	$O(In(n-1)m)$	TCMT	$O(Tnk)$
VF [13]	$O(n\log_n(n-1)!)$	A3 [51]	$O(n\log_n)$
GA [16]	$O(n^2\log_n)$	APDC-M [48]	$O(n^2)$
ACA [17]	$O(n^4)$	LEACH-C [52]	$O(n^2\log_n)$

When the number of mobile sensor nodes approaches n, all nodes in WSNs are mobile nodes, and then the computational complexity of our scheme degrades to $O(n^3)$. Under this circumstance, The GA algorithm is superior to our scheme in computational complexity. When the number of nodes in hybrid WSNs tends to infinity, the algorithm complexity of our scheme will be the lowest. Furthermore, our Mobile-Coverage scheme is more suitable for large-scale hybrid WSNs.

V. EXPERIMENTS

In this subsection, we focus on evaluating the computational performance of our Mobile-Coverage adjustment scheme in terms of the minimum number of *mobile* sensor nodes, coverage and energy consumption of WSNs. We conducted several sets of experiments proposed in [13] and [50] to compare with our scheme. The experiments were carried out on a Lenovo Laptop with 3.4GHZ Intel i5-7500 CPU and 24G DDR4 memory. The simulator we adopted is OMNET++ 5.5.1. The test region is 50*50m, and the minimum number of sensor nodes and *mobile* sensor nodes were calculated by III-A1 and III-A2, respectively, the sensing radius is $r_s = 4$ m, the communication radius is $r_c = 2r_s$, the iterations is $m = 100$. Initially, The sensor nodes are deployed randomly in the interested region with different initial energy. Table 5 gives the parameters used for setting up a WSN.

TABLE 5. Simulation parameters.

Parameters	Values
Interested region	50*50m
Initial Energy of static nodes	5J
Initial of *mobile* nodes	10J
Message Size	512bytes
Sensing radius	4m
Communication radius	8m
Iteration	100
E_{elec}	50nJ/bit
ε_{amp}	10pJ/bit/m^2

Fig. 3 presents the comparison of coverage and remaining energy between our scheme and the VF scheme, different number of *mobile* sensor nodes have different coverage and remaining energy under the minimum number of all sensor nodes is 60 got by III-A1. From Fig. 3 it can be observed that the coverage of our scheme is apparently higher than that of the VF scheme as the number of *mobile* nodes increases. Meanwhile, the remaining energy is also more than VF scheme. In addition, it also can be seen from Fig. 3 that, when the number of *mobile* sensor nodes is 25, the coverage and remaining energy achieve the suitable balance. Under this situation, the maximum coverage and remaining energy under the number of *mobile* sensor nodes are obtained. Fig. 4 shows that different total numbers of sensor nodes have different coverage of WSNs. As the number of sensor nodes increases, the coverage of WSNs increases significantly. Our

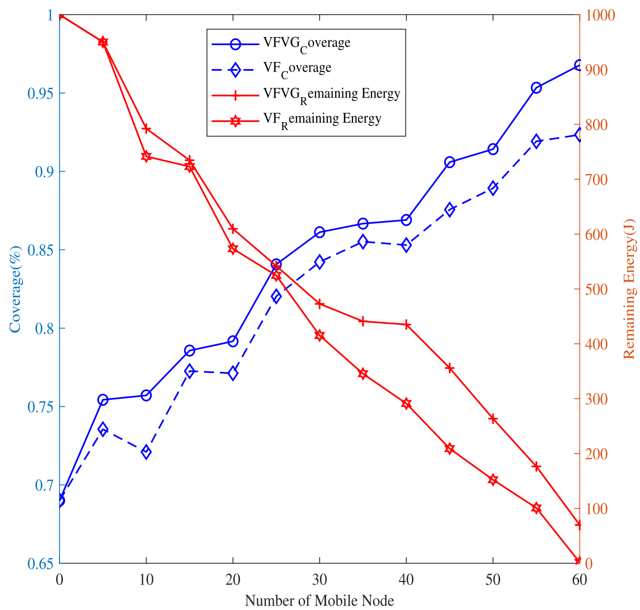

FIGURE 3. The different number of *mobile* sensor nodes can get different coverage and remaining energy between our VFVG algorithm and VF algorithm.

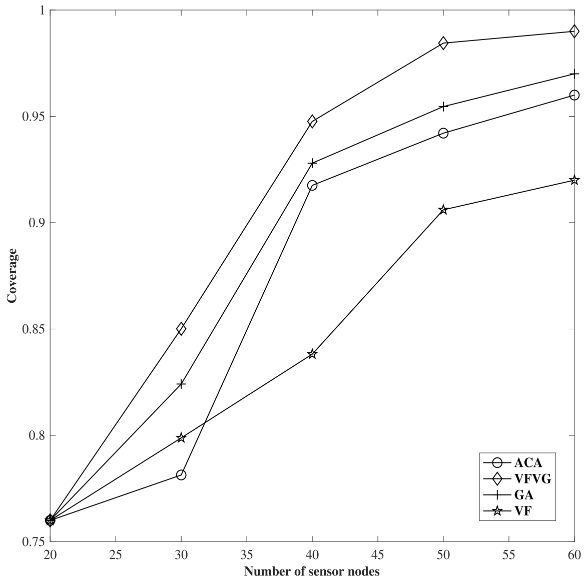

FIGURE 4. Different coverage of four algorithms.

Mobile-Coverage adjustment scheme has better performance than the competitive methods in [13], [16], [17], [50]. As the number of iterations continuously increases, the coverage of our method gradually increases as well. When the number of iterations reaches a certain level, the coverage is no longer increasing. From Fig. 5, it can be observed that when the mobile-coverage scheme is activated, rapid coverage growth will be achieved with fewer iterations in our scheme is compared with other three algorithms including GA [16], ACA [17], VF. In the end, the VFVG algorithm provides the highest coverage ratio of 98.7%. The simulation experiment shows that our VFVG algorithm has the ability to increase coverage more efficiently. Fig. 6 reports the connectivity rate in different adjustment schemes. GA achieves the fastest growth in connectivity, but the maximum connectivity is achieved in VFVG, which is 76.84%. Fig. 7 displays the moving path of the 25 *mobile* sensor nodes in the network (where the total number of nodes is 60).

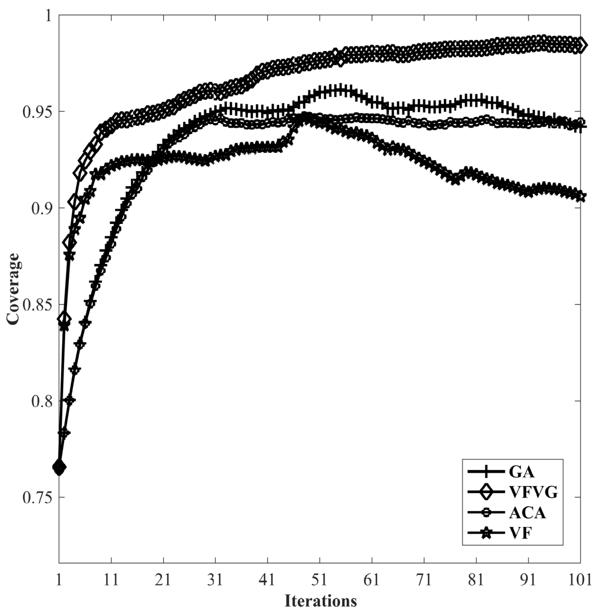

FIGURE 5. Coverage of different algorithms.

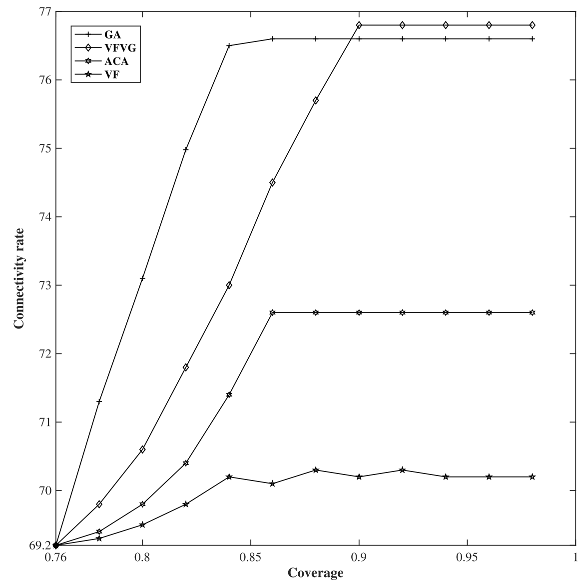

FIGURE 6. The connectivity rate during adjuesment scheme.

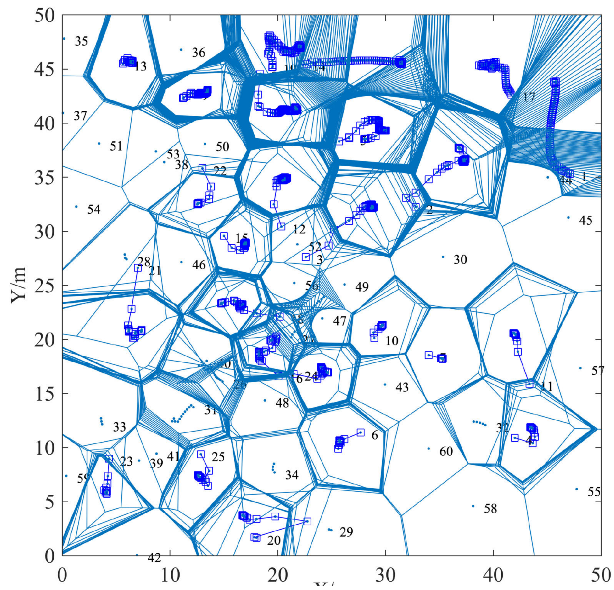

FIGURE 7. The moving distance of VFVG algorithm.

After the simulation is initiated, the VFVG algorithm is executed, where each *mobile* sensor node has different remaining energy due to different moving distance. After that, the TCMT algorithm is implemented to further extend the lifetime of WSNs. The simulation results of the TCMT algorithm are shown in Fig. 8, Fig. 9 and Fig. 10. It constructs

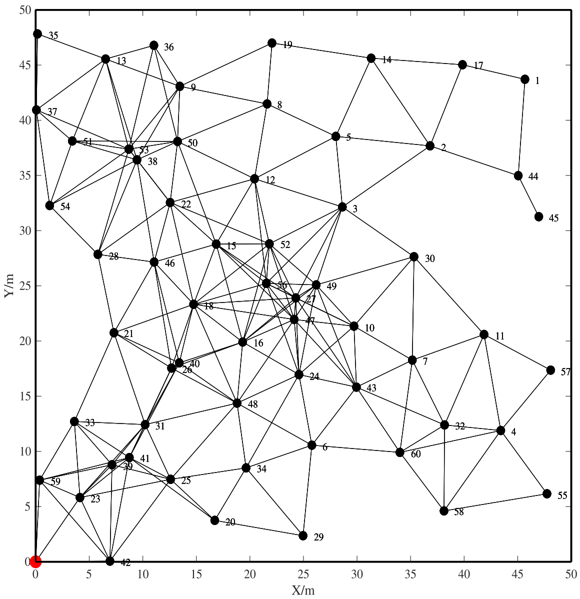

FIGURE 8. The topology of WSNs.

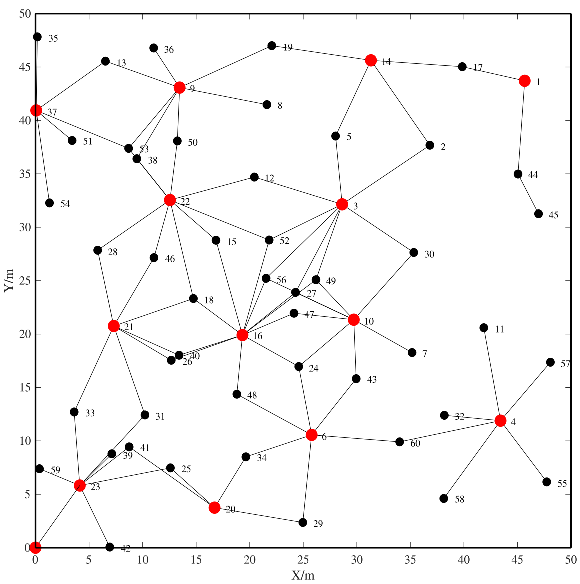

FIGURE 9. The red key nodes is selected from black ordinary nodes utilizing TCMT algorithm in WSNs.

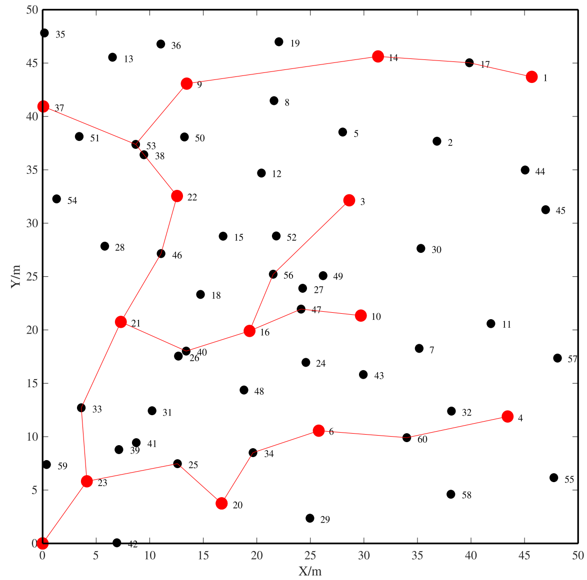

FIGURE 10. The red critical path based TCMT are constructed by connecting red key nodes in WSNs, some black high-energy ordinary nodes will be selected into the critical path to increase the stability of WSNs.

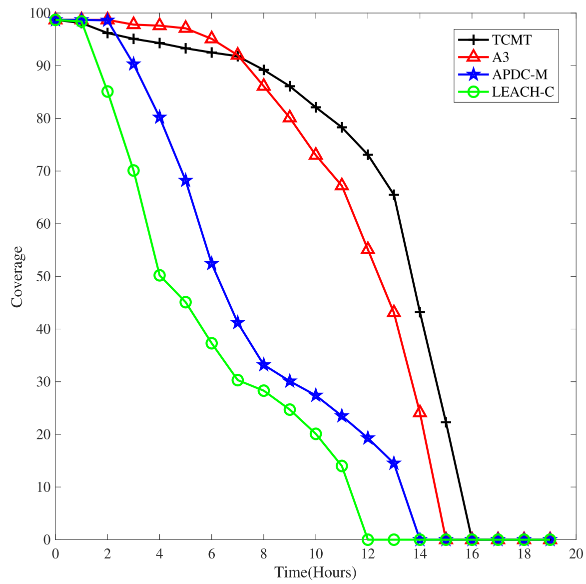

FIGURE 11. Lifetime between TCMT, A3, APDC-M, LEACH-C.

the topology of the WSN based on the degree of each node and the trust model. Under this particular circumstance, data transmission is one of the most energy-consuming operations. In the TCMT algorithm, when the engergy of cluster nodes is exhausted, the new cluster nodes will be elected. The lifetime of the WSNs is given in Fig. 11. After the WSNs are deployed and configured, the key nodes in the sensor network will die gradually due to energy exhaustion. As a result, the network coverage will be reduced as well. This paper compares three proposed solutions, including A3 [51], LEACH-C [52], and APDC-M [48]. From 0 to 2 hours, all algorithms work well and maintain the highest coverage above 98%. Afterwards, the coverage decays in all the algorithms simulated, yet the A3 algorithm provides the best coverage. After 7 hours, the TCMT algorithm achieves the longest lifetime, and the WSNs die at 16 hours.

Table 6 shows the total runtime of different algorithms. Compared with the other three scheme, GA has the shortest runtime is 2.89s in mobile scheme. In topology algorithm, A3 algorithm has the shortest runtime is 8.75s. Although the computational efficiency of our Mobile-Coverage scheme is not the best, our scheme can maximize coverage and lifetime in hybrid WSNs.

TABLE 6. Runtime.

Mobile scheme	Runtime	Topology algorithm	Runtime
VFVG	3.47s	TCMT	10.92s
VF	12.03s	A3	8.75s
GA	2.89s	APDC-M	18.74s
ACA	8.22s	LEACH-C	11.43s

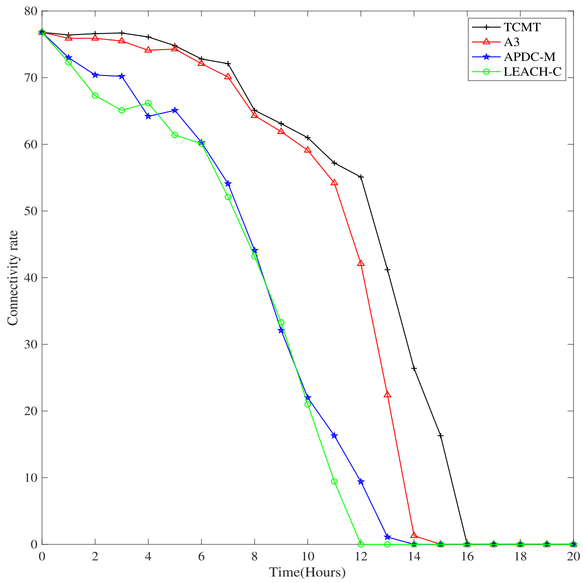

FIGURE 12. The connectivity rate during topology adjustment.

Connectivity is an important indicator to evaluate the stability of wireless sensor networks, which is shown in Fig. 12. During the execution of topology algorithms, the connectivity rate decreases with the death of nodes, while increases slightly as the topology is readjusted for a while. Compared with the other three algorithms, TCMT maintains the highest connectivity rate during the entire network lifetime. It is also worth mentioning that the experiments are performed to show that different topology construction and maintenance techniques do have an impact on the coverage and lifetime in large-scale WSNs.

VI. CONCLUSION AND FUTURE WORK

In this paper, we proposed a Mobile-Coverage adjustment scheme, which leverages the minimum number of sensor nodes to cover the interested area, and the minimum number of *mobile* sensor nodes to balance the coverage and the lifetime of WSNs. Compared to existing schemes, our scheme improved the area coverage with the minimum number of sensor nodes. We proved that the full construction of our scheme was correct, by firstly calculating the minimum number of sensor nodes in a regular region, and then getting the suitable number of *mobile* sensor nodes according to the balance between coverage and lifetime of the WSNs. Thereafter, we designed a novel algorithm based on Virtual Force and Voronoi Graph (VFVG) to increase the coverage of WSNs and reduce the moving distance of sensor nodes. Finally, we utilized the TCMT scheme based on the trust model to construct and maintain the topology of WSNs, so as to further improve the lifetime of wireless sensor networks. To compare our scheme with some previous schemes, We carried out extensive experiments on the coverage and the energy consumption of different procedures. The experimental results showed that our scheme was more efficient than the previous schemes simulated. We realized the maximization of coverage utilizing Mobile-Coverage scheme in hybrid WSNs. However, Large-scale hybrid WSNs are usually deployed in irregular regions, and our scheme focuses on improving coverage and lifetime in regular rectangular regions. Meanwhile, the security of WSNs is not considered. In real environment, WSNs are often subject to various malicious attacks.

Therefore, in our future work, we will devote the coverage and lifetime under irregular regions and the efficient trust management framwork in hybrid WSNs to prevent malicious attacks. Some professinal techniques will be used to improve coverage, lifetime and the security level of hybrid WSNs, such as fuzzy logic, trust evaluation model and game theory.

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