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Coverage Optimization Strategy for WSN based on Energy-aware

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Abstract: In order to optimize the wireless sensor network coverage, this paper designs a coverage optimization strategy for wireless sensor network (EACS) based on energy-aware. Under the assumption that the geographic positions of sensor nodes are available, the proposed strategy consists of energy-aware and network coverage adjustment. It is restricted to conditions such as path loss, residual capacity and monitored area and according to awareness ability of sensors, it would adjust the monitored area, repair network hole and kick out the redundant coverage. The purpose is to balance the energy distribution of working nodes, reduce the number of "dead" nodes and balance network energy consumption. As a result, the network lifetime is expanded. Simulation results show that: EACS effectively reduces the number of working nodes, improves network coverage, lowers network energy consumption while ensuring the wireless sensor network coverage and connectivity, so as to balance network energy consumption.
Keywords: WSN, coverage optimization, energy-aware, hole repair, sensing radius.

1 Introduction

Wireless sensor network (WSN) consists of many sensor nodes which draw on self-organization to transmit data between nodes. These sensor nodes are small in size with limited energy and certain awareness, making them widely applied to many fields, such as military, transportation, environment protection, medical care, disaster relief and agriculture. Currently, sensor nodes are distributed manually or randomly. Manual distribution is executed in certain circumstances requires high on environment. So in most cases, random distribution [1–3] is the primary choice as it is easy to operate and able to reduce the interference on human activities. However, under circumstances of high density and large area, wireless sensor network is weak in expansion, which results in that the transmission signal is easy to be disturbed, the network energy is unevenly distributed and network become unstable.

It is urgent to solve problems of increasing the effective coverage in monitored areas as much as possible, lowering network energy consumption, extending network lifetime, and improving network performance under the condition of limited energy and using the least sensor nodes. And network coverage is one of the most important indicators of network performance measurement.

Among existing studies, literature [4] proposes a method to calculate redundancy of probability node. With this method, nodes in the network can acquire information about their own, such as redundancy, without knowing the geographic position. It also proposes a node adjustment strategy without knowing node position. But this strategy neglects the awareness redundancy area within two-hop neighbor nodes, making many redundant working nodes exist during node adjustment. Literature [5] proposes a node distribution strategy based on wireless beacon self-adaption. This strategy repairs network coverage holes by adding wireless beacon to the network but fails to consider the cost of adding the beacon and the influence on monitored area. Literature [6] proposes to use a circle to solve node adjustment coverage. It calculates the angle between the awareness circle and the monitored area to get the minimum number of working nodes and reduces redundant working nodes. But under high coverage, the connectivity is weak. Literature [7] acquires information of null nodes and introduces mobile nodes. To be specific, it replaces null nodes with mobile nodes to fill the network holes. The network coverage is increased, but the energy of mobile nodes is limited and there are too many null nodes in the network. Literature [8] proposes a coverage strategy based on genetic algorithm. It selects the maximum solution set of coverage nodes. With genetic algorithm, it uses evaluation function to optimize random samples and reach a balance of network coverage. But the algorithm is relatively complicated and requires much calculate. To some extent, it increases network energy consumption.

In order to improve effective coverage, this paper proposes a coverage optimization strategy for WSN based on energy aware, establishes a network coverage model. Network nodes are distributed randomly; a network coverage model is established the relationship between node residual capacity and sensing range are examined to set reasonable sensing range of nodes, balance network energy consumption, repair network coverage holes, and extend network lifetime. Finally, a simulation experiment is conducted to prove the relationship between network energy consumption and coverage of the proposed algorithm under different circumstances. The proposed algorithm aims at balancing network energy consumption, improving network coverage, and minimizing node energy consumption. This paper establishes a non-linear model of coverage optimization strategy for wireless sensor network (EACS) and exercise stricter constraints to turn it to linear-constraints and get the second-best solution.

2 Network model and problem description

2.1 Analysis model of energy-aware node

Suppose the wireless sensor network consists of N randomly distributed nodes, during node awareness, the energy of physical signal changes inversely with the distance between the signal and the awareness target. Such tendency is mainly due to path attenuation during transmission, Select any source node s_i within the scope of monitoring, when target node s_j is anywhere in the plane, the awareness intensity $\Psi_i(j)$ of souse node to target node is expressed as:

$$\Psi_i(j) = \begin{cases} 0 & R_s < d(i,j) \\ \lambda e^{-kd(i,j)} & 0 < d(i,j) \leq R_s(1) \end{cases} \tag{1}$$

where k is the indicator of signal attenuation. R_s is the maximum effective sensing radius of the node. $d(i,j)$ is the Euclidean distance between node i and j. λ is a constant value. The awareness intensity $\Phi(j)$ of node j is expressed as:

$$\Phi(j) = 1 - (1 - \Psi_1(j))(1 - \Psi_2(j)) \cdots (1 - \Psi_i(j)) \cdots (1 - \Psi_n(j)) = 1 - \prod_{i=1}^{i=n} (1 - \Psi_1(j)) \tag{2}$$

When $\Phi(j) > \epsilon$, target node j is sensed. When $\Phi(j) < \epsilon$, target node j is not sensed, and at this time, j is the coverage blind-point (ε target node j is not sensed, and at this time, j is the coverage blind-point

$$\begin{array}{ll} H_0 : g(i) = \vartheta_i & i = 1, 2, \ldots, N \\ H_1 : g(i) = \vartheta_i + \psi_i(j) & i = 1, 2, \ldots, N \end{array} \tag{3}$$

Where ϑ_i is the background noise signal following the normal distribution $\vartheta_i \sim N(\mu, \sigma^2)$, and $\vartheta_i(j)$ is useful signal. The signal detected by sensor nodes is $g(i)$. The target that exits is expressed by H_0 and the target that does not exist is expressed by H_1.

2.2 Network model

N non-overlapped wireless sensor nodes, $S = \{s_i | 1 < i < n\}$, whose sensing radius is R_s are randomly distributed in a two-dimensional monitored area A. Suppose the network has the following features:

(1) The node position is permanent. There is no inherent relationship between the communication radius R_c and sensing radius R_s.

(2) All nodes have isomorphism. The wireless self-organized network is constructed in the monitored area.

(3) All nodes adopt the node probability awareness model.

(4) The sensing radius of sensor node can be adjusted according to node residual capacity.

(5) The initial energy of sensor nodes is W, and they have synchronous clock.

(6) Sensor nodes use the location technology in literature to acquire their own locations. At the same time nodes can acquire the information of neighbor nodes, such as residual capacity, node position within effective communication distance.

2.3 Problem description

A number of sensor nodes are distributed randomly within the monitored area A. Probabilistic sensing model is deployed, and network nodes are adjusted according to data from 2.2network model; a wireless sensor network is established to balance network energy consumption and network coverage, adjust sensing ranges based on residual capacities, reduce the possibility of "death node" and redundant network coverage, and extend network lifetime. This paper expects to reach a balance between residual capacity of any sensor node and sensing range in the monitored area (where W_i is the residual capacity, $\Im_i$ is the sensing range and A is the monitored area),

$$W_i < W_j \quad \&\& \quad \Im_i < \Im_j \tag{4}$$

$$A = \Im_1 \bigcup \Im_2 \cdots \bigcup \Im_i \cdots \bigcup \Im_n = \bigcup_{i=1}^{i=n} \Im_i \tag{5}$$

In the monitored area A, nodes should satisfy (3)(4) to reach the requirement of coverage. This paper also turns energy consumption and coverage balance strategy to a non-linear and multi-target optimization problem:

$$\begin{cases} 0 < Cov_{\max} = f(\sum_{i=1}^{i=n} cov_i) \leq A \\ 0 \leq W_{\min} = \varphi(\sum_{i=1}^{i=n} \Delta w_i) \leq nW_0 \\ T_{\max} = \max(\min(T_1, T_2 \cdots T_n)) \\ \zeta_{\min} = \Theta(\sum_{i=1}^{i=n} \zeta_i) \end{cases} \tag{6}$$

Given that path loss, node residual capacity [9] and monitored area are key factors [10–12] to realize network performance optimization and extend network lifetime, the constraint conditions are dealt with according to mathematical programming so that the optimized network has high accuracy. Construct the optimized model with maximizing the network lifetime as the target. The optimized model is restricted to constraint conditions. Adjust the monitored area, and optimize the network lifetime and the overall network overhead. In the non-linear and multi-target optimization, optimized factors are not in the optimal state, but the network overhead is almost the minimum and the convergence has high accuracy.

3 Energy coverage strategy

Coverage strategy of the wireless sensor network optimize network energy consumption while improving network coverage [13–15]; in addition, they should also balance energy consumption of single node and overall network energy consumption. If nodes with lower energy are assigned the same work load as nodes with higher energy, the former will end in “premature death” and the transmission and reliability of the entire network will be undermined. To reach the balance of two optimization coverage strategies and solve the contradiction between individual nodes and the overall performance, this paper proposes a coverage optimization strategy for WSN based on energy-aware, namely Energy-aware Coverage Strategy (EACS). The strategy is mainly divided into two phases: one is the energy-aware phase in which the sensing field of each node is confirmed by probability according to residual capacity of sensor node in the monitored area. The second is the network coverage adjustment phase where the sensing radius of node is adjusted effectively according to the sensing field of each node and the overall network coverage to lower the redundant coverage, reduce redundant coverage and unnecessary energy consumption, so as to extend network lifetime.

3.1 Energy-aware phase

In the wireless sensor network, sensor nodes in the monitored area transmit information through awareness coordination. Given that sensor nodes have limited energy, this strategy concerns not only about energy consumption of any node in the area, but also the equilibrium of the whole network energy consumption. As time goes by, survived nodes may suffer from breaking the equilibrium of energy consumption due to signal interference, resulting in the change of node residual capacity. Considering that node residual capacity is related to node sensing range, as shown in Fig.1, reasonable sensing range is set up for each node to balance the network energy consumption and finally, to extend network lifetime.

In the energy-aware phase, after time t of working, the relationship between the electric quantity W_i consumed by node si and the sensing radius R_i of sensing field A_i is (k is a constant value):

$$W_i = kR_i^2 \tag{7}$$

For any two neighboring nodes s_i and s_j, their residual capacity is Q_i and Q_j respectively. After time t, their electric quantity is consumed simultaneously. The sensing radius between two nodes fits expression (2):

$$R_i = d(i,j) \cdot \frac{\sqrt{Q_i}}{\sqrt{Q_i} + \sqrt{Q_j}} \tag{8}$$

Where d (i, j) is the Euclidean distance between nodes. According to expression (8), the sensing radius and residual capacity of s_i and s_j have the following relationship:

$$R_i : R_j = \sqrt{Q_i} : \sqrt{Q_j} \tag{9}$$

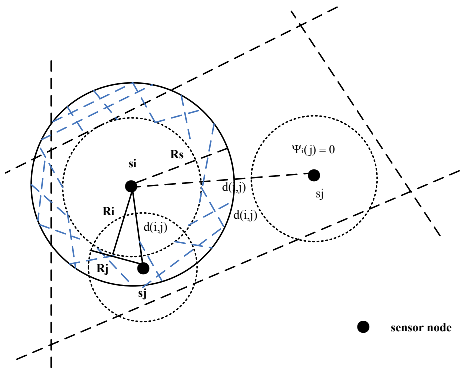


Figure 1: Node sensing range

Theory 1 The sensing filed of node S_i is Ω, its awareness is radius R_i. Ω falls in the set $\gamma(\gamma_1, \gamma_2, \cdots \gamma_i)$ and any γ_k satisfies $d(si, \gamma_k) < Ri$. If the probability of $X(X \in \Omega)$ sensed by any node in γ is p, there are Pxsensing fields in Ω on average that are sensed by γ.

Suppose the sensed set in the sensing field Ω is $\Pi\{x_1, x_2 \cdots x_n\}$, and these nodes are independent from each other following even distribution. If $k(k < n)$ nodes in being sensed by γ is called event X, so X follows binomial distribution, namely $X \sim B(n,p)$.

$$P\{X = k\} = C_n^k p^k (1-p)^{n-k}$$

where $E[X]$ is the expectation of X. When $n \to +\infty$, the average awareness in Ω is:

$$\lim_{n \to +\infty} \frac{E[X]}{n} = p$$

So there are psensing fields on average that are sensed by γ in Ω.

3.2 Network coverage adjustment

Select any node Si in the monitored area, according to the energy-aware strategy, acquire the energy-aware range and node residual capacity of last phase and send the information such as sensing radius and energy consumption to the neighboring node. According to awareness intensity, confirm the sensing range and monitored area of each node. When there produce holes in the monitored area, re-distribute the nodes. Given that the sensing field may overlap, when no new holes are produced, adjust the sensing radius based on node residual capacity to wipe out redundant monitored area, so as to reduce unnecessary energy consumption. Detailed steps are described below:

Step 1ŁşDivide the monitored area. For any node in the area, connect it with neighboring nodes and form the minimum triangle network as shown in 2(b). Subject each triangle to perpendicular bisector and connect the lines, as shown in 2(c). Finally, monitored area A consists of many regional polygons, as shown in 2(d).

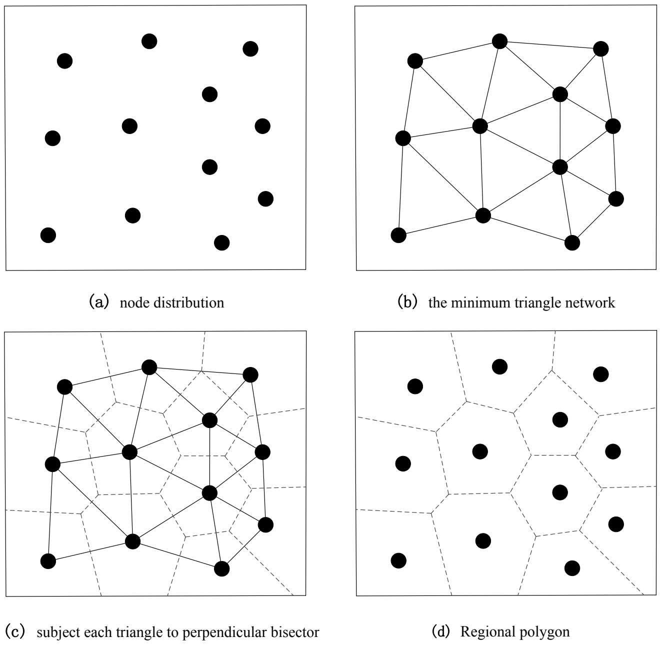
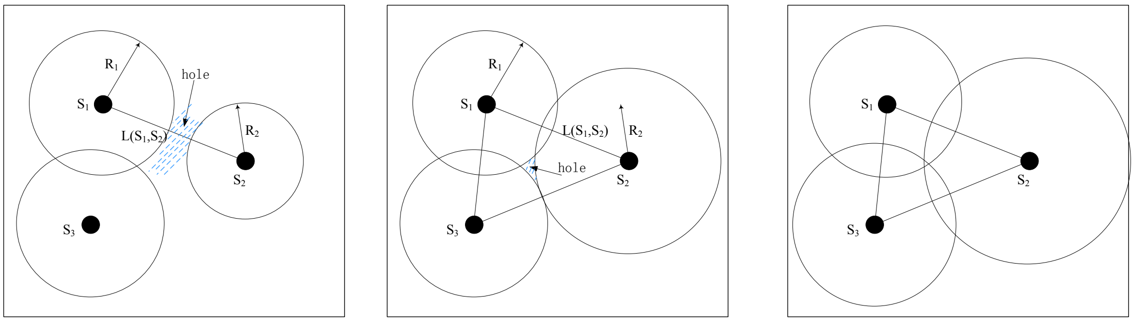


Figure 2: Distribution of monitored area

Step 2: detect irreparable holes and nodes filling. Firstly, detect holes on the edge of monitored area A. The polygon which cannot be fully covered by the minimum triangle network is called the edge monitoring polygon. Take the vertex of the polygon at the edge of the monitored area as the circle center and twice the maximum sensing radius of nodes R_{max} as the radius to draw a circle. Places that cannot be covered by the circle are irreparable holes and need to be filled. New nodes should fill in the middle of the vertex and original nodes. For any side of the triangle in the network $< S_1, S_2 >$, if the side is twice more than the maximum sensing radius of nodes, namely $L(S_1, S_2) >$ 2Rmax, it is also considered that there are irreparable holes. Thus, we should fill node in the middle of the triangle side. After nodes are filled, repeat step 1 to construct the new triangle network and the monitored polygon. Go on to step 3 until no new nodes should be filled.

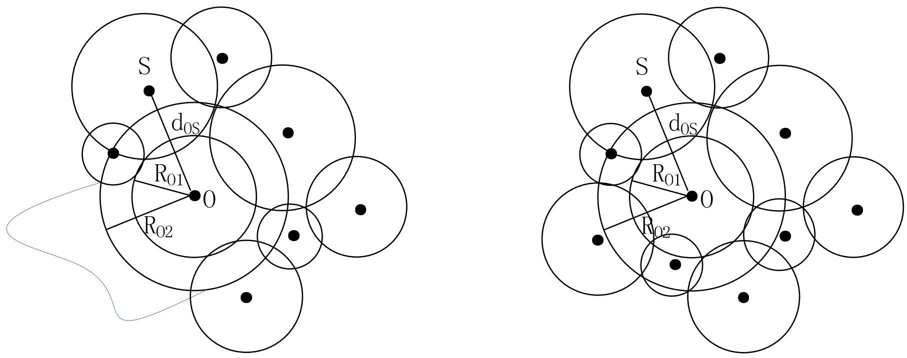
Step 3: detect regional holes. Confirm the initial sensing radius of nodes according to expression (9). Construct the network model with the minimum triangle and detect the triangle network. To be specific, judge whether a minimum triangle $S_1S_2S_3$ has sensing holes. If one side of the triangle $< S_1, S_2 >$ is longer than the total sensing radius of two tip nodes, namely $L(S_1, S_2) > R(S_1) + R(S_2)$, as shown in 3(a), then $\triangle S_1S_2S_3$ has holes. If three sides fit $L < R_i + R_j$, in other word, two circles intersect, the premise for no holes is that any circle intersects with the overlapping part of the other two circles. That is to say, the intersection of any two circles should fall within the sensing radius of the third one. Otherwise, $\triangle S_1S_2S_3$ has holes, as shown in 3(b) and 3(c). When all minimum triangles fit this rule, a set with holes is formed. Calculate the number of nodes that have appeared, and form the hole-node set $\{S_i, \ldots, S_j\}$.



(a) the total sensing radius < the triangle side (b) the intersection circles with hole (c) the intersection circles without hole

Figure 3: Network hole detection

Step 4: hole repair. Start repairing from the nodes that appeared the most times in the statistics in step 2. If two nodes appear the same times, the one with higher residual capacity is adjusted primarily. For example, S_i is the first one to be filled. Increase the transmitting power of S_i, by adding its sensing radius, until all triangles with S_i as the tip node do not have holes. Repeat step 4 until all holes are filled, as shown in Fig.4



(a) WSN with coverage hole (b) WSN without coverage hole

Figure 4: Coverage hole repair

Step 5: wipe out the redundant holes. Get the complementary set of the triangle set with holes in step 2, namely the minimum triangle set without holes. As the initial sensing range of nodes is big, or two neighboring nodes are close to each other, there may be redundant coverage. Related nodes with relatively large sensing radius may consume unnecessary energy. Thus, it is necessary to adjust the sensing range of nodes in the complementary set. Firstly, calculate the number of nodes that appeared and rank them from the most appeared to the least appeared. Priority is given to nodes with less residual capacity. Reduce the sensing radius of nodes gradually until no new holes appear in the triangle area. Repeat step 5 to all nodes in the complementary set.

4 Analysis of algorithm performance

4.1 Analysis of coverage quality

Conclusion 1 If the awareness intensity probability of j by node S in monitored area A is $P\{\tau < \Phi(j) < 1\}$, where $Ss_1, s_2 \dots s_n$ is the node set and τ is the threshold of awareness intensity. When and only when the expectation value of network coverage γ in A is bigger than γ_0 (where γ_0 is the coverage threshold), namely $E[\gamma] > \gamma_0$, the coverage in A meets the requirement of the network coverage.

Coverage connectivity is one of the important indicators to measure the service quality of wireless sensor network. According to the model, the probability of awareness intensity for node q in monitored area A is $P\{\tau < \Phi(j) < 1\}$. Elements in the node set S form a connected graph $G(V, E)$, where V is the node set, and E is the side set. Nodes are independent from each other. The connectivity degree of G is $\Xi(G)$ (n is the number of selected nodes).

$$\lim_{n \to +\infty} P\{\Gamma(Sn, V, \Xi(G)) \geq k\} = 1$$

When n approaches infinity, the awareness probability of node in the connected graph increases. So does the connectivity degree. According to the definition, the expectation value of network coverage γ is:

$$E[\gamma] = E[\iint_A Cov(i) dA / \|A\|] = P\{\tau < \Phi(i) < 1\} > \gamma_0$$

Select the sub-areas in the monitored area randomly. According to the probability event, when the connectivity degree has a high probability, the node sets in the area are all connectivity set and the network coverage would also meet the expectation.

4.2 Analysis of network lifetime

Conclusion 2 Distribute n sensor nodes in monitored area A. The node set is $S = \{s_1, s_2 \dots s_i \dots s_n\}$ and s_i and s_j are neighboring nodes. The neighboring node set of s_i is N$_i$. When the network parameters are set the same as that of the network model, the network lifetime is $Max\ t_i$ (t_i is the lifetime of node, $i = 1, 2......n$).

Node s_i can be any node in the network. Its neighboring node set is $N_i = \{s_j, s_k \dots\dots s_m\}$. Select one neighboring node s$_j$. At this moment, the communication distance of two nodes is within the effective sensing range of s_i. So the energy consumption between nodes is:

$$Q = \sum_{j \in N_i} \tau_{ij} \eta_{ij} + \sum_{j \in N_i} \nu \eta_{ji} \tag{10}$$

where η_{ij} is the information transmitted by s_i to s_j. τ_{ij} and ν_{ji} are energy loss factor when node receiving and transmitting information. Under normal condition, the lifetime of s_i is:

$$t_i = \frac{\varpi_i}{Q_i} \tag{11}$$

where ϖ_i is the residual capacity of s_i. According to expression (10) and (11), the network lifetime T_{life} is:

$$T_{life} = Max\{t_1 \dots t_i \dots t_n\}$$

5 Simulation experiment analysis

Through simulation experiment, this paper makes a comparative analysis on algorithm performance. The setting is described as follows: place 120 sensor nodes in the monitored area $100 \times 100\text{m}^2$. The sensing radius is 5-20m and the initial electric quantity is 200J. The ratio of energy consumption of working, leisure and dormant state is 24:5:0.02. EACS algorithm is compared with the distributed random algorithm and PAYY algorithm (Proposed Approach of yourim y) proposed by literature [5] to assess the performance of EACS algorithm. Network coverage, network overhead and network lifetime are important parameters in the comparison.

Table 1: Experiment parameter

Parameter	Value
M	100m*100m
N	120
To	120s
W	0.2J
Node Sampling Frequency	1Hz
R	10m
Initial Energy	200J
Minimum Energy Limit	0.02J
Ro	5m
Rm	20m

In the initial state of network operation, the performance parameters of all nodes in the monitored area are set the same, as shown in Fig.5(a). After working for some time, there produce difference on nodes. Adjust sensing radius of nodes according to their energy consumption. Nodes adjust themselves according to residual capacity and relationship with neighboring nodes, as shown in Fig.5(b). In the whole operation, due to differences between nodes and the change of sensing range, there may be redundant areas or coverage holes. Hole detection is conducted followed by hole repair and redundancy elimination in other to enhance the coverage, as shown in Fig.5(c).

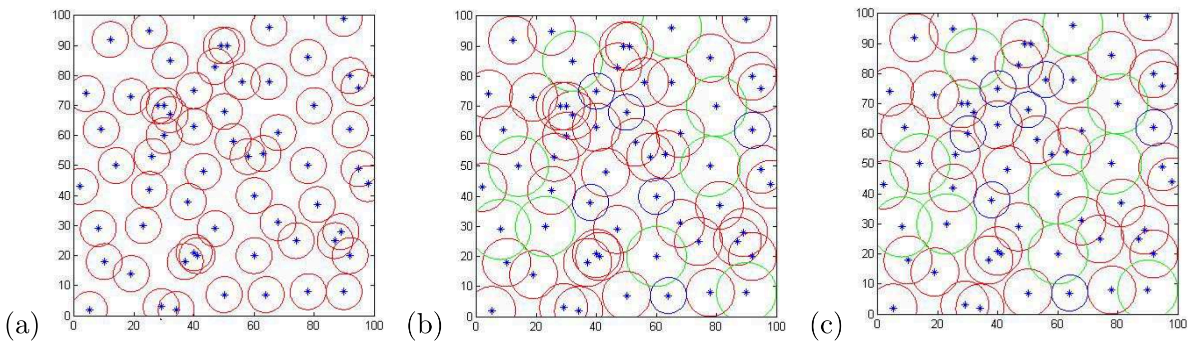


Figure 5: Network coverage

Network coverage ratio refers to the ratio of the effective coverage area by sensor nodes against the overall monitored area. For Random algorithm, operate it for 50 times and get the average coverage. Fig.1 shows the network coverage under different network scales of different algorithm. From Fig.6, it is known that with the increasing of the number of sensor nodes, the network coverage also increases. Under the same number of working nodes, the coverage of Random algorithm is relatively low. When 100 nodes are started, EACS algorithm can reach 90% coverage, 15% higher than Random algorithm. EACS algorithm is better that the other two algorithms in terms of coverage, because such algorithm can adjust the sensing radius according to residual capacity and reduces redundant monitored area. When sensor nodes increase in number, the coverage would increase rapidly.

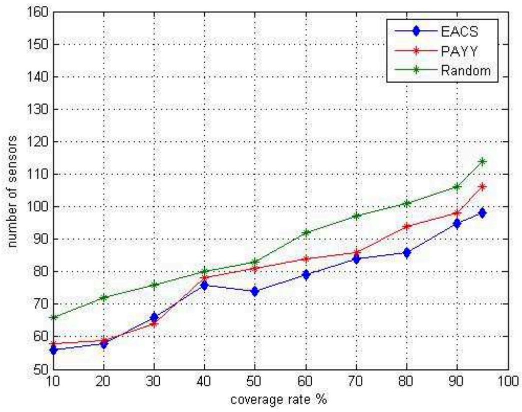


Figure 6: Working nodes and network coverage

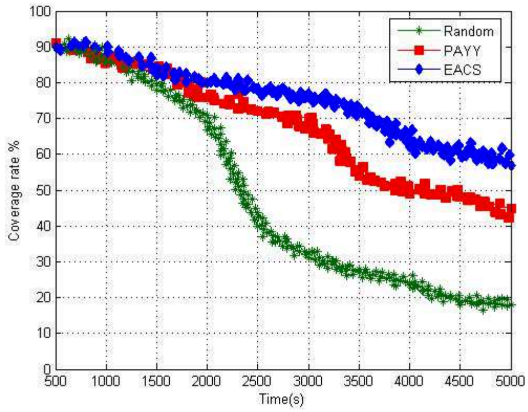


Figure 7: Coverage changes over time

Fig.7 shows network coverage of three algorithms changing over time. In the initial operation of network, the network coverage changes relatively slowly with little divergence. As time goes by, EACS algorithm witnesses the increase of network coverage, though the energy-aware and hole detection require some energy consumption. From Fig.7, it can be told that the coverage curve of EACS algorithm drops steadily, reflecting that the network energy consumption is distributed evenly.

Fig.8 compares nodes location of PAYY and EACS algorithm under the same initial settings and after the network operates for some time. Working nodes of EACS algorithm is more evenly distributed than those of PAYY algorithm. This is mainly because EACS algorithm adopts energy-aware model. The sensing radius of nodes is adjusted according to real situation of the network, so that the energy can be evenly distributed and the network lifetime can be extended.

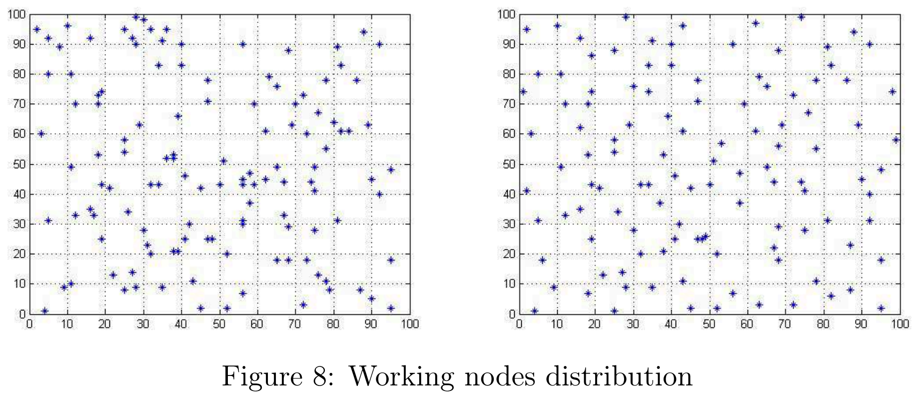


Figure 8: Working nodes distribution

Conclusion

This paper proposes a coverage optimization strategy for WSN based on energy-aware, namely EACS algorithm. It can reach energy balance of nodes in the wireless sensor network. Re-assign tasks of awareness according to working nodes residual capacity, and adjust the sensing radius of nodes according to probability awareness in order to repair the network holes and redundant areas, improve network coverage and reduce redundant coverage and overall network consumption. Results show that the method proposed in this paper takes node residual capacity as an important factor of adjusting sensing field to reduce the burden of nodes with little energy and save them from being "null" too early. Otherwise, it may affect the connectivity and the network lifetime. At the same time, when the coverage holes are under repair, adjust the redundant coverage so that the balance of coverage reaches a reasonable range and the network coverage satisfies actual need. As a result, the unnecessary network energy consumption can be reduced effectively, a balance between the network coverage and energy consumption can be reached and the network lifetime can be improved.

Acknowledgments

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