International Journal of Future Generation Communication and Networking
Vol.7, No.4 (2014), pp.35-48
http://dx.doi.org/10.14257/ijfgcn.2014.7.4.04

Optimization Coverage of Wireless Sensor Networks Based on Energy Saving

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Abstract

The separate situation of research has area coverage or target coverage in wireless sensor networks. Based on directional sensing model the algorithm used the virtual potential field to make the sensor nodes shift positions and change directions automatically in monitoring area, With the completion of multiple prior coverage of hot targets which needed higher quality requirements the algorithm could maximize the coverage rate throughout the monitoring area Simulation experiments show that the algorithm has a good ability of self-organizing. It can satisfy the requirements of coverage quality of the hot targets and the whole monitoring area and save resources effectively of the network.

Keywords: *wireless sensor networks, optimization coverage, probability model, sensor node*

1. Introduction

WSN (Wireless Sensor Network) is a kind of self-organization network system which consists of large number of inexpensive sensor nodes, and its nodes are characterized by a certain sensing ability, computing power and communication capabilities. It is widely used in the fields of defence and military, environmental monitoring, rescue works and *etc.*, WSN works in such a way that following way: large numbers of sensor nodes are distributed in discrete form within the coverage area, and data is sent to or collected from nodes directly or indirectly [1-3]. Usually the target node is covered in a manner that sensor nodes are high density deployed to monitor the target area, and to improve the quos of network, information is exchanged among sensor nodes to achieve target node coverage and information processing. But there're some defects, first, deployment of larger number of sensor nodes in target area results in existence of considerable amount of redundant nodes, which consume much network energy and reduce the network Qos. Second, due to the excessive consumption of node energy, and non-rechargeable feature of nodes, the network tends to collapse quickly. How to distribute sensor nodes in target area reasonably to determine the minimum point set under certain coverage requirement, and how to limit the power consumption maximally, become key problems which influence the network lifetime directly. In summary, the solving of energy issues and coverage problem means monitoring the given area at the minimum

ISSN: 2233-7857 IJFGCN

nodes number and low energy cost, meanwhile, the quality of coverage should be guaranteed. It is also the study focus of this paper.

2. Background

The methods of deployment of the wireless sensor network nodes can be divided into deterministic deployment and randomness deployment. Usually the deterministic deployment method is adopted when the network is small, and a good monitoring regional condition can be guaranteed. The advantage of this method is that by controlling the position of each node through artificially deployment, the optimal solution meeting the network coverage requirement can be achieved. On the contrary, if artificial way is not feasible, usually aircraft or other tools is used to randomly distribute sensor nodes in a certain area, because of the uncertainty of nodes' positions, more nodes will be needed compared to the deterministic method, then the node redundancy problem comes out. Thus, the problem of energy consumption and node coverage become one of the major research topics in the filed of wireless sensor network. In references [4.5], by exploiting the Force Filed Theory of mobile network and Round Coverage Thinking in wires sensor network, VFA algorithm is proposed. When the nodes in a wireless sensor network are distributed unevenly, this algorithm can be used to scatter the intensive nodes in order to effectively cover the target area, but the energy consumption problem of whole network is not fully considered. In references [6, 9, 18], a sensor network coverage and connectivity probability model in the case that nodes are random scattered is proposed. By exploiting this model, the node numbers which meet different coverage and connectivity requirement can be calculated and the calculation is simple; but this model is only studied with the complete coverage case, meanwhile, the connectivity rate under multi-network coverage is not considered. In references [10, 13, 15] proposed perception coverage and connectivity restore study in mobile sensor network, the idea is study the coverage area and connectivity issues as a whole, Coverage Conscious connectivity Restoration is used to restore one or more nodes from the failure nodes, thus the connectivity is restored and this node at initial position in coverage area are monitored. Because the energy consumed for data collection every time is not equal, and it is not suitable to re-divide the intersecting coverage set during the recovering process of the failure nodes [8, 11, 12]. To this end, by using the Gaussian density function and the coverage area probability function the quantitative comparison between the node sensing radius and the number of nodes is given in the minimum nodes set theory model, so that the coverage for the target area is done.

3. Modeling and Analysis

3.1. Basic Definition

The research work of this paper is based on the following assumptions:

Hypothesis 1: wireless sensor network communication radius and the sensing radius are disc-shaped.

Hypothesis 2: Coverage radiuses of each node are equal, and the movements of the nodes are synchronized parallel.

Hypothesis 3: through some positioning algorithm the specific location information and coverage area boundary information can be obtained.

Definition 1: if the coordinate of Node S is (x_s, y_s), the target node up's coordinates is (x_p, y_p), then the Euler distance between the node S and destination node p $D(s,p)$ is :

$$D(s,p)=\sqrt{(x_s-x_p)^2+(y_s-y_p)^2} \quad (1)$$

Definition 2:Let S be a collection of n nodes randomly distributed in the target area, that is $S = \{s_1, s_2, s_3 ... s_n\}$, E, is the set of edges of the network graph, which represent the set of edge whose e_{ij}=1, where e_{ij} denotes the positional relationship of node s_i and target node p_j, and e_{ij} = 1 if and only if the Euclidean distance of the two nodes is less than or equal to the sensing radius r_s, otherwise e_{ij} = 0. $W = \{w_1, w_2, w_3 ... w_N\}$ is a set of initial energy of the sensor nodes, W follows $W\sim N(u,\sigma^2)$ normal distribution, w_i represents the initial energy of the sensor nodes s_i, w_i is the maximum energy amount during the working process of node s_i.

Definition 3: if communication radius r_c of sensor node and sensing radius r_s follows $r_c/r_s \geqslant \sqrt{3}$, completely coverage and connectivity can be ensured.

Definition 4: the coverage rate of a wireless sensor network W deployed in the target region Ω is represented as follows:

$$C_r(W,\Omega)=\int_0^{\Omega} f(x)\,dx \Big/ f(\Omega) \quad (2)$$

$f(x)$ is the target function of optimal node subset; $f(\Omega)$ is the target area. $f(x)$ is defined as follows:

$$f(x)=w_1 f_1(x)+w_2\left(1-f_2(x)\right) \quad (3)$$

$f_1(x)$ and $f_2(x)$ denote the proportional function of the node set and the number of optimal sub, w_1 and w_2, respectively, expressed as the weight value.

Defining 5: Gaussian normal density function:

$$f(x)=\frac{1}{2\pi\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right) \quad (4)$$

Then the number of nodes randomly distributed is:

$$n=\lg(1-p)\Big/\lg\left(1-\frac{\pi r_s^2}{\Omega}\right) \quad (5)$$

Theorem 1: The probability that there is at least one node: $P(s)=1-\left(1-P(s)\right)^n$

Proof 1: Coverage probability event $P(A) = p$; then $P(A+A)=P(A)+P(A)-P(A)P(A)=p+p-p^2=1-(1-p)^2$ we can prove: $P(A+A+A)=P(A+A)+P(A)-P(A+A)P(A)=1-(1-p)^3$,$P(n*A)=1-(1-p)^n$, so Theorem 1 is established by mathematical induction provable.

Theorem 2: provided that n sensor nodes are randomly deployed in a network region whose area is Ω, and sensing radius of each node is r_s, then the probability that there is a k node in a region of area πr_s^2 is $\left(N\pi r_s^2\right)^k e^{-\frac{N\pi r_s^2}{\Omega}} \Big/ \Omega^k K!$.

Proof 2: By Poisson's theorem, when the number of number of sensor nodes N close to positive infinity, the probability P approaches infinity small, the secondary distribution $B(n,p)$ can be approximately regarded as following the Poisson distribution $p(n,\lambda)$, Let $\lambda = np$, and all the sensor nodes in the network coverage area πr_s^2 are randomly distributed, then the number of nodes in the network coverage area can be seen as following obedience secondary distribution $B\left(n,\pi r^2/\Omega\right)$, because when the sensor nodes are distributed in the coverage area, usually high-density deployment method is adopted, so that the sensing radius of each node is much less than the network area Ω, when the number of sensor nodes n within the coverage area is gradually increasing, $n\pi r_s^2/\Omega$ gradually approaches infinitely small, the binomial distribution can be approximated seen as the Poisson distribution, that is, the probability that at any point of the network the coverage rate is K, is $P = \lambda^k e^{-\lambda}/k!$, where $K \in N$.

3.2. Probability Model

Generally speaking, the coverage rate directly reflects the degree of concern of target [7]; nodes with high concern degree are usually accompanied by high coverage rate. In order to study such a problem, now network model of the relation between the sensor node and the destination node is given. This is shown in Figure 1:

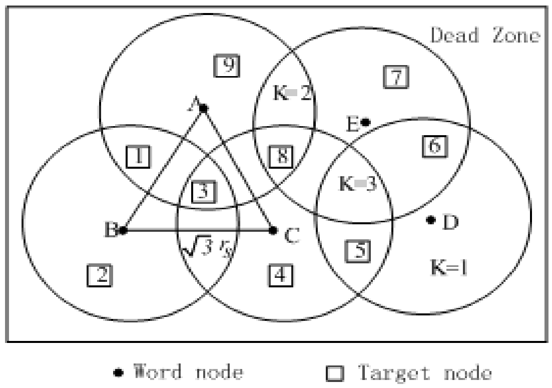

Figure 1. Network Model

Figure 1 shows the sensor layer, in which the network is a combination of five sensor nodes and nine target node, and it describes the relationship between the sensor node and the destination node, intersects of the coverage means it is covered by multiple nodes, where k = 1 denotes single node coverage, k=2 denotes covered by two nodes, and so on. For the sensor layer, each node covers certain number of target nodes, thus forming the relationship with the destination nodes[14,17], let the degree of association between the nodes is 2, its manifestations is: *A(*1,3,8,9*); B (*1,2,3*); C (*3,4,5,8*); D (*5,6*);E* (6,7,8), and on the contrary, 1 *(A, B);* 2 *(B);* 3 *(A, B, C);* 4 *(C);* 5 *(C, D);* 6 *(D, E) ;* 7 *(E);* 8 *(A, C, E);* 9 *(A); (*1,3*) (A, B); (*3,8*) (A, C).*

Theorem 3: In the case of multiple coverage, let $k \geq 3$, provided that within the network monitoring area, any arch region with an edge of r_s is adjacent to an arch region with an edge of r_i, and within the double curved area they formed, there exist k active sensor nodes; then this area is covered by k degree. Here r_i is the length of an edge of the equilateral triangle which is formed by the node center.

Proof 3: assume that the network monitoring area is an arch mesh region, which is formed by the arch area divided from the monitoring area itself, and for any arch region, there exists another adjacent arch region, within the double curved area formed by the two above arch area, there're k active nodes, and any of the arch area has a side length of r_i, the maximum distance between any node and the triangle within which the two curved area exists does not exceed r_i. Then any point in the two adjacent arch areas is at least covered by k nodes at the same time. Similarly, if through judgment other arch areas are also covered by k degrees. Then this area is k-degree covered.

3.3. Parameter Establishment

l: side length of the square coverage region
Ω: the network region, ie $\Omega = l^2$
n: number of randomly deployed network nodes
r_s: the sensing radius of sensor nodes, r_s<l
r_t: the communication radius of sensor nodes, r_t<l
$E(C)$: The expectations of sensor node coverage
$P(S_n)$: a network expect coverage rate of n randomly deployed nodes
$P(C_n)$: network connectivity probability of n randomly deployed nodes

Usually, coverage directly reflects the extent that the objectives are concerned, the concerned target node region having higher coverage, taking into account the functional relationship between sensor node p in the region II expectations and coverage region, shown in Figure 2.

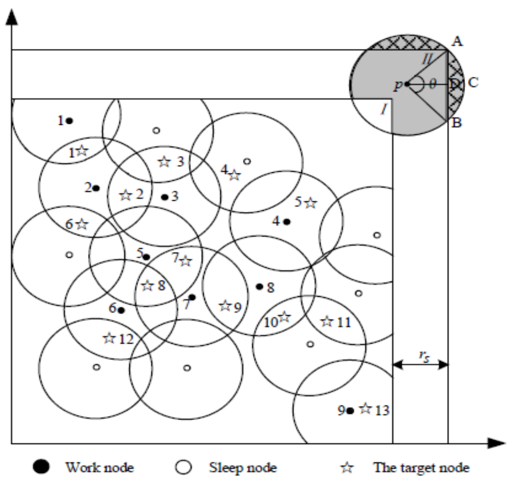

Figure 2. Target Region and Node p in II Region

Figure 2 shows the relation model of working sensor node, dormant node and target node and the diagram of sensor node p in coverage region II. Sensor nodes 1-9 are in working state, and the rest are in a dormant state. Relation among the information obtained by perception of the target node, the node coverage region and the target node is as follows:

Table 1. Relation of the Sensor Node and Target Node

target	node	target	node	target	node
1	1,2	9	7,8	2,6	2
2	2,3	10	8	7,8	5
3	3	12	6	7,9	7
5	4	13	9	7,8,9	7
6	2	1,2	2	8,12	6
7	5,7	1,2,6	2	8,9	7
8	5,7,8	2,3	3	9,10	8

Now take the analysis of Figure 2 as the example. The square region l is divided into Ⅰ and II two parts. Randomly deploy the nodes in the monitoring region to construct a finite set *S* with the coverage region of each node being *E*(*C*), so that the coverage probability of each node is *E*(*C*)/Ω. When the nodes set is empty, the network coverage of the *n* deployed nodes will be $P(S)=(1-E(C)/\Omega)^n$ Thus the network nodes probability value has been obtained in the situation that collective S is not an empty set.

$$p(s) = 1 - \left(1 - E(C)/\Omega\right)^n \tag{6}$$

When the number of nodes $n \to \infty$, $\lim_{x\to\infty} E(p(S)) = 1$ which indicates that the number of nodes is large enough, this coverage region is completely covered [16]. Considering the boundary effect in solving the node coverage region and expectations, because the square region is divided into region I and II, based on the concept of expectation value in probability, expectation value of the coverage of network nodes can be obtained:

$$E(C) = P(\Omega_{\mathrm{I}})E(C_{\Omega\mathrm{I}}) + P(\Omega_{\mathrm{II}})E(C_{\Omega\mathrm{II}}) \tag{7}$$

Among them, $P(\Omega_{\mathrm{I}})$ and $P(\Omega_{\mathrm{II}})$, respectively represents the probability values of the randomly deployed nodes in region Ⅰ and II. $E(C_{\Omega\mathrm{I}})$ And $E(C_{\Omega\mathrm{II}})$ denote the corresponding expectations of coverage. From the even distribution function of the random deployment of sensor nodes, then gets:

$$\begin{cases} P(\Omega_{\mathrm{I}}) = (1 - r_s)^2 / l^2 \\ P(\Omega_{\mathrm{II}}) = 2r(1 - r_s) / l^2 \end{cases} \tag{8}$$

Assume that node p is in the region Ⅰ, its coverage being completely contained, so the coverage expectation is:

$$E(C_{\Omega\mathrm{I}}) = \pi r_s^2 \tag{9}$$

When a node *p* is in region II, the region should equal to its sensing region of the circumference subtracting bow region S_{ABCD}. *A*, *B* is the intersection of the sensing circle of node *p* and network boundaries, whose angle is θ the central angle, formed by the node *p* and *A*, *B*. *i.e.* $\angle ApB = \theta$, $\theta = 2\arccos y/r_s$ so:

$$\begin{aligned} E(C_{\Omega\mathrm{II}}) &= 2\int_0^{l-r_s} \frac{1}{2} r_s^2 (2\pi - \theta + \sin\theta)\, dx \int_0^{r_s} \frac{1}{2(l - r_s) r_s} dy \\ &= \frac{r_s}{2(l - r_s)} \int_0^{l-r_s} (2\pi - \theta + \sin\theta)\, dx \int_0^{r_s} dy \end{aligned} \tag{10}$$

4. Design Algorithm

4.1. Idea Algorithm

Through Geometry theory, the multiple coverage areas formed by the sensor nodes are deployed in the range of the critical target node, and let the critical nodes reside in the coverage area of multiple sensor nodes, when redundant data appears in one node, node status scheduling mechanisms is adopted to allow some of the nodes switch into sleep state to reduce the consumption of network energy. By using Gaussian normality density function and of the probability function for coverage area, each sub-region is iterative optimized and the optimal subset is obtained, thus making the entire network nodes be optimized, and the number of minimum coverage nodes can be determined. The algorithm has a less computational overhead, low complexity, and effectively save the energy consumption of each node, which in turn prolong the network life cycle, and improve the quality of the network performance.

4.2. Dynamic Form

When the target into a cluster head monitoring area, to the neighbors cluster head node sends a packet containing the target information, all the monitoring to the target cluster are dynamically in the target around to form a group, cluster member nodes only with the cluster node communication, the cluster head and between cluster heads can be mutually communication. Involved in tracking has the cluster number depending on the size of the radius of the grid [14, 19, 20]. For example, if the access grid side length equal to the radius of communication node, then a maximum of only four cluster capable of simultaneously monitoring to the target. When at the same time two or more than two cluster head and monitoring to the target, we select these clusters in a cluster head node as a leader node, cluster head first to the neighbors hair to send their and monitoring the distance between the target data information, if the cluster head received a distance closer to the target hair to information, give up campaign to become leader node. Selection criteria for: first, choose from the closest cluster head node; second, if there is two or more than two cluster head node and the target and the distance between the same, residual energy larger the lead node. All the monitoring to the target cluster head node will be sent to a leader node data first, and then by the leading node calculation and data fusion are transmitted to a data centre node. As shown in Figure 3:

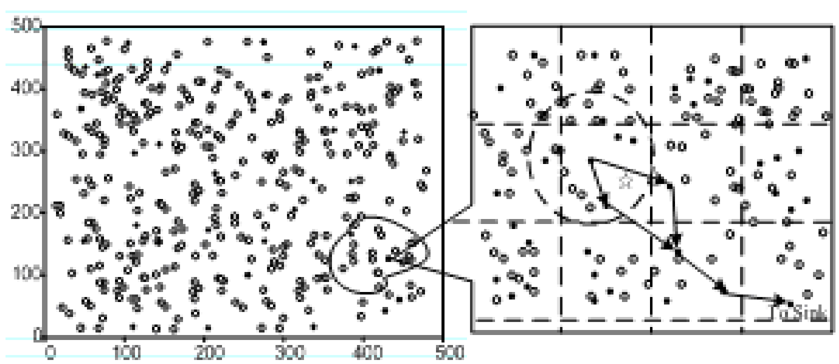

Figure 3. The Target Node Coverage Area Diagram

When the mobile target leading away from the node, because of the need to transmit data over long distances to the leader node, or a new cluster head node monitoring to the target, then a leader node is no longer applicable acts as a leader node, fast the election of a new leader node is very necessary. Here we shall, when there is a new cluster head node joins the mobile target tracking, under the leadership of node selection rules, in all involved in tracking the cluster head node selects a distance to a target the nearest cluster head node as its new leader node, data reported by the new leader node is sent to a data centre.

4.3. Description of the Algorithm

Step1: randomly deploy N sensor nodes in monitored region of the target, through the relationship among the area of coverage, sensor nodes and the target node, from the frequent item set the target node set with the most nodes, *T* max is selected, and sensor node set is selected from the sensor nodes with high-energy .

Step2: remove the frequent node set that has been selected in *T*, and then a new target node set T_{1k} is formed. Judge whether T_{1k} is empty. If it is, then turn to step 5.

Step3: Let the optimal subset, calculate the coverage set and energy consumption of the concerned target node through Gaussian normal density function and probability function of coverage area, when the energy consumption is less than a specific value, return *G'*, otherwise select the sensor nods with more energy as the overlay node.

Step4: calculate the probability of the node by using the formula (4-6) , then initialize $S_N = \varnothing$, $n = 1$, $G^{'}\left(S^{'}, T^{'}, E^{'}, W^{'}\right) = G\left(S, T, E, W\right)$, determine whether S_N is an empty set, and reset input items: $G = (S, T, E, W)$, the output items: optimal subset initialized, judge S_N is equal to the empty set. It is not an empty set. If it's not, set $S_N = S_N \cup S_{hn}$, $n = n + 1$.

Step5: determine the current energy of the sensor nodes within the target area which is covered the current sensor node, if $c_n \geq w$, go to Step 2.

Step6: calculate to determine whether there are still target nodes not covered. If there is, then the target is covered by only one sensor node. If the target nodes are all covered, then complete coverage is achieved.

Initialization: set number of sensor nodes to 0.
Input: sensor node set $S=\{s_1, s_2, ..., s_n\}$;
Target monitors area Ω: the maximum target set;
Output:the minimum node set S which covers the monitor area;

```
Begin
IF(N is empty )
 S=empty set (N=0) //cover node set s is empty
End IF
While (N)
  {Do
S=S+Si // input the number of sensor to node set S
 N=N+1 //increase the node number by 1
Do
{Switch (n)
n=1 IF (sensing area of node Si is not covered)
       Set itself into Active status; Send STATUS message to neighbor nodes; Si'←Si; Keep listening status;
     End IF
 n=2 for k=1 to N do
Transfer (Gaussian probability function)
IF (flag)
Flag=1 //meet the Gaussian probability function, and determine the minimum coverage set
 Else
             Flag=0 //call the Gaussian probability function again
       End IF
End For
}} while(S)
```


4.4. Node Scheduling Strategy

The sensor node is a round number as the cycle to work. During an initialization phase, the sensor node closed its induction module; update their information and the neighbors' node. In the scheduling process to go through five states, respectively, the start state, judge state of competition state, hibernation, the listening state, a five state conversion constitute the sensor node scheduling strategy. First of all, to judge if the node meet the dormancy condition, such as meet into hibernation, or into the competitive status, when entering into competition, start a timer; secondly, when the node competitive success, node to the start state, competition failure node into the listening state; again, in a sense node on success to receive the neighbors node to broadcast news On-duty Message, update its neighbors nodes' information, thus entering the judgment condition; fourth, in the starting state of the node to its neighbors node sends a On-duty Message, which contains the start node only ID identification and location information, and carries on the effective coverage of the work; fifth, in order to save the energy of the node, for accurate monitoring region to effectively cover, the sensor node will turn off unnecessary device to prolong the network life cycle. In practical application process, the sensor node according to the neighbors node's information to dispatch their information, until sure sensor node itself as the start state or resting state so far, as shown in Figure 4:

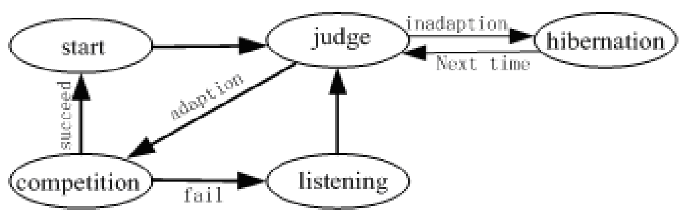

Figure 4. Node Scheduling State Diagram

5. Evaluation System

In order to evaluate the feature of the algorithm, this paper MATLAB6.5 is adopted as a simulation platform in this paper, the sensor nodes are randomly deployed in different network areas, the parameters are included in Table 2.

Table 2. Simulation Parameters

parameter	value	parameter	value
dimension 1	$100*100m^2$	ε_{amp}	$20(pJ/b)/m^2$
dimension 2	$200*200m^2$	$E_{R\text{-elec}}$	$30nJ/b$
dimension 3	$400*400m^2$	E_{min}	$0.02J$
Number	180	Header	$20B$
R_s	$2m$	Initial energy	$2J$
$E_{T\text{-elec}}$	$50nJ/b$	broadcast	$20B$
ε_{fs}	$10(pJ/b)/m^2$	each round	100ms

The wireless communication models for Sensor node transmitting data and receiving data are respectively the following:

$$E_{Tr}(k,d) = E_{T-elec}k + E_{amp}(k,d) = \begin{cases} E_{T-elec}k + \varepsilon_{fs}d^2k & d < d_0 \\ E_{T-elec}k + \varepsilon_{amp}d^4k & d \geq d_0 \end{cases} \tag{11}$$

In the above formula, $E_{T\text{-}elec}$ and $E_{R\text{-}elec}$ denote the energy consumption of wireless transmitting module and wireless receiving module; ε_{fs} and ε_{amp} stand for the energy consumption parameters of spatial model and multiple attenuation models; d_0 is a constant.

Experiment I: The first case is, with the same respective parameters, execute 50 times and get the mean value, then execute for 400 to compare with the LEACH protocol the quantitative relationship between number of remaining nodes and the number of turns, as shown in Figure 5:

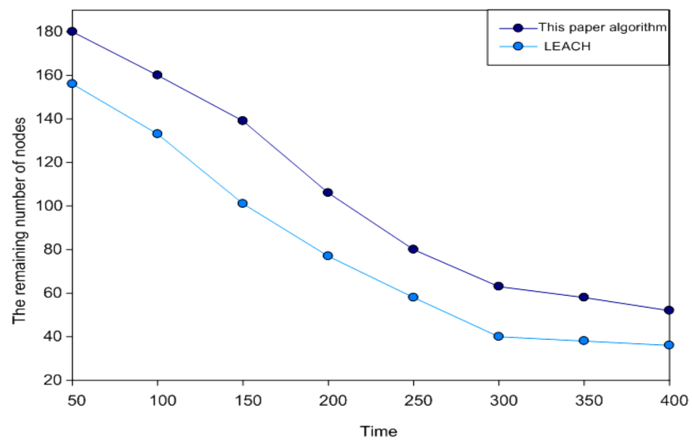

Figure 5. Remaining Nodes and the Round Number

As can be seen from Figure 5, with increasing of time, the number of remaining nodes of proposed algorithm is higher than the LEACH protocol, and then the conclusion that with the increasing of time, the energy consumption of the proposed algorithm is lower than that of LEACH protocol, and the network lifetime is extended, also the network resources are optimized.

Experiment II: In order to achieve the scale of network coverage, and thus better evaluate the performance of the model in different sizes, which mainly reflect the minimum number of nodes needs to by deploy in different network coverage, each simulation experiment executed 50 times at average. Curve of node coverage changes is shown in Figure 6:

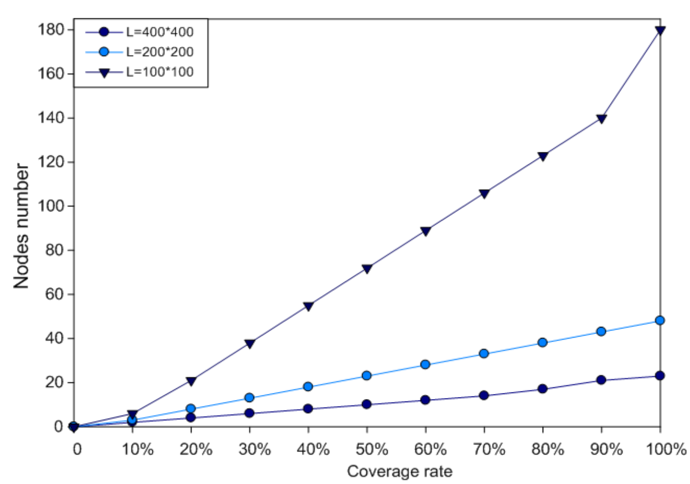

Figure 6. Coverage Rate for Different Coverage Area

Figure 6 shows the graph of the number of sensor nodes needed to deploy to achieve different node coverage under different network dimensions. The Figure 6 shows that, with the expansion of the network, to meet the demand for network coverage, the number of nodes required to be deployed will increase, and the higher the coverage of the network, the number of nodes need to be deployed increases can be obtained from Figure more fast, so that the concern target node can achieve complete coverage.

Experiment: Figure 7 shows a diagram of the number of sensor nodes need to be deployed for the same network size 400 * 400m2 under different node coverage requirement, and compare with the experiments of literature SCCP algorithm [21], to meet certain demand for network coverage, the number of nodes deployed will be gradually increased as time progresses, and the network coverage will also increase, so that completely coverage is achieved for the same coverage area and different nodes coverage for target area, as shown in Figure 7:

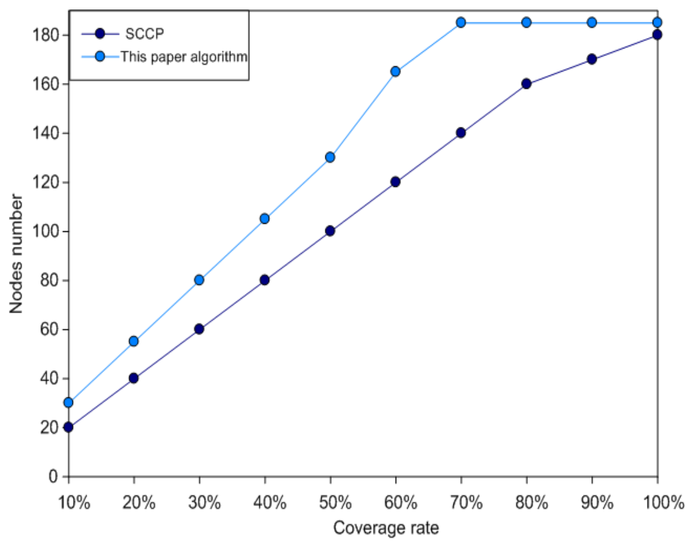

Figure 7. Coverage Comparison of Proposed Algorithm and SCCP

Consider coverage and connectivity rate influenced by the boundaries. Figure 8 shows the number of sensor nodes required to be deployed under the conditions without boundary effects with the same network size *l*=400m coverage and connectivity rate. From the Figure 8, with the increase of network coverage and connectivity, the number of nodes required increases substantially; and the influences gradually become smaller and in equilibrium at last when the network coverage and connectivity rate increases.

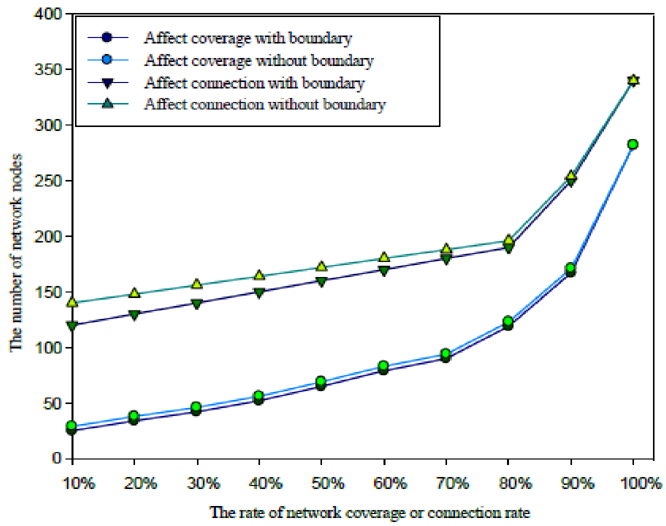

Figure 8. Curves of Network Coverage Rate/Connectivity Rate with/without Boundary Influence

Figure 8 reflects the number of nodes required to be deployed to achieve different coverage and connectivity rates without the boundary influence. Compared with the boundary influence, the number of nodes deployed increases slightly, and with the increase of nodes, node density will become larger, so the boundary influence becomes lower.

6. Conclusion

In this paper, the Gaussian normal density function and probability function of the coverage area are adopted to optimized set of sensor nodes to form a minimal subset and determine the maximum target set, by state transition of sensor nodes, nodes enter different states, work in turn, thus network energy consumption is saved, network lifetime is extended, the ratio of network resources and quality of service is improved, also redundant nodes are reduced, and last, the network performance is optimized [22]. Finally, through simulation, the effectiveness and stability of the algorithm are verified, due to the presence of vast network throughput and constrain by external factors, amativeness to very large sensor network is the next focus of the study subject.

Acknowledgements

Science and Technology Department of Henan Province Natural Science Fund Project: No.132300410085; Natural Science Foundation for Young Scientists of Shanxi Province under Grant No. 2013JQ8024; Scientific Research Program Funded by Shaanxi Provincial Education Department Project No.2013JK1139; Supported by China Postdoctoral Science Foundation Project No.2013M542370; Science and technology research key project in Henan province department of education Project No:14B520099; Natural Science and Technology Research of Foundation Project of Henan Province Department of Science under Grant No:142102210471; Supported by China Postdoctoral Science Foundation No:2013M542370; supported by the Specialized Research Fund for the Doctoral Program of Higher Education of China Grant No: 20136118120010.

This paper was also supported by The Key Science- Education Project of the Henan province 'Twelfth Five-Year-Plan' under Grant No. 2011-JKGHAB-0051"

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