

## RESEARCH ARTICLE

# Optimized relay placement for wireless sensor networks federation in environmental applications

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## ABSTRACT

Advances in sensing and wireless communication technologies have enabled a wide spectrum of Outdoor Environment Monitoring applications. In such applications, several wireless sensor network sectors tend to collaborate to achieve more sophisticated missions that require the existence of a communication backbone connecting (federating) different sectors. Federating these sectors is an intricate task because of the huge distances between them and because of the harsh operational conditions. A natural choice in defeating these challenges is to have multiple relay nodes (RNs) that provide vast coverage and sustain the network connectivity in harsh environments. However, these RNs are expensive; thus, the least possible number of such devices should be deployed. Furthermore, because of the harsh operational conditions in Outdoor Environment Monitoring applications, fault tolerance becomes crucial, which imposes further challenges; RNs should be deployed in such a way that tolerates failures in some links or nodes. In this paper, we propose two optimized relay placement strategies with the objective of federating disjoint wireless sensor network sectors with the maximum connectivity under a cost constraint on the total number of RNs to be deployed. The performance of the proposed approach is validated and assessed through extensive simulations and comparisons assuming practical considerations in outdoor environments. Copyright © 2011 John Wiley & Sons, Ltd.

## KEYWORDS

wireless sensor network (WSN); connectivity; relay placement; grid deployment; environmental applications

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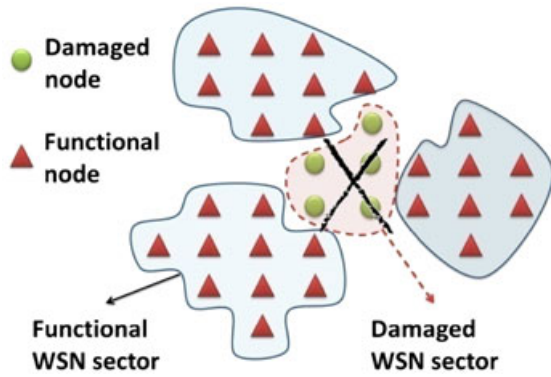
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## 1. INTRODUCTION

Advanced sensing technologies have enabled the wide use of wireless sensor networks (WSNs) in large-scale Outdoor Environment Monitoring (OEM) [1,2]. The most notable among these applications are those in harsh environments, such as forestry fires and flood detection applications [1,3]. WSNs in such applications are not only subject to severe damages that might partition the network into disjointed sectors as shown in Figure 1 but also can work together in detecting and preventing significant disasters that threaten the environment we are living in as shown in Figure 2 [4]. For their connection and interaction to be enabled, disjointed WSN sectors need to be (and to stay) reachable to each other in the presence of high probabilities of node failure (PNF) and probabilities

of link failure (PLF); thus, the connectivity has a significant impact on the effectiveness of federated WSNs in OEM.

In general, connectivity problems can be dealt with either by populating relay nodes (RNs) or by utilizing mobile nodes [5,6]. For example, in [5], the lowest number of relays is added to a disconnected static WSN, so that the network remains connected. In [6], mobile nodes are used to address  $k$ -connectivity requirements, where  $k$  is equal to 1 and 2. The idea is to identify the least RNs count that should be repositioned in order to reestablish a particular level of connectivity. However, connecting WSN sectors in OEM is more challenging because of expensive relays and the huge distances separating different sectors that might exceed twice the communication range of a RN. In this paper, we investigate an efficient



**Figure 1.** Vast damage partitioning a wireless sensor network (WSN) into disjointed sectors.

way for the RNs placement addressing the aforementioned challenges in OEM applications.

Such node placement problem has been shown in [7] to be NP-hard. Finding nonoptimal approximate solutions is also NP-hard in some cases. To address this complexity, we propose a two-phase optimized relay placement (ORP) approach. The first phase sets up a connected network backbone by using a reasonably small number of relays, which we call first-phase RNs (FPRNs). The first phase also finds a set of candidate locations for relays that are deployed in the second phase, which we call second-phase RNs (SPRNs). The second phase aims at deploying the available number of SPRNs in the candidate positions obtained from the first phase, in such a way that maximizes the WSN connectivity. The two schemes we present in this paper differ in the first phase. The first scheme is the grid-based ORP (GORP) in which all relays are assumed to be deployed on grid vertices as shown in Figure 3. The

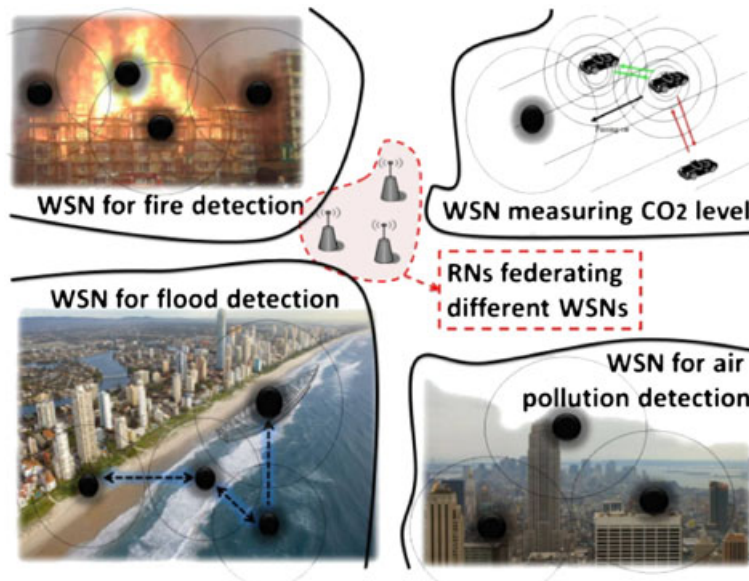
second scheme is a general ORP scheme where relays may be placed at any point in the field. The general ORP scheme utilizes some interesting geometrical structures to connect the disjointed sectors and to find candidate positions for the SPRNs. Once the candidate positions for SPRNs are found, selecting the locations of the SPRNs is carried out by formulating the problem as a relaxed semidefinite program (SDP) and solving it using a standard SDP solver.

Major contributions of this paper can be described as follows. We formulate a generic RN placement problem for maximizing connectivity with constraints on the relay count. We propose two optimized schemes for the deployment problem. Performance of the proposed schemes is evaluated and compared with other existing approaches in the literature.

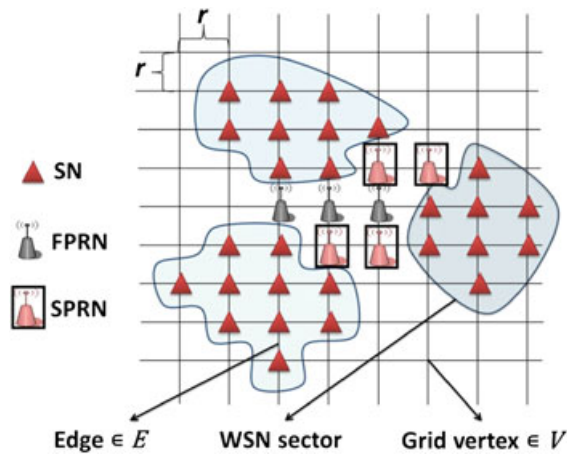
The remainder of this paper is organized as follows. In Section 2, related work is surveyed. In Section 3, our two-phase deployment strategy is described. The performance of the proposed strategy is evaluated and compared with other deployment strategies in Section 4. Section 5 concludes the paper.

## 2. RELATED WORK

In [8], Lloyd and Xue opted to deploy the fewest RNs such that each sensor is connected to at least one RN and that the inter-RN network is strongly linked by forming a minimum spanning tree (MST) and employing a geometric disk cover algorithm. Whereas in [9], the authors solved a Steiner tree problem to deploy the fewest RNs. Although the MST and the Steiner tree may guarantee the lowest cost by occupying the minimum number of relays, they tend to establish an inefficient WSN topology in terms of connectivity, as discussed in Section 4.



**Figure 2.** Wireless sensor networks (WSNs) collaborating in protecting our environment. RNs, relay nodes.



**Figure 3.** Grid-based network architecture. SN, sector node; FPRN, first-phase relay node; SPRN, second-phase relay node; WSN, wireless sensor node.

Unlike in [8] and in [9], Xu *et al.* in [10] studied a random RN deployment that considers the network connectivity for the longest WSN operational time. The authors proposed an efficient WSN deployment that maximizes the network lifetime when RNs communicate directly with the base station (BS). In this study, it was established that different energy consumption rates at different distances from the BS render uniform RN deployment a poor candidate for network lifetime extension. Alternatively, a weighted random deployment is proposed. In this random deployment, the density of RN deployment is increased as the distance to the BS increases; thus, distant RNs can split their traffic amongst themselves. This, in turn, extends the average RN lifetime while maintaining a connected WSN.

Furthermore, the approach presented in [11] aims at considering WSN connectivity in harsh environments. It counters faulty nodes causing connectivity problems by repositioning pre-identified spare relays from different parts of a two-dimensional grid model. The grid is divided into cells. Each cell has a head that advertises the available spare nodes in its cell or requests the spares for its cell. A quorum-based solution is proposed to detect the intersection of the requests within the grid. Once the spares are located, they are moved to a cell with failed nodes.

In [12], a distributed recovery algorithm is developed to address specific connectivity degree requirements. The idea is to identify the least set of nodes that should be repositioned in order to reestablish a particular level of connectivity. Nevertheless, these references (i.e., [10–12]) do not minimize the relay count, which may not be cost-effective in environmental monitoring applications. Consequently, considering both connectivity and relay count is the goal of [13] and [14]. In [13], Lee and Younis focused on designing an optimized approach for federating disjointed WSN segments (sectors) by populating the least number of relays. The deployment area is modeled as a grid with equal-sized cells. The optimization problem is

then mapped to selecting the fewest count of cells to populate RNs such that all sectors are connected. In an earlier work [14], we proposed an integer linear program optimization problem to determine sensor and relay positions on grid vertices that maximize the network lifetime while maintaining  $k$ -connectivity level.

Unlike [13] and [14], in this paper, ORP considers the network connectivity and the relay count in a different way. Bearing in mind that the disjointed sectors and the minimum number of RNs required to join them represents the WSN backbone, ORP aims at maximizing the backbone connectivity by placing a limited number of extra relays. This, in turn, renders more sustainable WSN topologies in harsh environments than those generated by [8] and [9], and unlike [10,11] and [12], ORP addresses the network connectivity problems without violating its cost-effectiveness.

### 3. OPTIMIZED WIRELESS SENSOR NETWORKS FEDERATION

In this section, we present our scheme for federating disconnected WSN sectors with the purpose of maximizing algebraic connectivity.

#### 3.1. Definitions and assumptions

A WSN sector is a set of connected relaying nodes that we call sector nodes (SNs). The exact location of each SN is assumed to be known in advance. Each WSN sector is represented using a virtual super single node (SSN). The  $x$ -coordinate ( $y$ -coordinate) of an SSN of a particular sector is the average of the maximum and the minimum  $x$ -coordinates ( $y$ -coordinates) of SNs in that sector.

An edge connecting two SNs from two different sectors is said to *connect* the two sectors. The distance between two sectors is the length of the shortest edge connecting them.

The transmission range of all relaying nodes is modeled as a circle with a radius of  $r$  m (i.e., identical transmission ranges).

Now, the problem can be defined as follows:

*Given a set of WSN sectors along with the locations of their SNs, determine the locations of  $Q$  RNs so that connectivity among WSN sectors is established and maximized.*

The network is modeled as a graph  $G = (V, E)$ , where  $V$  is the set of all RNs and SSNs and  $E$  is the set of edges connecting SSNs and RNs. An SSN shares an edge with an RN if the RN is within the transmission range of at least one SN belonging to the SSN's sector.

#### 3.2. Deployment strategy

The node placement problem addressed in this paper has an infinite search space; this is because each RN may be

placed at any point in a two-dimensional plane. We propose two schemes to restrict the search space to a finite number of locations and to make the optimization problem discrete. The first scheme is the grid deployment in which locations of RNs are limited to the vertices of a grid as shown in Figure 3. The second scheme constructs a set of edges connecting WSN sectors, and locations of new RNs are limited to a set of points along those edges. Those edges are derived from the Delaunay triangulation (DT) [15] and the Steiner tree [16] of the virtual SSNs.

### 3.2.1. Grid-based optimized relay placement.

This scheme assumes that SNs and RNs are placed on the vertices of a grid whose edges have a length equal to the transmission range of SNs and RNs (i.e.,  $r$  m). This grid architecture is shown in Figure 3. In this scheme, RNs are deployed in two phases.

#### (1) First-phase deployment

Relay nodes deployed in the first phase are called FPRNs. The purposes of the first phase are to deploy the minimum number of FPRNs to federate WSN sectors (i.e., SNs of all WSN sectors and FPRNs form a connected graph) and to construct a finite set of potential locations for the SPRNs. FPRN positions are determined using the MST of the SSNs. We find the MST of a complete graph whose vertices are the SSNs and the weight of each edge is the distance between the two sectors it connects. If two SSNs share an edge, we deploy the minimum number of FPRNs to connect them on the grid. If  $S_i$  and  $S_j$  are two WSN sectors, let  $Connect_G(S_i, S_j)$  denote the smallest cardinality set of grid vertices that form a path from an SN in  $S_i$  to an SN in  $S_j$ . If  $S_i$  and  $S_j$  share an edge in the MST,  $|Connect_G(S_i, S_j)|$  FPRNs are deployed to connect them. In other words, we deploy the minimum number of RNs on grid vertices to facilitate the communication between the two WSN sectors. Algorithm 1 presents a high-level description of the first phase.

#### (2) Second-phase deployment

In the second phase, we formulate and solve an optimized SDP with an objective function of maximizing the algebraic connectivity without exceeding a specific budget for the total number of SPRNs. The outcome of the first phase is a connected graph, which we denote by  $B$ , whose vertices are the SSNs and the FPRNs. It is a backbone that makes the whole network connected. Connectivity of  $B$  is measured by the second smallest eigenvalue  $\lambda_2$  of the Laplacian matrix  $L(B)$  [15]. The Laplacian matrix is a two-dimensional matrix that has  $-1$  in the element  $(i, j)$ , if there is a connection between nodes  $i$  and  $j$ , and 0 otherwise. It has the degree of node  $i$  in the element  $(i, i)$  (see Figure 4). Given  $L(B)$ , the algebraic connectivity of  $B$  is the second smallest eigenvalue  $\lambda_2$ . By increasing the value of

$\lambda_2$  in  $L(B)$ , we tend to increase the required number of nodes and communication links to disjoint (disconnect)  $B$ . This is because of the proportional relationship between the value of  $\lambda_2$  and the number of nodes/links that can cause network partitions as shown in Figure 4. A better connectivity improves the ability of the network to overcome significant topology changes caused by communication quality changes and node failures. This is achieved through deploying extra RNs, which are called the SPRNs, in the second phase of our deployment strategy. Deploying extra RNs means adding more nodes and edges to the graph  $B$ .

The objective in the second phase is to find the best positions for SPRNs, out of all grid vertices, such that  $\lambda_2$  of the resulting backbone graph is maximized with constraints on the total number of SPRNs to be deployed. Let  $N_{SPRN}$  denote the total number of SPRNs to be deployed. Assume we have  $n_c$  grid vertices as candidate positions for SPRNs. We want to choose the optimal  $N_{SPRN}$  grid vertices amongst these  $n_c$  vertices. We can then formulate this optimization problem, with reference to Table I, as

$$\begin{aligned} & \max \lambda_2(L(\alpha)) \\ & \text{s.t. } \sum_{i=1}^{n_c} \alpha_i = N_{SPRN}, \alpha_i \in \{0, 1\} \end{aligned} \quad (1)$$

where

$$L(\alpha) = L_i + \sum_{i=1}^{n_c} \alpha_i A_i A_i^T \quad (2)$$

However, an exhaustive search scheme is required to find the optimal solution, which is computationally expensive as it takes exponential time to find the best solution out of  $\binom{n_c}{N_{SPRN}}$  possible solutions; this is besides the cost of finding  $\lambda_2$  for each solution. Therefore, we need a computationally efficient means to find near-optimal solutions to this optimization problem. For that purpose, we reformulate the problem as a standard SDP optimization problem [15,16], which can be solved using any standard SDP solver.

However, we need to relax the Boolean constraint  $\alpha \in \{0, 1\}$  to be a linear constraint  $\alpha \in [0, 1]$  as follows:

$$\begin{aligned} & \max \lambda_2(L(\alpha)) \\ & \text{s.t. } \sum_{i=1}^{n_c} \alpha_i = N_{SPRN}, 0 \leq \alpha_i \leq 1 \end{aligned} \quad (3)$$

We remark that the optimal value of the relaxed problem in (3) gives an upper bound for the optimal value of the original optimization problem in (1). The optimal solution for (3) is obtained numerically using one of the standard SDP solvers (e.g., the SDPA-M software package). Finally, we use a heuristic to obtain a Boolean vector from the SDP optimal solution as a solution for the original problem in

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**Algorithm 1:** Grid-based deployment of FPRNs

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**Function Phase1** ( $S, N$ )

**Input:**

$S$ : The set of all SSNs.

$N$ : The set of all SNs (their locations and the sectors they belong to).

**Output:**

$F$ : A set of grid vertices where FPRNs are located so that all WSN sectors are connected.

$Gr$ : The set of all candidate positions for SPRNs.

**begin**

$F = \phi$ ;

$Gr$  = the set of all grid vertices;

Find MST( $S$ ) which is the MST of a complete graph whose vertices are  $S$  and the weight of each edge is the distance between the two sectors it connects;

**foreach** edge  $e$  in MST( $S$ ) **do**

$F = F \cup \text{Connect}_G(S_i, S_j)$ , where  $e$  is connecting the SSN of  $S_i$  and that of  $S_j$ ;

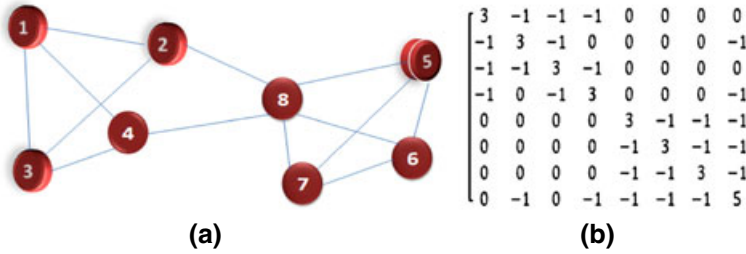
$Gr = Gr - \text{Connect}(S_i, S_j)$ ;

**end**

**Return** ( $F, Gr$ );

**End**

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**Figure 4.** (a) A graph with 8 nodes and 13 links. The graph's connectivity characteristics are the following: one node to disconnect (removal of node 8), two links to disconnect (removal of links connecting node 8 to nodes 2 and 4), and (b) Laplacian matrix for the graph in (a) and its corresponding  $\lambda_2$  is equal to 0.6277. As  $\lambda_2$  increases, the node/link count required to partition the network increases.

(1). In this article, we consider a simple heuristic, which is to set the largest  $N_{\text{SPRN}} \alpha'_i$ s to 1 and the rest to 0.

The optimization problem in (3) is convex with linear constraints [16]. Thereby, we introduce the following theorem.

**Theorem 1.** *The optimization problem in (3) is mathematically equivalent to the following SDP optimization problem:*

$$\begin{aligned} & \max S \\ & \text{s.t. } S \left( \mathbf{I}_{n \times n} - \frac{1}{n} \mathbf{1} \mathbf{1}^T \right) \preceq L(\alpha), \sum_{i=1}^{n_c} \alpha_i = N_{\text{SPRN}}, 0 \leq \alpha_i \leq 1 \end{aligned} \quad (4)$$

where  $S$  is a scalar variable and  $\preceq$  denotes the positive semidefiniteness (i.e., all eigenvalues of the matrix are greater than or equal to zero).

*Proof.* Let  $V \in \mathbf{R}^n$  be the corresponding eigenvector of  $\lambda_2(L(\alpha))$ . Thus,  $\mathbf{1}^T V = 0$  and  $\|V\| = 1$ . Since

$$L(\alpha)V = \lambda_2 V \quad (5)$$

hence,

$$V^T L(\alpha)V = \lambda_2 V^T V = \lambda_2 \quad (6)$$

$$\Rightarrow \lambda_2(L(\alpha)) = \inf_v \{V^T L(\alpha)V \mid \mathbf{1}^T V = 0 \text{ and } \|V\| = 1\} \quad (7)$$

**Table I.** Notations used in the placement problem.

Notation	Description
$\alpha_i$	A binary variable equals 1 when RN at vertex $i$ in the three-dimensional grid is allocated and 0 otherwise.
$A_i$	Incidence matrix that results from adding $RN_i$ in the three-dimensional grid; $A_i = [a_{i1}, a_{i2}, \dots, a_{im}]$ , where $a_{ij}$ is the vector that consists of $n$ elements that can take a value number of edges of either 0, 1, or $-1$ , and $m$ is the total that is produced by adding $RN_i$ . For example, if adding $RN_i$ will establish a connection between nodes 1 and 3, then the first element is set to 1 and the third element is set to $-1$ and all of remaining elements are set to 0s.
$n$	The total of FPRNs and BS.
$L_i$	Initial Laplacian matrix produced by the allocated FPRNs.
$I_{n \times m}$	Identity matrix of size $n$ by $n$ .

RN, relay node; FPRN, first-phase relay node; BS, base station.

Let

$$L'(\alpha) = L(\alpha) - S \left( I_{n \times m} - \frac{1}{n} \mathbf{1}\mathbf{1}^T \right) \quad (8)$$

Thus, for any  $V_{n \times 1}$ , where  $\mathbf{1}^T V = 0$  and  $\|V\| = 1$ , we obtain

$$\begin{aligned} V^T L'(\alpha) V &= V^T L(\alpha) V - S \left( V^T I_{n \times m} V - \frac{1}{n} (V^T \mathbf{1})(\mathbf{1}^T V) \right) \\ &= V^T L(\alpha) V - S \end{aligned} \quad (9)$$

Hence, for  $L'(\alpha)$  to be positive semidefinite, the maximum value of  $S$  should be

$$S = \inf_v \{ V^T L(\alpha) V | \mathbf{1}^T V = 0 \text{ and } \|V\| = 1 \} \quad (10)$$

From (7) and (11),

$$S = \lambda_2(L(\alpha)) \quad (11)$$

Therefore, maximizing  $S$  in (4) is equivalent to maximizing  $\lambda_2(L(\alpha))$  in (3) if the constraints are satisfied.  $\square$

For more illustration consider the following example.

**Example 1:** Assume we have up to two extra RNs (SPRNs) to maximize the connectivity of the backbone generated in the first phase. In this case,  $N_{\text{SPRN}} = 2$ . We start by calculating the initial Laplacian matrix  $L_i$  associated with the backbone to be used in (2). With reference to Table I, we set  $\alpha_i$  to 1 and calculate  $A_i$  for each vertex  $i$  on the grid. Now we solve the SDP in (4) for this specific example. As a result, candidate positions with the highest two values of  $\lambda_2$  will be chosen to allocate the available two SPRNs.

For a high-level description of the proposed second phase approach, consider Algorithm 2.

### 3.2.2. The general non-grid (optimized relay placement).

Although using grid vertices as candidate positions for SPRNs helps in discretizing the search space, it gives a relatively large number of candidate positions. This may affect both the time needed to solve an SDP and the quality of the obtained solution, especially in sparse networks.

In non-grid-based deployment, we try to construct a smaller set of candidate positions by selecting a set of points that have a geometrical property that makes them more likely to be used as a location for SPRNs. This scheme constructs a set of edges connecting WSN sectors, and the search space of SPRN locations is limited to a set of points along those edges. We use the DT and the Steiner tree of the virtual SSNs to construct these edges. These two geometrical structures possess several nice properties that make them good sources of potential SPRN locations. The DT, for example, is a supergraph of both the nearest neighbor graph and the Euclidean MST. The Steiner tree also has a nice property of connecting a set of points (i.e., the SSNs here) with a network of edges with a minimum length. These properties seem to be useful in federating WSN sectors; it is intuitive that SPRNs will be used to connect sectors that are close to each other; hence, the use of nearest neighbor graph edges. Meeting the limited budget of SPRNs requires using a minimum-length spanning edges, hence the use of Steiner tree and MST.

Grid-based and non-grid-based deployments differ in the first phase; that is, they differ in the way they build an initial connected graph and in the set of candidate positions for SPRNs. However, the second phase is the same for both deployment strategies; they both solve an SDP to deploy SPRNs.

**Algorithm 2:** SPRNs deployment**Function** SPRNs ( $B, Z$ )**Input:** $B$ : A connected graph of the SSNs and FPRNs. $Z = \{z_1, z_2, z_3, \dots, z_{|Z|}\}$ : The set of all candidate positions for SPRNs $N_{SPRN}$ : The total number of SPRNs.**Output:** $F$ : A set of points where SPRNs are located.**begin** $L_i =$  Laplacian matrix of  $B$ ;**for** ( $i = 1; i < |Z|; i++$ ) $A_i =$  coefficient matrix corresponding to the location  $z_i$ ;**end** $SP =$  Solution of SDP in (4);**Return**  $SP$ ;**End**

The non-grid-based deployment uses the Steiner tree to deploy FPRNs. A Steiner tree of all SSNs is constructed, and FPRNs are deployed along Steiner tree points and edges.

Before describing our non-grid-based deployment, we make some definitions.

If  $e$  is an edge,  $P(e, r)$  is the minimum cardinality set of points that partition  $e$  into smaller sectors of length, at most,  $r$ . For example if the Euclidean length of  $e$  is 8 and  $r = 2$ , then  $|P(e, r)| = 3$ . If  $S_i$  and  $S_j$  are two WSN sectors, let  $Connect(S_i, S_j) = P(e_{ij}, r)$ , where  $e_{ij}$  is the shortest edge connecting an SN in  $S_i$  to an SN in  $S_j$ .

In our non-grid-based deployment, we build the Steiner tree of all SSNs, and we consider Steiner tree points to be a WSN sector with a single SN. Then, if two sectors  $S_i$  and  $S_j$  share an edge in the Steiner tree,  $|Connect(S_i, S_j)|$  FPRNs are deployed to connect them. This makes a connected graph connecting all WSN sectors. We also use the DT to construct a set of candidate positions for SPRNs. Locations of SPRNs are limited to points along edges connecting SNs of WSN sectors that share a Delaunay edge. Algorithm 3 gives a high-level description of the first phase of the non-grid-based deployment.

## 4. PERFORMANCE EVALUATION

### 4.1. Simulation environment

Using MATLAB (The MathWorks Inc., Natick, MA, USA), we simulate randomly generated WSNs that have the graph topology proposed in the previous section and consist of varying number of partitioned sectors.<sup>†</sup> To solve the previously modeled SDP optimization problem, we used the SDPA-M MATLAB Package [17].

<sup>†</sup>Random in size (of SNs) and positions.

### 4.2. Performance metrics and parameters

To evaluate our ORP approach, we tracked the following performance metrics:

- Connectivity ( $\lambda_2$ ): This criterion reflects the federated network reliability under harsh environmental characteristics. It gives an indication for the designed WSN efficiency.
- Number of RNs ( $Q_{RN}$ ): This represents the cost-effectiveness of the deployment approach.

Four main parameters are used in the performance evaluation: (1) PNF, (2) PLF, (3) number of SSNs ( $Q_{SSN}$ ), and (4) deployment area. PNF is the probability of physical damage for the deployed node. PLF is the probability of communication link failure due to bad channel conditions and uniformly affects any of the network links. We chose these two parameters as they are key factors in reflecting harshness of the monitored site in terms of weak signal reception and physical node damage. As for the  $Q_{SSN}$ , it represents the degree of the network damage in case of partitioned WSNs and represents the problem complexity in case of federating multiple WSNs. And the deployment area reflects the scalability and applicability of the proposed deployment strategies in large-scale applications.

### 4.3. Baseline approaches

The performance of ORP is compared with the following three approaches: the first approach forms an MST on the basis of a single-phase RN placement [8], and we call it MST approach (MSTA); the second is for solving a Steiner tree problem with a minimum number of Steiner points [9], and we call it Steiner with minimum Steiner points (SwMSP); and the third approach is the GORP as described

**Algorithm 3:** Non-grid-based deployment of FPRNs**Function Phase1** ( $S, N$ )**Input:** $S$ : The set of all SSNs. $N$ : The set of all SNs (their locations and the sectors they belong to).**Output:** $F$ : A set of points where FPRNs are located so that all WSN sectors are connected. $Gr$ : The set of all candidate positions for SPRNs.**begin** $F = \phi$ ; $Gr = \phi$ ;Find  $ST(S)$  which is the Steiner Tree for the set of points in  $S$ ;**foreach** edge  $e$  in  $ST(S)$  **do** $F = F \cup \text{Connect}(S_i, S_j)$ , where  $e$  is connecting the SSN of  $S_i$  and that of  $S_j$ ;**end**Find  $DT(S)$  which is the DT of the points in  $S$ ;**foreach** edge  $e$  in  $DT(S)$  **do** $Gr = Gr \cup \text{Connect}(S_i, S_j)$ , where  $e$  is connecting the SSN of  $S_i$  and that of  $S_j$ ;**end****Return** ( $F, Gr$ );**End**

previously. The MSTA opts to establish an MST through RN placement. It first computes an MST for the given WSN partitions (SSNs) and then places RNs at the minimum number of grid vertices on the MST in accordance to Algorithm 1. The SwMSP approach pursues a Steiner tree model in which it places the least relay count to maintain connectivity such that the transmission range of each node is, at most,  $r$  (i.e., the maximum edge length in the Steiner tree is  $\leq r$ ). SwMSP first combines nodes that can directly reach each other into one connected group (CG). The algorithm then identifies for every three CGs a vertex  $x$  on the grid that is at most  $r$  (m) away. An RN is placed at  $x$ , and these three CGs are merged into one CG. These steps are repeated until no such  $x$  could be identified (i.e., no disconnected group). After that, each group is represented as a point  $y$ , and an MST is computed on the basis of the  $y$  points. Accordingly, the total number of populated relays using the SwMSP approach is

$$Q_{RN} = X + \left( \left\lceil \frac{1}{r} \right\rceil - 1 \right) \quad (12)$$

where  $X$  is the count of  $x$  points and  $(\lceil 1/r \rceil - 1)$  is the total relays populated on each edge of the computed MST (where  $L$  is the length of the edge). The total number of populated relays using MSTA and ORP equals  $Q_{FPRNs}$  and  $Q_{FPRNs} + Q_{SPRNs}$ , respectively.

In summary, all MSTA, SwMSP, and GORP deployment approaches are used as a baseline in this research because

of their efficiency in linking WSNs partitions while maintaining the minimum number of relays required in the network federation.

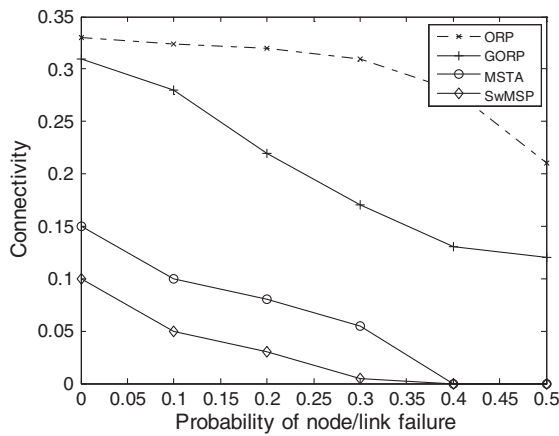
#### 4.4. Simulation model

The four deployment schemes, MSTA, SwMSP, GORP, and ORP, are executed on 500 randomly generated WSNs graph topologies in order to obtain statistically stable results. The average results hold confidence intervals of no more than 2% of the average values at a 95% confidence level. For each topology, we apply a random node/link failure on the basis of a prespecified PNF and PLF values, and performance metrics are computed accordingly. A linear congruential random number generator is used. Dimensions of the deployment space vary from 50 to 250 (km<sup>2</sup>). We assume a predefined fixed time schedule for traffic generation at the deployed WSN nodes. Relay positions are found by applying the four deployment strategies. To simplify the presentation of results, we assume all the transmission ranges of sensors and relays are equal to 100 m.

#### 4.5. Simulation results

For a fixed number of disjoint sectors (= 3) and deployment area (= 50 km<sup>2</sup>), Figure 5 compares ORP approach with MSTA, SwMSP, and GORP in terms of the federated WSN sectors connectivity. It shows how ORP and



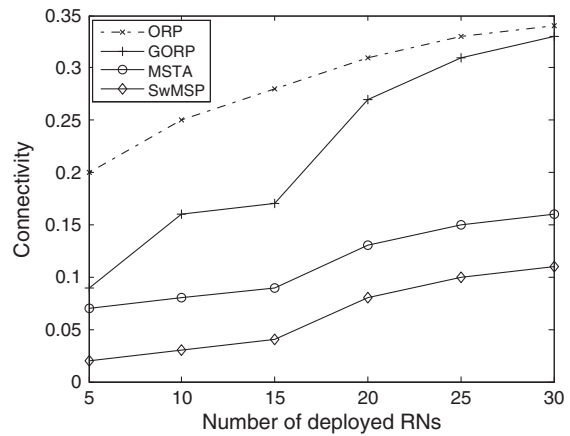


**Figure 5.** Connectivity versus the probabilities of node failure/ probabilities of link failure. ORP, optimized two-phase relay placement; GORP, grid-based optimized relay placement; MSTA, minimum spanning tree approach; SwMSP, Steiner with minimum Steiner points.

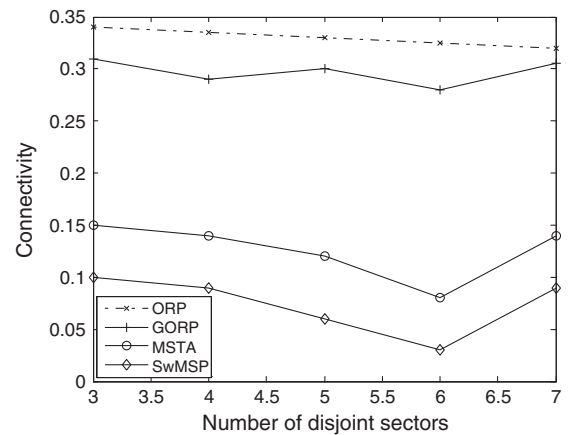
GORP outperform the other two approaches under different PNF/PLF values. Unlike the other two approaches, WSNs federated using the GORP approach stays connected even under  $PNF = PLF = 50\%$ . This is a very desirable behavior in harsh environments targeted by large-scale OEM applications. However, it shows a rapid decrement in the network connectivity while the PNF/PLF values increase, which is not the case with the ORP approach. Applying ORP provides a noticeable steady-state connectivity while node/link failure increases. This can be returned to the larger feasible search space that has been ignored while assuming the virtual grid. Moreover, connectivity levels achieved by the ORP outperform the levels achieved by the GORP because of considering the network connectivity while forming the network backbone in the first phase of the ORP approach.

Figure 6 depicts the effects of the RNs count on the interconnectivity of the federated WSN sectors. It shows the average  $\lambda_2$  (i.e., connectivity) for the federated WSNs by using different total numbers of RNs, where the number of disjoint sectors is fixed to 3 in order to see the effect of the RN placement, and  $PLF = PNF = 0.2$ . It is clear how an increment in the deployed RNs leads to a rapid increment in connectivity even in the presence of 20% nonfunctional nodes/links using the GORP approach. Moreover, using 15 RNs only, GORP achieves a connectivity value higher than the connectivity value achieved by the MSTA and SwMSP using 30 RNs, which indicates a greater savings in terms of the network cost. Nevertheless, more saving is reached while applying the ORP approach. This is also because of the consideration of connectivity since the early stages of the deployment (i.e., while constructing the backbone).

In Figure 7, GORP consistently outperforms MSTA and SwMSP with various disjoint sectors (i.e., different  $Q_{SSN}$



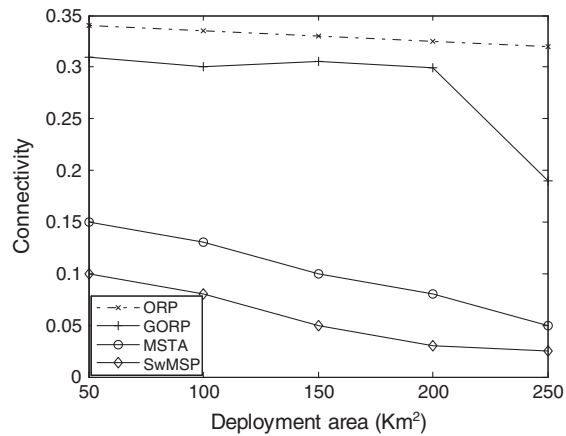
**Figure 6.** Connectivity versus the  $Q_{RN}$ . RN, relay node; ORP, optimized relay placement; GORP, grid-based optimized relay placement; MSTA, minimum spanning tree approach; SwMSP, Steiner with minimum Steiner points.



**Figure 7.** Connectivity versus the  $Q_{SSN}$ . RN, relay node; ORP, optimized relay placement; GORP, grid-based optimized relay placement; MSTA, minimum spanning tree approach; SwMSP, Steiner with minimum Steiner points.

values) and large PNF and PLF (= 40%). This is because of the placement of the SPRNs in ORP that aim always at maximizing the federated sectors connectivity regardless of their count. It is worth noting that as the  $Q_{SSN}$  becomes larger, the performance of MSTA and SwMSP becomes worse with such a large deployment area. However, ORP is not only providing better connectivity levels but also shows a steady-state output even while considering different sector counts. This has a great effect on the federated network scalability. We excuse the increase of connectivity when MSTA and SwMSP are used to federate more than six sectors by the dense distribution of sectors within a fixed deployment area (= 100 km<sup>2</sup>). For more elaboration upon the effects of the deployment area, consider Figure 8.

Again, in Figure 8, GORP constantly outperforms MSTA and SwMSP, with varying deployment areas and



**Figure 8.** Connectivity versus the deployment area. RN, relay node; ORP, optimized relay placement; GORP, grid-based optimized relay placement; MSTA, minimum spanning tree approach; SwMSP, Steiner with minimum Steiner points.

PNF and PLF values equal to 20%, as long as the deployment area is within a reasonable size ( $\leq 200 \text{ km}^2$ ). This gives more stability for the federated sectors in large-scale WSNs applications. Even with a very huge area ( $\geq 250 \text{ km}^2$ ), GORP is still much better than MSTA and SwMSP in terms of connectivity because of the deployed SPRNs. We remark that the sudden decrease in connectivity when we use GORP approach is due to lack of the SPRNs with respect to the huge targeted area. However, this does not happen while applying ORP, which again outperforms GORP, because of the well-planned FPRNs deployment.

## 5. CONCLUSION

In this paper, we look into the problem of deploying a fixed number of RNs to federate WSN sectors in OEM applications with the objective of maximizing network connectivity. An optimized two-phase approach is presented. The first phase utilizes some geometrical structures (namely MST, DT, and Steiner tree) to construct a backbone of RNs that connect all WSN sectors and finds a finite set of candidate locations for more RNs to be deployed in the second phase. The second phase deploys the remaining RNs in some of the candidate locations with the objective of maximizing connectivity of the network; this is carried out by solving a relaxed SDP.

The extensive simulation results, obtained under harsh operational conditions, demonstrate that the proposed two-phase strategy has the potential to provide tightly connected networks that are suitable for environmental applications. Moreover, deployment strategies presented in this paper can provide a tangible guide for network provisioning in large-scale environmental applications that require connecting vastly separated WSN sectors.

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