A Prescient Recovery Approach for Disjoint MSNs

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***Abstract*—In Mobile Sensor Networks (MSNs), limited transmission range of the sensor nodes requires nodes to collaborate with each other in order to send their data to the Base Station (BS) which acts as a gateway between the network and the remote user. However, nodes may fail arbitrarily due to battery depletion, hardware malfunction, or an external damage. Such failures may partition the network into multiple disjoint segments isolated from the rest of the network. To restore network connectivity, network topology can be restructured by employing node mobility. However, mobility incurs excessive energy consumption and must be limited to avoid further failures and extend the network lifetime. In this paper, we present a distributed mobility-based approach to restore network connectivity while minimizing the movement cost as well as the number of nodes to be relocated. While determining the movement target, we consider the former locations of the upstream nodes but designate an alternative spot for movement to avoid possible risks caused the failure and to minimize the movement cost. The experiment results indicate that the proposed approach outperforms the approaches currently used in terms of total movement distance, maximum movement distance and the number of relocated nodes.**

I. Introduction

Emerging technologies in node hardware have paved the way for employing wireless sensor networks to monitor an area of interest and track certain events unattended without risking human life. Such networks may also embrace mobility to enable MSNs and provide application level flexibility for data collection, improving coverage, extending network lifetime, and restoring connectivity [1]–[3]. In particular, we are interested in connectivity issues considering the limitations on the node hardware such as energy, transmission range, and computational power and exposure to harsh environmental conditions due to applications such as combat field reconnaissance, forest fire detection, volcano monitoring, and landslide detection.

Limited transmission range of the nodes imposes network wide collaboration to coordinate actions and sustain connectivity with the BS. However, network may be subject to node failures due to battery depletion, hardware malfunction, or an external damage inflicted by environmental conditions. Failure of a node may break communication paths in the network and leave other nodes unreachable unless alternative paths are available. The node which serves on a path exclusively is regarded as a cut-vertex node and removal of such nodes from the network partitions the network into multiple disjoint segments isolated from the rest of the network. Restoring inter-segment connectivity is essential so that the MSN becomes operational again.

Mobility-based connectivity restoration schemes have been applied in response to the loss of single [4]–[6] or multiple [7]–[14] nodes in the MSNs. The simultaneous failure of multiple collocated nodes is more challenging compared to the single node failures both in analyzing the scope of the failure and also providing a recovery solution [15]. The common approach is restructuring the network topology by exploiting mobility while minimizing the mobility cost. The fundamental issues of this process are identifying the node (leader) to be relocated and determining the target location for movement. If the movement of a single node is not sufficient to restore connectivity, a cascaded movement is pursued where a new leader node is selected in the successive steps to sustain recovery. To identify the leader node, various metrics can be considered such as node degrees [4], connectivity [5], or centrality [14].

In this paper, we present a novel approach to determine target locations for movement while avoiding former spots where the nodes were failed considering possible risks which may still persist. This approach not only avoids perilous spots, but also designates better trajectories while exploring alternative paths as indicated by the experiments. We employ a fundamental geometry concept to identify the movement target based on the leader node's location, immediate upstream node's location, and the location of the upstream node which is two hops away. The idea is defining a circle, centered at the upstream node which is two hops away with a radius equal to the transmission range, and a line which meets the positions of the leader node and its immediate upstream node. Then we determine the intersection point of the circle and the line as the alternative target for movement. We prove that such a line and circle can always be defined while exploring the path. We also prove that the defined circle and the line always intersect.

We considered [10] as the baseline with two different leader selection heuristics, namely Distributed Actor Recovery Algorithm (DARA) [4] and Partition Detection and Recovery Algorithm (PADRA) [5], to evaluate the presented approach. We conducted extensive simulations with various metrics and show that the presented approach not only minimizes the movement cost, but also limits the number of relocated nodes while avoiding perilous spots.

The rest of the paper is organized as follows. Related work is summarized in Section II. The assumptions and the problem definition are given in Section III. Approaches are presented in Section IV. The performance of the proposed approach is evaluated in Section V. The paper is concluded in Section VI.

II. Related Work

Fault-tolerance provisioning is regarded as a form of topology management in WSNs [15], [16]. The principal objective is adjusting the topology to sustain coverage while maintaining network connectivity. Fault-tolerance techniques, to tolerate permanent node failures, can be classified into two categories according to the resource provisioning time. Proactive approaches pursue a precautionary model where the resources are provisioned before failure. Solutions in this category exploits node redundancy to alleviate the consequences of node failures [17], [18]. However, due to unpredictability of the damage location and scale, approaches of this type may not be able to ensure a solution especially for multiple collocated failures. Reactive solutions, on the other hand, provide demand-based real-time restoration. Presented approach is a reactive fault-tolerance solution which can handle large scale simultaneous node failures.

Reactive schemes can be further classified into two broad groups based on the possibility of introducing additional nodes to the network. The first group assumes possible intervention to the deployment area and the placement of additional nodes [19], [20]. The second type of reactive schemes, on the other hand, assumes availability of mobile nodes as part of the network and restructures network topology through relocating mobile nodes to restore connectivity [4]–[6]. Both models can be further classified based on whether centralized or distributed recovery procedures are employed. Considering limited or no human intervention to the application area, presented approach pursues the second reactive strategy and exploits mobility of the existing nodes to restore connectivity in a distributed manner.

Mobility-based connectivity restoration solutions pose two different challenges that need to be addressed. First, determining target locations for movement. Second, identifying nodes to be relocated. For instance, DARA [4] and PADRA [5] focus on the second issue. While DARA evaluates node degrees to identify the node for movement, PADRA determines connected dominating set (CDS) of the network and picks dominatees for movement. There are approaches which focus on determining the target locations as well [7]–[9]. While [7] considers infinitely many number of locations where the mobiles can be relocated, [8] and [9] are motivated to reduce the number of locations where the nodes can move. [4]–[6] can only handle the loss of one node at a time and are not suitable for the considered problem. [7]–[14], on the other hand, can tolerate simultaneous failure of collocated nodes similar to our solution.

[7]–[9] are centralized solutions which assume the availability of the whole network state after failures. Obtaining such data from post-failure network in a centralized manner may be infeasible or even impossible and render such solutions inapplicable to the considered problem. [12] presents a distributed solution by employing game theory. However, this approach assumes visual sensors/cameras to identify the existence of other partitions. Another distributed solution was presented in [13]. Though, obstacles and terrain elevation were considered in this solution and the primary goal was attaining the most energy efficient trajectories for movement in the expense of the increased movement distance.

[10] and [14] are also distributed approaches which focus on the first and second issues of the mobility-based connectivity restoration solutions respectively. [14] employs betweenness and closeness centrality to evaluate the importance of the nodes and identify the node for movement. [10], on the other hand, utilizes Ad-Hoc On Demand Distance Vector Routing (AODV) [21] algorithm to determine the stopping points of the trajectory to reach the BS through the shortest path. We follow the approach presented in [10] to collect the upstream node locations to reach the BS. Next, we improve the trajectory by designating alternative spots for movement based on the subsequent locations in a prescient manner.

III. Preliminaries

A. Assumptions

We assume a set of battery-operated mobile sensors which are spatially distributed over a region where some phenomenon is to be monitored. A stationary BS, which is free from failures, is assumed to act as a gateway between the network and the end user. Due to their limited transmission range, sensors cooperatively pass their data through the multi-hop network which is assumed to be connected initially. We assume a catastrophic event which leaves multiple sensors inoperative simultaneously. The damage is assumed to occur at a random time but after nodes establish their paths to the BS. Failure of cut-vertex nodes partitions the network into disjoint subgroups which are isolated from the rest of the network as illustrated in Fig. 1. We assume the lack of any external intervention to adjust network topology and therefore, require an unattended recovery approach using existing nodes. The nodes are assumed to be able to detect interrupted data delivery to the BS and initiate recovery [11].

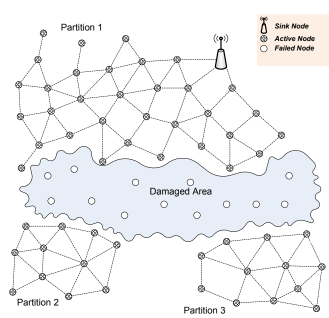


Fig. 1: Limited transmission range enforces forming a multi-hop mesh network to pass the data in a collaborative manner through the multi-hop network. Sensors in $Partition_2$ and $Partition_3$ are still operational but isolated from the rest of the network.

Unless the nodes have inherent mobility capabilities, node mobility can be enabled by attaching nodes to mobile robots [22]. Energy consumption of movement is known to consume much more energy compared to other network activities such as messaging [23]. Due to the high energy cost of mechanical motion on the batteries, the burden of mobility should be limited and balanced uniformly among the mobiles so that the movement shall not cause further problems of energy drain.

We assume one of the localization methods [24] to obtain initial locations of the sensors.

B. Problem Definition

A connected MSN is given, composed of n mobiles and one BS, with a transmission range of TR. At some arbitrary moment, $1 \leq f \leq n-1$ mobiles are removed from this network creating $k > 1$ partitions. Our problem can be formally defined as follows: "Given a MSN of $n-f$ mobiles, the goal is to provide a distributed solution which integrates k partitions into a single connected network by relocating the mobiles such that the total number of nodes to be relocated and their movement cost (i.e., $\sum_{i=1}^{n-f} d_i$) are minimized where d_i is the movement distance of $node_i$"

IV. Proposed Heuristic

A. Proactive Path Discovery

Considering the whole region for movement target implies infinitely many number of possible positions that can be visited in the application area when the location space is considered in real numbers. Obtaining the optimal solution is regarded as NP-Hard [7] and we will pursue a heuristic to limit the candidate target locations instead. Since the network is initially connected, it is possible to ensure recovery by replacing failed nodes with the remaining operational nodes in the partitions. It should be noted that movement of a single node may not be sufficient to ensure recovery and even create further partitions.

Presented approach requires nodes to be aware of their own locations and collecting location information in a proactive manner. Given the abundance of nodes, it is desirable to limit the scope of such a data collection. Since the damage scale and the nodes to be affected cannot be known in advance, we follow the approach presented in [10] to determine the data collection scope. The idea is determining the shortest path to reach the BS, which can be obtained through the routing algorithm, and collecting the locations of the upstream nodes in the obtained path. Once the locations are collected in the full path in advance, the nodes can follow the same path in their movement trajectory until discovering a live node to connect with in case of a partitioning. In the worst case, node moves until reaching the BS.

If the route construction phase is over before the partitioning, this approach ensures recovery. The nodes can detect a partitioning if the immediate upstream node is not reachable and an alternative path cannot be found in a reasonable amount of time. Afterwards, recovery phase can be initiated.

B. On-demand Connectivity Restoration

Permanent failure of cut-vertex nodes partitions the network into multiple disjoint segments. Loss of the links are, primarily, noticed by the nodes with a failed immediate upstream node after multiple unsuccessful attempts to find an alternative path. Once the partitioning is concluded, such nodes become a candidate node to initiate recovery, the routes are invalidated, and the BS is marked unreachable. Among the candidate nodes, one node is selected to be the leader node and initiate recovery. Different heuristics can be applied to identify the leader node when multiple candidate nodes are available. In this paper, we follow the approach DARA [4] to select the leader node. The idea is evaluating the node degrees and selecting a node with fewer neighbors to limit the impact of node relocation.

Target location for movement must be determined once the selection of the leader node is completed. Leader node, at this point, has the sequence of locations of its upstream nodes and by visiting these locations iteratively, it will explore an alternative path. However, visiting the exact locations may not be the best option due to the following reasons: First, considering the random deployment of the nodes, movement trajectory can be improved by examining the subsequent locations. Second, the damage may block movement or the leader node may be subject to another failure due to the surroundings. Thus, we opt to determine an alternative location for movement by investigating the subsequent locations in the former path.

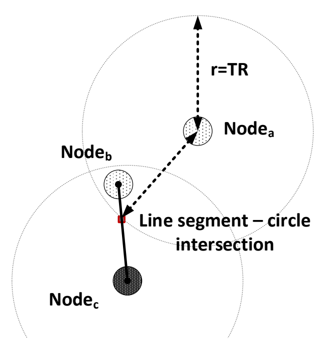


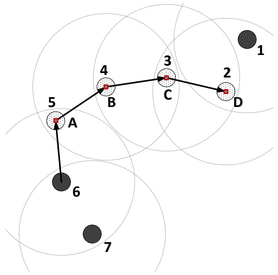
Fig. 2: Identifying an alternative target point for movement.

Consider the scenario in Fig. 2. $Node_c$ has failed upstream nodes $Node_b$ and $Node_a$. Instead of relocating $Node_c$ to the position of $Node_b$, we consider subsequent locations as well and determine an alternative target location to improve the trajectory as illustrated in Fig. 3 and decrease the overall movement cost. The idea is defining a line segment which connects the current position of the leader node and the location of its immediate upstream node and a circle centered on the upstream node which is two hops away with a radius (r) equal to the transmission range (TR) and determining the line segment-circle intersection point as the new movement target.

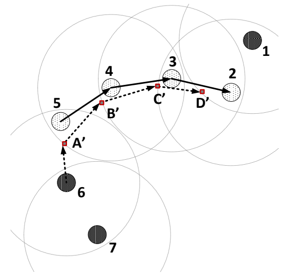
In geometry, an infinite line may or may not intersect a circle. If they intersect, it can be in exactly one point (tangent line) or exactly two points (secant line). Since we use the line formula Eq. (2), we claim that there will be at least one intersection point. For two intersection points, we pick the point closer to the leader node as the movement target. Intersection points can be obtained by solving the line equation for x or y and substituting it into the equation of the circle defined in Eq. (1) and deriving the solution using the formula of a quadratic equation.

$$(x - x_a)^2 + (y - y_a)^2 = r^2 \tag{1}$$

$$(y - y_c) = \frac{(y_b - y_c)}{(x_b - x_c)} \times (x - x_c) \tag{2}$$



(a)



(b)

Fig. 3: Before; A-B-C-D is the initial trajectory of $Node_6$ (a). After; A′-B′-C′-D′ is the improved trajectory (b).

Lemma 1. *Given the leader node does not have a valid path to the BS, there are locations x_c, y_c and x_b, y_b to define a line, and a location x_a, y_a to define a circle with a radius $r = TR$.*

Proof. If the leader node does not have a valid path to the BS, then there must be at least one unvisited location in the upstream nodes' locations list. Otherwise, final location of the leader node (x_i, y_i) is on the point where the line segment $(x_c, y_c)(x_b, y_b)$ and the circle centered at (x_a, y_a) intersects. Since, there is no more location in the list, BS must be positioned at (x_a, y_a). Considering the fact that (x_i, y_i) is within the TR of (x_a, y_a), which is the BS, then the leader node has a valid path to the BS which is a contradiction. □

Lemma 2. *The line l, defined by x_c, y_c and x_b, y_b, intersects circle C, centered at x_a, y_a, with a radius $r = TR$.*

Proof. Since an initially connected network is assumed, x_b, y_b must be within the circle, C, centered at x_a, y_a with a radius TR. Therefore, line, l, always intersects C. If we assume that l does not intersect C, then x_b, y_b must be outside of C which means that x_b, y_b and x_a, y_a are apart from each other more than TR. This contradicts the assumption of an initially connected network. □

V. Experimental Evaluation

A. Experiment Setup

Efficiency of the proposed approach is validated through simulations. We consider an application area of 600 meters × 600 meters to deploy nodes in a random fashion. Nodes and the BS have a transmission range of 30 meters and form a connected network initially. Two sets of topologies are formed to observe the effect of the node density and the damage scale on the recovery cost. In the first set, the number of partitions is set to 3 and the number of nodes is varied from 50 to 200. In the second set, the number of nodes is set to 100 and the number of partitions is varied from 2 to 5. For each case, 100 different topologies were created and tested for significance and the average is reported.

B. Performance Metrics

- *Total movement distance*: This metric is to measure the total distance traveled by the nodes involved in recovery.
- *Participation to recovery*: This metric indicates the number of mobiles involved in recovery.
- *Maximum movement distance*: The last metric reveals the maximum distance traveled by any of the mobiles.

C. Baselines

We employ [10] as the baseline by considering two different heuristics for leader selection, namely DARA [4] and PADRA [5]. DARA evaluates node degrees and favors nodes with fewer neighbors for movement. PADRA, on the other hand, determines minimum connected dominating set (MCDS) of the partition and favors dominatee nodes for movement.

D. Performance Results

This subsection presents the performance evaluation of our solution with respect to total movement distance, participation to recovery, and maximum movement distance. The experiments are conducted on topologies with varying network size and damage scale. *DPR* represents Distributed Prescient Recovery in the rest of the paper.

1) Total movement distance: Recovery costs of the approaches in terms of total movement distance are presented in Figs. 4 and 5, respectively, for various node densities and damage levels. Fig. 4 reveals the negative correlation between the network size and the total distance to be traveled for recovery. This is expected due to increased node redundancy which provides alternative paths for recovery. Distance between the partitions is also expected to be shorter due to increased node density for the given application area.

Fig. 4 suggests that the minimum recovery cost can be attained by employing *DPR* for both sparse networks as well as dense networks. *DPR*, not only scales well but also reduces total movement distance by 22.4% in dense networks compared to PADRA. DARA performs worst among the considered approaches.

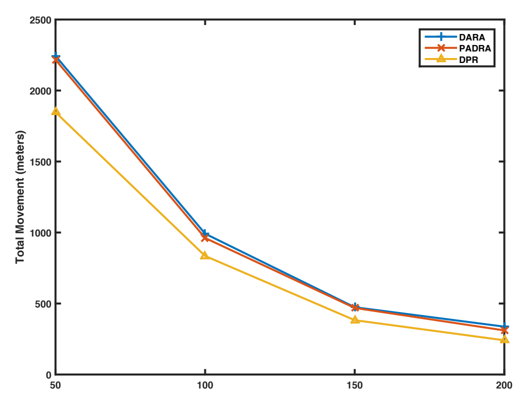


Fig. 4: Total movement distance with varying number of nodes.

It can be observed from Fig. 5 that the total movement cost increases with the extended damage scale. This is expected due to the increased demand for recovery from additional partitions. *DPR* provides the most cost-effective solutions for all damage levels. For the topologies with the largest damage scale, *DPR* alleviates the cost by 21.6% compared to PADRA. DARA is outperformed by PADRA and *DPR*.

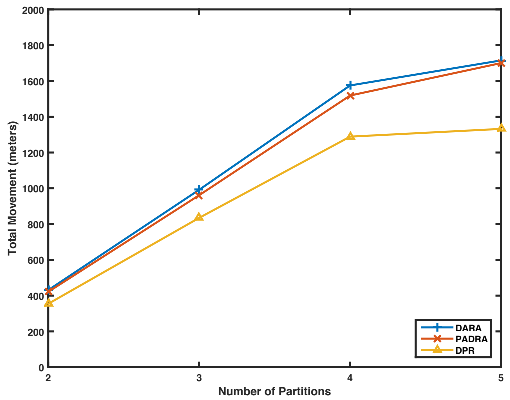


Fig. 5: Total movement distance with varying number of partitions.

2) Participation to recovery: Movement of the leader node initiates recovery. However, connectivity may not be restored by a single node movement. Furthermore, movement of the leader node may cause further partitions in the network. In such a case, recovery should be proceeded with further attempts involving more nodes in a cascaded manner. Considering the cost of mobility, it is desirable to limit the number of nodes involved in recovery. In this subsection, we report the number of mobiles participated to recovery. Figs. 6 and 7 depict the results for varying network size and damage scale, respectively.

Fig. 6 indicates that the scope of the recovery decreases with the increased node density. This can be attributed to the increased likelihood of discovering alternative nodes for connection when the network size is larger. Consequently, the number of nodes involved in recovery declines. *DPR* outperforms DARA and PADRA in all node densities and reduces recovery scope by 8.7% compared to PADRA in sparse networks. DARA, on the other hand, requires the most nodes involved in recovery.

It can be observed from Fig. 7 that the scope of the recovery increases when the damage scale is extended. This is expected due to the increased number of partitions which needs to be recovered. *DPR*, again, outperforms the baselines and requires the least nodes to be involved in recovery. *DPR* decreases recovery scope by 9.3% compared to PADRA in topologies with higher partition counts. PADRA performs slightly better than DARA.

3) Maximum movement distance: Finally, we evaluated the approaches in terms of the maximum distance traveled by any of the mobiles involved in recovery. The results are depicted in Figs. 8 and 9 for varying node density and damage scale, respectively.

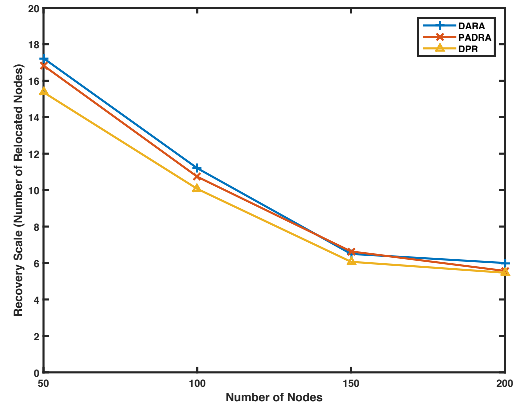


Fig. 6: Recovery scale with varying number of nodes.

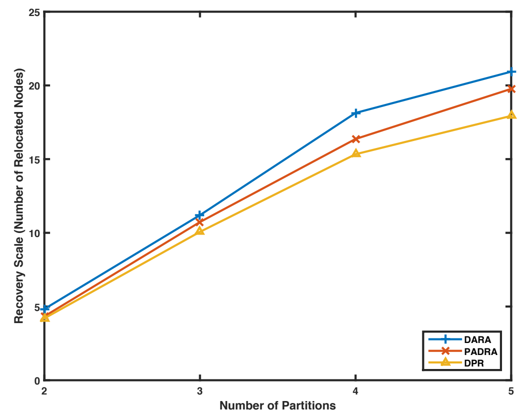


Fig. 7: Recovery scale with varying number of partitions.

Fig. 8 indicates that the maximum movement distance declines for all approaches when the node density is increased. This is expected due to the reasons justified earlier. In sparse networks, *DPR* performs slightly better than the baselines and outperforms PADRA by 11% when the network size is set to maximum. DARA and PADRA performs very similar.

As expected, Fig. 9 denotes that the maximum travel distance increases for all approaches when the damage scale is extended. *DPR* performs slightly better than DARA and PADRA. The results for the maximum distance are very close in all approaches for various node densities and damage levels. This can be attributed to the movement of the leader node. Leader node initiates recovery by its movement and performs the longest travel. After the movement of the leader node, the next nodes' movements are expected to be shorter due to decreased distance between respective partitions. Therefore, leader node's movement is expected to dominate the maximum movement.

VI. Conclusion

In this paper, we have presented a distributed connectivity restoration solution for partitioned MSNs. Considering the possible risks on the movement trajectory, we adapted an

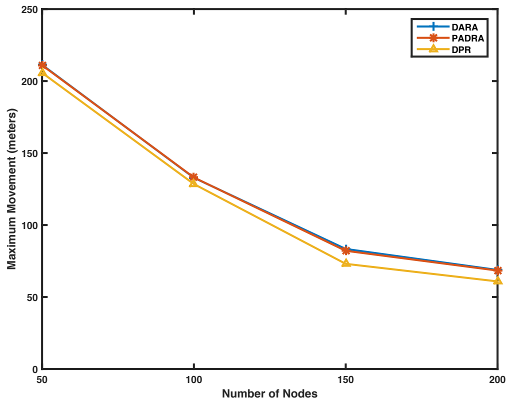


Fig. 8: Maximum movement distance with varying number of nodes.

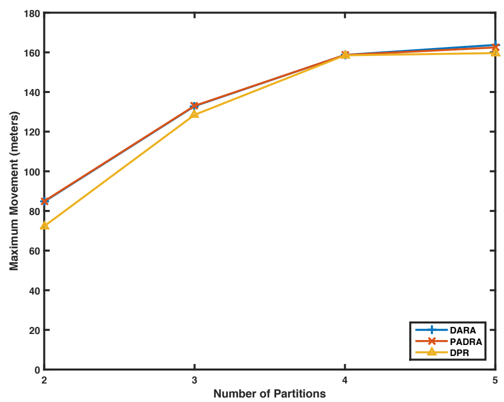


Fig. 9: Maximum movement distance with varying number of partitions.

existing approach to designate alternative spots as movement targets based on the set of upstream node locations collected before failures. This not only avoids positioning nodes to locations where the failures occurred earlier, but also reduces the movement cost as the experiments reveal.

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