Mobility Based Energy Efficient Coverage Hole Maintenance for Wireless Sensor Network

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Abstract. Wireless Sensor Networks (WSNs) are a special class of wireless networks where randomly and densely distributed sensor nodes take local measurements of a phenomenon. Coverage is a fundamental measure of QoS which represent how well the Area of interest is monitored. Considering the limited battery power of sensors, this paper presents an Energy Efficient Coverage Hole Maintenance (EECHM) algorithm where redundant sensor nodes move towards coverage hole. In EECHM we have used probabilistic method to calculate the direction and magnitude of nodes that helps to migrate the redundant sensor nodes. Further, it also reduces the consumption of energy and thus enhances the network lifetime.

Keywords: Wireless Sensor Networks, Coverage hole, Energy, EECHM, Network lifetime.

1 Introduction

Wireless sensor network have attracted enormous research curiosity due to their wide range of applications such as temperature monitoring, environment monitoring, military surveillance, habitat monitoring, health care, etc. Each sensor node consists of three basic unit; sensing unit, processing unit and communication unit. The sensing unit senses the phenomenon of interest in the target area; processing unit processes the sensed data; and transmission unit sends the data to the base station. A WSN consists of a large number of sensor nodes, but they have limited memory, computational speed and battery power.

These limitations of sensor nodes affect the QoS [1].For example; the Art Gallery Problem [2] determines the minimum number of cameras necessary for art gallery area such that every point is observed by at least one camera. Sensor nodes can be deployed randomly or deterministically to collect the information. A well-planned deployment can help to maximize the sensing coverage area but it is impossible to deploy the sensors deterministically in hostile environments. Since sensors may be spread in an arbitrary manner, therefore, coverage becomes a fundamental research issue in WSN. Generally coverage reflects how well the deployed sensors monitor the area of interest. The coverage of WSNs could be classified into three types - Area

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Coverage, Point Coverage and Barrier Coverage. Area Coverage finds minimum number of sensors such that each physical point in the area is monitored by at least a working sensor. Point Coverage is used to cover a set of given targets. It only monitors a finite number of discrete points in target area. In Barrier Coverage sensors form a barrier for intrusion detection. There are mobile sensors such as MICAbot [3] and Robomote [4] which provide better coverage result as compared to static sensors. Random deployment or failure of sensor nodes may cause coverage holes that reduce the performance of the network. Therefore, it is important to identify these coverage holes and fill it with other redundant neighbor nodes.

The rest of the paper is organized as follows. Related work is given in section 2. Section 3 introduces problem description and proposed model. Section 4 describes the coverage hole maintenance of network by considering energy constraint of sensor nodes. Performance and Result analysis of our algorithms are done in Section 5. The work is concluded in section 6.

2 Related Work

Archana Sekhar et al. in [5] proposed a dynamic coverage maintenance scheme with limited mobility such that the neighboring node moves towards the dead node as much as possible and also the existing coverage region is not affected. In[6] authors uses the concept of voronoi diagram to find out the coverage holes and move mobile sensors from densely deployed areas to sparsely deployed areas. In [7], authors proposed algorithm to maintain the coverage and connectivity of the WSNs with limited mobility. Only one hop neighbors of the dead node are allowed to move towards coverage hole without disturbing existing communication and coverage. In [8] authors power off the redundant nodes and find the minimal set of sensors to maintain the desired level of coverage. Amitabha Ghosh in [9] uses Voronoi diagram to estimate the exact number of coverage holes and also proposes a collaborative algorithm to calculate the number of additional mobile sensor nodes to be deployed and relocated to the coverage hole area. Yu-Chen Kuo et al. In [10] have proposed a fast sensor relocation algorithm to arrange redundant nodes without GPS. Prasan Kumar Sahoo et al. In [11] use the concept of distributed algorithm and vector method to calculate the magnitude and direction of movement of mobile nodes for coverage hole recovery in wireless sensor network. To minimize the energy consumption sensor nodes with only one hop neighbors of coverage hole are allowed to move. Authors in [16] proposed a protocol (Co-Fi) for coverage hole maintenance with the help of mobile sensor nodes. In this protocol high energy nodes move towards the coverage hole without losing its existing coverage. Kazi Sakib et al. In [18] give three policies to repair coverage hole. In Directed Furthest Node First (DFNF) policy an active node selects it's one of deactivated neighbor based on distance from coverage hole. In Weighted Directed Furthest Node First (WDFNF) selects and replace deactivated node by considering both the distance and direction of a node from coverage hole. In Best Fit Node (BFN) all the active neighbors of a dead node participate and make decision to identify the appropriate replacement. Authors in [19] uses tracking and a robot repairing mechanism for maintaining coverage hole. Tracking mechanism calculates the movement trajectory information of the robot then robot repairing algorithm constructs the shortest path for repairing multiple coverage hole regions. This algorithm takes minimal time and energy to recover from coverage hole.

3 Definitions, Problem Statement and Network Model

3.1 Definitions

Definition 1. The sensing range R_S of a sensor is an area in which occurrence of an incident is sensed by the sensors.

Definition 2. The communication range R_C of a sensor is an area in which sensors can communicate with one another directly.

Definition 3. The sensing neighbor set of a node S, is a set of nodes located in the sensing range R_S of S.

Definition 4. The communication neighbor set of a node S, is a set of nodes located in the communication range R_C of S.

3.2 Problem Statement

The unmonitored parts of a coverage area are called coverage holes, which may exist due to the initial random deployment of the sensor nodes unable to cover the whole area. Coverage holes can also occur due to dead nodes. One of the prime reasons for a node to become dead is energy exhaustion of sensor nodes or due to environmental factors such as fire, storm etc. These coverage holes results in the ineffectiveness of the whole network, while most of the sensors are still working normally. If the coverage holes can be detected and removed with other redundant nodes, the whole network will work again effectively and efficiently.

3.3 Network Model

For large scale sensor network applications, deterministic deployments of sensor nodes is not feasible, therefore Sensors nodes are randomly and densely deployed into a 2-dimensional field as shown in fig.1. Each node has the same sensing and transmission range, and is assumed to be perfect disk. Each sensor node knows its location with the help of positioning system such as GPS or with some other localization technique [12]. Each node collects the location of its neighbors as soon as the deployment process is over. Each node is mobile can travel at a constant speed.

When a mobile sensor moves from one location to another, it consumes energy according to the distance traveled. Initially, each node has the same amount of energy. It is assumed that there are no obstacles on their way and there are multiple coverage holes after the deployment of sensor nodes.

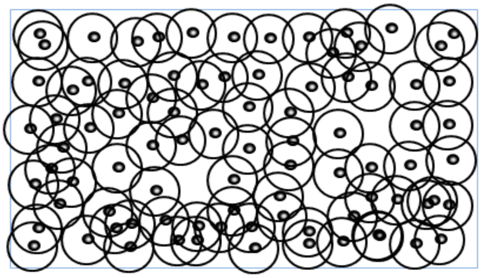

Fig. 1. Random Deployment of Sensor Nodes

4 Proposed Solution

In this section we have explained the algorithm devised for maintenance of coverage holes occurring due to uneven distribution of sensor nodes or due to failure of sensor nodes. The main objective of our work is to recover from these coverage holes by minimizing energy consumption. As sensor nodes are randomly and densely deployed over a square area, coverage area of many nodes may overlap with each other due to this uneven distribution of sensor nodes. Our main goal is to select and move high energy redundant nodes towards coverage hole area. In the proposed work, we calculate the residual energy E_{res} of each neighboring node around the coverage holes.

If the residual energy E_{res} of a node is more than threshold, it is allowed to move and fill the coverage hole. We calculate the magnitude and direction between a coverage hole and sensor node with the help of probabilistic method.

4.1 Random Node Distribution

Nodes are distributed in a square region. For our analysis, the sensor nodes are considered randomly distributed over two-dimensional geographical region. In many remote hostile environment sensors may be scattered with the help of aircraft. Since there are N sensor nodes uniformly deployed in region R_A, we have average node density $\lambda = N/R_A$. The number of sensors located in the region R_A, is $N\ (R_A)$ that is considered as parameter $\lambda \| R_A \|$of a Poisson process, where $\| R_A \|$ is the area of the region

$$P(N(R_A) = x) = \frac{e^{-\lambda \| R_A \|} (\lambda \| R_A \|)^x}{x!}.$$

4.2 Common Sensing Region

When there is random distribution of sensor nodes, it may happen that two or more sensor nodes can monitor the common sensing region. Let the Euclidean distance between two sensor nodes is d_o. From fig. 2 the overlap area [15] of two sensor nodes Φ is given by

$$\Phi = 2(\frac{1}{2}r^2\alpha - \frac{1}{2}r^2 \sin\alpha). \tag{1}$$

The value of angle α is calculated as

$$\cos\left(\frac{\alpha}{2}\right) = \frac{d_o/2}{r}.$$

$$\left(\frac{\alpha}{2}\right) = \cos^{-1}\left(\frac{d_o}{2r}\right).$$

$$\alpha = 2\cos^{-1}\left(\frac{d_o}{2r}\right).$$

Substituting the value of α in equation (1) we can find the overlap area of two sensor nodes as

$$\Phi = r^2\{\ 2\cos^{-1}\left(\frac{d_o}{2r}\right) - \sin(2\cos^{-1}\left(\frac{d_o}{2r}\right)\ \}.$$

This overlapping area can be reduced with increase in the Euclidean distance between the nodes.

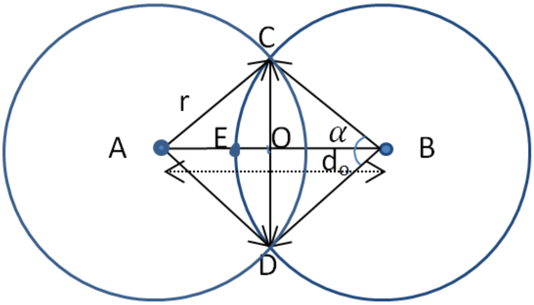

Fig. 2. Overlapped Coverage area of two Sensor Nodes

4.3 Probabilistic Method to Calculate Mobility of Redundant Nodes

In Fig.3 one hop redundant sensor nodes can move from its current position to dead node's position so that the coverage hole area is eliminated.

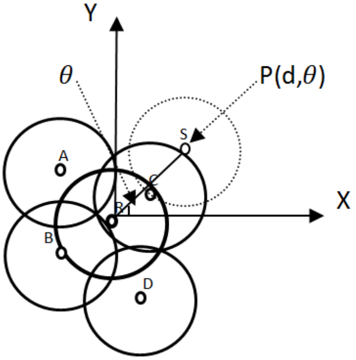

Fig. 3. Migration of Redundant Node

Let the coordinate of a dead node *S* is *(X_S, Y_S)*. Suppose one hop redundant neighbor of dead node *S* is *R* and its coordinate are *(X_R, Y_R). A, B, C, & D* are neighbor nodes of redundant node *R*. Now, node *R* moves towards *S* with angle θ such that the coverage hole created by the dead node *S* can be filled. The distance d_m between node *R* and *S* is calculated as

$$d_m = \sqrt{(X_R - X_S)^2 + (Y_R - Y_S)^2} \quad . \tag{2}$$

This is the distance which a sensor is required to move for coverage hole maintenance. Now we can find angle θ by solving the following equation:

$$\tan\theta = \frac{Y_s}{X_s} . \tag{3}$$

$$\theta = \tan^{-1}\frac{Y_s}{X_s} . \qquad \text{If} \quad -\frac{\pi}{2} < \theta < \frac{\pi}{2} \tag{4}$$

$$\theta = \tan^{-1}\frac{Y_s}{X_s} + \pi . \qquad \text{If} \quad \frac{\pi}{2} < \theta \le \frac{3\pi}{2} \tag{5}$$

In our network model nodes are deployed with homogeneous Poisson process. The probability of coverage hole is given by 1-P (no other node in the area of πx^2) and x is the radius of a coverage hole.

$$F(x) = 1 - \frac{\| \pi x^2 \|^k \, e^{-\lambda \| \pi x^2 \|}}{k!}.$$

$$F(x) = 1 - e^{-\lambda \pi x^2}.$$

Now we can compute the probability density function by differentiating the F(x)

$$f(x) = \frac{d}{dx} F(x) = 2\lambda\pi \times e^{-\pi x^2}.$$

The probability of covering a coverage hole of radius x is given as

$$f(x) = \frac{d}{dx} F(x) = 2\pi \times e^{-\pi x^2}, \; for \; \lambda = 1.$$

4.4 Residual Energy Calculation

Residual Energy information of a sensor node is the total consumed energy by a sensor node. Generally, the main consumption of energy occurs during transmitting, receiving, sensing and amplifying and migration process. Let the total initial energy of a sensor node is denoted by E_{tot} .We use the first order radio model of [13] and according to this model, energy required to transmit *n* bit long message over distance *d* is

$$E_{TX}(n,d) = E_{diss} n + \Sigma_{amp} n d^x, where (x \geq 2). \tag{6}$$

Where, E_{diss} is the energy required by the electronic component for transmitting and receiving, and $\sum_{\mathrm{amp}}$ is the transmitting amplifier energy. For receiving n bit long message energy required by a receiver is given by

$$E_{RX}(n) = E_{diss} n. \tag{7}$$

Similarly according to [14] energy consumption in sensing an event of interest, is given by

$$E_{sx} = V_s I_{sx} T_{sx}. \tag{8}$$

Where V_s is the voltage supply, I_{sx} is the current supplied and T_{sx} is the time desirable to sense the activity.

Energy Consumption during Sensor Node Movement: Energy consumption by a mobile sensor to move distance d_m is calculated as [17]

$$E(d_m) = \int_0^T p_{mov}(t) dt.$$

Where T is the time for migration of a sensor node. Let T be a function of ω and d_m Then

$$E(d_m) = \int_0^{f_T(\omega, d_m)} p_{mov}(t)\,dt. \tag{9}$$

Where,

$$P_{mov}(t) = V_{mov}(t) I_{mov}(t).$$

$$V_{mov}(t) = R I_{mov}(t) + K_e \omega(t).$$

$$I_{mov} = \frac{1}{K_t}[(J_m)\frac{d\omega(t)}{dt} + T_f + D\omega(t)].$$

Therefore, the residual energy of a sensor node is calculated as

$$E_{res} = (E_{tot} - (E_{TX}(n,d) + E_{RX}(n) + E_{SX} + E(d_m))). \tag{10}$$

A sensor node with residual energy higher than threshold value is selected for coverage hole maintenance.

Table 1. Notations

Symbol	Description
N	Total no of sensor nodes deployed
n	Number of bits in message
R_A	Deployment region
λ	Average node density
d_m	Distance between sensor node and coverage hole
E_{res}	Residual energy of a sensor node
E_{tot}	Total initial energy of a sensor node
E_{TX}	Energy required to transmit message
E_{diss}	Energy required by electronic component
ε_{amp}	Transmitting amplifier energy
E_{RX}	Energy required for receiving a message
E_{RX}	Energy required for receiving a message
E_{sx}	Energy required for sensing an event
Φ	Overlap Area of two sensor nodes
$E(_{dm})$	Energy consumption during motion
$P(t)$	Power consumption by motor
$V(t)$	Voltage supply to motor
$I(t)$	Current flow to motor
R	Armature resistance
T	Time for movement
$\omega(t)$	Angular velocity
J_m	Inertia of motor
K_T	Torque constant of motor
D	Viscous damping
T_f	Friction torque

Algorithm. Energy Efficient Coverage Hole Maintenance

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Step1. Select one hop redundant neighbors in the coverage hole and assign them to set
        $N_n$
Step2. Calculate the residual energy of each node in the set $N_n$
            Step2.1  Select a node $N_i$ from set $N_n$
            Step2.2  Initially $N_{TE} := \infty$;
            Step2.3  for all neighbor node $N_i \in N_n$ if the residual Energy
                $E_{res} > E_{th}$ (threshold)
                        $N_{TE} = N_i$;
                        $i = i + 1$;
                End if;
Return to step 2.1
Step3.Calculate the required distance and direction for movement by each node from
        set $N_{TE}$
Step3.1 Select a node from set $N_{TE}$.
Step3.2 Calculate distance of selected node from node $S$ and assign it to set
          $N_{diss}$.
            Step3.3 Initially $N_{diss} := \propto$
Step3.4 Repeat until $N_{TE} := \propto$;
Step4. Find node with minimum distance and Migrate it with angle $\theta$ towards $S$
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5 Result Analysis and Performance Evaluation

We have simulated and tested the proposed protocol. The simulation parameters are given in the following table 2. Initial deployment of the sensor node is random. The results obtained through simulation show the performance of the proposed model.

In the Fig. 4 shows that the overlapped sensing area of two nodes decreases with increase of Euclidean distance between two sensor nodes. Initially when the Euclidean distance between two sensor nodes is zero, overlapping area is maximum. It is evident from the results that for sensing range of *5m* and *10m*, if the Euclidean distance between two nodes becomes *10 m* and *20m*, respectively, the overlapping area is minimum.

Table 2. Simulation Parameter

Simulation parameter	Values
Simulation time	140s
R_A	500m×500m
E_{diss}	50 nj/bit
E_{tot}	3j
$_{amp}$	100pj/bit/m^2
V_s	3v
I_{sx}	25mA
T_{sx}	2ms
R	22•
J_m	3.824*10^{-6} z-in-sec^2
K_e	0.682 mv/rpm
K_T	0.923 oz-in/A
T_f	0.014 oz-in
D	4.85 * 10^{-8}Nm/(rad/s)

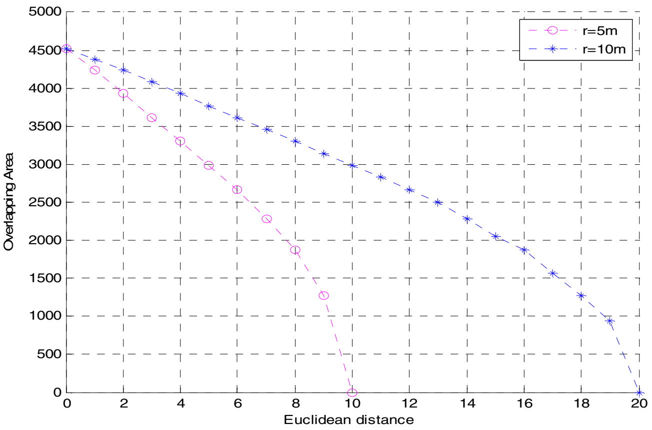

Fig. 4. Overlapping Coverage Area

Fig.5 shows that the energy consumption by sensor node is linear to the moving distance. When the moving distance of a sensor node is zero, energy consumption is greater than zero. This shows that there is always some energy consumed during startup.

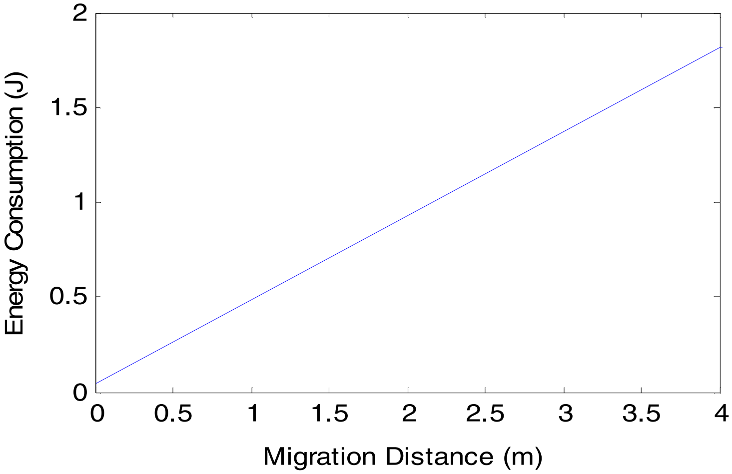

Fig. 5. Energy Consumption of Sensor Node during Mobility

Fig.6 shows relationship between migration of redundant sensor node and coverage probability. As the migration distance towards the coverage hole increases, the coverage probability also increases. It is evident from the figure that initially when the migration distance is 1m, the coverage probability is 0.72 but as the migration distance increases to 1.7m, the coverage probability becomes 1 since the coverage holes are covered by redundant sensor nodes.

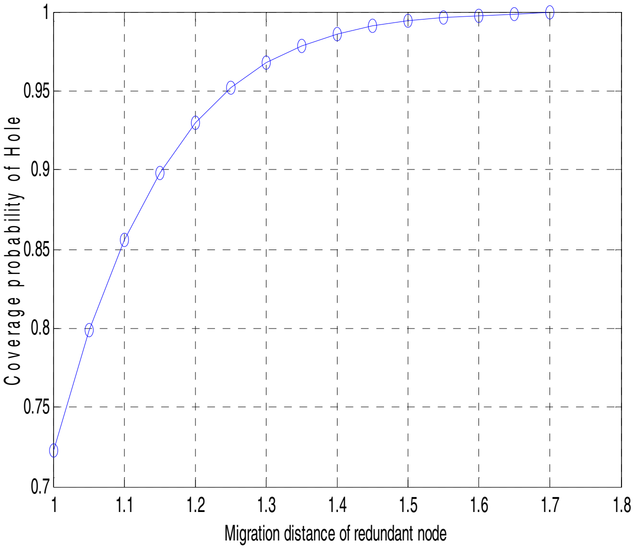

Fig. 6. Coverage Probability of Hole after Migration of Redundant Sensor Nodes

As shown in Fig.7, we have compared our algorithm with Co-Fi and DCM in terms of residual energy and time for different communication range. We know that communication consume more energy as compared to sensing activity of sensor nodes. The communication range of EECHM is 10m which is just half as compared to Co-Fi and DCM, therefore we get better result in terms of residual energy of sensor nodes.

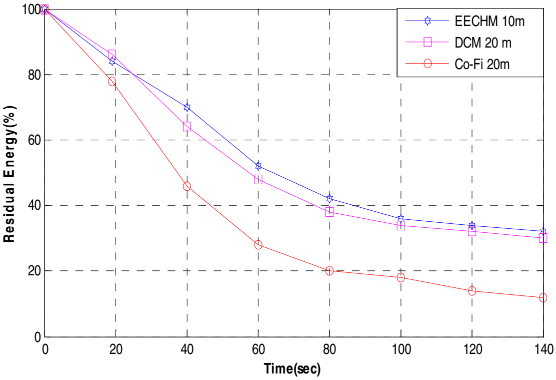

Fig. 7. Percentage remaining energy of sensor node for different time slots

6 Conclusion

In this paper we have proposed a solution for coverage hole maintenance problem. This solution is suitable for networks where sensor nodes distribution is non-uniform or failure of sensor nodes occur due to battery exhaustion, fire, storm etc. It is applicable for a network with restricted node mobility. Decision of distance and direction of mobility considers only one hop redundant neighbor nodes of coverage hole area. Due to limited mobility and least communication range, the energy consumption of sensor nodes is small and therefore, lifetime of the network is increased.

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