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Redeployment Based Sensing Hole Mitigation in Wireless Sensor Networks

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***Abstract*—Environmental factors such as unavoidable physical constraints, intentional destruction of the sensors or asymmetric load distribution will lead to formation of holes in the wireless sensor networks. Holes hinder the operational quality of the network, where earlier formations have higher impact. In this paper, we study the sensing hole problem and propose a redeployment method to mitigate it. Image processing algorithms are used for identifying the sensing holes. A portion of the sensors are kept as spare; after identifying the holes, they are redeployed over the holes. The results indicate that the method leads to a considerable increase on the sustainable sensing quality of the network.**

***Index Terms*—Wireless sensor networks, sensing hole, redeployment, deployment quality measure, image processing.**

I. Introduction

Battery depletions or intentional destruction of the sensors may result in nonuniform sensor deployments. Due to this nonuniformity, holes, areas not covered by any sensor may exist. Holes can be classified as sensing or communication holes [1]. A wireless sensor network (WSN) is operational until the network dies according to a given criteria such as the death of the first or the last node, or the loss of coverage of a certain portion of the sensed area. During the lifetime of the WSN, various sensor nodes deplete their individual battery capacities and die. As the number of dead sensors increases, sensing holes arise. Hole formations deteriorate the overall quality by changing the network structures like the breach paths or communication routes. Such changes quicken the battery capacity loss on the remaining nodes which also have to perform the duties of the dead nodes.

In this paper, we study the sensing holes and propose a redeployment method to mitigate the adverse effect of the holes on the sensing coverage. How to identify the holes and how many sensors should be redeployed over the holes are the key questions addressed in this paper. While addressing the sensing hole problem, we particularly concentrate on the border surveillance application where sensors detect unauthorized intruders. The sensing service provided by the network is intolerable to holes that may produce breach paths through the field-of-interest. The WSN becomes insecure when holes exist. If the intruders detect the deployment operation, they may destruct the network. For example, they may eliminate sensors

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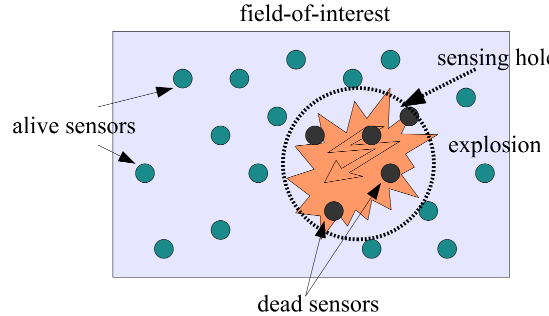

Fig. 1. A simple border surveillance scenario where sensors are intentionally destructed.

by bombing as shown in Fig 1. Such intentional destructions deteriorate the deployment quality drastically by creating holes and lead to a nonuniform WSN deployment.

Various methods have been proposed to identify the sensing holes in WSNs. Funke proposes an algorithm that make use of specific beacon nodes to detect the communication holes [2]. However, the algorithm proposed does not present a solution for locating sensing holes. Vieira et al. present a method based on the largest empty circle problem [3]. Their approach finds local holes as circles for the sensor deployment. However, to mitigate the holes, multiple iterations are required and the number of iterations is not known a priori and depend on the performance of the intermediate steps. Fang et al. find the hole boundaries using a distributed algorithm to enable the formation of new routes [4]. This method, albeit useful for route formation, does not offer a solution for mitigating the hole problem. The holes defined by the authors are not actual sensing/communication voids but rather the nodes that does not offer routing improvements. Wang et al. propose a topological algorithm to detect the network boundaries in terms of communication, which is the dual of the hole detection problem since communication regions are mainly bounded by the holes within the sensor network [5]. Those methods present ways to locate the communication holes for better route formations. The route changes aim to avoid the problems caused in the holes, however the nodes in the newly calculated routes may deplete their battery energies and lead

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to further holes, causing an avalanche effect. In our work, it is proposed that by performing small redeployments in the initial phase of the network, such problems can be avoided or postponed to later stages of the network lifetime [6], [7].

In this paper, we propose the iterative deployment algorithm (IDeA) in which a portion of the sensors are reserved and the remaining sensors are deployed in the initial phase. Based on the observed sensing quality, further redeployment iterations can be made to the holes using the spare sensors. Such a modification will help to overcome the hole occurrences in initial steps. The proposed algorithm uses fast image processing methods to identify possible sensing holes. For quality measurements, it uses a robust deployment quality metric to understand the overall sensing quality.

II. Iterative Deployment Algorithm (IDeA)

Assume a border surveillance scenario where some set of sensors are deployed to the field-of-interest to detect unauthorized intrusions. For a required security level, the number of sensors to be deployed can be determined as described in [8]. Assume that right after deployment, the intruders destroy some set of sensors intentionally as seen in Fig. 1. After the destruction, what the deployment quality is, which parts of the network become useless or what should be done to mitigate this problem are several questions to be answered. Redeployment of a set of spare sensors can be a solution. First, the holes must be located. After identifying the holes, redeployment is possible to those regions. To find the hole locations, a sensing coverage model referred to as iso-sensing graph is utilized. Through the iso-sensing graph, it is possible to measure the deployment quality [8].

A. Iso-sensing Graph and Deployment Quality Measure

To analyze the sensing quality of a WSN, we utilize the deployment quality measure proposed in [8]. To apply this method, the sensor detections are modeled as defined by Elfes [9]. Given a sensor k, the probability of detecting a target on grid point (x, y) is

$$p_{xyk} = \begin{cases} 0 & \text{if } r + r_e \leq d_{xyk}, \\ e^{-\lambda\alpha^\beta} & \text{if } r_e > |r - d_{xyk}|, \\ 1 & \text{if } r - r_e \geq d_{xyk}, \end{cases} \quad (1)$$

where $r_e < r$ are the thresholds for the sensing distance, d_{xyk} is the distance between the sensor k and the target and $\alpha = d - r + r_e$. The characteristics of different sensors can be reflected with parameters λ and β. Additionally, r_e ($r_e < r$) is a measure of uncertainty in sensor detection. If the sensor-to-target distance is smaller than $r - r_e$, the target is absolutely detected. If the sensor-to-target distance is larger than $r + r_e$, the target cannot be detected.

The individual decisions of a subset of sensors may be highly correlated, particularly if the deployment is dense. That is, if a sensor detects a target, it is highly probable that another sensor which is located in similar proximity as the first one will also detect the same target, assuming homogeneous environmental factors. Hence, the performance of the sensor with the best detection capability is more valuable. We model the field as an 8-connected grid and assume correlated-detections. Then the detection probability for a grid point (x, y) is

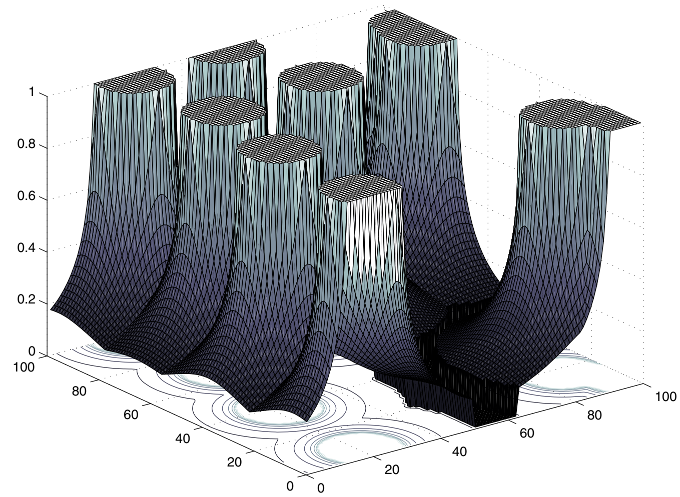

Fig. 2. A sensor network iso-sensing map example.

$$P_{xy} = \max_{1 \leq k \leq N} p_{xyk} \quad (2)$$

where N is the total number of sensors deployed in the region.

Modeling the field as a two-dimensional grid and adding the detection probability as the third dimension, a three-dimensional surface which is referred to as the iso-sensing graph is obtained [8]. The graph resembles the contour lines of a topographic map, where the altitude can be mapped to the detection probability and the grid points can be mapped to the two-dimensional locations. Therefore, it is named as iso-sensing graph.

A sample iso-sensing graph is shown in Fig. 2. To evaluate the sensing quality of the network for the given model, the watershed deployment quality measure (WDQM) presented in [8] is used. The WDQM model is primarily based on watershed segmentation [10]. Given the iso-sensing graph, it can be assumed that at the minima points of the topography there are water pumps through which water is continuously pumped. As water rises up, dams are built to avoid merging of water sources from different valves. Finally, the dams called the watershed contours, segment the topographic map into different partitions. From the security view-point, the breach paths follow the watershed contours. The WDQM is the minimum of the maximum detection probabilities of these contours and gives an insight about the security level provided by the network.

B. Hole Identification

In this section, we present how to identify the locations of the sensing holes using the iso-sensing graph. We use a topography analysis based approach making use of morphology based image processing operations. Assume that the sensor positions are known, the iso-sensing graph is calculated as the initial step. Note that this step is performed after the hole

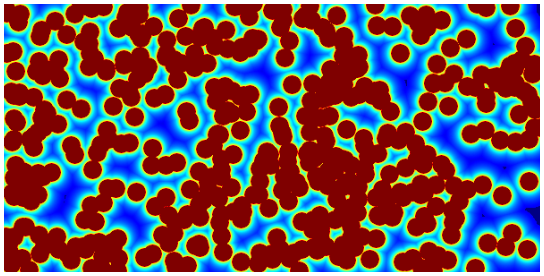

Fig. 3. Iso-sensing graph converted to a grayscale image.

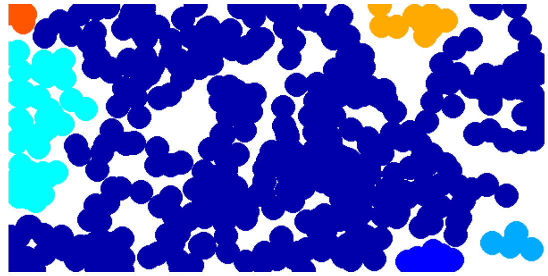

Fig. 4. Grayscale image formed after filtering low sensing quality areas, applying connected component analysis and filtering small sized groups in the initial image.

are formed, by bombing or any other means. Another possible way is to run the network until the overall sensing quality falls below some predefined value. At this step the quality loss is caused by the sensing holes as a result of the energy depleted intermediate nodes. The hole identification can be performed at this step by forming the related iso-sensing graph which is used to differentiate the areas with high or low sensing quality. Highly sensed parts of the graph are the higher planes on the topography and will be used as auxiliary means to locate the holes.

Given the iso-sensing graph, image processing algorithms are employed to detect the candidate areas. In the initial step, the graph is converted to a grayscale image. The $2D$ coordinates, denoted by (x, y), of the map are used as the pixel coordinates of the image and the sensing quality of grid points (P_{xy}) are used as the intensity value at the corresponding pixel. An example for the resulting grayscale image is given in Fig. 3. All gray scale images presented in this work are colored to increase the visibility. Each color corresponds to a different gray scale (equally sensed) area.

To reveal the highly sensed parts, the initial step of the algorithm is to discard segments that have low sensing quality values. For this purpose, a filter,

$$w_1(x, y) = \begin{cases} P_{xy} & \text{if } P_{xy} \geq \dfrac{\sum_{x,y} P_{xy}}{lh}, \\ 0 & \text{otherwise,} \end{cases} \quad (3)$$

is applied to the grayscale image. Here, l and h are the length and the height of the image respectively. The filter isolates the grid points that have a sensing quality above the average, which in turn allows for connected component analysis to differentiate those highly sensed groups. The component labeling step groups and labels pixels with similar intensity values and are connected to each other. The particular approach used is the 8-connectivity connected component labeling algorithm which groups grid points whose all 8 neighbors have higher than the average sensing quality values [11].

After this step, there may be small area segments left behind. These are insignificant compared to the main segments and to remove them, the second filter,

$$w_2(x, y) = \begin{cases} P_{xy} & \text{if } (x, y) \in G_i \text{ and } A(G_i) \geq lh\gamma, \\ 0 & \text{otherwise,} \end{cases} \quad (4)$$

is applied where G_i denotes the ith component group, A is the area of the corresponding group, γ is the filter cut-off value. By using the filter w_2, the regions smaller than γ of the total area are discarded. For this work, the cut-off value is chosen empirically as 1% with initial runs of the algorithm. For values below 1%, the filter does not efficiently ignore the small sized hole areas. Redeployment over such small sized areas does not effect the overall sensing quality and the running time of the further steps is increased with the increasing number of areas. However, increasing the cut-off value increases the risk of discarding holes which may have higher impact on the DQM values. Based on the average of 20 different scenarios, 20 repetitions for each scenario, 1% is found as the suitable cut-off value.

As a result of the filtering operations, groups with comparatively higher sensing values are left behind in the image. Those groups are important to locate the poorly sensed regions. An example image after applying w_2 filter is given in Fig. 4.

C. Redeployment

At this point, the parts of the network that have high sensing quality values are isolated. Redeployment must be done in between these areas which are the topographic valleys between the higher planes of the iso-sensing map. In the corresponding grayscale image, such areas lie between the connected components. To locate the areas for any two components in the image, we wrap both components with a convex hull. During the redeployments inside the area defined by the hull, the areas spanned by the components themselves are ignored and the sections that reside between them are taken into consideration. In this manner, the area surrounded by both the hull perimeter and component borders is a sensing void candidate and is a redeployment site. Each site is denoted as R_t, where t is the site index. Once all such regions are found, the redeployment is performed and the algorithm stops. An example final image is shown in Fig. 5. The overall pseudocode of the steps of IDeA is presented in Algorithm 1.

Such a strategy follows the real life procedure that the initial deployment is done by a plane, then losses due to physical constraints, explosions due to grenades and bombs and other factors are subdued with the help of a small site redeployment done by a cheaper method like deployment using an off-road vehicle.

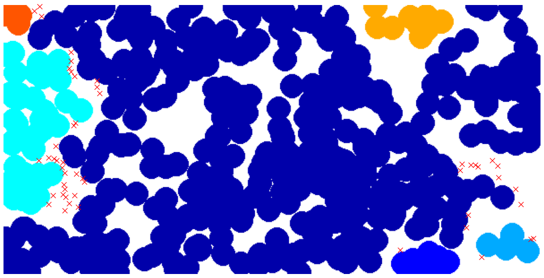

Fig. 5. Final grayscale image formed after redeployment is performed, 'x' sign denotes the sensors deployed in the redeployment phase.

Algorithm 1 IDeA steps.

1: N sensors given
2: $N * z$ sensors separated away, z is the redeployment percentage.
3: $N * (1 - z)$ sensors deployed over the terrain

Require: $(x_k, y_k), k = 1..(N * (1 - z))$ known

4: S (ISO-SENSING graph) is formed
5: $I = GSI(S)$, form the grayscale image
6: $I' = w_1(I)$, apply connectivity filter
7: $I'' = w_2(I')$, apply small region filter

Require: G_i's (highly sensed area groups) are known

8: $R_t = \text{Poly}(G_i, G_j) \setminus (G_i, G_j)$, find the deployment region between groups G_i and G_j.
9: Deploy $N * z$ sensors over t regions, each region gets a sensor count proportional to its area size.

III. Results and Discussions

To evaluate the performance of the proposed algorithm, we have set up some test scenarios that are based on the task of border surveillance. It is assumed that a set of holes are formed as a result of intentional destruction of sensors. We assume that the effect of explosion decreases with the increasing distance from the explosion center. Consequently, the probability of finding undamaged sensors increases with the increasing distance.

Holes are formed with characteristics that are obtained from a Gaussian probability distribution over two dimensions, defined by the tuple $(\overline{e}, d)$. In the tuple, $\overline{e}$ is a two dimensional vector showing the coordinates of the center of the explosion, and d is the radius of the area affected by explosion. Deployments over the terrain are uniform, and the two dimensional vector $\overline{c}$ denotes sensor placement candidate coordinates. However, deployment over the holes are further subject to deployment probability,

$$P(\overline{c}) = \begin{cases} 1 & \text{if } Q > \Phi_{0,d}(d_{ce}), \\ 0 & \text{otherwise}, \end{cases} \quad (5)$$

where d_{ce} is the distance between $\overline{c}$ and $\overline{e}$, Q is a random value in the $[0, 1]$ range and $\Phi_{0,d}$ is the CDF of a Gaussian distribution with parameters $(0, d)$. According to Eq. 5, the probability increases as the candidate location goes away from the hole center. Similar to the assumption that the effect of an explosion decreases with the increasing distance, the chance of sensor survival is characterized by the inverse Gaussian distribution. IDeA does not require any knowledge about the location and the characteristics of the explosions and the decisions made by the algorithm are based on the current configuration of the network using image processing tools.

TABLE I
Test parameters for the base scenario.

Parameter	Values
Maximum sensing range	20 meters
Area shape	900×200 m^2
Number of holes	10
Initial network node count	500
Hole radius range	uniformly distributed between $20 - 50$ meters
Redeployment percentage	10%

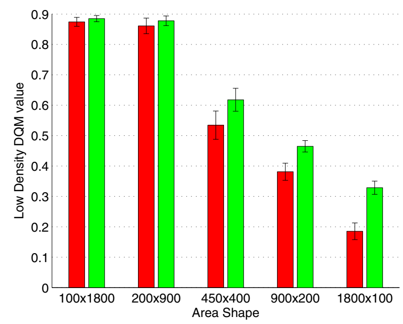

Fig. 6. WDQM results together with the corresponding confidence intervals at 95% levels for changing area shapes.

The simulations are implemented in MATLAB. The IDeA results are compared with the scenario where all of the sensors are deployed without reserving any portions. The values of the parameters are shown in Table I. To emphasize the effects of hole formation, the deployments are made rather sparse. The results are the average of 30 runs.

Fig. 6 shows the effect of area shape on the deployment quality and the performance of IDeA on different area shapes. WDQM values are near 1 (well sensing quality) for area width measures up to 200 meters. Large values are obtained for areas corresponding to vertical strips. As the strip gets narrower, the number of possible paths decreases. Given a large vertical strip, it is very unlikely to find a breach path from the unsafe side to safe side (or vice versa). Since the deployment quality measure is near the asymptotic limits, redeployment produces slight enhancements. The sensing quality erodes as the area gets wider and the proportional gain by IDeA increases up to 70%. The trend indicates that IDeA is crucial for narrow and long borders.

The effect of the number of holes and the hole radius on the WDQM are shown in Figures 7 and 8, respectively. Increasing the number of holes decreases the WDQM values. However, the gain produced by IDeA is around 35% on average. Moreover, the sensing quality gain produced by the IDeA gets

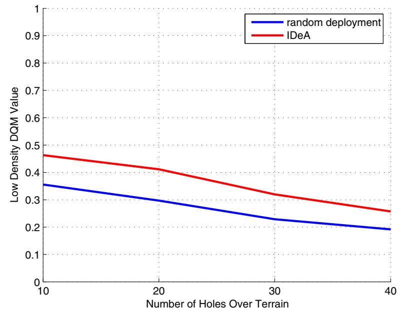

Fig. 7. WDQM results for hole count changes.

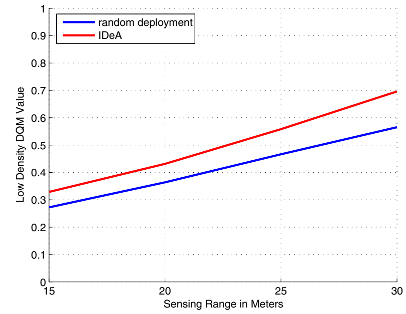

Fig. 10. WDQM results for different sensing range values.

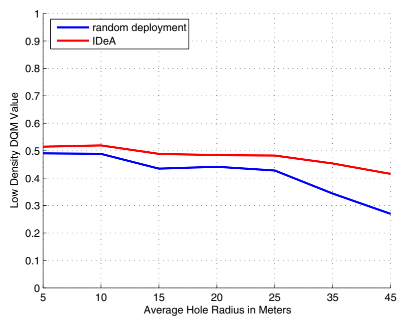

Fig. 8. WDQM results for changing hole ranges.

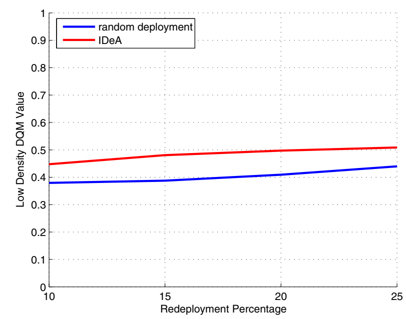

Fig. 11. WDQM results for different redeployment percentage values.

even better than the random deployments as the number of holes increases. For varying hole radius values, the IDeA is mandatory since the sensing quality is stable compared to one-time deployment method. The WDQM values vary in a margin between 0.5 and 0.4, whereas the relative loss for random redeployment is more than double. For the average hole radius values of 45m, the proportional gain is around 50%.

The deployment quality values with respect to the number of sensors are presented in Fig. 9. The IDeA becomes more critical as the sensor count increases, because of the increasing number of sensors lost due to the destruction and increasing distribution asymmetry over the terrain. As the number of redeployed sensors increase, the IDeA produces much better results by providing better sensing coverage over the redeployment regions. The relative difference increases up to 45% for the cases where the initial sensor count is 700.

The sensing range of a sensor is a characteristic mostly associated with the hardware. By increasing the energy expenditure for the sensing operation, it is possible to increase the sensing span. Fig. 10 represents the results for different sensing range values. The proportional increase by the method is consistent at 20% on the average with different sensing range values.

As can be seen in Fig. 11, deployments where the spare percentage is around 10% and 15% are acceptable choices that provide relative gains of 20% on the average. A redeployment percentage of 10% is more favorable compared to 15%, since by keeping the redeployment count lower, it is possible to keep the overall cost lower.

IV. Conclusion

Sensor failures or intentional destructions can create sensing holes in wireless sensor networks. Such holes degrade the service quality and the lifetime of the network. Morphological image processing tools are used to locate the sensing holes in the network. Once holes are identified, small redeployments using the initially reserved sensors are performed over the holes to increase the sensing quality of the network. The results have demonstrated that keeping the number of sensors constant, it was possible to increase the sensing quality. Constant number of sensors also kept the sensor cost constant. Our experiments with different scenarios showed that such a procedure increases the deployment quality considerably on the average. In this work, we have not included the cost

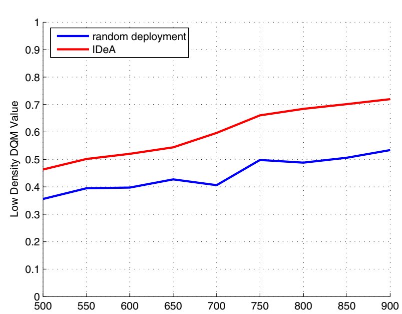

Fig. 9. WDQM results for different node counts.

of deployment and we plan to incorporate the cost into the engineering decisions, for studying the tradeoff between the cost and the performance of the proposed methodology.

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