Towards Augmented Connectivity in Federated Wireless Sensor Networks

Fadi M. Al-Turjman[1], Waleed M. Alsalih[2], and Hossam S. Hassanein[1,2]
[1]School of Computing
Queen's University, Kingston, Ontario, Canada, K7L 3N6
{fadi, hossam}@cs.queensu.ca
[2]Department of Computer Science,
King Saud University, Riyadh 11543, Saudi Arabia, P.O. Box 51178.
wsalih@ksu.edu.sa

***Abstract*—Advances in sensing and wireless communication technologies have enabled a wide spectrum of Outdoor Wireless Sensor Network (OWSN) applications. Some applications require the existence of a communication backbone federating different OWSN sectors, in order to collaborate in achieving more sophisticated missions. Federating (connecting) these sectors is an intricate task due to the huge distances between them, and due to the harsh operational conditions. A natural choice in this case is to have multiple Relay Nodes (RNs) that provide vast coverage and sustain the network connectivity in harsh environments. However, these RNs are not cheap and, thus, a constraint on their count holds. That being said and considering the harsh conditions in outdoor environments, placement of the RNs becomes crucial and has to be in a way that tolerates failures in communication links and deployed nodes. In this paper, we propose a novel approach in optimizing the RNs placement, called ST-DT approach, with the objective of federating different OWSNs with the maximum connectivity under a cost constraint on the RNs count to be deployed. The performance of the proposed approach is validated and assessed through extensive simulations and comparisons assuming practical considerations in large-scale outdoor environments.**

Keywords- Outdoor Wireless Sensor Network (OWSN), Federated OWSN, Cost, Harsh environments, Relays placement.

I. INTRODUCTION

ADVANCED sensing technologies have enabled the wide use of Wireless Sensor Networks (WSNs) in large-scale outdoor environments [1][2]. The most notable among these applications are those in harsh environments, such as forestry fires and flood detection applications [3][4]. WSNs in such applications are not only subject to severe damages that might partition the network into disjointed sectors, but also can work together in detecting and preventing significant disasters that threaten the environment we are living in [5]. To enable their federation (connection and interaction), different 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). Federation in WSNs can be achieved either by populating relay nodes [6], or by utilizing mobile nodes [2]. For example, in reference [6], Minimum Spanning Tree (MST) algorithm is applied on a 2D virtual grid to add the least number of relays, so that the disjointed WSNs can be federated together. In [2], mobile data collectors are used to federate the disjointed sectors while maintaining energy consumption constraints. However, federating WSNs in outdoor environments is more challenging due to expensive relays and the huge distances separating different WSNs which might exceed twice the communication range of a relay node. In this paper, we investigate a relay-based WSNs federation approach addressing the aforementioned challenges in large-scale applications. Such WSN federation problem has been shown to be NP-hard [6]. Finding non-optimal approximate solutions is also NP-hard in several cases. To address this complexity, we propose a Steiner Tree and Delaunay Triangulation (ST-DT)-based approach. This approach is applied in two phases. The first phase sets up a connected network backbone using a reasonably small number of relays, called First Phase Relay Nodes (FPRNs), while considering the most suitable backbone topology shape in harsh outdoor environments. The first phase uses minimum Steiner tree points for FPRNs positioning and using Delaunay Triangulations it finds a set of candidate locations for other extra relays, which are deployed in the second phase and called Second Phase Relay Nodes (SPRNs). The second phase aims at deploying the available number of SPRNs in the candidate positions obtained from the first phase, such that the WSN connectivity is maximized.

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

The remainder of this paper is organized as follows. In Section II, related work is outlined. System models and problem definition are presented in Section III. In Section IV, the deployment strategy is described. The performance of the proposed scheme is evaluated and compared in Section V. Conclusions are outlined in Section VI.

II. Related Work

In [8], Lloyd and Xue opt to deploy the fewest RNs such that each sensor in the WSN 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. Although the MST may guarantee the lowest cost by occupying the minimum number of relays, it tends to establish an inefficient WSN topology in terms of connectivity. While in [9], the authors solve a Steiner tree problem to deploy the fewest RNs while maintaining a better topology shape in terms of connectivity.

The approach presented in [10] 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. In [11], 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], and [11]) do not minimize the relay count, which may not be cost effective in large-scale applications. Consequently, considering both connectivity and relay count is the goal of [12] and [13]. In [12], Lee and Younis focus on designing an optimized approach that achieve federated WSN by populating the least number of relays. They divide deployment area into equal-sized cells. The optimization problem is then mapped to select the fewest count of cells to populate relay nodes such that all sectors are connected. Similarly, in an earlier work [13], we proposed an Integer Linear Program (ILP) to optimize sensors and relays positions on virtual grid vertices that maximize the network lifetime while maintaining *k*-connectivity level.

Unlike [12] and [13], in this paper, the non-grid-based ST-DT approach 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, ST-DT aims at generating a better topology structure in the WSN backbone and then maximizing its connectivity by placing a limited number of extra relays. In this way we achieve more sustainable WSN federation than those proposed in [8] and [9], and unlike [10], and [11], ST-DT addresses the network connectivity problems without violating its cost-effectiveness.

III. System Models & Problem Statement

In this section, we explain the system models we used in our approach in terms of networking, communication and lifetime. These models were specifically configured to address aspects related to WSN federation in 3D applications.

A. Network Model & Problem Statement

In this work we assume different disjointed WSN sectors to be federated (connected) into a single global network. Each sector is composed of a set of connected sensing nodes which 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 center of mass 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. Accordingly, the network is modeled as a graph $G=(V,E)$, where V is the set of all RNs and SSNs. E is the set of edges connecting SSNs and RNs. A SSN shares an edge with a RN if the RN is within the transmission range (which is based on a probabilistic communication model as described in the following section for more realistic assumptions) of at least one SN belonging to the SSN's sector. Now, the problem can be defined as follows:

Definition 1. *(Problem Statement): Given a set of WSN sectors along with the locations of their SNs, determine the locations of Q Relaying Nodes (RNs) so that connectivity among WSN sectors is established and maximized.*

B. Communication Model

In practice, the signal level at distance d from a transmitter varies depending on the surrounding 3D outdoor environment. This variation causes an irregular communication range and is captured through the so called log-normal shadowing model [14]. According to this model, the signal level at distance d from a transmitter follows a log-normal distribution centered around the average power value at that point. This can be written as

$$P_r = K_0 - 10\gamma \log(d) - \mu d \tag{1}$$

where d is the Euclidian distance between the transmitter and receiver, γ is the path loss exponent calculated based on experimental data, μ is a normally distributed random variable with zero mean and variance σ^2, i.e. $\mu \sim \mathcal{N}(0, \sigma^2)$, and K_0 is a constant calculated based on the mean heights of the transmitter and receiver. Using the model in (1), the probability of successful a communication between two wireless devices separated with a distance d can be calculated as follows. Assume $P_{\min}$ be the minimum acceptable signal level for successful communication between a transmitter and a receiver separated by the distance d. The probability of successful communication is $P_c = \Pr[P_r(d) \geq P_{\min}]$. Thus, the ability to communicate between two wireless devices in this work is defined as follows:

Definition 2. *(Probabilistic Connectivity): Two nodes separated by a distance d are probabilistically connected with a threshold parameter* τ *(*$0 \leq \tau \leq 1$*), if* $P_c \geq \tau$.

IV. Deployment Strategy

The relay placement problem addressed in this paper has an infinite search space; this is because each RN may be placed at any point in the 3D space. We propose a novel scheme to restrict the search space to a finite number of locations and to make the optimization of relays positions discrete. The 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 [15] and the Steiner Tree [16] of the virtual SSNs, and thus, called Steiner Tree and Delaunay Triangulation (ST-DT) approach. This approach is applied in two phases. The first phase is used to place a minimum number of relay nodes, called First Phase Relay Nodes (FPRNs) to establish a connected network. The second phase is used to choose the optimal positions of extra relay nodes, called Second Phase Relay Nodes (SPRNs), required to maximize the network connectivity with constraints on cost.

A. First Phase of ST-DT approach

This phase constructs a set of edges using the FPRNs to connect disjoint WSN sectors, and thus, the search space of SPRN locations is limited to a set of points along these edges. We use the Delaunay Triangulation (DT) and the Steiner tree (ST) of the virtual SSNs in conjunction with FPRNs to construct these edges. These two geometrical structures, the DT and the ST, possess several attractive properties that make them good sources of potential RNs locations; viz., satisfying the limited count of RNs and connecting the closest partitions first. For more explanation on this phase, we assume the following. 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*, where *r* is the communication range. 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 (ST-DT)-based deployment, we build the Steiner tree of all SSNs sectors, 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 1 gives a high level description of the first phase of the ST-DT deployment.

Algorithm 1: Deployment of FPRNs

```
Function First_Phase(S, N)
Input:
        A set S of all SSNs.
        A set N of all SNs (their locations and the sectors they belong to).
Output:
        A set F of points where FPRNs are located so that all WSN sectors
        are connected.
        A set Gr of all candidate positions for SPRNs.
begin
        F = ϕ;
        Gr =ϕ;
        Find ST(S) which is the Steiner Tree for the set of points in S;
foreach  edge e in ST(S) do
                F = F∪Connect (Si,Sj), where e is connecting the SSN of Si
                and that of Sj;
        end
        Find DT(S) which is the DT of the points in S;
         foreach  edge e in DT(S) do
                Gr = Gr∪Connect (Si,Sj), where e is connecting the SSN of
                Si and that of Sj;
        end
        Return (F, Gr);
End
```

B. Second Phase of ST-DT approach

Connectivity of the Backbone generated in the first phase of the deployment, which we call *B*, is measured by constructing its Laplacian matrix *L(B)* [17]. Given *L*(*B*), the backbone connectivity (or algebraic connectivity) is mathematically measured by computing the second smallest eigenvalue λ_2. By maximizing λ_2, 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 a network partitions [17]. In order to *maximize* the backbone connectivity λ_2, extra relays (SPRNs) are placed in the second phase of the ST-DT approach.

In order to maximize λ_2 in the second phase, assume we have n_c candidate positions generated by Steiner tree and Delaunay Triangulations in first phase of ST-DT approach 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. The cost budget is modeled by the RNs count. We can then formulate this optimization problem as

$$\max \ \lambda_2\big(L(B)\big) \quad (2)$$
$$s.t. \quad \sum_{i=1}^{n_c} \alpha_i = Q_{SPRN},\ \alpha_i \in \{0,1\},$$
$$L(B) = L_i + \sum_{i=1}^{n_c} \alpha_i A_i A_i^T$$

where α_i is a binary variable equals to 1 when a RN is allocated at position *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 (2), we reformulate it as a standard Semi-Definite Program (SDP) optimization problem [7], which can be solved using any standard SDP solver. In the following, Algorithm 2 summarizes the second phase deployment where the search space is limited to n_c.

Algorithm 2: Deployment of SPRNs

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

V. PERFORMANCE EVALUATION

A. Simulation Environment

Using MATLAB, we simulate randomly generated WSN sectors [1]. To solve the previously modeled optimization

[1] Random in count of SNs and positions.

problem, we used the SDPA-M MATLAB Package [7].

B. Performance Metrics & Parameters

To evaluate our ST-DT approach, the following two metrics are tracked: *1)* Connectivity (λ_2), and *2)* Number of RNs (Q_{RN}). λ_2 reflects the federated network reliability under harsh conditions. And Q_{RN} represents the cost-effectiveness of the deployment approach.

Two main parameters are used in the performance evaluation: *1)* Probability of Node Failure (PNF), and *2)* the Deployment Space (DS). PNF is the probability of physical damage for the deployed node, and it's a key factor reflecting the harshness of the outdoor monitored sites. As for the *DS*, it reflects the scalability and applicability of the proposed deployment approach in large-scale applications.

C. Baseline Approaches

The performance of ST-DT is compared to the following two approaches: the first algorithm forms a minimum spanning tree based on a single-phase relay node placement [8], and we call it Minimum Spanning Tree Approach (MSTA); the second is for solving a Steiner tree problem with minimum number of Steiner points [9], 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 MST points. 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 $\leq r$). 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 ST-DT, are executed on 600 randomly generated WSNs graph topologies in order to get statistically stable results. The average results hold confidence intervals of no more than 5% of the average values at a 95% confidence level. For each topology, we apply a random node failure based on a pre-specified PNF value, and performance metrics are computed accordingly. Dimensions of the deployment space vary from 50 to 1000 (Km^3). 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. Based on experimental measurements [14], we set the communication model variables to be as follows: γ=2, P_r= -104 (dB) and μ to be a random variable that follows a log-normal distribution function with mean 0 and variance of 10.

E. Simulation Results

For a fixed number of disjoint sectors (=5) and deployment space (=50 Km^3), Fig. 1 compares ST-DT approach with MSTA, and SwMSP in terms of the federated WSN sectors connectivity. It shows how ST-DT outperforms the other two approaches under different PNF values. Unlike the other two approaches, WSNs federated using the ST-DT do not show a rapid decrement in the network connectivity while the PNF values increase. This is due to the larger feasible search space that has been considered by ST-DT approach. Moreover, connectivity levels achieved by the ST-DT outperform the levels achieved by other approaches due to considering the network connectivity while forming the network backbone in the first phase.

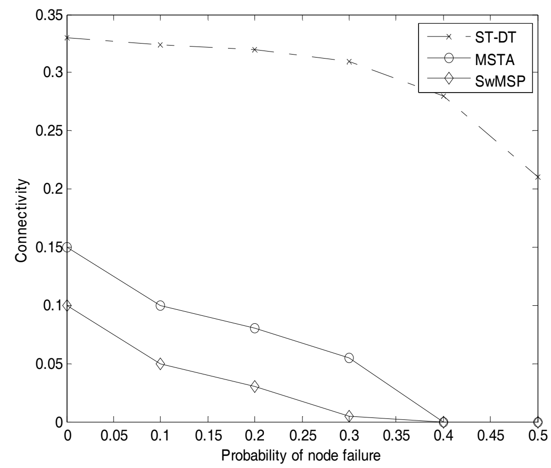

Fig. 1. Connectivity vs. the PNF.

Fig. 2 depicts 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 counts of RNs, where the number of disjoint sectors is fixed to 5 in order to see the effect of the relay node placement, and PNF = 0.2. Obviously, more saving is reached by applying the ST-DT approach. This is also because of the consideration of connectivity since the early stages of the deployment (i.e. while constructing the backbone).

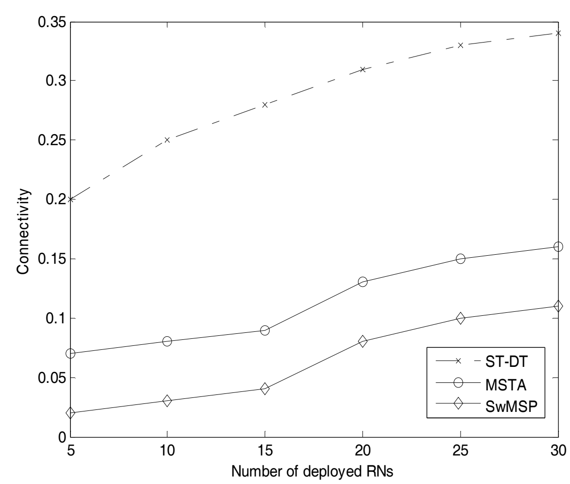

Fig. 2. Connectivity vs. the Q_{RN}.

In Fig. 3, ST-DT constantly outperforms MSTA and SwMSP, with varying deployment space volumes and PNF value equal to 20%, as long as the deployment space is within a reasonable size (≤600 Km^3). This gives more stability for the federated sectors in large-scale WSNs applications. Even with a very huge spaces (≥1000 Km^3), ST-DT is still much better than MSTA and SwMSP in terms of connectivity because of the deployed SPRNs.

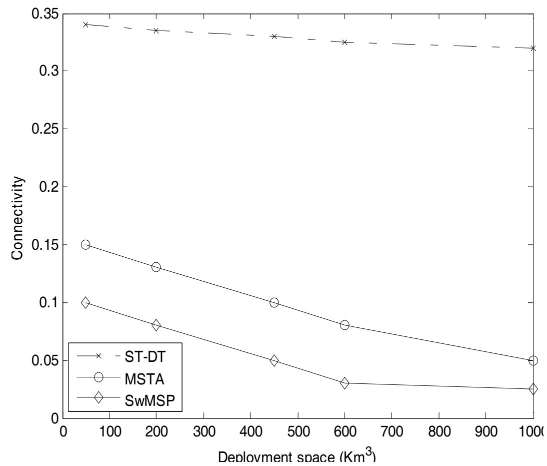

Fig. 3. Connectivity vs. the DS.

VI. CONCLUSION

In this paper, we explored the problem of federating separate WSNs in outdoor applications, aiming at maximizing network connectivity with constraints on the available cost-budget. An optimized two-phase approach was presented using Steiner tree, Delaunay Triangulation and Semi-Definite programming. For practical solutions, varying probabilities of node failures were considered, in addition to limiting the huge search space of the targeted deployment problem. The extensive simulation results, obtained under harsh conditions, indicated that the proposed two-phase strategy can provide tightly-connected networks and practically-applied federation scheme in outdoor applications. Moreover, deployment strategy and results presented in this paper can provide a tangible guide for network provisioning in large-scale applications which require linking between vastly separated WSN sectors. In addition, they are applicable for different setups (e.g., 2D/3D) and outdoor characteristics (e.g., various probabilities of node/communication link failures).

VII. ACKNOWLEDGMENT

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