Abstract—Due to low cost devices used in wireless sensor networks (WSNs), their applications in harsh surroundings, i.e. combat field reconnaissance, border protection, space exploration, etc. have become very common in the recent years. Due to unhealthy environments in which the network has to be operated sometimes result in large scale damage of the backbone nodes that causes the network to split into multiple disjoint segments. Placement of healthy relay nodes (RNs) as recovery nodes is the only way to connect the partitioned network, but the higher cost of RNs then becomes an addressable issue of their placement. With this motivation, we have suggested a new solution based on spiral format of Fermat points towards the centre of deployment called Restore Relay Lost Connectivity using CenTroiD (RRLC-CTD) for RNs' placements. The simulation results confirm the effectiveness of our proposed approach.

Keywords—Connectivity Restoration, Nodes Failure, Relay Node Placements, Spider Web-1C.

I. INTRODUCTION

The role of wireless sensor networks (WSNs) has become really useful in the real life in the recent years. The applications such as combat field reconnaissance, border protection, space exploration, etc. operate in the harshest environments, where sensor nodes reduce the danger of the human life [1, 2]. Since a sensor node is typically constrained in its energy, computational and communication resources, a large set of sensors is involved to ensure area coverage and increase the fidelity of the collected data. Due to small form factor and limited on board energy supply, a sensor is very susceptible to the failure. Due to hostile environments in which the network operates result in large scale damage of the nodes that causes network partitioning and converts into disjoint segments as shown in Fig. 1. For e.g., some sensors may be buried under snow or sand after the storm or in the field of battle, a component of the deployment area may be assaulted by the explosives and, thus a set of sensor nodes in the neighborhood would be ruined. Thus, repairing of large scale partitioned WSN is the latest hot research topic in the recent years. Deploying the RNs in the disconnected network is the solitary path to tie the large scale damaged network. RN is a more up to node with significantly more energy reserve and longer communication range than sensor nodes. Although RNs can, in principle, be equipped with sensor circuitry; mainly perform data aggregation and forwarding. Unlike sensor nodes, a RN may be mobile and has some navigation capabilities. The RNs is favored in the retrieval process, because these are easily to accurately place relative to the sensor nodes, and their communication range is even larger, which facilitates and expedites the connectivity restoration among the disjoint segments effectively and efficiently. Intuitively, RNs are more expensive and thus, minimum number of RNs should to be used for the recovery of the partitioned network. The minimum number of RNs can be found out using Steiner Minimum Tree (SMT), but it is shown to be NP-hard problem [3]. Therefore, some good heuristics are to be required to find the minimum number of deployed RNs in the partitioned network.

Two major RNs placement heuristics are published in the recent years. In the first approach, the authors proposed bio-inspired heuristic and use a spider web like RNs placement technique known as Spider Web-1C approach [3] with the
segments situated at the perimeter of the network. The idea is to form the stronger connectivity, achieve better sensor coverage and enables balanced distribution of traffic load on the employed relays as well. One of the primary advantages of the Spider Web-1C approach that it plugs into the segmented network very efficiently and effectively, but the major issue is the big number of deployed RNs for the retrieval.

The second approach is based on SMT called ORC-SMT [4]. The idea is the use of SMT by considering three outer segments that are formed after applying the convex hull algorithm recursively in the cyclic fashion. The points thus obtained are then applied recursively to find more Steiner Minimum Point (SMP) for the RNs placements. The multiple points that come in the radio range of the node then become a single point for RN placement. In this manner, the process repeats itself till all the outer segments for which the run was made are not less than three. Then, RNs are placed on these points by applying Minimum Spanning Tree (MST) algorithm such as Kruskal or Prim algorithm. The main advantage of ORC-SMT that it connects various segments quickly and efficiently with a small number of RNs placements. In this research paper, we consider the similar type of problem, i.e. a large scale node failure with large number of partitions in the network. The distinction of our work as compared with previous proposed works is that in our proposed approach a large scale node’s failure issue is addressed and solved by using of spiral format of Fermat points, which is not as yet proposed in other resolutions. However, in [13], the authors have considered Fermat point in the data propagation to reduce data transmission distance among the nodes to enhance network lifetime.

The remainder of the paper is organized as follows: In Section II, related work is described. Section III gives the problem statement of our proposed approach. Section IV explains the various approaches for comparison and section V shows performance evaluation of our proposed approach through simulations and compares with traditional approaches to prove its effectiveness. In section VI, the article is concluded with future scope.

II. RELATED WORKS

Many advances have been proposed till last one year to endure a large scale node failure in WSNs. The authors of [1, 2] have given the comprehensive survey of the network partitioning recovery approaches based on different standards. All approaches are classified into two broad categories: a) Centralized approaches, and b) distributed or semi-distributed approaches. The classification is further divided into three different categories, i.e. proactive, reactive and hybrid approaches. For proactive schemes, many approaches have been pursued to tolerate node’s failure in the works. A similar method is applied for reactive and hybrid approaches. In all proposed approaches, controlled node mobility has been used to restore the partitioned network. For example, in [5], a robot called Packbot has been used to serve as a mobile RN. The use of robot enables the recovery of partitioned network, or break links. An algorithm is applied to determine the trajectory of moving robot in the network. A similar type of work is presented by Wang et al. [6]. The authors have used mobile RNs within 2-hop of the sink in the network to restore the partitioned network. Unlike [5], the idea is that RNs do not need to travel the long distance in the network. The use of Packbots and similar types of devices is inefficient due to unexpected delays in data delivery even multiple such devices are used in the network. The reason is the slow motion of devices to cover every individual best point in the network.

Wang et al. [7] exploited node controlled mobility in order to cover the coverage holes which are not covered by sensor nodes during their initial deployment. The idea behind this work is to identify some spare nodes from different parts of the network that can be relocated to coverage-hole places. Since moving a node for long distance can drain significant node power, a cascaded movement is proposed if the sufficient number of sensor nodes is available on the way.

Recently, some centralized/ semi-centralized approaches have been proposed to handle large scale failures in the network by using cascaded control mobility of the nodes. In [8], the recovery problem is formulated as an Integer Linear Program (ILP). The objective of the ILP based optimization model is to form a connected topology while minimizing the individual travelling distance of the nodes.

The author of [9] strives to restore connectivity by a Multi-Integer Linear Program (MILP) based on transportation network flow model. The idea is to restore the connectivity with minimum travelling distance of nodes with the assumption that every node should be able to go to all destinations i.e. reach to all other nodes when network connectivity restoration is to be required. Due to centralized in nature, this approach does not scale well.

Another approach is proposed by Sentruk et al. [10] to improve the scalability by reducing the number of candidate locations. A RN placement algorithm is used to find the set of locations which can guarantee the connectivity if RNs are to be deployed to these locations.

Vemulapalli et al. [11] described another distributed approach based on nodes’ knowledge of full path to sink. The pre-failure route information is used to determine the location of the failed nodes. The location of nodes is obtained when paths are established. Thus, upon partitioning, nodes can attempt to re-establish the path towards sink node by moving to the next hop location. However, many nodes do the same in the partition, recovery cost can be high. To limit the recovery cost, the recovery process elects only one node as a leader node based on its distance from the failed node or sink. When the leader node moves towards sink, a cascaded movement of nodes within the partition is also required in order to sustain intra-segment connectivity.

Another approach based on game theory is proposed by Senturk et al. [12] by assuming the complete knowledge of the location of partitions, number of partitions, and failed nodes. Each partition is used as a player in the game. The payoff function is based on nodes' degree and elects a partition
The elected representative \( P_{a} \) opts to maximize the payoff of its partition which motivates the partitions to move each other. Due to the centralized nature of this approach, each representative node must know the payoff function of the other partitions and eventually network reaches to Nash equilibrium when all partitions are connected with each other.

### III. SYSTEM MODEL AND PROBLEM STATEMENT

We assume a WSN in which a large number of sensor nodes are deployed throughout an area of interest and sink node is located in the middle of deployment. Without losing the generality, this assumption ensures that there is a balanced traffic load in the network. Due to the harsh environment of the application like in a battlefield, where sensor nodes could be destroyed by enemy explosives, thus causing a large scale node’s failure which leads to multiple disjoint partitions in the network. For e.g., Fig. 1 shows the partitioned WSN with 8 segments having sink node is in the middle of the network. Thus, RNs are used to connect this disjoint network.

Our problem can be defined as follows: “\( N \) sensor nodes that know their location using some localization algorithm are randomly deployed in an area of interest. Let us assume that \( j \) disconnected sub-networks are formed as a result of failure of a large scale nodes in the network. Each sub-network \( G_{i} \) has \( n_{i} \) sensor nodes where \( 0 < n_{i} < N \). Our goal is to implement an algorithm that will ensure the lost connectivity among the disconnected sub-networks \( G_{i} \) by using minimum number of RNs placements and thus, create a new connected network.”

### IV. COMPARISON WITH SIMILAR SOLUTIONS

The following approaches are used to compare with our proposed solution, i.e. RRLC-CTD:

#### A. Basic Deployment (BD):

It is a very basic approach in which the isolated segments apply the Graham Scan i.e. convex hull algorithm in the partitioned network. The outer segments then deploy the RNs along the borders of the convex hull in the circular fashion. Similarly, the inner segments deploy the RNs towards the nearest RN as shown in Fig. 2. It is assumed that all nodes know the complete topology of the network. The main issue of this proposed approach is the number of required RNs for the repairing of the disjoint network.

#### B. Centre Deployment with Convex Hull (CDCH):

In this approach, first we calculate the representative nodes like ORC-SMT. Then, all representative nodes apply the convex hull algorithm to find the outer segments. The obtained outer segments calculate the centre of mass (CoM). Further, each representative node of the outer segment deploys the RNs towards CoM. Moreover, the inner representative nodes deploy the RNs towards the nearest deployed nodes as shown in Fig. 3. The main advantage of CDCH is that it requires a small number of RNs placements as compared with the BD approach.

#### C. Spider Web-1C heuristic:

The key idea behind Spider Web-1C deployment strategy is to place the RNs inwardly of the damaged area to yield better network connectivity and coverage. To balance the inter-segment path length in terms of the number of hops, RNs are placed toward the estimated CoM of the segments. Basically, from each partition to the CoM, Spider Web-1C has gradually deployed nodes until all the partitions are connected efficiently. In this way, it not only increases the total coverage of the network, but also reduces the possible number of cut vertices in the network as well. Before placing of RNs, Spider Web-1C first needs to identify the outer segments in the area of interest. To do this, it randomly picks the representative nodes from each partition and runs a convex hull algorithm. The convex hull algorithm returns a subset of representative nodes that sit on the corners of a convex polygon. After finding the convex polygon, it determines the CoM of the polygon. RNs are then deployed along the line between a segment and the CoM. Obviously, the relays around the CoM will be in the communication range of each other, and the segments then become connected. Fig. 4 shows the pictorial representation how to connect the disjoint network by using Spider Web-1C heuristic approach.
D. Optimal Relay Node Placement Algorithm using Steiner Minimum Tree (SMT) on Convex Hull (ORC-SMT): ORC-SMT pursues greedy heuristic that has two main phases: (1) identify the Steiner points (SPs) at which RNs would be placed with the objective of minimizing the number of deployed RNs to connect the segments, and (2) deploy additional RNs in order to form a fully connected inter SPs topology considering the communication range \((P_i)\) of a RN. The first phase has further two main steps that are repeated until all the necessary SPs are calculated. In the first step, ORC finds the convex hull to identify the boundary segments. Then, the SPs that connect every three neighboring boundary segments are identified. These SPs, is called first tier SPs. For the unengaged segments, the convex-hull is again computed to identify boundary terminals (i.e. segments or first tier SPs) that are used in the second round and then the second tier SPs are found. The third tier SPs will be identified based on the second tier and so on. In other words, the two steps are repeated recursively for \(m\) rounds until the number of points considered for computing a convex hull is less than three or they form a complete graph in terms of communication range of a RN. ORC-SMT then switches to the second phase in which the identified SPs and segments are stitched together. Basically, every segment \(Seg_i\) identifies the closest SP and RNs get placed on the line from \(Seg_i\) to such SP. The same procedure applies for the first tier SP to connect them to the second tier and so on. As mentioned above, in the first phase, ORC operates in rounds. In the first round \((m = 0)\), ORC identifies a set of segments in the damaged area, which forms the smallest polygon that contains the other segments. Considering the segments as terminals, the convex hull of all segments is used to identify the boundary segments. The authors assume that there exist at least three non-collinear segments such that the convex hull \(ch\) found in the first round forms a closed polygon as seen in Fig. 5. To find a convex hull the authors use the Graham Scan algorithm. The main advantage of this approach is that it requires small number of RNs to connect the large damaged area.

![Fig. 5 Network partitioning recovery using ORC-SMT approach](image)

E. Restore Relay Lost Connectivity using Centroid (RRLC-CTD): This approach, unlike ORC-SMT, considers three segment groups as a triangle and finds the centroid (CoD) of triangle instead of calculating SMT that behaves like a Fermat point \(F_p\) of a triangle for angle less than 120 degree. The Fermat point is a point within a triangle at which the sum of the distances between a point and the three vertices of the triangle is minimized [13]. Our proposed approach exploits this mathematical property of \(F_p\) to place the RNs. Fig. 6 shows an example how to calculate \(F_p\). The point \(F_p\) denotes the Fermat point of \(\Delta xyz\). It can be defined as follows. First three equilateral triangles i.e. \(Ax, Ay, Az\) and \(Ay, Az, x')\) are drawn on each side of \(\Delta xyz\). These equilateral triangles are connected with three extended straight lines i.e. \(xx', yy', and zz'\). The common point of intersection of three straight lines is a Fermat point \(F_p\). Three angles \(\angle xF_py, \angle xF_pz\) and \(\angle yF_pz\) will be equal to 120 degrees such that the sum of the distances between \(F_p\) and vertices \(x, y, z\) is minimized. Our proposed approach RRLC-CTD adopts the algorithm proposed by Su et al. [13] to perform vector calculations which quickly converges to an approximate value of the \(F_p\) for the placement of RNs. We also check to see whether \(F_p\) exist inside the triangle or not. If it is the case, we use Weiszfeld algorithm proposed in [13] to identify the \(F_p\) locations. Otherwise, CoD of the triangle will be chosen as \(F_p\) for the convergence. In case multiple segments exist in the network as we have taken in our scenario, then the idea is to place the RNs on the chaining path of the multiple consecutive \(F_p\). Initially three random segments are chosen and calculate the first \(F_p\). Consequently, the given segments are sorted in clockwise direction from the first segment. To understand this, let us consider the scenario as shown in Fig. 7 where first \(F_p\) is computed by taking three segments at a time. Indeed, we get a chain of connected tree by combining the calculated \(F_p\). Thus, in the nutshell; the key idea is to deploy the RNs towards the CoD of the triangle instead of finding the SPs. Moreover, tons of algorithms are available in the literature to find the centroid of the triangle (in case triangle is not an equilateral triangle) like Napoleon point, Spieker Center and Nine-point Center etc. The Spieker Center is an easiest and simplest method to find the centroid of a triangle [14]. Furthermore, the main advantage of our proposed RRLC-CTD is that it requires a small number of RNs to connect disjoint network and can work for any number of disjoint segments. Fig. 8 shows the connected network using RRLC-CTD. The key idea is to deploy the RNs towards the CoD of the triangle instead of finding the SPs separately.

![Fig. 6 Example of calculation of \(F_p\) of three segments](image)
V. SIMULATIONS AND PERFORMANCE EVALUATION

The purpose of simulation experiments acts as a proof of concept for the designed protocol. Using simulations, it can be determined whether the designed protocol adheres to the design criteria and requirements. This section evaluates the performance of our proposed approach RRLC-CTD through simulation. The goal of simulation is also to observe that the proposed approach outperforms over other approaches like ORC-SMT, CDCH and Spider Web-1C. Our proposed approach is implemented and validated in C++ environment.

Table 1 shows the simulation parameters used in the simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Area</td>
<td>2000m X 2000m</td>
</tr>
<tr>
<td>Nodes</td>
<td>100-500</td>
</tr>
<tr>
<td>Radio Model</td>
<td>Path loss model</td>
</tr>
<tr>
<td>MAC Layer</td>
<td>IEEE 802.15.4</td>
</tr>
<tr>
<td>Communication Range (R)</td>
<td>50m-200m</td>
</tr>
<tr>
<td>Node Initial Energy (Ei)</td>
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</tr>
<tr>
<td>Total Number of Partitions</td>
<td>6-13</td>
</tr>
<tr>
<td>Channel Frequency</td>
<td>2.4GHz</td>
</tr>
<tr>
<td>Packet Size</td>
<td>512 bytes</td>
</tr>
<tr>
<td>Antenna Model</td>
<td>Omni-directional</td>
</tr>
<tr>
<td>Mobility Model</td>
<td>On demand mobility</td>
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<tr>
<td>Failure Model</td>
<td>Random</td>
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<tr>
<td>Data Transmission Rate</td>
<td>15 packets/sec</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>1000s</td>
</tr>
</tbody>
</table>

The following three parameters are considered in our experiments for simulation:

a) Number of segments (N2).
b) Communication range (r) of an RN.
c) Number of placed RNs.

In the simulation experiments, we have taken different topologies with the number of outer segments varies from 4 to 8 and inner segments varies from 2 to 5 i.e. total disjoint segments varies from 6 to 13 that are randomly located in an area of interest (i.e. 2000m x 2000m). While studying the impact of r on the performance, it is varied between 50m to 200m. The results of the individual experiments are averaged over 30 trials of different topologies. We have observed that with 95% confidence level, the simulation results stay within 5%-10% of the sample mean. We consider the number of placed RNs for evaluating the performance of our proposed approach and compare with the existing approaches.

Fig. 8 Partitioned recovery using RRLC-CTD

A. Number of placed RNs. This metric reports the total number of required RNs to restore the lost connectivity in the network. As aforementioned, RNs are usually more expensive than sensor nodes. Thus, this metric reflects the total cost of repairing the partitioned network. Figs. 9a, 9b show the number of required RNs while varying node radio range in the configuration. Therefore, it is clear from the simulation graphs that ORC-SMT performs better than our proposed approach RRLC-CTD only when the number of partitions is less than 5, however our proposed approach performs well for any number of partitions. Moreover, BD approach shows a large number of RNs placements for the repairing of partitioned network due to deployment of nodes along the border of the convex hull in the circular fashion. Furthermore, Spider Web-1C shows similar result like our proposed approach RRLC-CTD as the node radio range increases due to making of large size web structure for the placement of RNs towards CoM. The ORC-SMT fails when the number of outer segments is more than 5 as shown in Fig. 10 and Fig. 11. The reason is that in the random topologies, when number of outer segments becomes larger than 5, more than one of the angles of the Steiner triangle of SMT comes out to be greater than 120 degree (obviously some are less than 120 degree), therefore, the calculated SPs comes out to be on the segment itself. This questions the convergence ability of the ORC-SMT algorithm towards the centre for which the authors have claimed. The situation becomes more intensive as the number of segments grows and algorithm fails in the simulations as we observed in our experiments. In a nutshell, we can say that ORC-SMT behaves best when it serves with a small number of segments (i.e. less than 5), as we have verified in the simulation. Furthermore, The Spider Web-1C heuristics run almost parallel to the CDCH when the node radio range is smaller. This is because the web formed by Spider Web-1C would be much closer to the CoM as explained earlier, and lesser number of nodes is required for the repairing of the lost connectivity. The RRLC-CTD shows good results as compared with ORC-SMT, Spider Web-1C, CDCH and BD as the number of outer segments increases. The reason is the deployment of small number of
RNs towards CoD as explained earlier. Figs. 10-11 also confirm the effectiveness of our proposed approach.

VI. CONCLUSION AND FUTURE WORK

In this paper, we have proposed a novel solution based on spiral format of Fermat points called Restore Relay Lost Connectivity using CenTroiD (RRLC-CTD) for RNs’ placements in large scale nodes failure WSN. The main strength of our proposed approach is the use of small number of RNs placements and works for any number of disjoint segments as compared with the existing approaches. The simulation results confirm the goodness of our proposed approach over previously proposed approaches. In the future, our study can focus on simulation of our proposed approach RRLC-CTD to evaluate the actual network performance parameters like throughput, end-to-end delay, packets loss, delivery ratio, etc. with recovery process.

REFERENCES


Fig. 9 Number of relay nodes (a) vs. node radio range when outer segments are 4 and inner segments vary from 2-8, (b) vs. node radio range when outer segments are 5 and inner segments varies from 2-8

Fig. 10 Number of relay nodes vs. number of outer segments with node radio range 100m

Fig. 11 Number of relay nodes vs. number of outer segments with node radio range 200m