Energy Hole Healing Protocol for Surveillance Sensor Networks

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Abstract

In literature, the property of energy consumption spatial locality of sensor networks has been discussed [1]. Because of the energy consumption spatial locality, neighboring sensor nodes deplete their energy off almost simultaneously. In this circumstance, the requirements of surveillance applications can not be satisfied. In this paper, an algorithm is proposed to resolve the energy hole problem. The distribute algorithm ranges energy holes and uses mobile sensors to heal energy holes. Mobile sensors heal energy hole in parallel way to avoid the large cost of manual sensor deployment. The energy hole expansion problem is overcome by hexagon mechanism. Experimental results demonstrated that with small number of mobile sensors, the proposed algorithm can enhance the lifetime of entire network.

Keywords: Wireless sensor networks, surveillance, mobile sensor

1. Introduction

Wireless sensor networks are composed of many low cost, low power devices with sensing, processing and wireless communication capabilities. Typical applications of wireless sensor networks are battlefield surveillance, intruder detection of high emergency area, living environment investigation of wild animals, and user dynamic query of wireless sensor networks. The energy required to operate sensor nodes usually come from limited battery power. If sensor nodes run out of their energy, they could be malfunctioned. Therefore, energy management is an important research topic in sensor networks.

Surveillance is usually applied in high emergency area, like battlefield or surrounding area of city hall. All events happened in the high emergency area should be detected by a surveillance sensor networks. The surveillance problem can be described as: given a fixed target area and distributed sufficient enough sensor nodes, maintain full coverage in target area and no events leaks with time goes by. Many wireless sensor networks researches assume that events are uniformly distributed in target area. However, this is not practical in real environment of sensor networks. The power consumption in hot spot area is larger than other area.

Previous work [1] observes the facts of energy consumption spatial locality: 1. The sensor nodes within a certain neighborhood participate in the processing of similar events. 2. The sensor nodes spend similar energy costs on the same sensing task. We can infer that the distribution of power consumption for sensor nodes which impoverish their residual energy is continuous. The neighboring sensor nodes which may exhaust their residual energy are called energy hole. Energy hole may malfunction sensor network and cause large coverage hole if the problem is not properly handled. When sensor nodes within energy hole run out of their energy and becomes coverage hole, the sensor network may miss more events and encounter harmful injuries for surveillance application. In order to resolve energy hole problem in surveillance sensor networks, a energy hole detection algorithm is proposed to detect energy hole. When the area of energy hole is determined, mobile sensors can be used to heal energy hole.

General surveillance sensor networks are composed by stationary sensor nodes. The energy hole can be used to fill the hole. Mobile sensors can move to energy hole, and energy hole can be “healed” by mobile sensors. “Heal” is meant that mobile sensors can cover the lost coverage of the dying nodes. In most coverage hole healing researches, they assume that mobile sensors are uniformly distributed in sensor networks. We make a more practical assumption for mobile sensor nodes. We assume that the mobile sensors reside in a particular place called mobile sensor pool. Mobile sensor pool provides power supply facility which can charge up batteries of mobile sensors. Mobile sensor pool also has computation and wireless communication capability. When there is energy hole in surveillance sensor networks and coverage hole detection algorithm figures out where should be healed, sensor nodes can send request message to mobile sensor pool for healing energy hole. Mobile sensors then move to the energy hole to prevent the generation of coverage hole.

The proposed protocol is categorized into three parts. In the first part of, sensor nodes use the neighbor information and exchange packets to determine the role of each device in energy hole healing protocol. The second part is that boundary nodes collect information of energy holes for energy hole healing decision. The third part is that leader node requests mobile sensors to heal energy hole.

2. Backgrounds And Basic Concepts

A. Energy consumption spatial locality

In the work [1], the authors observe an important phenomenon called energy consumption spatial locality. If the residual energy of all sensor nodes in the dark area is under certain critical threshold, they may deplete their residual energy in near future. We call these sensor nodes form an *energy-hole*. The energy hole is usually located at a place where events happen frequently. If the energy-hole area is not processed properly, it may cause event loses after sensor nodes depleting their residual energy.

B. Protocol overview

The proposed Energy Hole Healing Protocol of this work contains three phases. They are Role Determination, Energy Hole Information Collection, and Energy Hole Healing phases. The operations of these phases are summarized as follows:

Phase I: Role Determination

When energy hole occurs in a sensor network, the sensor nodes in or near the energy hole have to determine their roles. This arrangement is necessary because the sensor node with residual energy below a critical threshold may generate energy hole. The actual coverage hole has to be recognized by the neighboring nodes near the energy hole which residual energy is above the critical threshold.

Phase II: Energy Hole Information Collection

In this phase, the right-hand rule is used for leader election and energy hole information collection. The ***intersection points*** of boundary node have to be collected for mobile sensors dispatching in the next phase.

Phase III: Energy Hole Healing

In this phase, all necessary information of the energy hole are available and a leader node is elected to plan for the target locations of mobile sensors. Leader node calculates the coverage area by intersection points with some additional information. After the leader node finishes its computing, it sends a request to the mobile sensor pool. The mobile sensor pool dispatches some mobile sensors to their target locations. So, the sensor network can heal the energy hole and prolong their functionality after the movement of mobile sensors.

3. Energy Hole Healing Protocol

We explain the energy hole healing protocol with examples and describe the detail of each phase as follows.

A. Role Determination

To resolve the energy hole problem, the first stage is to determine roles of sensor nodes. There are three roles in the proposed energy hole healing protocol, and each sensor node may be one of the three roles. Each role is described as follows.

1. *Hazard node*: A sensor nodes with residual energy below certain critical threshold is called Hazard node. Hazard node is always in energy hole. They may generate coverage hole after they run out of their residual energy.

2. *Boundary node*: A sensor node whose residual energy is above certain critical threshold and is most proximal to an energy hole is called Boundary node. Boundary nodes do not run out of their residual energy in short duration.

3. *Common node*: A sensor nodes whose residual energy is above certain critical threshold and is not proximal to energy hole is called a common node. Common nodes do not run out of their residual energy in short duration.

We set two thresholds for the residual energy of each sensor node.

1. Threshold α: A small threshold which is used to trigger the role determination event.
2. Threshold β: A threshold which is a little larger than α. A sensor node which residual energy is below threshold β and may create coverage hole

is considered as a hazard node. The critical threshold we mentioned in previous section is β.

It is easy to check whether a node's role is hazard, boundary, or common node in distributed mechanism. To heal energy hole, the first step is computing intersection points. Intersection point is defined as follows: *A point I is called the intersection point of boundary node A and B if point I lies on the sensing circles of the both two boundary nodes. And intersection points must be satisfied the condition that its location should be more proximal to hazard node.*

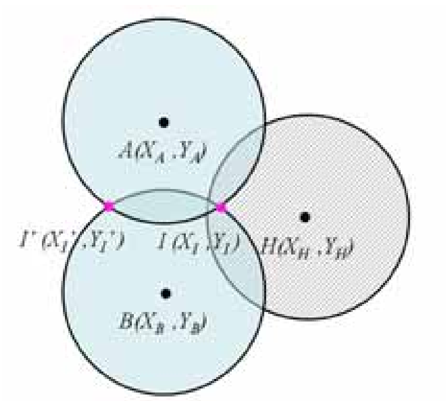

Fig. 1: Intersection points calculation

The computation of intersection points are as follows. Eq. (1) and (2) show that intersection points should lie one boundary of sensing area. Eq. (3) shows the distance between sensor *A* and *B*. A point with coordinate (*X*, *Y*) which satisfy Equations (1), (2) and (3) simultaneously is a candidate intersection point.

$$(X - X_A)^2 + (Y - Y_A)^2 = R_S^{\ 2} \qquad ---(1)$$

$$(X - X_B)^2 + (Y - Y_B)^2 = R_S^{\ 2} \qquad ---(2)$$

$$D_{AB} = \sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2} \; ---(3)$$

$$X \; = \frac{X_A + X_B}{2} \pm \frac{Y_B - Y_A}{2D_{AB}^{\ 2}} \sqrt{D_{AB}^{\ 2}(4R_S^{\ 2} - D_{AB}^{\ 2})}$$

$$Y \; = \frac{Y_A + Y_B}{2} \mp \frac{X_B - X_A}{2D_{AB}^{\ 2}} \sqrt{D_{AB}^{\ 2}(4R_S^{\ 2} - D_{AB}^{\ 2})}$$

The intersection point can be used to find out potential coverage hole. The characteristics of intersection points are as follows: 1. The number of boundary nodes is equal to the number of intersection points. 2. When the sensing range of all sensor nodes is the same, it is able to derive locations of boundary nodes by intersection points.

B. Energy Hole Information Collection

The energy hole information collection phase is describe as follows: When stationary sensor nodes confirm their roles, they go the next phase to perform Energy Hole Information Collection. All stationary sensor nodes know the location of mobile sensor pool. We use the *Energy_ Hole_ Information_ Collection* (*EHIC*) packet for information collection and leader collection.

After the Role Determination phase, each boundary node waits a duration T_C. The duration T_C of a sensor node is proportional to the distance between mobile sensor pool and its location. The longer the distance between a sensor node and mobile sensor pool, the longer the duration a sensor node should be waited. The formula to calculate T_C is as follow:

$$T_C = \frac{d_{MSP,i}}{d_{MAX}} \times T_{C,MAX}$$

$d_{MSP,i}$: the distance between sensor node i to mobiles sensor pool

d_{MAX} : the Maximal distance among all sensor nodes to mobile sensor pool

$T_{C,MAX}$: the Maximal T_C

Only the *EHIC* packet which initiator is most proximal to mobile sensor pool can completely traverse entire boundary nodes. The boundary nodes form a ring structure. If the *EHIC* packet can traverse the entire boundary nodes and comes back to the initiator, the initiator is able to confirm it is most proximal to mobile sensor pool. The initiator can determine that it is the leader node and can get all energy hole information. In the Energy Hole Information Collection phase, it is not necessary to planarize graphs because of a simple ring structure. And it needs not do many face traverse steps like [3].

C. Energy Hole Healing

After the leader node collects entire energy hole information, it then switches to the Energy Hole Healing phase. The objective of this phase is using mobile sensors to cover all intersection points which are found in Role Determination phase and computed in Energy Hole Healing phase. If all intersection points could be covered by mobile sensors, then the energy hole could be healed. Leader node plans for target location of mobile sensors by *hexagon* arrangement, and calculate whether energy hole is fully covered through *circle* computation. Through hexagon arrangement, the best utilization of mobile sensors can be achieved in the internal area of energy hole. Due to the characteristic of hexagon arrangement, when the target location of first hexagon is decided, then the location of the remaining hexagons are determined accordingly.

The leader node firstly calculates the target location of mobile sensor which covers the farthest intersection point from mobile sensor pool. In fig. 2, assume the farthest intersection point is $I(I_X, I_Y)$, and the target location of first mobiles sensor is $M(M_X, M_Y)$. The relations between these two locations can be computed as follows:

$$M_X = I_X - \frac{1}{2} R_S$$

$$M_Y = I_Y$$

where R_S is the sensing range of mobile sensor.

Although this arrangement could waste a little coverage area, but it is able to guarantee that other intersection points do not stay in the right side of mobile sensors.

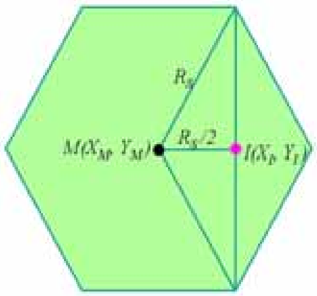

Fig. 2: The relation between the farthest intersection point and the first mobile sensor

The intersection points covered by mobiles sensor are considered as been healed. Let all intersection points be sorted according to the order of right-hand rule traversal. The next intersection point which is not covered by previous mobile sensors in right-hand rule traverse order could be computed. And we also are able to find the final intersection point which is covered by first mobile sensor. These two intersection points together with sensing range of sensor node could be used to calculate an equation of circle. Use the equation of circle and the equation of mobile sensor we can find out new intersection point. The location of new intersection points is where the next mobile sensor should be arranged. The way to calculate new intersection point is the same as that shown in Fig. 1. In the same way, it is able to cover all intersection points of boundary nodes. When all intersection points of boundary nodes are covered by mobile sensors, then we cover all intersection points between mobile sensors. The way to calculate the intersection points of mobile sensors is the same as Fig. 1. When all intersection points have been covered, the entirely calculation of mobile sensor target location is terminated. Then the leader node transmits the mobile sensor target location table to mobile sensor pool. Mobile sensor pool dispatches the required number of mobile sensors to their target locations and the energy hole is healed by these mobile sensors.

When all intersection points are covered, the calculation of mobile sensor target location is terminated like Fig. 3. Then S_1 transmits the mobile sensor target location table to mobile sensor pool. Mobile sensor pool dispatches the required mobile sensors to their mobile sensor target locations. The energy hole is healed by mobile sensors.

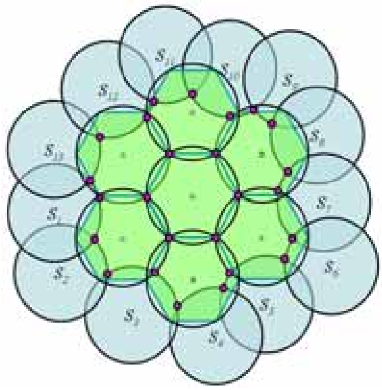

Fig. 3: The locations of all mobile sensors

4. Simulation

To validate the proposed protocol, experiments are conducted and described in this section. The simulation includes four parts. First, to evaluate the effectiveness of leader election method, the modified right-hand rule is compared with the flooding method. Second, the effectiveness of using mobile sensors to heal energy hole is demonstrated. Third, we show the effectiveness of using mobile sensors to overcome energy hole expansion. Fourth, we evaluate the effectiveness of honeycomb sensor placement in the circumstance of energy hole problem.

The simulator is written in C++ language. The simulation parameters are arranged as follows. The target field is a 200m*200m square. The stationary sensor nodes are uniformly distributed in target field and the node density is uniform everywhere. Although the stationary sensor nodes are uniformly distributed, any coverage void is not allowed in initial sensor deployment. The numbers of stationary sensor nodes are 200 nodes, 300 nodes, and 400 nodes, respectively. The sensing range of each sensor node is 20m. The communication range of each sensor node is 45m. The energy consumption of mobility in mobile sensor is 8.267 Joule/m. The initial energy of each stationary sensor node is 100 Joules, and the initial energy of each mobile sensor is 32400 Joules. The moving capability of a sensor node consumes more energy than packet transmission and packet reception. The location of mobile sensor pool is located at the top left corner, and the location of sink node is also the same as mobile sensor pool. We put an event generator which regularly generates events in constant rates in the center of target field. The frequency of event generation is 10 events/s. Simulation results are averaged in ten independent runs.

A. Effectiveness of modified right-hand rule -based leader election algorithm

Fig. 4 is the comparison of flooding mechanism and modified right-hand rule. The simulation not only compares flooding mechanism and modified right-hand rule, but also compares different number of stationary sensor nodes. The number in parentheses means the number of stationary sensor nodes in target field. For example (400 nodes) means that there are 400 stationary sensor nodes in target field. It is obviously modified right-hand rule reduce the total number of control packets. When the number of boundary nodes is increased, the number of control packets in flooding mechanism increases hugely and the number of control packets in modified right-hand rule only increase a little amount. The reason is as follows. In flooding mechanism, each boundary node has to trigger network-wide flooding for electing leader node. When the number of boundary nodes is increased or the number of stationary sensor nodes is increased, there may cause a lot of control packet in sensor networks. In modified right-hand rule, the number of control packets is only restricted by the number of boundary nodes. And boundary nodes only relay packet which the initiator is the most proximal than all initiators it relayed before. So only a few control packets are needed by modified right-hand rule with respect to flooding mechanism in Energy Hole Information Collection phase.

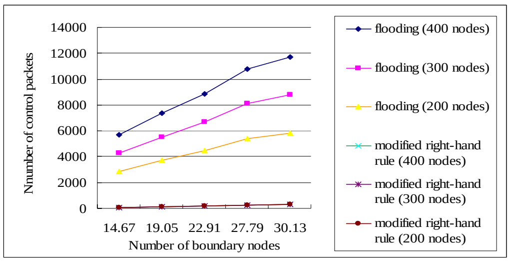

Fig. 4: Control overhead between modified right-hand rule and flooding

B. Effectiveness of mobile sensors to heal energy hole

Fig. 5 show the average number of hazard node which can be contained by a mobile sensor versus the change of energy hole area. In Fig. 5, “400 nodes” means that there are 400 stationary sensor nodes in the target field. It is obvious that each mobile sensor can contain more hazard nodes in higher node density environment. The three lines in the figure are almost horizontal. It means that the utilization of mobile sensor can still be guaranteed even in different size of energy hole. The reason is as follows. Mobile sensors are arranged as cellular style. Although utilization of the outer mobile sensor can not achieve full utilization, the inner mobile sensor can achieve full utilization. So the utilization of inner mobile sensor can compensate the utilization of outer mobile sensor. And the average number of hazard nodes being contained by a mobile sensor can be maintained in a certain value. There is still an interesting observation. Many surveillance applications require high density environment. Our proposed algorithm can be suited in high node density environment.

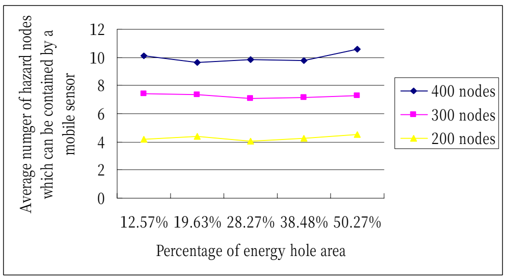

Fig. 5: The average number of hazard nodes which can be contained by a mobile sensor

C. Overcome energy hole expansion

Fig. 6 shows the number of hazard nodes can be contained by a mobile sensor while there happens energy hole expansion. In Fig. 6, for example "400 nodes" means that there are 400 stationary sensor nodes in the target field. The three lines are almost maintained in horizontal style and the utilization of mobile sensor is approximate to the Fig. 5. It can be concluded that mobile sensor can still achieve high utilization while energy hole expansion is occurred. The reason is as follows. When there occurs energy hole expansion, new mobile sensors should move to expansion area to avoid generating coverage hole. The new mobile sensors are arranged by the fashion of honeycomb, so the overlay area is reduced as much as possible. When the expansion area is large, it can still keep high utilization.

Fig. 7 is the number of additional mobile sensors when energy hole expansion occurs. From the figure, we can observe that the relation between the number of additional mobile sensors and the energy hole expansion area is linear relation. When energy hole expansion occurs, it only needs constant times mobile sensors to heal the expansion area. In Fig. 7, the first and the second X coordinates both correspond to the same Y coordinates. It is because that when expansion area is small, the original mobile sensor can still fully cover expansion area. And it doesn't need to add new mobile sensor to heal these expansion area.

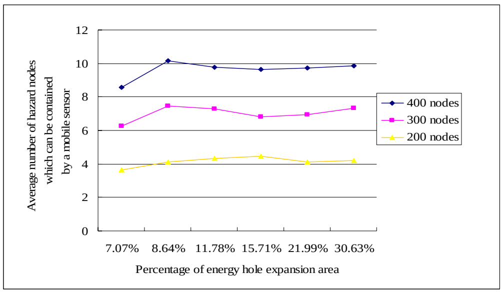

Fig. 6: The average number of hazard nodes which can be contained by a mobile sensor when energy hole expansion

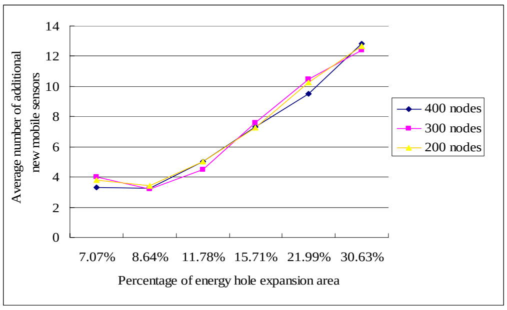

Fig. 7: The average number of additional new mobile sensor when energy hole expansion occurs

D. Effectiveness of hexagon placement to energy hole problem

Fig. 8 is the comparison between our proposed algorithm and ideal mobile sensor placement in terms of energy hole area. Ideal (400 nodes) means that there are 400 nodes uniformly distributed in the sensor networks and use the ideal mobile sensor placement. The three lines Ideal (400 nodes), Ideal (300 nodes), and Ideal (200 nodes) are almost the same. Our proposed algorithm keeps about constant difference to Ideal mobile sensor placement. This is because when the energy hole is larger, the inner nodes which can achieve fully utilization are larger. The required mobile sensors number of Proposed (400 nodes) is less than Proposed (300 nodes), and the required mobile sensors number of Proposed (300 nodes) is less than Proposed (200 nodes). This is because when node density is low, the coverage hole which may generate from energy hole is highly changeable. And we have to deploy more mobile sensor to these highly changeable area. However the difference among the three proposed placement is not much.

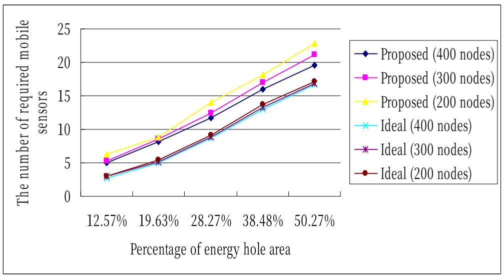

Fig. 8: The number of required mobile sensors

5. Conclusion

Energy consumption spatial locality is that the neighboring sensor nodes consume energy in similar patters. In this work, we proposed a new model and an algorithm to overcome the energy hole problem. Simulation results showed that we can heal energy hole with small control overhead and high utilization of mobile sensor. When energy hole expansion occurs, we can easy overcome energy hole expansion with our proposed algorithm. It can combine our protocol with robot redeployment algorithm to heal energy hole entirely. Our future work is to design an algorithm with multiple mobile sensor pools to overcome energy hole problem.

5. Acknowlegement

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