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Coverage Optimization Deployment Based on Virtual Force-Directed in Wireless Sensor Networks

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Abstract—Combining with virtual force model, this paper presents a strategy based on virtual force-directed coverage optimization (VFCSO) in wireless sensor network, taking node energy and centroid distance as parameters, considering virtual force between sensor nodes as well as nodes and centroid, electing the node which is close to centroid and with more energy as cluster head to optimize network coverage and node survival time. Theoretical analysis and simulation results indicate the effect of network coverage and node survival time by comparing with GAF.

Keywords-Wireless sensor networks; GAF algorithm; Virtual force; Clustering; Network coverage

1. Introduction

Wireless sensor networks (WSN for short) are widely used in target tracking and environmental monitoring as the ability of collaborative processing information. According to the monitoring environment, network layout optimization is helpful to improve the network coverage as well as target detection probability and to reduce the network energy consumption. Therefore, network layout optimization has become a key part of network performance optimization of WSN [1,2].

In the densely deployed case, if each node communicates under a certain power, that would increase communication jamming and cause redundancy of coverage. Therefore, a certain node dormancy mechanism can not only balance node energy consumption and optimize the network coverage but also prolong the network life time [3]. Reference [4] proposes a GAF (adaptive geographical fidelity) algorithm, which is a classical algorithm based on the cell division of cluster. GAF introduces the node state transition mechanism and the thought of dividing cluster according to virtual cell, which elects cluster at random. Reference [5] proposes a GAF improved algorithm, which designs two different cluster head election mechanism and elects cluster combining with residual energy, experimental results indicate it is beneficial to prolong the network life time.

Virtual force algorithm gets a lot of attention recently, which determines node location according to the virtual force between sensor nodes as well as nodes and centroid. Reference [6] proposes a particle swarm optimization (PSO) algorithm, which can effectively achieve the effect of layout optimization in WSN.

This paper presenting a kind of dynamic sensor deployment strategy based on virtual force-directed cover optimization in WSN, combining with virtual force model to present a new cluster head election strategy, taking node energy and centroid distance as parameters, considering virtual force between sensor nodes as well as nodes and centroid, electing the node which is close to centroid and with more energy as cluster head to reduce the redundancy of coverage and achieve the effect of improving the network coverage

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and optimizing node survival time, presenting a new wireless sensor network coverage algorithm. At last, theoretical analysis and experimental results indicate the effect of network coverage and node survival time by comparing with GAF.

2. Problem Model and Assumptions

Assuming coordinate of node s_i is (i_x, i_y) with sensor radius R_s, and coordinate of monitoring target R is (R_x, R_y), then the distance between node s_i and target R is $d(s_i, R) = \sqrt{(i_x - R_x)^2 + (i_y - R_y)^2}$. $C(s_i)$ is expressed as sensor probability of s_i, if R is inside of a circle with its center at s_i and of radius R_s, $C(s_i)$ is considered to 1, otherwise 0. Therefore, the expression of $C(s_i)$ is:

$$C(s_i) = \begin{cases} 1 & d(s_i, R) < R_s \\ 0 & otherwise \end{cases} \tag{1}$$

In fact, there is a close relationship between judgment of sensor nodes and the distance with monitoring target, generally speaking, the closer the node with the target is, the high credibility on target judgment will be; conversely, the farther with the target is, the more fuzzy credibility will be. Therefore, the sensor model appears certain character of probability distribution, that is:

$$C(s_i) = e^{-\alpha d(s_i, R)} \tag{2}$$

α is expressed as an attenuation parameter, which reduces with the increase of distance. This paper uses Boolean sensor model.

3. Virtual Force-Based Coverage Optimization Strategy

GAF is a clustering algorithm based on node location, which divides area monitoring into several virtual cells and delimits nodes into corresponding cells according to location; each cell elects cluster head regularly, only keeping cluster head active, other nodes in a suspended state. GAF includes virtual cell division and cluster election.

3.1. Cell Division

If the node knows the whole monitoring area as well as own location information, it can calculates own cell. Assuming that communication radius and sensor radius are R_c and R_s, monitoring area is divided into some r-by-r-meter-square virtual cells. To make sure that any node can communicate with each other in neighboring cells, it should meet the following expression:

$$r^2 + (2r)^2 \le R_c{}^2 \Rightarrow r \le \frac{R_c}{\sqrt{5}} \tag{3}$$

Therefore, from the view point of grouping, the node belongs to the same cell can be considered to be equivalent, each cell only need to keep a node active.

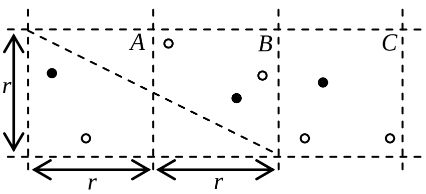

Fig. 1 Virtual cell division

3.2. Virtual Force Model

Among coverage algorithms, force analysis of nodes usually references existing force model in physics, such as the gravitation, coulomb force between molecules and the elastic force in the hooker law etc. Hereby we elect the representative of force and analyzes its influence on the performance of coverage algorithm [7]. Independent two objects, if they are electric charge, then coulomb force is: $F = K\frac{q_1 q_2}{r^2}$, here, q_1 and q_2 are power of electric charge; and r is the distance between them; and K is a constant. Gravitation is: $F = G\frac{mM}{r^2}$, as the same, m and M are quality ; and r is the distance; and G is a constant. The structures of coulomb force and gravitation are very similar, then we can define virtual force model as well for WSN:

$$F = \begin{cases} 0 & d \geq d_{th} \\ \dfrac{\kappa E_i E_j}{d^2} & d < d_{th} \end{cases} \tag{4}$$

d_{th} is expressed as distance threshold, which is to judge the nature of the force, attraction or repulsion; E_i and E_j are similar to power or quality, κ is a scale factor.

According to the formula 4, the repulsion that s_i receives from s_j is:

$$F_{ij} = \begin{cases} 0 & d_{ij} \geq d_{th} \\ \dfrac{\kappa E_{current}(s_i) E_{current}(s_j)}{d_{ij}^2} & d_{ij} < d_{th} \end{cases} \tag{5}$$

According to the formula 4, the attraction that s_i receives from centroid R is:

$$F_{iR_i} = \begin{cases} 0 & s_i \notin N_i \\ \dfrac{\kappa E_{current}(s_i) E_{centroid}(i)}{d_{iR_i}^2} & s_i \in N_i \end{cases} \tag{6}$$

$E_{current}(s_i)$ and $E_{current}(s_j)$ are expressed as residual energy of s_i and s_j ,and $E_{centroid}(i)$ is expressed as energy of centroid R of virtual cell (it's position center); d_{ij} is expressed as distance between s_i and s_j, d_{iR_i} is expressed as distance between s_i and centroid R; N_i is number of nodes in cell i; κ is a scale factor.

3.3. Cluster Head Election Parameter

Assuming sensor nodes, as well as nodes and monitoring target are subjected to the action of attraction or repulsion. As shown in Fig. 2, we assume that the repulsion that s_i receives from s_j is $\vec{F}_{ij}$, and the attraction that s_i receives from centroid R is $\vec{F}_{iR}$, therefore, the resultant that s_i receives is $\vec{F}_i$:

$$\vec{F}_i = \sum_{j \neq 1, j \neq i}^{k} \vec{F}_{ij} + \vec{F}_{iR} \tag{7}$$

$\vec{F}_{ij}$ is the repulsion that node s_i receives from nodes in distance threshold in neighboring cells; and $\vec{F}_{iR}$ is the attraction that node s_i receives from centroid R.

According to the formula 5, the repulsion that s_i receives from s_j is:

$$F_{ij} = \left(\kappa E_{current}(s_i) E_{current}(s_j) / d_{ij}^2 , \theta_{ij} \right) \tag{8}$$

θ_{ij} is the angle between s_i and s_j; and θ_{iR} is the angle between s_i and R.

According to the formula 6, the attraction that s_i receives from centroid R is:

$$F_{iR} = \left(\kappa E_{current}(s_i) E_{centroid}(i) / d_{iR}^2 , 0 \right) \tag{9}$$

According to the formula 5, 6, 7, the resultant that s_i receives is:

$$F_i = \Bigg(\kappa E_{current}(s_i) E_{centroid}(i) / d_{iR}^2 + \sum_{j \neq 1, j \neq i}^{k} \left(\kappa E_{current}(s_i) E_{current}(s_j) / d_{ij}^2 \right) \times \cos\theta_{ij} , 0 \Bigg) \tag{10}$$

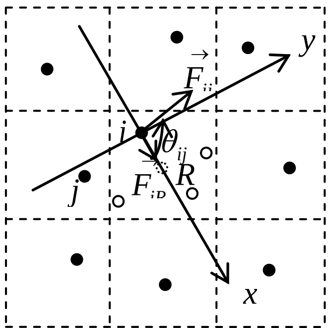

Fig. 2 Force analysis

Cluster head election model elects the cluster head according to different weights, the node with smaller weight can be preferred become cluster head [8,9]. In order to balance the whole network of the energy consumption and to avoid cluster head continuously energy consumption, W_i (weight of s_i) is introduced as the cluster head election parameter, other nodes are also use this method to calculate the cluster head parameters. By formula 10, the node which has more residual energy and near centroid will reach the greater virtual force F_i, that is to say the node with smaller W_i is more likely to be cluster head. Therefore, F_i and W_i become inverse ratio. We assume the scale factor is α, W_i is expressed as:

$$W_i = \alpha / F_i \tag{11}$$

According to the formula 10, 11, W_i is:

$$W_i = \beta \Big/ \left(\kappa E_{current}(s_i) E_{centroid}(i) / d_{iR}^2 + \sum_{j \neq 1, j \neq i}^{k} \left(\kappa E_{current}(s_i) E_{current}(s_j) / d_{ij}^2 \right) \times \cos\theta_{ij} \right) \tag{12}$$

$\beta = \alpha / \kappa$, which is a constant.

3.4. Algorithm Specific Description

Each node is required know about ID (which can be easily obtained from the GPS signal) of other nodes in this cell. During the initialization stage, each node sends a message containing its node ID, which is form 0 to $n-1$, as well as the id of cell. At this stage, since intra-cell synchronization is not yet established, which conflicts to access the wireless channel must be solved using traditional backoff-based technique. According to the characteristics of WSN, we assume that the following information is initially available to nodes:

1) There is a Sink node with strong information processing capability in WSN.
2) Every node knows its location.
3) In particular, each node knows its cell id and maintains strict time synchronization in same cell.

Algorithm realization process (time synchronization): assume that there are n_i nodes cell i, each node p has its ID, whose values are from 0 to $n_i - 1$. Meanwhile, p knows its cell id and ID s of others in this cell. Assume that the re-election process starts at time T_r, each step below will take time T_s, algorithm can accomplish calculations in the time of turning the radio on and sending the message to others in this cell.

Protocol for generic node p with $ID \in (0, n_i - 1)$, specific cluster head election process is as follows:

1) At time $T_r + (p-1) \times T_s$

a) To turn radio on and receive message $M = (W_{\min}, ID)$ from node $p-1$, $W_{\min}$ and ID respectively represent minimum cluster head election parameters and its $ID \in [0, p-1)$.

b) W_p is estimate weight of p at the end of the algorithm execution.

c) $W_{\min} = \min(W_{\min}, W_p)$, if $W_{\min} = W_p$, then $ID \leftarrow p-1$.

2) At time $T_r + p \times T_s$

a) To send message $M = (W_{\min}, ID)$ to others in this cell, if $p - 1 \neq ID$, then to turn radio off and to enter a sleeping state.

b) Other nodes turn radio on and receive message from p.

3) At time $T_r + n_i \times T_s$

a) To turn radio on and receive message $M = (W_{\min}, ID)$; the node of ID is elected to be the cluster head for the next sleep period; and $W_{\min}$ is the weight of it.

b) END; cluster head election process is over, a new cluster head is elected, just to keep cluster head active and others to enter a sleeping state.

The algorithm for nodes 0 and $n_i - 1$ is slightly different: node 0 simply sends message $(W_0, 0)$ at time T_r, and wakes up at time $T_r + n_i \times T_s$ to know the cluster head identity; node $n_i - 1$ ends the algorithm after sending the message $M = (W_{\min}, ID)$ at time $T_r + n_i \times T_s$. In case it is not the cluster head, it turns its radio off before ending the algorithm.

4. Simulation and Analysis of Results

100 nodes are random uniform deployed in a 100-by-100-meter-square monitoring area, this area is divided into 25 virtual cells which are 20-by-20-meter-square, each cell has 4 nodes on average. In order to ensure nodes can communicate with each other in neighbor cells, which communication radius is $45m$ (formula 3). Meanwhile, assuming that the initial energy of each node is $50J$, the energy consumption of the cluster head is $1J$ each round, and it keeps working in a same time. There is no energy consumption if the node in a sleeping state; the initial energy of centroid is $50J$, which does not consume along with the network operation. As each cell has 4 nodes on average, and each node will die after being elected as the cluster head for 50 rounds. All nodes will die after 200 rounds each cell, and the lifetime of the cell is the product of rounds and period of time when working as a cluster head.

As the sensor nodes are random uniform deployed in the monitoring area in the initial stage. Fig. 3 shows the initial position of 100 nodes after deployment.

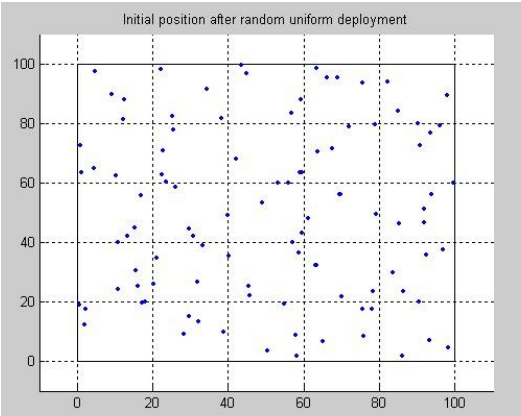

Fig. 3 Initial position after random uniform deployment

After network being deployed, we compare the initial coverage of VFCSO and GAF. First, network coverage is defined as the ratio of a total covering area with monitoring area, and covering area is the union are of all nodes.

$$C = \bigcup_{p=1,\dots,n}^{n} A_p / A \tag{13}$$

A_p is covering area of p; n is the total number of nodes; A is total covering area of monitoring region.

Fig. 4 and Fig. 5 respectively represent the location of initial cluster head by GAF and VFCSO after random uniform deployment. Meanwhile, spots are expressed as cluster heads, and circles are expressed as coverage radius. The initial coverage of cluster heads after the first round is 81.4% by GAF, as well as 94.3% by VFCSO, which is 1.16 times than GAF.

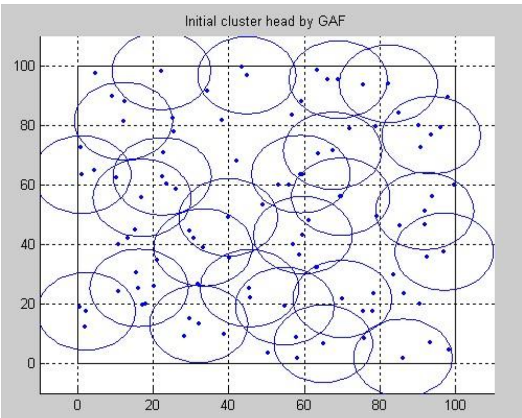

Fig. 4 Initial cluster head by GAF

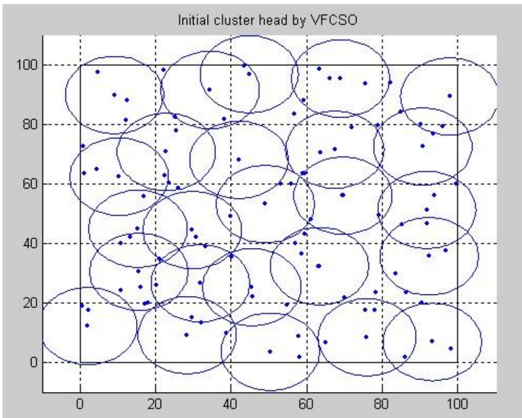

Fig. 5 Initial cluster head by VFCSO

Fig. 6 represents Election rounds — Coverage curve by VFCSO and GAF through 200 rounds of cluster election. The above (red) curve is expressed as curve of network coverage change through 200 rounds by

VFCSO; while the below (black) curve is expressed as curve of network coverage change by GAF. Coverage at rounds of 40, 80, 120, 160 respectively are 86.3%, 83.1%, 83.3%, 84.1% by VFCSO; while they are 81.7%, 81.9%, 81.8%, 81.6% by GAF. Therefore, the network coverage of VFCSO is higher than that of GAF. Coverage hole refers to the area without coverage, which is related to information gathering and a certain extent embodies accuracy and reliability of information. Meanwhile, the higher the network coverage is, the smaller coverage hole will be; otherwise, the lower the coverage is, the bigger coverage hole will be. By Fig. 6, the coverage hole of VFCSO is smaller than that of GAF. Therefore, it can be improved that VFCSO is better than the existing GAF during the optimization network coverage.

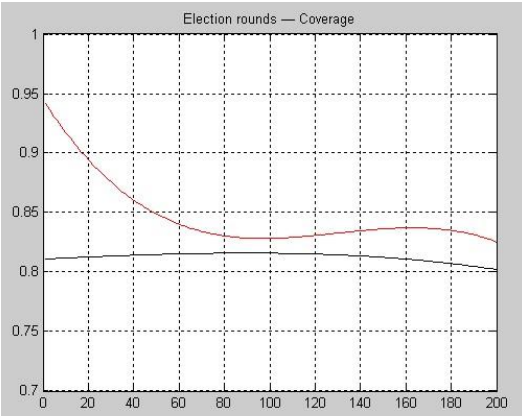

Fig. 6 Election rounds — Coverage

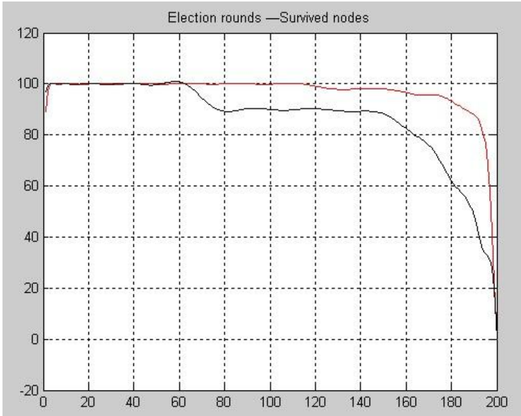

Fig. 7 Election rounds —Survived nodes

Fig. 7 represents Election rounds —Survived nodes curve by two algorithms through statistic data of node survival time. Since each node has certain initial energy, that is no death node in the early network, while the survived nodes of GAF are fewer than those of VFCSO, In Fig. 7, the above (red) curve is expressed as number of survived nodes through 200 rounds by VFCSO; while the below (black) curve is expressed as number of survived nodes by GAF. Number of survived nodes at rounds of 80, 120, 160, 180 respectively are 100, 98, 96, 92 by VFCSO; while number of survived nodes respectively are 89, 87, 81, 62 by GAF. Experiments show that VFCSO is superior to GAF in the number of survived nodes

5. Conclusion

This paper combines with virtual force model to present a new strategy based on virtual force-directed coverage optimization (VFCSO) to optimize the network coverage in wireless sensor network, and the simulation tool MATLAB is used to study on the simulation. Simulation results indicate that VFCSO is superior to GAF in the effect of network coverage and node survival time.

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