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A Hierarchical Structure based Coverage Repair in Wireless Sensor Networks

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***Abstract*—In this paper, we propose a new control method to cover "holes" in wireless sensor networks. Many applications often face the problem of holes when some sensor nodes are disabled from the collaboration due to their failures and misbehavior. These holes may occur dynamically, and such a problem cannot be solved completely by simply deploying more redundant sensors. With synchronization around each hole based on a hierarchical structure, one (and only one) snake-like cascading repair process will be initiated in the local area in order to fill in that vacant space with a spare node. In this way, network connectivity and coverage can be guaranteed. The analytical and experimental results show substantial improvements of our approach compared with the best result known to date.**

I. INTRODUCTION

Recent attention has been drawn to use mobility for improving the communication performance in wireless sensor network (WSN) [2]. Due to the fact that sensors can very easily fail or misbehave, many nodes could be isolated from the network collaboration [4]. Thus, a "hole" in the surveillance area may occur in the deployed area, and such an occurrence may be dynamic. Rather than preventing the occurrence of holes, a new solution is proposed in this paper to repair the coverage by moving some spare nodes into the vacant area. A spare node is the node that will not cause any loss of connectivity (as well as coverage) upon removing it. Due to critical resource constraints, such a solution must be controlled within a small area in order to avoid getting too many other nodes involved. We attempt to provide an optimization in reducing the cost of repair process: not only the moving distance of node(s) in each single repair process, but also the total number of repair processes required for any hole that has occurred in the networks. The challenge to achieve such an optimization is the lack of global information. In this paper, we provide a hierarchical structure information model based on eye theory [3] to maintain the information of coverage and connectivity. Such information will be used to synchronize the repair processes and determine the spare node for moving.

There are three major contributions in this paper. First, a new information model is proposed for determining where the hole is and where the spare node to fix the hole lies, in a localized manner. This is the first time that an infrastructure to maintain the information of the coverage redundancy and deficit has been considered in WSNs. Second, under the hierarchical information model, a localized solution is provided to quickly locate a spare node and move it into the vacant area. Compared with other repair schemes that require real-time detection to blindly seek the spare node [8], [12] or a global balancing [10], the new approach is more efficient. Third, both the analytical and the experimental results are provided to show substantial improvement of using such a hierarchical structure in coverage repair, compared with the best results known to date.

A short summary of our approach follows. First, we build a surveillance with a virtual grid model [11] to detect the occurrence of a hole. According to the location of each grid, the entire network is connected under a hierarchical structure with Hamilton cycles [1]. Each cycle will dominate a certain area and the head node in its unique eye grid will maintain all the coverage and connectivity information of that dominated area. When a grid does not have the head, the directed Hamilton cycle turns into a directed Hamilton path. One (and only one) *repair process* will be initiated along that path to move a spare node into the vacant area. Whenever a local area does not have any spare node, the request will be sent along an upper level cycle in a bigger area. Inspired by the early work for deadlock-free routing around a faulty area that uses mutual exclusion at only one vertex [9], any request conflict can be avoided in the spare node localization. Moreover, in such a solution, the cost can be minimized in terms of the number of total node movements and the total moving distance. In both analytical and experimental results, we will show the substantial improvement of our approaches compared with the best results known to date. Throughout the paper, proofs to theorems are omitted. Details can be found in [5].

II. PRELIMINARY

We assume that all the nodes have the same sensing range and communication range R. The nodes inside the communication range are called neighbors and two neighboring nodes are directly connected. Each node u has its location, which is simply denoted by $L(u)$. The location information can be discovered by having Global Positioning System (GPS) receivers at some fixed nodes or a mobile beacon node, or

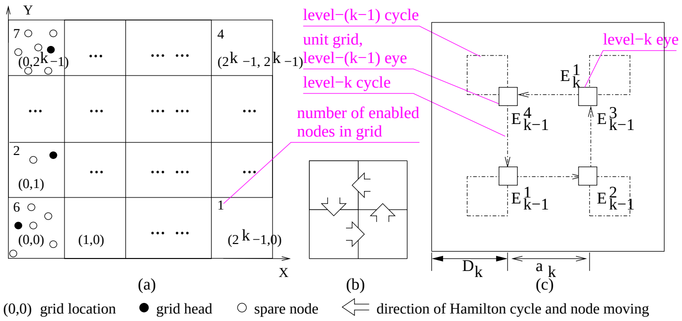


Fig. 1. (a) Virtual grid system and grid heads. (b) Directed Hamilton cycle in local unit grids. (c) Hierarchical Hamilton cycle structure.

by relying on the relative coordinate system. We partition the whole network into an $m \times n$ 2-D grid system (see Figure 1 (a)). To simplify the discussion, assume $m = n = 2^k$ where all the results can be extended easily to a general grid system (see details in [5]). Each grid is a square of size $r \times r$ and is denoted by its relative location in the entire system, say (x, y) $(0 \leq x, y \leq 2^k - 1)$. Two grids (x_1, y_1) and (x_2, y_2) are called neighboring grids if their location addresses differ in one (and only one) dimension, say X. Moreover, $\mid x_1 - x_2 \mid + \mid y_1 - y_2 \mid = 1$. Each grid (x, y), except the one at the edge of grid system, has four neighbors $(x, y+1)$, $(x-1, y)$, $(x, y-1)$, and $(x+1, y)$, with one in each of four directions: north, south, east, and west. In general, $[x : x'$, $y : y']$ represents a rectangular region with four vertex girds: (x, y), (x, y'), (x', y'), and (x', y).

After many faulty nodes and misbehaving nodes are disabled from the collaboration, the rest of the nodes, also called enabled nodes, will constitute the WSN. According to the results presented in [11], when $R = \sqrt{5}r$, each enabled node can communicate with nodes in the neighboring grids. In each grid, one of the enabled nodes will be elected as the grid head. The rest of the enabled nodes in the same grid are called spare enabled nodes, or simply, spare nodes. In this way, when each grid has its own head, the connectivity of all the heads and the coverage of the entire network can be guaranteed. As a result, each movement monitored by a head will be limited within two neighboring grids. Each head knows the following information: (1) its grid location, and (2) the number of enabled nodes in the grid and their locations (i.e., coverage redundancy). Moreover, each head monitors the area of the neighboring grids and detects the coverage deficit if any (i.e., possible occurrence of the hole). It is also in charge of communication with the corresponding head in neighboring grids to keep the connectivity of the entire network. The role of each head can be rotated within the grid.

It is noted that the grid partition with global information can ensure that only one head exists in each grid territory. In a grid partition with only 1-hop neighborhood information, we can guarantee the existence of heads in any $r \times r$ square territory by using a localized coverage scheduling algorithm. Then, the synchronization between those local heads is needed for any decision making in the repair process. After that, all the schemes presented in this paper can be extended easily under such a partition with local views. To make our movement control schemes clear, we only use the global partition model.

To minimize the coverage overlaps between the heads, we do not pursue the surveillance of diagonal neighboring grids for each head, which requires a larger communication range $R = 2\sqrt{2}r$ $(> \sqrt{5}r)$. It is also noted that when a grid does not have any enabled node, its area may still be covered by its neighboring heads and does not really need a repair. However, in our approach, the repair process will be initiated under such a case to provide a redundancy precaution. This will help to balance the enabled nodes more evenly so that the occurrence of a real hole can be avoided. This kind of redundancy is also a tradeoff for providing a localized solution.

We describe the schemes in a round-based system. All the schemes presented in this paper can be extended easily to an asynchronous system. However, to simplify the discussion, we do not pursue the relaxation. To make the entire system more scalable, all data communication is implemented in the information exchanges between two neighboring grids.

III. Hierarchical Structure and the Corresponding Coverage Repair

This section introduces our control scheme that will fill in any vacant grid with enabled nodes. As a result, with a minimum moving cost, each grid will have its own head and the coverage problem will be solved. Obviously, such an optimization relies on the availability of the information of coverage deficit and coverage redundancy. In this section, we first introduce the proposed hierarchical structure and then, the corresponding coverage repair.

Hierarchical structure information model. In the local area, each four neighboring unit grids constitute a Hamilton cycle, i.e., the level-1 cycle in the hierarchical structure (see Figure 1 (b)). One of the unit grids is selected as the eye of such a cycle based on the eye theory [3]. The head of this eye will collect the information of the existence of spare nodes in these unit grids along the cycle. Such a head and the region covered by these unit grids are called the dominating node and the dominated area, respectively. Then, each of the four level-1 eyes will form a higher level (i.e., level-2) Hamilton cycle to share the information. This process will continue until a level-k cycle for the entire region $[0 : 2^k - 1, 0 : 2^k - 1]$ is built on four level-$(k-1)$ eyes (see Figure 1 (c)). Finally, one level-$(k-1)$ eye is selected as the dominating node of the entire grid system, i.e., the level-k eye.

Obviously, any selected grid on a level-i cycle $(i > 1)$ is also a level-j eye $(i > j \geq 1)$. Its position can be determined as the follows. For the region $[0 : 2^k - 1, 0 : 2^k - 1]$, four grids $E^1_{k-1}(D_k, D_k)$, $E^2_{k-1}(2^k - 1 - D_k, D_k)$, $E^3_{k-1}(2^k - 1 - D_k, 2^k - 1 - D_k)$, and $E^4_{k-1}(D_k, 2^k - 1 - D_k)$ are selected as the level-$(k-1)$ eyes and constitute the level-k directed Hamilton cycle, where D_k is defined in [3] as

$$\begin{cases} 0 & k = 1 \\ 2^{k-1} - 1 - D_{k-1} & k > 1 \end{cases} \quad (1)$$

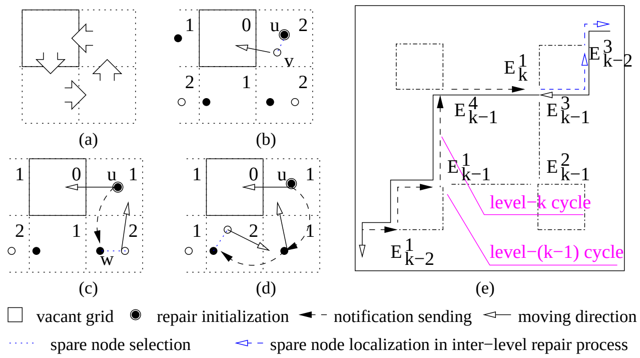


Fig. 2. (a) Level-1 directed Hamilton cycle, (b), (c), (d) Samples of the repair along level-1 cycle (intra-level repair), and (e) sample trajectory in an inter-level repair.

E^3_{k-1} is also selected as the level-k eye, i.e., E^1_k. These grids are connected by four a_k-hops-distance paths [3] where

$$a_k \;=\; \tfrac{1}{3}(2^k-(-1)^k)\ . \qquad (2)$$

The entire region is partitioned into four parts with one level-$(k-1)$ eye in each: $[0:2^{k-1}-1, 0:2^{k-1}-1]$, $[2^{k-1}:2^k-1, 0:2^{k-1}-1]$, $[2^{k-1}:2^k-1, 2^{k-1}:2^k-1]$, and $[0:2^{k-1}-1, 2^{k-1}:2^k-1]$. After that, the above procedure can continue to apply in each sub-region. The definition of D_k ensures that a selected grid eye on level-k cycle is also selected for the level-$(k-1)$ cycle (see Figure 1 (c)). Therefore, the information of spare nodes to be shared along the level-k cycle can be collected through those level-$(k-1)$ eyes. Such a process will continue until the unit grid is reached. The details are shown in Algorithm 1.

Algorithm 1: Construction of hierarchical directed Hamilton cycles with the information of the existence of spare nodes.

1) For the region $[0:2^k-1, 0:2^k-1]$, four grids $E^1_k(D_k, D_k)$, $E^2_k(2^k-1-D_k, D_k)$, $E^3_k(2^k-1-D_k, 2^k-1-D_k)$, and $E^4_k(D_k, 2^k-1-D_k)$ are selected as level-$(k-1)$ eyes and constitute the level-k directed Hamilton cycle, connected by four a_k-hops-distance paths where D_k and a_k are defined in Equation 1 and Equation 2 respectively. Among them, E^3_{k-1} is also selected as the level-k eye.
2) The entire region is partitioned into four parts: $[0:2^{k-1}-1, 0:2^{k-1}-1]$, $[2^{k-1}:2^k-1, 0:2^{k-1}-1]$, $[2^{k-1}:2^k-1, 2^{k-1}:2^k-1]$, and $[0:2^{k-1}-1, 2^{k-1}:2^k-1]$.
3) Repeat the above Hamilton cycle construction and the partition in each sub-region until reaching unit grids.
4) The head node in each grid on a level-1 Hamilton cycle maintains the information of the spare nodes in its own grid. The head node of the level-i eye ($1 \le i \le k$) collects such spare node information along its level-i cycle via those a_i-hops connecting paths.

Repair process. With the proposed hierarchical structure, each grid is not only directly threaded by a level-1 directed Hamilton cycle with other 3 neighboring grids, but also indirectly connected to all other grids in the entire network. Each grid head not only monitors the existence of spare nodes in its grid (i.e., coverage redundancy), but also monitors the existence of a head in each neighboring grid. Whenever such a head detects that a neighboring grid does not have any enabled node inside, a repair process is initiated to fix that detected vacancy. The proposed repair process has two phases. We summarize the repair process as follows.

In phase one, which is also called intra-level phase, the spare node is quickly located in neighboring grids along a level-1 Hamilton cycle. First, the repair process is initiated at a grid head, say node u, only when it detects the vacant neighboring grid in the direction of the level-1 directed Hamilton cycle (see the repair initialization in Figure 2 (b)). Then, node u will select one spare node v in its grid to move to the vacant neighboring grid (see Figure 2 (b)). If such a spare node cannot be found, u itself will move to the vacant grid. Before the movement, u will send a notification to the head w of its preceding grid (see the order in Figure 2 (a)). When the head w receives such a notification (in the next round), the above selection process will be repeated (see Figure 2 (c)), causing a so-called cascading movement. The whole moving process is snake-like while each movement is limited within two neighboring grids. For each movement causing the change of spare nodes in a grid, the new spare node information will be collected by the head of unit grid. And then, such information will be updated in the hierarchical cycles in the way in step 4 in Algorithm 1. The details intra-level repair are shown in the following algorithm.

Algorithm 2: Mobility control within neighboring grids (intra-level repair).

1) At a head u, the following repair process will be initiated when u cannot find the head in the successor grid along the level-1 directed Hamilton cycle; i.e., a vacant grid in such a direction is detected.
2) Find a spare node in the grid of u, say node v, to move into that vacant neighboring area before the next round starts.
3) If the above step fails, repeat the follows until the notified node u can find a spare node in the above step: (a) Send the notification to the preceding grid along the level-1 directed cycle to ask for a repair for u itself. (b) Wait until the corresponding head w receives this notification. (c) Move u to the vacant neighboring grid before the next round starts; i.e., leaving the current grid vacant for cascading repair.
4) Each head u detects the spare nodes existing within the same grid. The new information will be updated in the hierarchical structure in the way in step 4 of Algorithm 1.

In phase two, the required spare node is searched in the entire gird system. This phase is conducted with the hierarchical structure information and it is also called inter-level repair. First, whenever the head node of the level-1 eye, say node u, realizes the lack of the spare node in all neighboring grids along the level-1 Hamilton cycle, a notification will be sent along level-2 Hamilton cycle, which also passes through u. That is, the repair process is applied to an upper level cycle. This process will continue until the spare node is found at a level-i eye ($i \le k$). That is, a spare node can be provided in the partition region dominated by that eye. After that, the spare node will be localized from that eye down to unit grid as follows. A search for the spare node is initiated at that level-i eye and will go along the corresponding level-i cycle. It will reach a level-$(i-1)$ eye that has at least one spare node in its dominated area. Then, from that lower level eye, the above search process will continue until it reaches the unit grid along level-1 cycle. Then, from that unit grid, a spare node will be selected. Eventually, the nodes will move in the cascading way to fill in the detected vacant grid with one spare node, along the path that is constituted in the above process. Figure 2 (e) shows an example of the reservation, localization, and cascading filling-in processes in an inter-level repair process. The spare node information will be updated to date as well as the node moving. Algorithm 3 shows the details of the inter-level repair process.

Algorithm 3: Mobility control with hierarchical directed Hamilton cycles (inter-level repair).

1) Reservation process. The notification for a spare node is sent along the upper level cycle until such a spare node can be provided in the record of an eye (say node u). Then, this spare node will be reserved unless there is another request for it coming from higher level cycle.
2) Spare node localization. From that eye u, the existence of such a spare node is verified level by level among the cycles down to unit grid.
3) Cascading filling-in process. The nodes will move in the cascading way along the path constituted in the above to fill in the detected vacant grid with a spare node, unless a localization process from higher level cycle seizures this cascading movement. In that case, the reservation process for a spare node will re-start.
4) Information update. The spare node information will be updated to date in the way in step 4 of Algorithm 1.

Performance Discussion. After the construction of the hierarchical structure, all the unit grids are connected. Any repair process is able to find the spare to cover the detected vacant grid wherever such a node exists in the network. This will favor networks with sparse deployment, or in the case when some critical condition disables the most of deployed nodes.

Under the virtual grid model, the communication range of each grid head is set large enough to cover all neighboring grids in order to detect the vacant neighboring grid. In other words, each grid can be monitored by as many as 4 grid heads from all its neighboring grids. Without synchronization, the existence of a vacant grid may incur 4 repair processes simultaneously, causing redundant processes and some unnecessary node movements.

To reduce the redundant repair processes that might be initiated for the same vacant grid, the directed path is used to determine one and only one neighboring grid head that conducts a valid detection and then initiates the corresponding repair process. The Hamilton cycle is used to guarantee the unique detection direction for each grid. This can ensure the initialization of repair and only the necessary initialization for each vacant grid occurred.

Another synchronization issue occurs when multiple holes appear in the networks, especially when a hole occurs during the ongoing process to repair a previously detected hole. To solve the conflict of spare node requests, some synchronization schemes, as shown in Figure 3, must be provided.

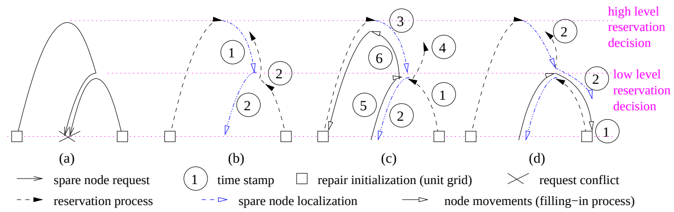


Fig. 3. (a) Request conflict, and our solutions (b), (c), and (d).

First, the detection direction is used to help the grid head to forward the spare node request. Those requests initiated within the level-1 cycle cannot form any loop in their stretch paths due to the existence of that vacant grid. However, when a spare node exists in the neighbor grid in the reverse direction along such a cycle, it cannot be located quickly. Although this inefficiency is reduced to a minimum by connecting only 4 neighboring grids in a cycle in our approach, the intra-level repair is still not optimal. This is the tradeoff for reducing spare node request conflict.

Second, information regarding the existence of spare nodes will be collected by the head of each unit grid and then will be maintained in the hierarchical structure up to the top level cycle (i.e., level-k cycle). It is noted that the reservation for a spare node is only made in the eye that dominates both the detected vacant grid and the grid containing that spare node. For any two inter-level repairs locating the same spare node, the reservation cannot be made in the same eye. The one made in the eye of a higher level cycle which has started the information update in upper level cycles will have the higher priority. When the localization process of a higher priority repair reaches the eye v that made the lower priority reservation, it will seizure the cascading movements of the lower priority repair by (a) redirecting filling-in process of the lower priority repair to its own detected vacant grid, and (b) restarting the reservation process at v to locate another available spare node for the lower priority repair, as well as the information updates. Such a case will be treated as a restart of an asynchronous reservation process after a holding period.

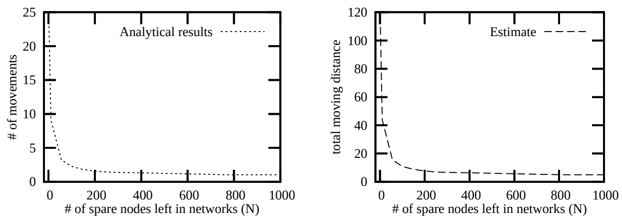
It is noted that, for the purpose of avoiding request conflict, the spare node cannot move directly to that detected vacant grid and must follow the exact stretch path of request process.

Theorem 1: *Any vacant grid will be filled with a new head node in the above control schemes.*

Theorem 2: *In a $2^k \times 2^k$ grid system under the above hierarchical structure model, the maximum length of the stretch path in the repair process is $O(2^k)$.*

The following theorem provides an estimate on the average node movements, $\overline{M}$, in any single repair process when nodes are deployed in a uniform distribution, with N spare nodes still available in the entire network.

Theorem 3: *If a $2^k \times 2^k$ grid system still have N spare nodes*



(a) The number of node movements (analytical results).
(b) The total moving distance when $R = 10$ (estimated).

Fig. 4. Cost of a single repair in the hierarchical repair process in a 16×16 grid system.

available, for any converged repair process, $\overline{M} = \sum_{i=1}^{k} \overline{M_i}$, *where* $\overline{M_i}$ *is the average length of the stretch path that reaches level-*i *cycles.* $\overline{M_i} =$

$$\begin{cases} \sum_{j=1}^{3} j \times P_k(1,j) & i = 1 \\ (2a_i + \sum_{j=1}^{i-1} 4a_j) \times P_k(i) & 1 < i \le k \end{cases} \qquad (3)$$

where $P_k(1,j) =$

$$\begin{cases} 1 - (1 - \frac{1}{2^{2k}})^N & j = 1 \\ (1 - (1 - \frac{j}{2^{2k}})^N) \prod_{t=1}^{j-1} (1 - \frac{t}{2^{2k}})^N & otherwise \end{cases}$$

and $P_k(i) =$

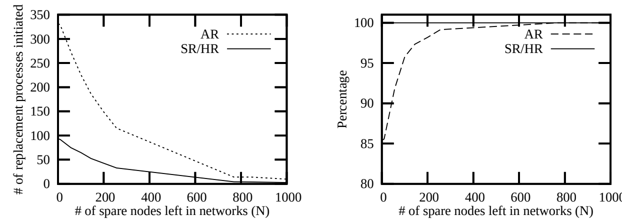
$$\begin{cases} (\prod_{t=1}^{3} (1 - \frac{t}{2^{2k}})^N)(\prod_{t=2}^{i-1} (1 - \frac{2^{2^t}-1}{2^{2k}})^N) & i = k \\ (\prod_{t=1}^{3} (1 - \frac{t}{2^{2k}})^N)(\prod_{t=2}^{i-1} (1 - \frac{2^{2^t}-1}{2^{2k}})^N) & i < k \\ \quad \times (1 - (1 - \frac{2^{2^i}-1}{2^{2k}})^N) & \end{cases}$$

Figure 4 (a) shows our analytical results for a $2^4 \times 2^4$ grid system. Even when there is only one spare node available in the entire network, the number of node movements for a single repair process can be controlled to 24.5. Based on the analytical results, Figure 4 (b) shows our estimate on the corresponding total node moving distance in that single repair.

IV. Simulation Results

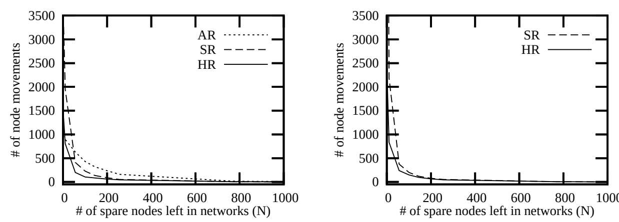
In this section, we verify the improvement of our control scheme based on the hierarchical Hamilton cycles (HR). We also compare our approaches with other repair solutions, as seen in AR [6] and SR [7]. The results show that our snake-like cascading movement will successfully cover any hole while substantially lowering the cost. For the deployed sensors with communication range $R = 10m$, we determine the grid size $\frac{R}{\sqrt{5}} \times \frac{R}{\sqrt{5}}$ and then form the virtual grid system [11] in the target surveillance area.

After deploying all the nodes in the uniform distribution, we randomly disable some nodes from the collaboration and create the holes. The rest of the nodes are enabled and they constitute the WSN. One of enabled nodes in each grid (if any) will be elected as the head node. Then, we apply schemes SR, HR, and AR to fix the hole. At last, we test the performance of different control schemes AR, HR, and SR in terms of their success in finding a spare node to fill in the hole. We also test the cost of these schemes in



(a) The number of repair processes initiated.
(b) The success rate (%).

Fig. 5. Repair process and its success rate.



(a) Experimental results.
(b) Analytical results.

Fig. 6. The number of node movements.

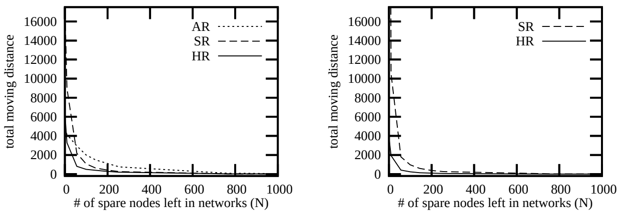
terms of the number of repair processes initiated, the total number of node movements and the total moving distance. Some analytical results of our HR scheme are compared with the results in [7] of SR scheme. These analytical results will also be compared with the corresponding experimental results to verify the correctness of our approaches. It is noted that each node from one grid moving to its neighbor will randomly select the destination location in the target grid.

The tunable parameters in our simulation are as follows. (1) Number of grids $2^k \times 2^k$. We use $k = 4$ in the simulation. (2) Number of spare sensors N in the networks. In [10], it has been mentioned that the control scheme can guarantee the coverage with at least 3×2^{2k} spare nodes. Therefore, we deploy 5000 sensors and select those cases when N's value is in the range from 10 to 1000 ($\simeq 4 \times 2^{2k}$).

Figure 5 (a) shows the number of repair processes initiated in schemes AR, HR, and SR in the cases with $(N + 2^{2k})$ enabled nodes. Figure 5 (b) shows how many of them (percentage-wise) will approach a spare node in the networks and converge successfully. We also show the number of node movements in all schemes in Figure 6 (a), and the total node movement in meters/distance for all schemes in Figure 7 (a). For the comparison, Figure 6 (b) and Figure 7 (b) show our analysis on the number of movements and the total moving distance, respectively, for both SR and HR.

Results can be summarized as follows.

1) [7] claims that among all the existing movement-assisted methods to fix the hole, scheme SR has the best performance insofar as the total number of node movements and the total moving distance are concerned. As a result, scheme HR achieves the same success as scheme SR does. Fewer than 50% processes are needed in SR and



(a) Experimental results. (b) Analytical results.

Fig. 7. The total moving distance of nodes (meters).

HR, compared with the results of AR.

2) When $N < 55$, scheme AR has $10\% \sim 20\%$ failures in repair processes while the success rate is always 100% in schemes SR and HR; that is, the surveillance coverage is less robust in AR with lower node density. However, SR requires more node movements and moving distance due to the use of a long path to approach the spare node. With the hierarchical structure, HR can ensure the success of each repair while keeping both the node movements and the total moving distance minimal.
3) When $N \geq 55$ (i.e., > 1.22 enabled nodes per grid) which is more common in real applications, SR and HR requires fewer node movements and less moving distance while keeping the success rate higher than AR. But HR is the more cost-effective.
4) The cascading movement is adopted in all schemes. The repair process in SR or HR is just one of the cases of in AR that are along a special path. SR and HR have the same bound of converging speed as AR which has been presented in [6].

V. Related work

Recently, rather than preventing the occurrence of the holes, some extended virtual force methods [8], [12] that simulate the attractive and repulsive forces between sensor nodes have been proposed to fix the hole. In these methods, sensors in a relatively dense region will move slowly towards the relatively sparse region according to each other's repulsive force and head towards a hole in the network. However, as indicated in [10], without global information, these methods may take a long time to converge and are not practical for real applications due to the cost in total moving distance, total number of movements, and communication/computation. Then, in [10], a more practical balancing method under the virtual grid model [11] is discussed. This method allows for quick convergence but requires node adjustments in the entire grid network, causing many unnecessary node movements just for providing the coverage for a single hole.

In the early work [6], a localized control method based on the 1-hop neighborhood is proposed. Whenever a vacant area is detected, a snake-like cascading repair process is initiated to move nodes to cover the hole area. However, due to the lack of synchronization, the existence of a hole will incur multiple repair processes, causing redundant processes and some unnecessary node movements. In the early work [7], a synchronization based on a single Hamilton cycle connected the entire network is provided. However, due to the length of such cycle, a long stretch path in the repair process is needed even when a spare node nearby the detected vacant grid is available. A more efficient localized repair solution is needed.

VI. Conclusion

In this paper, we have presented a more cost-effective, snake-like repair process to cover the surveillance holes of WSNs where some sensors deployed in certain sensing areas are disabled from the collaboration. As a result, the connectivity and coverage of WSNs can be guaranteed, even when the working status of nodes changes dynamically. In our methods, only the 1-hop neighborhood is used, and the adjustment of nodes can be controlled within the local area more efficiently, under a synchronization model based on the hierarchical Hamilton cycles. The analytical and experimental results show the proposed method to be robust and scalable with a minimized cost. This verifies the correctness and the effectiveness of our new information model in coverage repair and its conflict control. In our future work, the energy consumption model will be considered in the node adjustment so that the lifetime of the complete coverage can be extended.

Acknowledgment

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