Optimized Relay Placement to Federate Wireless Sensor Networks in Environmental Applications

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***Abstract*—Federating Wireless Sensor Networks (WSNs) in Outdoor Environment Monitoring (OEM) becomes a necessity as advances in sensing technologies are achieved. Where several WSN sectors pursuing identical/different tasks intend to collaborate with each other in order to achieve more sophisticated and challenging missions, or intend to recover a significant damage in the network. Connecting (federating) these sectors is an intricate task due to the huge distances between the sectors, and the harsh operational conditions. A natural choice in defeating these challenges is to have multiple relay nodes that provide vast coverage areas and sustain the network connectivity in harsh environments. However, these relays are expensive and thus, the least number of such devices has to be populated. In this paper, we propose a grid-based deployment for relay nodes in which the relays are efficiently placed on the grid vertices to connect the disjointed WSN sectors. Towards this efficiency, we design an Optimized Relay Placement (ORP) approach that maximizes the disjointed sectors connectivity while maintaining cost constraints. The performance of the proposed approach is validated and assessed through extensive simulations and comparisons assuming practical considerations in outdoor environments.**

***Index Terms*—Wireless Sensor Network (WSN), Connectivity, Relay placement, Grid deployment, Environmental applications.**

I. 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][4]. WSNs in such applications are not only subject to severe damages that might partition the network into disjointed sectors as seen in Fig. 1, but also can work together in detecting and preventing significant disasters that threaten the environment we are living in (Fig. 2). To enable such linking and interaction, disjointed WSN sectors need to be (or stay) reachable to each other in the presence of high Probabilities of Node Failure (PNF) and Probabilities of Link Failure (PLF), and thus, the connectivity has a significant impact on the effectiveness of federated WSNs in OEM.

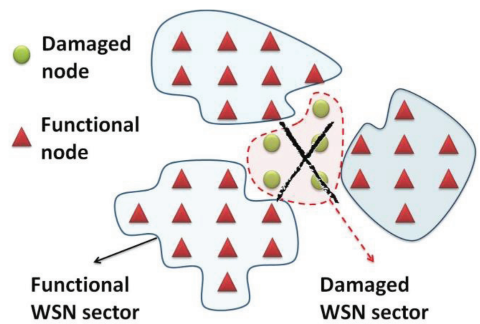

Fig. 1. Vast damage partitioning a WSN into disjointed sectors.

In general, connectivity problems can be repaired either by populating relay nodes, or by utilizing mobile nodes [6][8]. For example, in reference [6], the lowest number of relays is added to a disconnected static WSN, so that the network remains connected. While in [8], mobile nodes are used to address *k*-connectivity requirements, where *k* is equal to 1 and 2. The idea is to identify the least node count that should be repositioned in order to re-establish a particular level of connectivity.

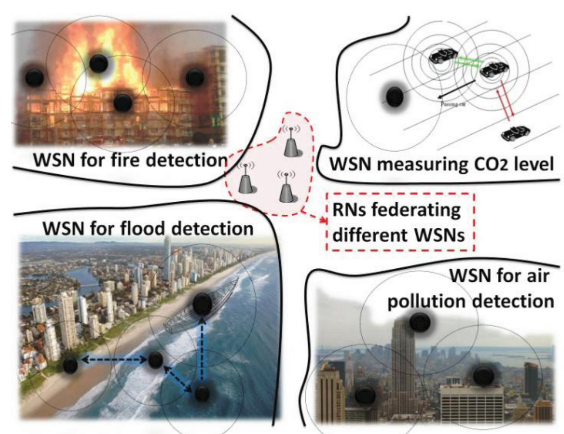

Fig. 2. WSNs collaborating in protecting our environment.

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However, connecting WSN sectors in OEM is more challenging due to expensive relays, and huge distances separating sectors which might exceed twice the communication range of a relay node. In this paper, we investigate an efficient way for the relay placement addressing the aforementioned challenges in OEM applications. Such node placement problem has been shown in [7] to be NP-hard. Finding non-optimal approximate solutions is also NP-hard in some cases. To address this complexity, we propose an Optimized two-phase Relay Placement (ORP) approach. The first phase is used to setup a connected network backbone using the minimum number of relays, called First Phase Relay Nodes (FPRNs), on a grid model (see Fig. 3). In the second phase, we aim at finding a set of a relatively small number of candidate positions, such that we optimize the Second Phase Relay Nodes (SPRNs) placement on these positions to achieve the maximum backbone connectivity within a limited cost budget.

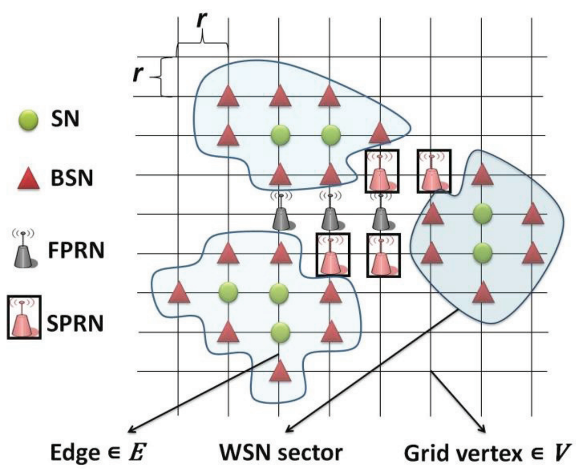

Fig. 3. Grid-based network architecture.

Major contributions of this paper are listed as follows. We introduce a generic relay node placement problem, which aims at maximizing connectivity with constraints on the relay count. We propose an optimized two-phase solution for the deployment problem, which considers a search space limited to the grid vertices, and harsh operational conditions characterized by the PNF and the PLF. Performance of the proposed two-phase solution is evaluated and compared to other efficient approaches in the literature.

The remainder of this paper is organized as follows. In Section II related work is outlined. In Section III our two-phase deployment strategy is described. The performance of the proposed strategy is evaluated and compared to other deployment strategies in Section IV. Conclusions and future work are given in Section V.

II. Related Work

In [11], Lloyd and Xue opt to deploy the fewest RNs such that each sensor is connected to at least one RN, and the inter-RN network is strongly linked by forming a Minimum Spanning Tree (MST), and employing a Geometric Disk Cover algorithm. While in [12], the authors solve 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 IV.

Unlike [11] and [12], Xu *et al.* [13] study 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 RNs deployment is increased as the distance to the BS increases, and 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 [14] 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 2D 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 [15], 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.,* [13], [14], and [15]) 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 [16] and [17]. In [16], Lee and Younis focus 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 relay nodes such that all sectors are connected. In an earlier work [17], we proposed an Integer Linear Program (ILP) optimization problem to determine sensors and relays positions on grid vertices that maximize the network lifetime while maintaining *k*-connectivity level.

Unlike [16] and [17], 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 aim 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 [11] and [12], and unlike [13], [14], and [15], ORP addresses the network connectivity problems without violating its cost-effectiveness.

III. Optimized WSNs Federation

A. Problem Definition

Given the pre-deployed WSNs sectors with pre-specified locations of their constructing Sector Nodes (SNs), determine the positions of the Relay Nodes (RNs) so that connectivity between the disjoint sectors is established and maximized while maintaining cost constraints.

B. Deployment Strategy

In this section we present our system model and deployment strategy.

1) Modeling

The relay node placement problem proposed in this paper has infinitely large search space and finding the optimal solution is very intricate. Therefore, we propose a grid model that limits the search space to a more manageable size.

Fig. 3 shows the network architecture assumed in this work, where each Sector Node (SN), which may be a sensor or a relay, is assumed to be on a specific grid vertex and the grid edge lengths are proportional to the identical nodes' transmission ranges ($=r$). RNs are assumed to be placed at one of the grid vertices; such that the Boundary Sector Nodes (BSNs)[1] are federated together using the minimum FPRNs, and the SPRNs are used to maximize the federated sectors' connectivity while maintaining the cost constraint (represented by the RNs count).

We model the WSN as a graph $G = (V, E)$, where $V = \{n_0, n_1, \dots, n_v\}$ is the set of v candidate grid vertices for the RNs, E is the set of bidirectional edges between the deployed nodes. There exists an edge between two nodes i and j, if there is a communication link between the corresponding two nodes i and j. We assume each WSN sector is a Super Single Node (SSN) of a communication range limited by the external communication range of the BSNs, as depicted in Fig. 4. Finally, we assume that the total available number of relay nodes to federate these SSNs is equal to Q_{RN}.

2) The Optimized Relay Placement (ORP) Approach

The ORP approach proposed in this paper depends on two main phases. The first phase constructs an Optimally Connected Sectors (OCS) in terms of the number of deployed FPRNs ($=Q_{FPRNs}$). OCS should form a connected graph that includes all SSNs and FPRNs, as shown in Fig. 3. In this phase, we determine the FPRNs positions on the grid by applying the MST as described in Algorithm 1. In the second phase, we formulate and solve an optimized Semi-Definite Program (SDP) with an objective function maximizing the OCS connectivity without exceeding a specific SPRNs count.

[1] Of different disjointed sector.

Algorithm 1: MST to construct the OCS

Function ConstructOCS (*IS*: Initial Set of nodes to construct OCS)
Input:
A set *IS* of the SSNs coordinates
Output:
A set *OCS* of the SSNs, and FPRNs coordinates forming the network Backbone
begin
OCS = set of closest two nodes in *IS*;
OCS = *OCS* ∪ minimum RNs needed to connect them on the grid;
IS = *IS* – *OCS;*
N_d = number of remaining *IS* nodes which are not in *OCS*;
i = 0;
foreach remaining node n_i in *IS* **do**
Calculate M_i: Coordinates of minimum number of RNs required to connect n_i with the closest node in *OCS*.
i = i + 1;
end
M **=** { M_i }
while $N_d > 0$ **do**
SM **=** Smallest M_i;
OCS = *OCS* ∪ *SM* ∪ n_i;
IS = *IS* - n_i;
M **=** ***M*** **-** M_i;
$N_d = N_d - 1$;
end
end

Connectivity of the Backbone *OCS* generated in this phase of the deployment is measured by considering *OCS* as a connected graph which has a Laplacian matrix *L(OCS)* [9].The Laplacian matrix is a two dimensional matrix that has -1 at the element (*i*,*j*), if there is a connection between nodes *i* and *j*. It has an integer positive number at the element (*i*,*i*) that represent the number of edges connected to the node *i*.

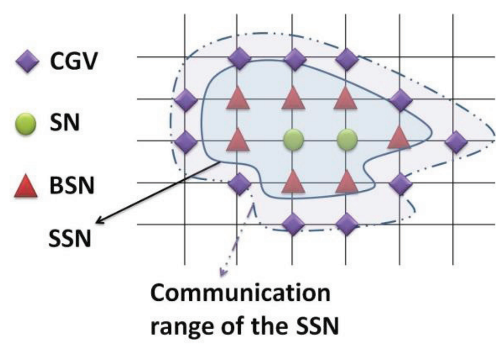

Fig. 4. Communication range of a SSN, where CGV is a Covered Grid Vertex.

Given *L*(*OCS*), the backbone connectivity (or algebraic connectivity) is mathematically measured by computing the second smallest eigenvalue λ_2. Where λ_2 indicates the minimum number of nodes and links whose removal would disconnect the graph *OCS*. By maximizing λ_2 of *L*(*OCS*), we maximize the required number of nodes and communication links to disjoint (disconnect) paths in the network backbone. This is because of the proportional relationship between the value of λ_2 and the number of nodes/links which can cause network partitions [9]. In order to *maximize* the backbone connectivity λ_2, extra relay nodes (SPRNs) are placed in the second phase of the ORP approach.

In order to maximize λ_2 in the second phase, assume we have n_c grid vertices as candidate positions for the SPRNs. We want to choose the optimum Q_{SPRN} relay nodes positions amongst these n_c positions with respect to connectivity; where Q_{SPRN} is constrained by a cost budget. We can then formulate this optimization problem as

$$\max \lambda_2\big(L(OCS)\big) \tag{1}$$
$$s.t. \quad \sum_{i=1}^{n_c} \alpha_i = Q_{SPRN},\ \alpha_i \in \{0,1\},$$
$$L(OCS) = L_i + \sum_{i=1}^{n_c} \alpha_i A_i\, A_i^T$$

where α_i is a binary variable equals to 1 when a RN is allocated at vertex i and 0 otherwise, A_i is the incidence matrix that results by adding the i^{th} RN, and L_i is the initial Laplacian matrix produced by the allocated SSNs and FPRNs. To efficiently solve the optimization problem in (1), we reformulate it as a standard Semi-Definite Program (SDP) optimization problem [9], which can be solved using any standard SDP solver, as described in (2).

$$\max S \tag{2}$$
$$s.t. \quad S\left(\boldsymbol{I_{nxn}} - \frac{1}{n}\boldsymbol{1}\boldsymbol{1^T}\right) \preccurlyeq L(OCS),$$
$$L(OCS) = L_i + \sum_{i=1}^{n_c} \alpha_i A_i\, A_i^T,$$
$$\sum_{i=1}^{n_c} \alpha_i = Q_{SPRN},\ 0 \le \alpha_i \le 1,$$

Where S is a scalar variable, I_{nxn} is an identity matrix of size n by n, and $\preccurlyeq$ denotes the positive semi-definiteness (i.e. all eigenvalues of the matrix are greater than or equal to zero). In the following, Algorithm 2 summarizes the second phase deployment where the search space is limited to n_c positions on the grid vertices.

Algorithm 2: SPRNs deployment

```
Function SPRNs (OCS:  Backbone constructed by SSNs & FPRNs)
Input:
        A set OCS of the SSNs and FPRNs nodes' coordinates.
Output:
        A set SP of the SPRNs coordinates maximizing connectivity of
        OCS with cost constraints
begin
        Li = Laplacian matrix of OCS
        for (i = 1; i < nc; i++)
            Ai = coefficient matrix corresponding to vertex i on the grid
        end
        SP = Solution of SDP in (2).
End
```

IV. Performance Evaluation

A. Simulation Environment

Using MATLAB, we simulate randomly generated WSNs which have the graph topology proposed in the previous section and consist of varying number of partitioned sectors[2]. To solve the previously modeled SDP optimization problem, we used the SDPA-M MATLAB Package [10].

[2] Random in size (of SNs) and positions.

B. Performance Metrics & Parameters

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

- Connectivity (λ_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)* Probability of Node Failure (PNF), *2)* Probability of Link Failure (PLF), *3)* Number of SSNs (Q_{SSN}), and *4)* the Deployment Area (DA). 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 DA reflects the scalability and applicability of the proposed deployment strategies in large-scale applications.

C. Baseline Approaches

The performance of ORP is compared to the following two approaches: the first algorithm forms a minimum spanning tree based on a single-phase relay node placement [11], and we call it Minimum Spanning Tree Approach (MSTA); the second is for solving a Steiner tree problem with minimum number of Steiner points [12], and we call it Steiner with Minimum Steiner Points (SwMSP). 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 relays 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 $\le r$). 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. A 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 based on the y points. Accordingly, the total number of populated relays using the SwMSP approach is

$$Q_{RN} = X + \left(\left\lceil \frac{L}{r} \right\rceil - 1\right) \tag{3}$$

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

In summary, both MSTA and SwMSP deployment strategies are used as a baseline in this research due to their efficiency in linking WSNs partitions while maintaining the minimum number of relay nodes required in the network federation.

D. Simulation Model

The three deployment schemes: MSTA, SwMSP, and ORP, are executed on 500 randomly generated WSNs graph topologies in order to get 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 based on a pre-specified 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^2). We assume a predefined fixed time schedule for traffic generation at the deployed WSN nodes. Relay positions are found by applying the three deployment strategies. To simplify the presentation of results, all the transmission ranges of sensors and relays are assumed equal to 100 (m).

E. Simulation Results

For a fixed number of disjoint sectors (=3) and deployment area (=50 km^2), Fig. 5 compares ORP approach with MSTA and SwMSP in terms of the federated WSN sectors connectivity. It shows how ORP outperforms the other approaches under different PNF/PLF values. Unlike the other approaches, WSNs federated by using the ORP approach stays connected even under PNF=PLF=50%. This is a very desirable behavior in harsh environments targeted by large-scale OEM applications.

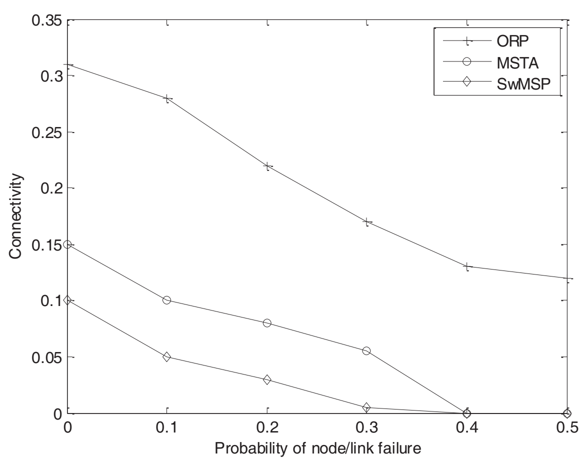

Fig. 5. Connectivity vs. the PNF/PLF.

Fig. 6 draws the effects of the RNs count on the inter-connectivity of the federated WSN sectors. It shows the average λ_2 (i.e., connectivity) for the federated WSNs using different total numbers of RNs, where the number of disjoint sectors is fixed to 3 in order to see the effect of the relay node 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 ORP approach. Moreover, using 15 RNs only, ORP 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.

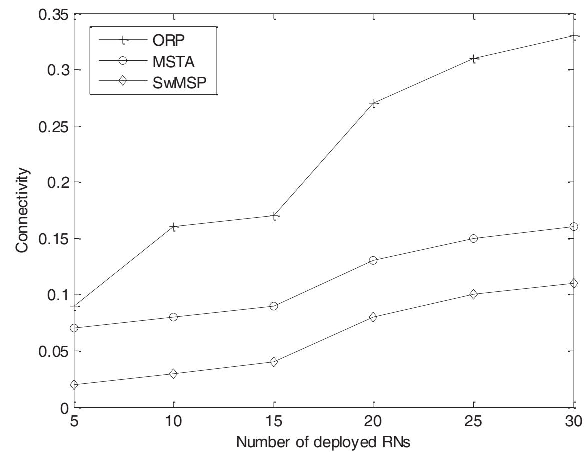

Fig. 6. Connectivity vs. the Q_{RN}.

In Fig. 7, ORP consistently outperforms MSTA and SwMSP with various disjoint sectors (i.e., different Q_{SSN} values) and large PNF and PLF (=40%). This is because of the placement of the SPRNs in ORP which aim always at maximizing the federated sectors connectivity regardless of their count. It is worth noting that as the Q_{SSN} gets larger, the performance of MSTA and SwMSP becomes worse with such a large deployment area. We justify the increase of connectivity when MSTA and SwMSP are used to federate more than 5 sectors by the dense distribution of sectors within a fixed deployment area (=100 km^2). For more elaboration upon the effects of the deployment area consider Fig. 8.

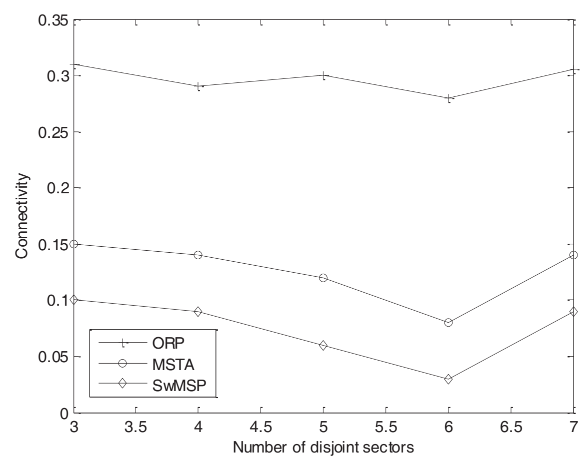

Fig. 7. Connectivity vs. the Q_{SSN}.

Again, in Fig. 8, ORP constantly outperforms MSTA and SwMSP, with varying deployment areas and PNF and PLF values equal to 20%, as long as the deployment area is within a reasonable size (≤200 Km^2). This gives more stability for the federated sectors in large-scale WSNs applications. Even with a very huge areas (≥250 km^2), ORP 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 ORP approach is due to lack of the SPRNs with respect to the huge targeted area.

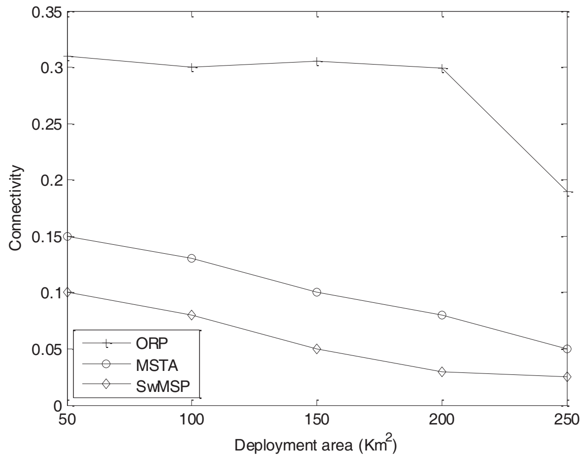

Fig. 8. Connectivity vs. the DA.

V. CONCLUSION

In this paper, we explored the problem of federating grid-based WSNs in OEM applications, aiming at maximizing network connectivity with constraints on the available cost-budget. An optimized two-phase approach was presented using minimum spanning tree and semi-definite programming. For practical solutions, varying probabilities of node and/or link failures were considered, in addition to limiting the huge search space of the targeted deployment problem. The extensive simulation results, obtained under harsh operational conditions, indicated that the proposed two-phase strategy can provide tightly-connected networks and practically-applied federation scheme in environmental applications. Moreover, deployment strategy and results presented in this paper can provide a tangible guide for network provisioning in large-scale environmental applications which require linking between vastly separated WSN sectors. In addition, they are applicable for different grid shapes and environment characteristics (e.g., various probabilities of node/link failures).

Future work would investigate optimal deployment problem in further environment monitoring scenarios, where a subset of the relay nodes may have the mobility feature to repair connectivity and prolong the network lifetime.

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