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Towards Augmenting Federated Wireless Sensor Networks

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Abstract

Environmental Monitoring (EM) has witnessed significant improvements in recent years due to the great utility of Wireless Sensor Networks (WSNs). Nevertheless, due to harsh operational conditions in such applications, WSNs often suffer large scale damage in which nodes fail concurrently and the network gets partitioned into disjoint sectors. Thus, reestablishing connectivity between the sectors, via their remaining functional nodes, is of utmost importance in EM; especially in forestry. In this regard, considerable work has been proposed in the literature tackling this problem by deploying Relay Nodes (RNs) aimed at re-establishing connectivity. Although finding the minimum relay count and positions is NP-Hard, efficient heuristic approaches have been anticipated. However, the majority of these approaches ignore the surrounding environment characteristics and the infinite 3-Dimensional (3-D) search space which significantly degrades network performance in practice. Therefore, we propose a 3-D grid-based deployment for relay nodes in which the relays are efficiently placed on grid vertices. We present a novel approach, named FADI, based on a minimum spanning tree construction to re-connect the disjointed WSN sectors. The performance of the proposed approach is validated and assessed through extensive simulations, and comparisons with two main stream approaches are presented. Our protocol outperforms the related work in terms of the average relay node count and distribution, the scalability of the federated WSNs in large scale applications, and the robustness of the topologies formed.

Keywords: Wireless Sensor Network, Sparse Connectivity, Relay placement, Grid deployment, Environmental applications

1. Introduction

Many factors are attributed to the wide use of Wireless Sensor Networks (WSNs) in today's applications and across different environments. Improvements in micro-electromechanical systems (MEMS), transceiver hardware, sensing platforms and energy harvesting have all aided the design of more efficient WSNs. As such, WSNs are now deployed in many capacities over various domains, most notably in Environmental Monitoring (EM). Generally identified as harsh environments for WSNs, they extend to cover natural disasters, such as volcanoes, floods [2] and fires in forests [1].

As these scenarios encompass many harsh physical factors, they are more prone to failures. The scope of failure does not affect nodes in singularity, but often significant sectors of the deployed WSN; causing sizable partitioning in the underlying topology. Since multiple networks are often deployed, at large, to serve multiple applications, it is imperative to maintain connectivity between them to achieve the global goal of efficient and real-time monitoring of that environment. This entails maintained connectivity even under high probabilities of failure. We refer to failures at the node level as $\boldsymbol{P_{NF}}$ and at link levels as $\boldsymbol{P_{LF}}$ to caliber network operation. Understanding the performance of the global network under these failures, and the resulting connectivity measures, dictate the effectiveness of the WSN witnessing federation.

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Establishing, or often re-establishing, connectivity has been approached in multiple ways in the literature of WSNs. Mainstream approaches include deploying relay nodes (RNs) to establish (often multiple) paths in the network [3] as a whole, or utilizing mobile nodes that are able to re-connect partitions by moving into a median location [4]. A solution scenario of the former is seen in [3] whereby a minimum threshold for relay nodes is established to deploy in a disconnected static WSN to regain connectivity. Another example of the latter [4] adopt mobile nodes that would re-locate to establish *k*-connectivity properties, as required by the application. This is also optimized by determining a minimum on the number of nodes that need to re-position to establish this metric.

The previous approaches could be utilized in benevolent environments, where probabilities of failure are under control, or witness a pattern which we can model. Nevertheless, in forestry EM scenarios, re-establishing connectivity between federated networks entails more hindrances. Dominantly, the irregularity of communication regions of such networks, not adhering to the regularly assumed disc-shape [13], dictate a hard-to-model partitioning problem; hence making the establishment of re-connection zones a major issue. Challenges from significant distances between sectors, which might reach further than twice the communication range of a RN, added to the cost of RNs, are among the dominant hindrances.

Our contribution solves the problem of RN placement by dissecting the problem to polynomial time operations; to leverage the intractable issues with the inherently complex re-connection problem. We adopt a two-fold approach to this problem, namely Fixing Augmented network Damage Intelligently (FADI). The base protocol adopts a grid-based approach to dissect the search space into a set of finite points, where in RNs would be deployed to re-establish connectivity. The second fold uses the derived sets of points to determine the optimal assignment of RNs to these points; herein minimizing the number of relay nodes while maintaining connectivity. Moreover, the $\boldsymbol{P_{NF}}$ and $\boldsymbol{P_{LF}}$ metrics form constraints on the optimization problem.

The remainder of this paper is organized as follows: Section 2 outlines the background to this problem, and the related work carried out in re-connecting federated WSNs. Then, Section 3 details the system level assumptions and parameters, all invoked by the problem definition. The proposed approach (FADI) is presented in detail in Section 4, with elaborated explanations and full pseudocode for all the underlying algorithms in this approach. This is followed by performance evaluation in comparison to two dominant contenders in this domain in Section 5. The paper is concluded in Section 6 with directions of future work.

2. Background and Related Work

WSNs can be federated either by employing mobile nodes in the originally deployed network, or by populating a few relay nodes based on the network damage size. In this paper we focus on the latter approach due to its cost efficiency and applicability in outdoor large-scale forestry environments. In [6], Lloyd and Xue opt to deploy the fewest RNs such that each sensor node 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 [7], the authors solve a Steiner tree problem to deploy the fewest RNs. Although the Steiner tree approach may guarantee the best network topology, it may not encompass the minimum number of relay nodes, as shown in Section IV.

Unlike [6] and [7], Xu et al.[8] study a random RN deployment that considers network connectivity for the longest WSN operational time. The authors proposed an efficient WSN deployment that maximizes 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 approach is proposed. In this random deployment, the density of RNs deployment increases 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.

In reference [10], a distributed recovery algorithm is developed to address specific connectivity degree requirements. The contribution is identifying the minimal set of relay nodes that should be repositioned in order to re-establish a particular level of connectivity. Nevertheless, these references (i.e.,[8], and [10]) do not minimize the relay count, which may not be cost effective in forestry applications.

In contrast, considering both connectivity and relay count was the goal of [11]. In it, 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.

Unlike [11], in this paper, FADI considers the relay count and neighborhood degree in a different model. It derives positions of highest potential in establishing connectivity between the disjointed functional nodes. This in turn renders more time efficient approach than those generated by [6] and [7]; and unlike [8] and [10], FADI addresses the network federation problem without violating the WSN cost-effectiveness.

3. System Model

The system is inherently designed as an augmentation approach for connectivity re-establishment in forestry applications. As such, it is important to rigorously define the parameters of the system according to which our model operates. This section presents the problem definition in terms of how it would relate to a general forestry application, and the framework of the required solution. An elaborate explanation follows to highlight the network parameters which our system operates upon, the governing communication metrics, and the foundation for grid based approach adopted in the model.

3.1. Problem Definition

Consider a WSN which underwent partitioning into multiple sectors; often the result of a physical phenomenon or cascading failure in a given region. Without loss of generality, we assume that each sector is represented by a node, which we call a functional node. This is justified by locating the nearest node to the border of the damaged region, which is connected to the rest of its sector. As such, re-establishing connectivity with that node will re-introduce a path to every other node in that sector. Thus, our problem is formulated as follows:

> *Given **n** functional nodes, determine the minimum number of relay nodes required to establish intra-functional-node connectivity, and their positions respective to the network at large.*

An optimal solution to this problem can be derived from the Minimum Spanning Tree (MST) algorithm; especially beneficial due to its dominantly polynomial-time solution (e.g. using Kruskal's algorithm). Forming a MST involves spanning the functional nodes with minimum weight edges; where the weight reflects the number of relays required to establish an edge between two functional nodes. We note that edge weight in this research reflects the cost of establishing an edge between the disjointed functional nodes. In forestry applications relay nodes are the most dominant expense in network hardware.

3.2. Communication model

Evidently, establishing the metrics and bounds of communication are important for accurate resemblance of environmental monitoring applications; which we target in this research. Unlike traditional scenarios of flat-earth communication and simplistic paradigms, many efforts have been invested in identifying the dominant factors of communication hindrance in long-range and outdoor treed environments like forests. It is imperative that signal power faces significant decay as it travels for longer distances, yet that is not straight forward to model in our scenario domain. As per the constraints of our problem formulation, we have adopted the communication model presented in [5], referred to as the log-normal shadowing model, since it accounts for irregular communication range scenarios. Thus, we represent the signal level at distance d from a given transmitter as:

$$P_r = K_0 - 10\gamma\, log(d) - \mu d \quad (1)$$

which follows a log-normal distribution centered around the average power value at that point. Here K_0 is a constant incurred at transmission (of transceiver electronics), which is derived from the mean heights of Tx and Rx. Having d as the Euclidean distance (in 3-D space) between the transmitter and receiver, and γ as the path loss exponent, we adopt μ as a normally distributed random variable (r.v.) with zero mean & variance, i.e. $\mu \sim \mathcal{N}(0, \sigma^2)$. Since the received signal could be quantified using Pr, we devise a lower threshold on the signal level to deem communication successful. Denoting it as $P_{\min}$ over distance d (between transmitter and receiver), we denote the probability of successful communication as:

$$P_c = P(P_r(d) \geq P_{min}) \quad (2)$$

Which could be presented, after substitution from (1) and algebraic manipulations, as:

$$P_c(d,\mu) = Ke^{-\mu d^{\gamma}} \quad (3)$$

where $K_0 = 10\log(K)$. This equation emphasizes the important role of surrounding factors in the environment, in signal attenuation due to obstacles and terrain properties; not simply the direct relationship with distance. Thus, we formalize the connectivity (symmetric communication) between two nodes in the network as:

Definition 1. *A "probabilistic connection" exists between two nodes, of distance **d** apart, if for a given threshold parameter **τ** we assert that* $P_c(d,\mu) \geq \tau$*, where* $0 \leq \tau \leq 1$*.*

3.3. Network model

We regard the network as a heterogeneous WSN with two tiers. The first is formed by functional nodes, and the second is a layer of RNs which establish long-range communication across the network and to the sink. Nevertheless, where partitioning happens and when the topology dictates long range communications, optimal placement for RNs is adopted to federate the network.

Since network lifetime is an aggregation of that of its nodes, we elaborate on what terminates lifetime in this model. It is important to note that in forestry applications in general, P_{LF} is quite elevated. As such, a fully operable node, with significant energy reservoir, may become useless to the network when its communication capabilities are jeopardized. As such, simply measuring the remaining pool of energy at nodes is not a significant indicator. Instead, the most applicable and realistic measure of lifetime would take into consideration the connectivity of its nodes. Hence, we formally define network lifetime as the duration before a partition occurs.

3.4. Grid model

As the search space for possible locations for RNs is inherently intractable, the task of identifying the best candidate points is imperative yet non-intuitive. Therefore, the protocol presented in this paper identifies the potential positions for RNs as an initial phase in the solution. These positions are used in placing relays which establish the MST based on a ranked approach; to achieve an optimal RN deployment scheme. Our approach here is adopting a 3-dimensional grid which uniformly dissects the region covered by the network – into virtual cubes – and reduces the infinite search space to a discrete and finite set. Accordingly, the intersection points of these grid lines (cube corners) are referred to as grid unit centers. Eventually, RNs will only be positioned at a defined set of grid unit centers. As such, we caliber the potential of a grid unit center as a candidate for RN placement according to the nodes able to communicate to that point; based on the communication metrics outlined in subsection 3.2. Formally, we caliber the nodal coverage of a grid center as:

Definition 2. *Given a grid unit center **c** in the deployment space, a functional node **x** is said to cover c if and only if* $P_c(x, y) \geq \tau$*. Where **y** is a RN placed at **c**.*

Thus we are able to quantify the potential of a grid center, in terms of its connectivity, as an aggregation of the nodes covered by it; more formally:

Definition 3. *Connectivity potential of a grid center **c** is proportional to the sum of functional nodes covering **c.***

Hence, choosing the most representative parameters for the communication model of the network, we are able to assign a set of potential nodes for each grid unit center, which cover it, and use that as a ranking scheme for optimal locations for RN redeployment. Formally:

Definition 4. *The Grid Unit Potential Set (GUPS) of a grid center **c** holds all the functional nodes covering **c**. The degree* $D = |GUPS|$*. It is Maximal GUPS (MGUPS) if there exists no set* θ *s.t.* $|MGUPS| \subseteq \theta$

4. Fixing Augmented network Damage Intelligently – The Approach

The proposed approach, namely **F**ixing **A**ugmented network **D**amage **I**ntelligently (FADI) is presented in this section. Given a network facing significant dissection/partitioning, we underline the procedural approach to efficiently locate positions for RN placement, and detail the scheme for re-connecting it. Since the system is based on interchangeably operating procedures, the protocols are elaborately explained and their formal algorithms are presented.

The first phase of the approach identifies the set of grid centers that would satisfy the optimality highlighted earlier. Then, the connectivity potential of each is determined. Following that, the MGUPs are derived, and the MST approach is utilized to federate the network. Having the set of functional nodes to start with, we present the iterative approach is proposed in Algorithm 1. Moreover, this meta-algorithm invokes the procedures highlighted in Algorithms 2-5, serving all together to identify MGUPS and assigning RNs to them until connectivity is re-established. The constraints, inputs and outputs are all detailed in their respecitve algorithms, as presented below.

Algorithm 1: An overview for FADI Algorithm

1. **Function FADI** (*F*: Initial Set of nodes to construct FN)
2. **Input:**
3. A set *F* of the functional nodes' coordinates.
4. **Output:**
5. A set *GC* of the intelligently selected grid centers for RNs placement.
6. **begin**
7. **while** WSN is partitioned **do**
8. *C* = **FindGridUnitsPotential**(*F*);
9. *M* = **FindMGUPs**(*F, C*);
10. *GC* = **IMST** (*F, M*);
11. **endwhile**
12. **end**

Algorithm 2: Test the grid unit potential for connectivity repair.

1. **Function FindGridUnitsPotential**(*F*)
2. **Input:**
3. A set *F* of the functional nodes' coordinates.
4. **Output:**
5. A set $C = \{C_i \mid \forall\ i \in$ grid units centers$\}$.
6. **Begin**
7. **foreach** grid unit center *i* **do**
8. C_i:=∅; //the set of covered functional nodes by center *i*.
9. **foreach** functional node *j* **do**
10. Compute $P_c(i, j)$;
11. **If** $P_c(i, j) \geq \tau$
12. C_i:= $j \cup C_i$; //Add the coordinates of *j* to C_i
13. **endif**
14. **endfor**
15. **endfor**
16. **End**

Algorithm 3: Testing whether a grid unit set $\boldsymbol{C_i}$ is maximal or not.

1. **Function Maximal**(C_i, *C*)
2. **Input:**
3. A set C_i of functional nodes covering a specific grid unit center *i* and a set *C* of all non-empty C_i sets.
4. **Output:**
5. True if C_i is MGUPS and False otherwise.
6. **Begin**
7. Search for a set *C'* such that $C_i \subseteq C'$.
8. **If** *C'* := ∅ **do**
9. **return** True;
10. **else**
11. **return** False;
12. **endif**
13. **End**

Algorithm 4: Finding all *Maximal Grid Unit Potential Set* MGUPS

1. **Function FindMGUPs**(*F, C*)
2. **Input:**
3. A set *F* of the functional nodes' coordinates.
4. A set *C* of all non-empty C_i sets.
5. **Output:**
6. A set *M* that contains one position from every MGUPS.
7. **Begin**
8. *M* := ∅;
9. **foreach** $C_i \in \{C\}$ **do**
10. **If Maximal**(C_i, *C*) **do**
11. $M := \{i\} \cup M$;
12. **endif**
13. **endfor**
14. **End**

Algorithm 1 provides the high-level pseudo code of FADI. The algorithm takes the list of nodes which are still functional as an input. The detailed pseudo-code of finding the grid centers potential for connectivity, the grid centers of the highest potential, and the set of grid centers used to place the relays constructing the MST are shown in Algorthims 2 to 5. Algorithm 2 associates each grid center with its connectivity potential. In lines 9 to 14 of Algorithm 2, FADI computes the probability of the grid unit center *i* being connected with each functional node individually based on Eq. (3). This is repeated by lines 7 to 15 until all probabilities between the grid units' centers and all functional nodes are computed. Based on these probabilities the set C is initialized in line 12. Algorithms 3 and 4 check for grid centers that have the highest potential for connectivity (see Definition 3), which we call MGUPs.

Algorithm 4 calls Algoritm 3 to test whether the set of functional nodes covering a specific grid unit center is maximal or not. In line 7 of Algorithm 3, FADI searches for any set (other than C_i) in *C* that has the same functional nodes which cover the grid center *i*. if such set is found, Algorithm 3 returns false, otherwise it returns true; meaning that the set C_i is maximal. After discovering the grid centers which have the highest potential for connectivity (i.e. the set *M* in line 9 of Algorithm 1), FADI calls Algorithm 5 to construct the MST using these grid centers (or MGUPs). Line 10 of Algorithm 5 search for the closest two functional nodes. If the closet two nodes are not

Algorithm 5: Intelligent Minimum Spanning Tree (IMST)

```
1.  Function IMST (F, M)
2.  Input:
3.  A set F of the functional nodes' coordinates.
4.  A set M of the MGUPs.
5.  Output:
6.  A set GC of the intelligently selected grid centers for RNs
    placement.
7.  begin
8.  GC := ∅;
9.  FN := ∅;
10. If Pc(i, j) ≤ τ
11. Search for the least grid centers c required to connect i and j, such
    that c ∈ M and Pc(i,c) ≥ τ and Pc(c, j) ≥ τ;
12.   GC := c ∪ GC; //Add the coordinates of j to GC//
13.   FN := c ∪ FN;
14.   F := F – I – j;   //Set of Functional nodes//
15. endif
16. N = no. of remaining F nodes which are not in FN;
17. i = 0;
18. foreach remaining node ni in F do
19.     Find coi;
20.     i = i + 1;
21. endfor
22. Let CO = { coi }
23. i = 0;
24. while i < N do
25.     S = Smallest coi in CO;
26.     GC := S ∪ GC;
27.     FN = FN ∪ S ∪ ni;
28.     F = F - ni;
29.     CO = CO - coi;
30.     i = i + 1;
31.     foreach remaining node nj in F do
32.         Find coj;
33.            j = j + 1;
34.     endfor
35. endwhile
36. end
```

connected (i.e. $P_c \leq \tau$), it looks at line 12 for the minumum number of grid centers in which the relays have to be placed to connect these two nodes. After connecting the closest two functional nodes (i.e. a connected component), we iterativelly look for the next closest functional node that has to be connected to them. And, in lines 20 to 36 of Algorithm 5, FADI iterativley searches for the least grid centers to be used for placing the relay nodes that will connect the next closest node with the connected component.

5. Performance Evaluation

Using MATLAB, we simulate randomly generated WSNs which have a graph topology and consist of varying number of partitioned functional nodes[a]. We simulate a realistic communication channel characteristics taken from experimental measurements in a densely treed environment [13].

5.1. Performance Metrics & Parameters

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

- Average RNs degree (*D*): This is the number of functional nodes in the neighborhood of a RN. It reflects the federated network reliability under harsh forestry characteristics. It gives an indication for the federated WSN robustness. Where higher node degree yields stronger connectivity and enables better load balancing.
- Average RNs count (Q_{RN}): This represents the cost-effectiveness of the deployment approach and the main objective targeted by our approach.
- Recovering time (RT): the time required to federate the disjointed functional nodes and remove any partitioning.
- Time to Partition (TtP): is time span before the network experience a partition after being federated.

Three main parameters are used in the performance evaluation:

- Number of functional nodes (Q_{FN}): this represents the complexity of the addressed problem.
- Node density (ND): this measures the federated network scalability in large scale forestry applications.
- Probability of Failure (PoF): is the probability of physical damage for the deployed node and the probability of communication link failure due to bad channel conditions, and uniformly affects any of the network nodes/links. We chose this parameter as it reflects the harshness of the monitored forest.

5.2. Baseline Approaches

The performance of FADI is compared to the following two approaches: the first algorithm forms a minimum spanning tree without considering the intersections of the irregular communication ranges [6], and we call it

[a] Random in terms of functional nodes' count and positions.

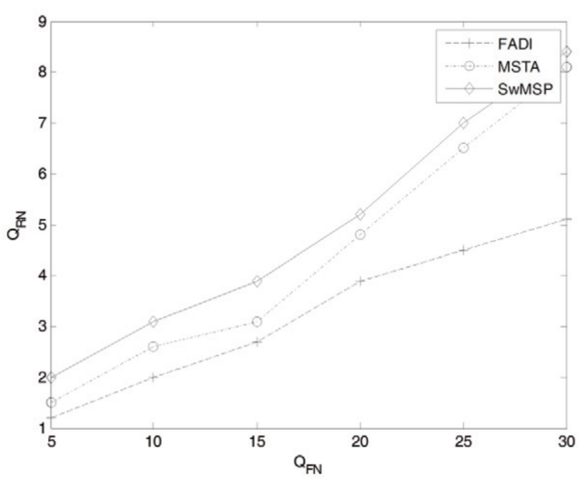
Minimum Spanning Tree Approach (MSTA); the second is for solving a Steiner tree problem with minimum number of Steiner points [7], and we call it Steiner with Minimum Steiner Points (SwMSP). The MSTA opts to establish an MST based on the Euclidean distance separating two functional nodes bearing in mind that the communication range is depending on the distance only. It first computes an MST for the given WSN partitions and then places RNs at the minimum number of grid vertices on the MST. The SwMSP approach places the least relays count to repair connectivity such that the maximum edge length in the Steiner tree is $\leq r$. SwMSP first combines functional nodes that can directly reach each other into one Connected Component (CC). The algorithm then identifies for every three CCs a vertex x on the grid that is at most r (m) away from the CC boundary nodes. A RN is placed at x and these three CCs are merged into one CC. These steps are repeated until no partitioning in the network is found. In summary, both MSTA and SwMSP deployment strategies are used as baseline approaches due to their efficiency in linking WSNs partitions using the minimum relays count.

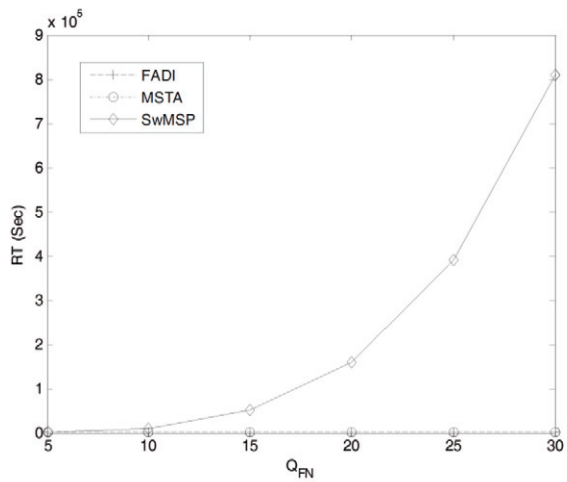
5.3. Simulation Setup & Results

The three deployment schemes: MSTA, SwMSP, and FADI, are executed on 500 randomly generated partitioned networks for 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 PoF, and performance metrics are computed accordingly. A Linear Congruential random number generator is employed. Dimensions of the deployment space 900*900*300 (m^2). Based on experimental measurements [13], we set our communication model variables as follows: $\tau = 70\%$, $d = r = 100m$, PoF=35%, γ =4.8, and μ to be a r.v. that follows a log-normal distribution function with mean 0 and variance of 10. We assume a predefined fixed time schedule for traffic generation at the deployed WSN nodes. To simplify the presentation of results, all the transmission ranges of functional nodes and relays are assumed equal to 100 (m).

For varying number of disjointed functional nodes, Fig. 1 compares FADI approach with MSTA and SwMSP in terms of the total required relays. It shows how FADI outperforms the other approaches under different complexities of the targeted federation problem. Unlike the other approaches, the required relays count is slightly increasing when FADI approach is utilized as the total partitioned nodes are increasing. This indicates more savings in cost which is very desirable in harsh environments targeted by large-scale forestry applications. Fig. 2 depicts the efficiency of MST-based approaches in terms of time complexity with respect to other approaches such as the SwMSP. It is clear how an increment in the disjointed functional nodes leads to an exponential increment in the time required for recovering (federation) when a Steiner tree approach is utilized. This has a great draw back on forestry applications which are most often time sensitive.

Fig. 3 justifies the optimality of FADI in terms of finding the least relays positions federating all partitioned functional nodes. Where the average relays degree achieved by FADI is much better than the average degree reached by MSTA and SwMSP with various counts for the disjointed functional nodes (i.e., different Q_{FN} values). This in turn provides a robust network topology structure under harsh operational conditions in the forest. In Fig. 4,





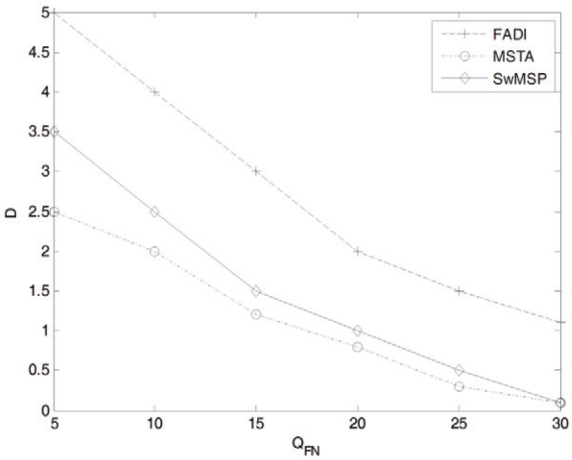


Fig. 3. Functional nodes vs. the relays neighborhood degree.

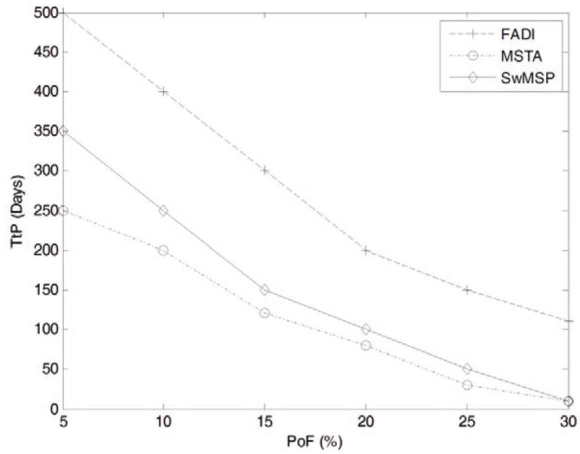


Fig. 4. PoF vs. the time to partition.

we examined the practicality of our placement methodology under harsh operational conditions. FADI was able to generate a federated WSN that stays connected for long lifetime periods with respect to MSTA and SwMSP.

6. Conclusion

In this paper, we explored the problem of federating grid-based WSNs in forestry applications. A relay-based approach, called FADI, was presented using the minimum spanning tree algorithm. For practical solutions, varying probabilities of 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 approach can efficiently federate the disjointed WSNs. Moreover, the deployment approach 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. Future work would investigate the 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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