A Three-Dimensional Network Coverage Optimization Algorithm in Healthcare System

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***Abstract*—This paper presents a healthcare monitoring architecture coupled with a wireless sensor network and wearable sensor systems which monitor chronic patients in nursing house or the elderly in their home. With this architecture, we investigate how sensor nodes are deployed in the three-dimension (3D) monitoring region to achieve uniform distribution, which directly determines the Quality of Service (QoS). Based on the existing two-dimension (2D) coverage-enhancing algorithms for wireless sensor networks, a 3D sensing model and a coverage optimization algorithm are proposed in this paper. Firstly, an intelligent optimization algorithm is utilized to adjust the position of sensor nodes. Then, we pick out the redundant nodes with the set coverage algorithm, and move them into the uncovered area to increase the coverage ratio. The simulation results show that the coverage ratio increased by the coverage optimization algorithm compared with the other coverage algorithms.**

***Keywords*—Healthcare, three-dimension sensing model, coverage, intelligent optimization, redundant nodes.**

I. INTRODUCTION

Wireless sensor networks (WSNs) are widely used in industry, agriculture, military, medical care, and safety monitoring [1]. Mobile, wireless, pervasive computing and communication environments are changing the way that medical staffs interact with their patients and the elderly. By deploying self-organized sensor nodes for physiological monitoring reasonably, it is convenient to guarantee timely intervention by a physician with continual patient monitoring information.

Deploying nodes in nursing-house, home or disaster area reasonably is important to the healthcare practitioners or emergency personnel. As a fundamental problem in WSNs, network coverage reflects the perceived performance of the network, which can provide the QoS (Quality of Service). Traditional researches have focused on the two-dimension (2D) network [2, 3]. However, with the demand for practical application, the ideal 2D sensing model couldn't always be applied in the realistic environment, such as home, hills and the volcano [4]. Recently, the emerging field in underwater coverage promoted the development of the research in three-dimension (3D) WSN [5].

There are two types of deployment in 3D WSNs. One is deterministic deployment [6], and the other is random deployment. To obtain the expected coverage ratio, we need to adjust the nodes' locations or other parameters of the random deployment strategies [7]. The current studies are mainly divided into two ways. One is putting 3D problems into the 2D plane [8], which couldn't be solved efficiently just by the extension of the 2D solutions. The other is using the 3D mathematical model and space geometric theory [4] to solve the 3D coverage problems.

In summary, some coverage optimization algorithm are based on graph theory and detection algorithm. It is impractical to apply Graph theory in the monitoring area where any point is covered by a sensor node [9]. The detection algorithm is just suitable for small-scale WSNs since it can't ensure a complete coverage [10]. Recently, with the development of the heuristic search algorithms, we take advantage of their properties to solve the coverage problems, such as the fast searching speed and strong processing. To solve the coverage ratio, the researchers proposed the genetic algorithm (GA), particle swarm optimization algorithm (PSOA), and ant colony algorithm (ACA) which all improved the overall performance to a certain extent, such as raising the coverage ratio or saving energy. However, for different topologies of WSNs, it is rather complicated to adjust the genetic operation of GA [11]. PSOA [12] is easily trapped in local minima value, which is difficult to converge to the global extreme value. Local search ability of ACA is strong, but the solving speed is too slow to operate initially, which affects the real-time performance of the coverage optimization [13]. The drawbacks of GA, PSOA and ACA limit their applications in the network coverage optimization. In some cases, they even lead to a low coverage ratio, the ineffective use of energy and a short lifetime. The artificial fish swarm algorithm (AFSA) [14] overcomes the defects of these algorithms, and we propose an optimal algorithm based on it in this paper.

The rest of the paper is structured as follows. A healthcare monitoring architecture with its applications and a three-dimension sensing model are introduced in Section II. Furthermore, in Section III, a coverage optimization algorithm-AFSOA is proposed to deploy sensor nodes in the 3D environment. Section IV presents the simulation results that the optimal coverage in 3D WSN is achieved by using AFSOA, and the algorithm increases the coverage ratio. Finally, our conclusions are offered in Section V.

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II. SYSTEM MODELS

2.1 Architecture Overview

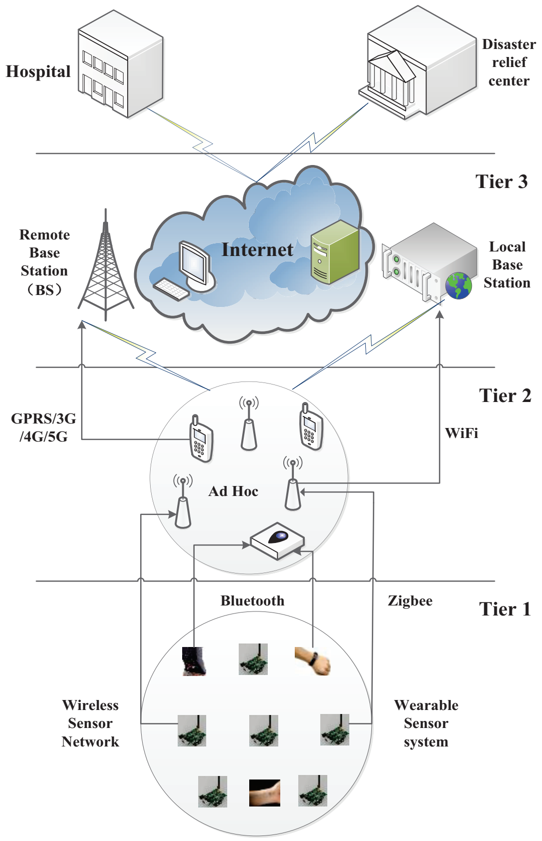

Fig. 1. Healthcare monitoring architecture in wireless sensor networks.

In Fig.1, healthcare sensor systems are required to be connected directly or indirectly to the Internet at all times, which allow medical staffs to timely acquire arrhythmia events and abnormal signals for correcting medical procedures [15]. There are four tiers in the proposed healthcare architecture, introduced as follows.

Tier1— WSNs and wearable sensor systems (WSS): Sensor nodes placed in the 3D surveillance region are self-organized into WSNs to gain the environmental parameters transmitted through a wired or wireless network, communicating using Zigbee wireless technology. To capture the individuals' vital signals, WSS with Bluetooth wireless transmission technology are integrated with biomedical sensor nodes installed in patient identification wristband or fabric belt.

Tier2— Ad Hoc Network: In this tier, several wireless routers (WTs) and mobile terminals (MTs) are organized regionally into an ad hoc network, which connect to a fixed remote base station (BS) or local BS through multiple hops or an infrastructure-based network. If BS is destroyed by disasters, the communication command vehicle will be a substitute for the BS. One MT with enough computation capabilities must capture and analyze physical records from the WSS or WSN because the device doesn't possess mass data storage capability over a long period of time such as a few months or years.

Tier3— Back-end Network: This tier has fixed stations and serves to provide application-level services for the low tiers and process various sensing data from numerous MTs, which is structured on the Internet. The server-side database stores physicality records from monitored individuals and their residential environment data for long-term periods.

Tier4— Command Network: The data are delivered to the hospitals or disaster relief center. Then, physicians can provide accurate diagnoses and correct treatment, and commanders give timely and accurate orders to the emergency rescue.

In each tier, physiological records are collected or transmitted securely by all kinds of protocols or algorithms [16] so that physicians or commanders can provide accurate diagnoses, correct treatment or timely orders.

2.2 In nursing-house , in-home applications

The proposed architecture can be implemented in a lot of scenarios. In this section, we illustrate two implemented nursing-house and in-home healthcare scenarios using this architecture. According to the nursing-house example in Fig. 2 (left), a lot of sensor nodes deployed in a nursing house can form a wired or wireless network. Based on the limited power of sensor nodes, some of them should have a sleep mode to stop automatic monitoring and reporting in order to reduce power consumption. Sensor nodes also can organize an alarm network to forward emergency data over all networks when there is a severe environmental condition. Wearable sensor nodes designed with the Zigbee technology could directly connect to WSNs.

Fig. 2 (right) shows the example of healthcare monitoring applications at home. It is timely for wearable sensor nodes on a monitored individual to obtain physiology signals and transmit them timely to the computing devices which are held by nurses or family members. The WSS monitor the sustained physical postures of the elderly or chronic patients on the computing devices which perform a healthcare analysis process to search for abnormal findings. The application to analyze physical records will be applied in the back-end networks for the analysis quality improvement.

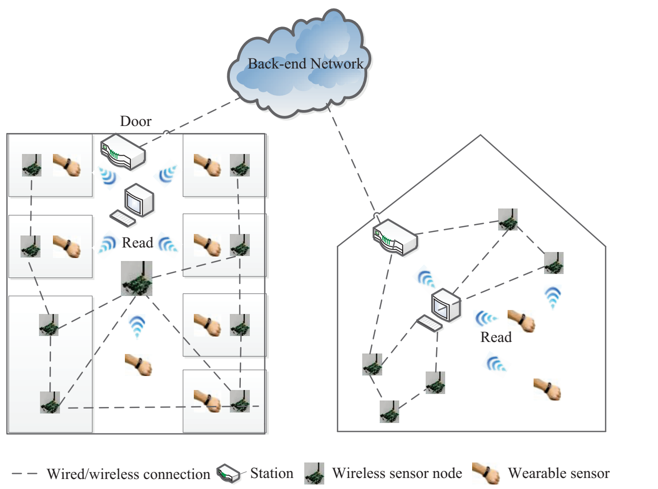

Fig. 2. Healthcare monitoring applications in nursing-house and in-home.

From the analysis of the proposed healthcare monitoring architecture and its applications, we know that how the sensor nodes to deploy in the 3D space is an urgent issue to be solved. In the following section, we investigate a 3D sensing model.

2.3 3D sensing model

In this paper, a random deployment is considered within a large-scale 3D WSN. A spherical omnidirectional coverage model is adopted, and sensor nodes can move in the network. The sensing area of a sensor node is the sphere centered at the sensor node and with radius R. So, the sensing area of each sensor node is $\frac{4\pi R^3}{3}$. We call the point being sensed when it locates in the sensing area of sensor nodes.

On the study of the continuous regional coverage problems in 3D network, we first select discrete points with equal interval in the coordinate axis X, Y, Z, which simplifies the problem into the coverage of discrete points. The set of discrete points is assumed as Ω, and Ω_C is the set of discrete points covered by sensor nodes. Then we have

$$\Omega_C = \bigcup_{1\le i\le n} \Omega_{C_i} , \tag{1}$$

where Ω_{C_i} ($i = 1,2,...,n$) is the set of discrete points covered by sensor node i. Then, the coverage ratio of the 3D monitoring area is defined as

$$\gamma = \frac{\|\Omega_C\|}{\|\Omega\|} . \tag{2}$$

We assume the volume and achieved coverage ratio of the monitoring area are V and γ_a, respectively. The number of sensor nodes distributed in monitoring area is N, and the sensing area of those nodes is assumed to be non-overlapping. The relationship between the achieved coverage ratio γ and the needed sensor nodes m can be derived from

$$\gamma_a = 1-(1-\frac{4\pi R^3}{3V})^m , \tag{3}$$

$$m = \frac{\ln(1-\gamma_a)}{\ln(1-4\pi R^3/(3V))} . \tag{4}$$

We choose the set Ω with equal interval in the $X-$, $Y-$, $Z-$ axis direction. The collection of n coverage sets is $F = \{\Omega_{C_1},...,\Omega_{C_i},...,\Omega_{C_n}\}$ ($i = 1,2,...,n$), and the weight is $w(\Omega_{C_i}) = 1$. Then, $w(F) = n$. The goal of this paper is to find a subset C of F to minimize the sum of weight, which covers Ω by coverage ratio γ. Namely, it satisfies the following formulas at the same time.

$$\bigcup_{\Omega_{C_i}\in C} \Omega_{C_i} / \Omega = \gamma , \tag{5}$$

$$\min \sum_{\Omega_{C_i}\in C} w(\Omega_{C_i}) . \tag{6}$$

After the study of heuristic search algorithms-GA, PSOA, ACA and AFSA, we know that the drawbacks of GA, PSOA and ACA limit their applications in the network coverage optimization. In some cases, they even lead to a low coverage ratio, the ineffective use of energy and a short lifetime. However, AFSA overcomes the defects of the local minima of the other algorithms. AFSA is a new kind of intelligent bionic random searching algorithm which is raised to simulate the fish feeding and survival activities to search. It isn't sensitive to the selection of initial value and parameters, and it is simple, robust, and easy to implement. At present, AFSA has a beneficial effect on the engineering field for a long time [14]. Therefore, based on this algorithm, we put forward an artificial fish swarm optimization algorithm (AFSOA) to find out the solution of (5)-(6), as shown in the following sections.

III. Coverage Optimization Algorithm

In this section, we introduce AFSOA that adjusts the locations of sensor nodes by AFSA to reduce the overlapping coverage area and make nodes uniformly distributed in the 3D monitoring area. Although the coverage ratio of the monitoring area increases, the coverage area is still redundant. Namely, there are a few redundant nodes in the monitoring area. So we pick up the redundant nodes with the set coverage algorithm, and move them to the uncovered area to improve the coverage ratio.

We assume the initial number of sensor nodes is n, and the initial location of sensor node S_i is $<x_i, y_i, z_i>$. So the set of the initial sensor nodes is $I = (<x_1, y_1, z_1>, <x_2, y_2, z_2>, ..., <x_n, y_n, z_n>)$. The probability of S_i to search the target $T(x_t, y_t, z_t)$ is

$$p(S_i,T) = \begin{cases} 1, & d(S_i,T) \le R_s - R_e \\ e^{-\lambda_1\alpha_1^{\beta_1}(\alpha_2^{\beta_2}+\lambda_2)}, & R_s - R_e < d(S_i,T) < R_s + R_e \\ 0, & otherwise \end{cases} , \tag{7}$$

where R_s is the sensing range of sensor nodes, and R_c is communication radius between sensor nodes. λ_1, λ_2, β_1, β_2 are the measurement parameters related to the characteristics of sensor nodes. $R_e (0 < R_e < R_s)$ is the measurement reliability parameter. $d(S_i,T)$ is the Euclidean distance of node S_i and the target T.

$$\alpha_1 = R_e - R_s + d(S_i,T) , \tag{8}$$

$$\alpha_2 = R_s + R_e - d(S_i,T) . \tag{9}$$

We assume S is the set of sensor nodes monitoring the target T, and the probability of target T being sensed by sensor nodes is

$$p(S,T) = 1 - \prod_{i=n} (1 - p(S_i,T)) . \tag{10}$$

If p_{th} is the probability threshold of the monitored target, the condition of the target being monitored effectively is

$$\min_{(x_t,y_t,z_t)} \{p(S,T)\} \ge p_{th} . \tag{11}$$

The searching space of the artificial fish swarm is D. In this paper, we should get the solution $(<x_1, y_1, z_1>, <x_2, y_2, z_2>, ..., <x_n, y_n, z_n>)^*$ which makes all $(<x_1, y_1, z_1>, <x_2, y_2, z_2>, ..., <x_n, y_n, z_n>)$ satisfy the inequality

$$\gamma(<x_1,y_1,z_1>,<x_2,y_2,z_2>,...,<x_n,y_n,z_n>) \le \gamma(<x_1,y_1,z_1>,<x_2,y_2,z_2>,...,<x_n,y_n,z_n>)^* . \quad (12)$$

The procedure of AFSOA is as follows:

3.1 Search based on AFSA

Initially, sensor nodes are randomly deployed in 3D monitoring area. The location adjustment of sensor nodes is limited by the neighbor nodes' locations. Using the network coverage ratio as the optimal objective function, we search the global optimal distribution through AFSA. In this section, we expatiate this algorithm which makes the sensor nodes deploy uniformly in the monitoring area.

AFSA is an optimization algorithm of simulating the fish swarm behavior and using the foraging, clustering and trailing behaviors to search the global optimal solution quickly. The simulation results demonstrate that the optimal coverage in 3D WSN using AFSA is achieved in a short time [14]. The food concentration is the target. Therefore, AFSA has a robust adaptive capacity.

(1) The Foraging Behavior

We denote $STEP$ as the maximum moving step length, and SR is the sensing range of the artificial fish swarm. Current status of artificial fish swarm is X_i, and we randomly choose a state X_j in the visible domain. If the food concentration of X_j is greater than the current concentrations, the fish step forward in this direction. Otherwise, we should randomly select a state again. After several times, if it still can't meet the above conditions, the fish randomly step forward. Namely,

$$\begin{cases} x_i(k+1) = x_i(k) + \dfrac{1}{\|x_j - x_i\|}(step)(x_j - x_i), FC_j > FC_i \\ x_i(k+1) = x_i(k) + (step), \qquad FC_j \le FC_i \end{cases}, \quad (13)$$

where $i = 1,2,...,k$, and x_i, x_j is the state vector. FC_i, FC_j are the food concentration of x_i and x_j, respectively. $x_i(k+1)$ is the i th element of $X_i(k+1)$.

(2) The Clustering Behavior

There are n partners in the visible area of artificial fish swarm. The center of the number of partners is X_C. If there are a lot of food and not too crowded in the center of partners, the fish step 1 forward in the direction of the center. Otherwise, perform the foraging behavior.

(3) The tailgate behavior

$X_{\max}$ means the status that the maximum food density is in the visible domain of partners. If $FC_{\max} > \delta FC_i$, the food density in this area is the highest, and it can be set as the center. Otherwise, carry out the foraging behavior.

(4) The bulletin board

The bulletin board is used to record the optimal individual status of artificial fish swarm and the location of the food concentration. After one action, the artificial fish swarm will be compared with the bulletin board. If it is superior to the bulletin boards, it will take the place of the bulletin board.

(5) The behavior choice

According to the different problems, the artificial fish swarm will evaluate the surrounded environment and choose the appropriate behavior.

3.2 The selection of redundant nodes

After AFSA, it really makes the distribution of sensor nodes uniform and the coverage ratio improved. But in fact, there are still overlaps among the sensing area of those nodes in the 3D WSN. In other words, there are always a lot of redundant nodes whose selection is based on the set coverage model that is a NP-hard problem [13]. In this paper, to get a decent performance approximation algorithm of set coverage problem, we adopt the idea of greedy algorithm to solve it.

The complementary set C' of C consists of redundant nodes. The design of this algorithm is as follows: select a point set $\Omega_{C_i} \in F$ every time, and its weight is w. To make $\dfrac{w}{|\Omega_{C_i} \cap \Omega|}$ minimum, for $w=1$, so $|\Omega_{C_i} \cap \Omega|$ is maximum. We select sensor nodes until the coverage ratio of a point set Ω is γ. The algorithm is described as follows:

Algorithm 1: The redundant nodes selection

(1) The initial number of sensor nodes is 0.
(2) Select the maximum value from $\{\Omega_{C_1},...,\Omega_{C_i},...,\Omega_{C_n}\}$ as the first one.
(3) $m+1$, and add the number of this node in the array a.
(4) Remove the covered point from Ω, and get a new point set.
(5) Select the maximum value of $\Omega_{C_i} \cap \Omega'$ from the remaining nodes as the next one.
(6) $m+1$, and add the number of this node in the array a.
(7) Repeat (4)-(6) until the covered point sets are $\gamma \times \Omega$.
(8) Return m and the array a.

3.3 The movement of redundant nodes

In WSNs, to obtain a higher coverage ratio γ and reduce the blind spot, we need to increase the deployment density of sensor nodes. However, if the deployment density is larger, there are more redundant nodes which cause a large number of data transfer conflicts and energy consumption. Then, the lifetime of WSN is very short. For one sensor node, if its sensing area can be fully covered by other nodes, we call it redundant. Different from the algorithms [18] that make the redundant nodes enter a dormant state, we move them into the uncovered area to improve the whole coverage ratio of the monitoring area in this paper.

We assume that the number of needed nodes is m in practice. Then, the number of redundant nodes is N-m. The redundant nodes are moved to the selected uncovered network grids. The ultimate target locations of redundant nodes are the grids whose sensing area contain the highest number of neighbor grids. We eliminate the covered grids in step 1 and repeat this procedure until redundant nodes are completely placed.

IV. SIMULATION RESULTS

In this section, a series of simulation experiments with Matlab 7.0 are presented to verify the validity of the proposed algorithm. We assume that the size of the 3D monitoring area is $100\times100\times100m^3$, and there are 85 sensor nodes in the area randomly. The sensing radius of sensor nodes is $R=20m$, and the side length of divided grid is $4m$.

The comparison between the initial coverage ratio and the optimal coverage ratio of the 3D network is illustrated in Fig.3. We can note that the distribution of sensor nodes is more uniform after AFSA. The coverage ratio increases from the original 83.67% to 92.24%. Further, we eliminate the redundant nodes from the optimal network. As a result, the number of sensor nodes is from initial 85 to 75 after the redundancy elimination. So the number of the redundant nodes is 10. For 10 redundant nodes, we can make them either sleep or move them into the uncovered area. In order to improve the coverage, we adopt to move 10 redundant nodes into the uncovered area, and the coverage ratio increases to 96.98%, as shown in Fig. 3.

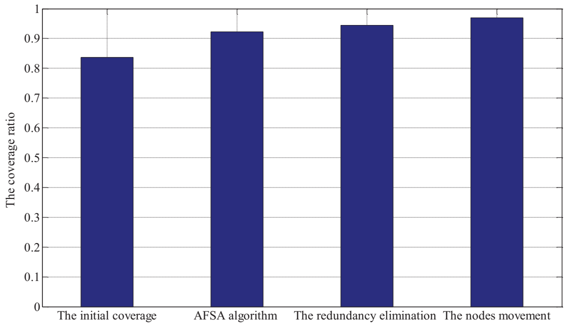

Fig. 3. The comparison of different conditions

To achieve a specified coverage ratio, we need to know the condition of redundancy elimination. The experiments are finished with the initial number 65, 75, 85, 95, 105, respectively. We record the needed number of sensor nodes for the coverage ratios of 70%~ 71%, as shown in Table 1. To achieve the given coverage range, the number of sensor nodes is 35 in theory, while the number is 36 experimentally. Through the analysis, we get the causes that the theoretical value is derived in the continuous space, while the experimental value is gotten by the discrete grid coverage. Though there are some deviations, but they are basically consistent with the theoretical values.

Table 1. The conditions of the nodes redundancy

The initial number	The coverage ratio (%)	The practical number	The redundant number
65	70.47	36	21
75	70.57	36	31
85	70.57	36	41
95	70.67	36	51
105	70.80	36	61

To further enhance the coverage ratio, we move the redundant nodes to the uncovered area. Table 2 shows that the coverage ratio rises after AFSOA, and the number of redundant nodes are 5, 9, 10, 11, 18, respectively. We also do similar experiments with $R=20m$ and γ=73.26%. Then, 11 sensor nodes are needed in order to achieve the ratio, i.e., the number of redundant nodes increases.

Table 2. The conditions of the coverage ratio

The initial number	The initial coverage ratio(%)	The optimal coverage ratio(%)	The final coverage ratio (%)
65	75.32	87.05	90.54
75	82.94	89.45	94.99
85	83.67	92.24	96.98
95	85.67	94.29	98.13
105	90.97	94.84	99.75

To illustrate the advantages of AFSOA for the coverage optimization problem in 3D WSNs, we compare the random distribution algorithm (RDA), GA, PSOA, ACA, AFSOA with the same simulation environment, and the contrast results are shown in Fig.4. We know that the coverage ratio of RDA is less than 80% which can't meet the practical demand. However, the coverage ratios of GA, PSOA, ACA and AFSOA are more than 90%, the degree of redundancy is small and the network costs are reduced. Among all the algorithms, AFSOA proposed in this paper is more efficient to realize the global optimization deployment, and maintains a superior network coverage ratio and balanced energy for a long time. Thus, it prolongs the network lifetime, and has a wider application scope.

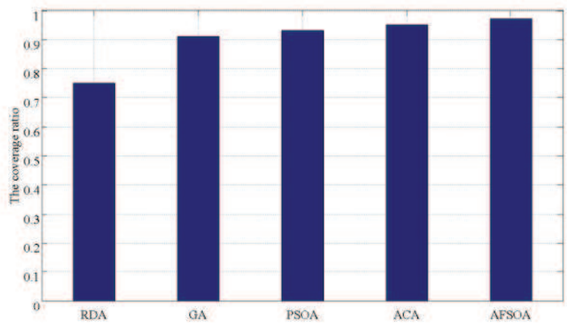

Fig. 4. The comparison of different algorithms

V.CONCLUSION

Coverage is one basic topic in 3D WSNs, which directly determines the QoS of network. In this paper, we study the random coverage and redundancy problem in the 3D healthcare system. A healthcare monitoring architecture coupled with a WSN and WSS is first presented to monitor chronic patients in nursing-house or elderly in their home. Then, we propose AFSOA to optimize the nodes deployment, which improves the network coverage ratio. Extensive simulation results evaluate the effectiveness of our proposed algorithm. In this paper, we take the 3D coverage into consideration, but not the complex environment and energy balance that play an important role in the healthcare system. So our next research field is the convoluted surface coverage in a 3D environment with the consideration of the energy balance in WSN.

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