Connectivity Optimization for Wireless Sensor Networks Applied to Forest Monitoring

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***Abstract*—Device Deployment plays a key role in the performance of any large-scale Wireless Sensor Network (WSN) application. WSN device deployment (i.e. the numbers and positions of the devices) must consider several design factors, viz. coverage, connectivity, lifetime, etc. However, connectivity remains the most fundamental factor especially in a large scale harsh environment. In this paper, we explore the problem of Relay Node (RN) placement in 3D forestry space. We formulate a generalized RN deployment optimization problem aimed at maximizing the network connectivity with constraints on RNs count. We investigate how the number of RNs can affect the connectivity of a WSN in a harsh environment. Based on quantitative analysis of such effects, the paper sets a threshold on the minimum number of required RNs.**

I. Introduction

Wireless Sensor Networks (WSNs) can enable long-term monitoring at scales and resolutions that are difficult, if not impossible, to obtain using conventional techniques. WSNs can be re-tasked after deployment in the field based on changes in the environment, conditions of the sensor network itself, or scientific endeavor requirements [2]. This paper focuses on the application of WSNs to forest monitoring. Currently, WSNs are used in several applications related to forestry, such as soil moisture monitoring [11], river sensing experiments [11], forestry fire detection [12], and in redwood tree observation [13]. Such applications require large-scale WSN deployment. In the literature, two types of WSN deployment are used for large-scale applications, random or grid-based. In random deployment, nodes are randomly scattered and they organize themselves in an ad hoc manner. In grid-based deployment, nodes are placed on grid vertices leading to more accurate measurements in terms of collected data [14]. Most work in deployment has been targeted to the 2D space [18]. However, in forest monitoring applications, animals and birds can move between ground surface and trees, gases exist at different concentrations in the 3D forestry space, and different plant species can grow in any direction.

Grid deployments have shown accuracy in the 2D and 3D space [18]. In this paper, we introduce an optimal 3D grid-based device deployment strategy for WSNs in forestry applications. Applying grid deployment in 3D space has several benefits. It can precisely limit the search space, simplify the formulation of the placement optimization problem, easily isolate any faulty node, efficiently provide possible paths to the Base Station (BS), and provide scalability and flexibility because of its well-organized structure. Device deployment (i.e. the number and positions of devices) must consider several factors such as coverage, connectivity, lifetime, etc. [2]. However, in harsh environments like forests, connectivity is one of the most important factors. Existing WSN deployment schemes for forestry applications, however, have not addressed the problem of connectivity optimization in 3D and/or harsh environments. The forestry environment is harsh since WSN nodes and edges are subjected to several risks. Nodes may fail because of the extreme weather conditions, wild animals, new growing plants, falling and growing leaves on trees, etc. Also, communication is highly affected by weather condition, plants, etc. In this paper, we propose a connectivity-optimized robust 3D WSN deployment strategy for forestry applications. By considering a WSN as a graph, we measure how well the WSN is connected using the second smallest eigenvalue of the graph Laplacian [5]. This eigenvalue is called also algebraic connectivity. Increasing the algebraic connectivity means increasing the required number of nodes and links to disjoint paths in the graph leading to robust network architecture [8] and a more reliable WSN [1].

The major contributions of this paper are as follows. Firstly, we propose essential models for WSN forestry deployment. Secondly, we introduce a 3D RN placement optimization problem in the forest with the objective of maximizing connectivity with constraints on the number of RNs. Finally, we propose an optimal solution for that 3D deployment problem. Performance of the optimal solution is evaluated and compared to two possible random deployments in the presence of different node/edge failure probabilities.

The remainder of this paper is organized as follows. In Section II, related works are outlined. In Section III, system models and placement problem are described. In Section IV, an optimal 3D deployment strategy is proposed. In Section V, the performance of the proposed strategy is evaluated and compared to the random deployment strategy. Finally, the paper is concluded in Section VI.

II. Related Work

Extensive work has been reported in the literature relating to sensor and relay node deployment. WSN deployment in

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large-scale applications has been classified into random or grid-based deployment in 1D, 2D, or 3D space targeting connectivity, coverage, lifetime, and/or data fidelity [18]. Connectivity can be considered as a primary/secondary objective or as a constraint in the deployment problem [18]. The majority of published work on random and grid-based deployment is limited to 1D and 2D space. For example, in [7] an outdoor random deployment which targets the connectivity as a primary objective in 2D space is investigated. In [4], connectivity is used as a constraint in 1D deployment. In [15], a hybrid deployment strategy is introduced to balance the network lifetime and connectivity goals for outdoor applications where RNs can communicate directly with the BS [15]. The work is extended in [16] to include the case in which RNs can communicate with the BS through multi-hop relay paths. Reference [17] investigates device placement with minimum number of RNs that can directly reach the BS in indoor applications with constraints on lifetime and connectivity. In [12], WSN architecture and implementation in 2D is proposed for forestry fire detection application.

We remark that some attempts have been made towards 3D deployment. However, connectivity optimization has not been investigated yet. For example, in [3], maximal 3D coverage with the least number of sensors is discussed without considering the connectivity issue. Reference [9] considers the implications of sensing and communication ranges on the connectivity in random 3D deployment. Optimizing WSN deployment in 3D large-scale applications is still considered an open issue.

Our work focuses on optimizing connectivity in 3D forestry deployment. Motivated by the benefits of grid deployment as well as the wide range of forestry applications, our research provides a feasible approach to connectivity maximization under the constraint of required RNs.

III. System Models & Placement Problem

A. Network Model

In this paper we assume a large-scale WSN is deployed in a forest with three types of the devices, SNs, RNs, and BS. A SN senses the targeted phenomena and periodically transmits the measured value(s) to the BS via active RNs (if applicable). SNs have no relaying functionality (reducing device cost and energy dissipation). Let N_{SN} be the number of active SNs to be deployed. A RN, which has a fixed transmission range, receives the sensed data, aggregates it and transmits it to the BS directly (if applicable) or via other RNs. Traffic aggregation is used to reduce redundant information, leading to communication and energy savings. We assume we can use a maximum of N_{RN} RNs. These RNs may be placed in optimized locations according to the optimal 3D grid deployment or randomly (if random deployment is used). Finally, a BS, which communicates via satellite, is placed in the most appropriate location in the forest (see Fig. 1)

B. Energy Model

The energy supply of an RN can be unlimited or limited. When an RN has an unconstrained energy supply (rechargeable or simply have enough energy relative to the projected lifetime of the SNs), the placement of RNs is to provide connectivity to each SN with the constraint of the limited communication range of SNs. When the energy supply of RNs is limited, the placement of RNs should not only guarantee the connectivity of SNs but also ensure that the paths from RNs to the BS are established without violating the energy limitation. In this research we assume a fixed and unlimited (relative to the network lifetime) power supply at the RNs in the deployed WSN. In addition, we assume the exact communication power consumption model used in our previous work [15].

C. Sensing Model

We consider the binary disk (or sphere in case of 3D) sensing model. Although, other sensing models exist in literature, the binary disk model is predominant due to its simplicity.

The sensed data may be wind speed, CO_2 concentration, humidity, temperature, etc. We assume that data samples are taken frequently by SNs and transmitted back to the BS via data aggregation centers (or Cluster Heads (CHs)) based on a synchronized schedule. CHs aggregate sensed data and coordinate medium access. CHs relay information to BS through RNs.

D. Signal Propagation Model

Signal propagation models are fundamental in WSN forestry applications. There are several parameters that affect the signal propagation in the monitored environment, such as fading and shadowing. Fading, is the rate at which the magnitude and phase of a propagated signal changes. Shadowing refers to the fluctuation of the average received power. Signal attenuation, due to shadowing and fading can decrease the quality of the WSN communication links. Therefore, the same path with vegetation has larger attenuation than a path without any foliage [10]. Hence a signal propagation model that can describe the path loss in the monitored environment is needed. Modeling signal propagation in densely forested environments is challenging because of the variety of the tree heights and densities. In the literature there are some attempts to model the path loss in a vegetated field. As for the forestry monitoring application, the signal propagation model should consider different parameters such as the heights of the trees and vegetations, transmitter antenna height and transmitter-receiver distance [10] Knowing that the path loss is the difference between transmitting and receiving power, and from [10], we can conclude that the received power (P_r) in a non-homogenous forestry environment can be modeled using equation (1), where d is the desistance between the transmitter and receiver, χ is a random variable describes the environment, γ is the path loss exponent, α is the specific attenuation, h_t, h_r and h_f are the transmitter, receiver and forest mean heights, respectively. Notice that χ is obtained by computing the Probability Distribution Function (PDF) of experimental data as well as its average and standard deviation δ.

$$P_r = K_0 - 10\gamma \log(d) - 8.686\alpha d + \chi \quad \textbf{(1)}$$

$$K_0 = -0.00169\left(\frac{ht}{hr}\right)^3 + 0.18269\left(\frac{ht}{hr}\right)^2 - 6.2337\left(\frac{ht}{hr}\right) + 98.254 \quad \textbf{(2)}$$

$$\alpha = \left(\frac{1}{1000}\right)\left(\frac{h_f}{h_t\left(h_t + h_f\right)}\right) \quad \textbf{(3)}$$

Using this signal propagation model we can calculate the distance l between vertices in the 3D grid; where l is the minimum distance d that can be achieved using equation (1) given that P_{min}, the minimal acceptable signal level to maintain a connection, and all other variables are known for the targeted forestry site. Therefore, two nodes are connected if the distance between them is $\leq l$. In other words, two nodes in the 3D grid are connected if they are adjacent vertices.

E. WSN Topology Model

3D grid models with multi-hop communication between RNs and the BS can either have a *star* or a *mesh* topology. The star topology has edges (connections) between the BS and the SNs only (i.e. no connections between the SNs themselves). It can be implemented using our proposed optimal algorithm by enforcing the candidate locations of the RNs to start from the BS in a centralized manner. The mesh topology may have an edge between any two nodes in the network. Therefore we do not enforce the RNs edges to start from the BS only. In this research we consider the mesh topology.

F. Placement Problem

We assume SNs and CHs placement is determined by the application in order to achieve desired data sampling. We focus on the issue of optimal placement of RNs in 3D forestry space. Notice that not all of the grid vertices can be RN candidate positions. This is due to the forestry environment parameters, such as obstacles or unreachable places. Therefore, we identify the RN placement problem as:

Given a specific sensing task with pre-specified SNs, CHs and BS locations, determine the number and positions of RNs that maximizes the connectivity between the SNs (or CHs) and the BS with constraint on the maximum number of RNs.

We use the following notations in the placement problem:

- α_i: Allocate RN at vertex i in the 3D grid.
- A_i: Incidence matrix that results by adding RN_i in the 3D grid; $A_i=[a_1, a_2, .., a_m]$, where a_i is the vector that consists of n elements that can take a value of either 0, 1 or -1 and m is the total number of edges that is produced by adding RN_i. For example, if adding RN_i will establish a connection between node 1 and 3, then 1^{st} element is set to 1 and 3^{rd} element is set to -1 and all of remaining elements are set to zeros.
- n_c: Total number of possible locations for a RN.
- n: is equal to N_{SN}+1 (which is the total of SNs (or CHs) and BS).
- $L(\alpha)$: Laplacian matrix which has -1 at the element (i,j) if there is a connection between node i and j. it has an integer +ve number at the element (i,i) that represent the number of edges that are connected to node i.
- s: Scalar variable that represents the 2^{nd} smallest eigenvalue of the Laplacian matrix.
- I_{nxn}: Identity matrix of size n by n.
- L_i: Initial Laplacian matrix (without adding any RN).
- N_{MST}: Number of allocated RNs using the MST algorithm.

$$L(\alpha) = L_i + \sum_{i=1}^{n_c} \alpha_i A_i A_i^T \quad \textbf{(4)}$$

IV. Deployment Strategy

In this section, we propose an optimal 3D deployment strategy for forestry WSN applications. Firstly, detailed 3D description of the forestry site to be monitored should be given. This 3D forest description can be achieved from the leaser imagery (LiDAR) technology [6]. LiDAR makes a leaser scan for the forest from an airplane. Then it provides images which describe the trees density and heights in addition to other obstacles specifications in the site. By drawing a 3D grid (with a distance of l (m) between each two adjacent vertices) on that leaser image (see Fig. 1), we can specify which of the grid vertices can serve as candidate positions for WSN nodes. For example, SNs that lay on the ground surface can have better channel conditions for communication than the ones that are above the ground surface in the presence of trees due to reflection caused by the trees downward to ground surface. Given that the locations of SNs and BS are predefined on the 3D grid vertices, the identified candidate positions represent a limited search space for the placement problem defined in the previous section. In the following subsection, we formulate the RN placement problem as an optimization problem.

Optimal 3D Grid Deployment (O3D)

The O3D strategy depends on three main steps. First, we construct an optimal connected Backbone (B) in terms of number of deployed RNs. B should form a connected graph that includes all SNs and BS. Second, we formulate a Semi-Definit (SD) optimization program with objective function to maximize the connectivity of B with constraints on the number of deployed RNs. Third, we use integer linear programming to solve the SDP optimization placement problem.

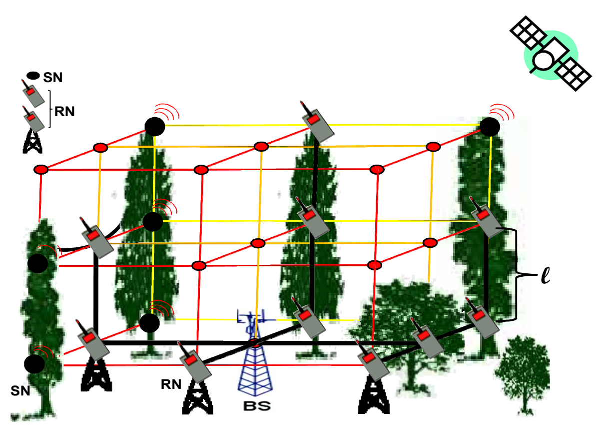


Fig. 1. 3D grid deployment in the forest.

Since SNs (or CHs) and BS are placed to satisy a desired application, they may not be initially connected as shown in Fig. 2 (a). Therefore, we use a Minimum Spanning Tree (MST) algorithm to connect these SNs (or CHs) to the BS using a minimum number of RNs as shown in Fig. 2 (b). In this way any two nodes (CH or BS), which are non-adjacent nodes on the 3D grid vertices, can be connected together by allocating one or more RN(s). For example, in Fig. 2 (b), CH at vertex number 4 can be connected to the BS at vertex 14 by allocating one RN at vertex 9.

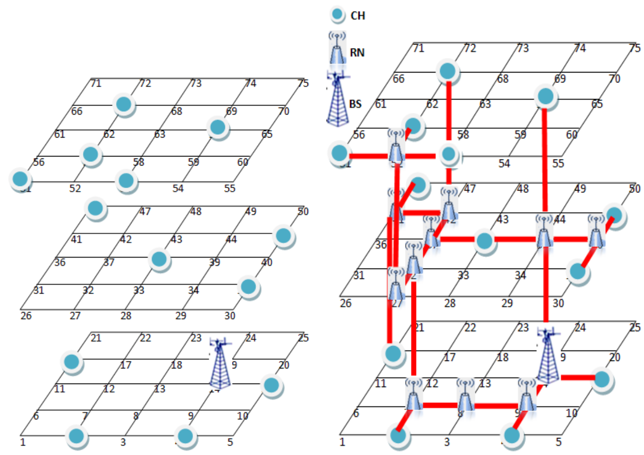
The MST algorithm can be applied as follows:

1. *Connect the closest two nodes in WSN (i.e. the nodes that need the minimum number of RNs to be connected) by allocating RNs that establish a communication path between these two nods. Let's call these two nodes with the allocated RNs a Connected Component (CC).*
2. *For each remaining unconnected node (CH or BS node), calculate the minimum number of RNs required to connect it to the CC.*
3. *Connect the closest unconnected node (i.e. the node that needs the minimum number of RNs to be connected to the CC) by allocating the RNs that establish a communication path between the unconnected node and the CC. Again, let's call the set of connected nodes and the allocated RNs a CC.*
4. *Repeat 2 to 4 until all unconnected nodes are connected to the CC as shown in Fig. 2 (b).*

Now, since we have a connected graph (i.e. the CC), we can apply the concept of the algebraic connectivity in [5] to maximize the connectivity of the CC. Note that CC represents the Backbone (B) of the deployed WSN. Therefore, if we can allocate extra (N_{RN} – N_{MST}) RNs, we have to find the optimized locations in order to achieve the highest algebraic connectivity of that B which in turn maximize the WSN robustness and reliability as mentioned previously. These optimal RNs locations can be found by solving the following Semi-Definite optimization problem which is a generalization of the Integer Linear Programming (ILP) optimization problem:

$$\begin{aligned}
&\max\ s \\
&S.T. \\
&\sum_{i=1}^{n_c} \alpha_i \le (N_{RN} - N_{MST}) \\
&s\left(I_{nxn} - \frac{1}{n}11^T\right) \le L(\alpha) \\
&0 \le \alpha_i \le 1
\end{aligned} \qquad \textbf{(5)}$$

The objective function in (5) and second constraint result in maximizing the connectivity of the deployed WSN [5]. This is because we are considering the effect of the resultant edges associated with each α_i on the algebraic connectivity of the deployed WSN. The first and third constraints in (5) maintain the limit on available number of RNs for deployment. Since the SDP cannot solve ILP optimization problem, we have to resort to heuristic approaches to find the optimal solution. This heuristic approach could be either by allocating the highest (N_{RN} – N_{MST}) α, or by iteratively allocating the highest α_i in each iteration.



(a) (b)

Fig. 2. An example of WSN of 14 CHs and 1 BS.
(a) Before applying MST.
(b) After applying MST.

Therefore, we can summarize our O3D deployment in the following steps:

1. *Optimize the required number of RNs to construct WSN B.*
   - 1.1. *Determine the location of the minimum number of required RNs to connect the SNs (or CHs) with the BS using the MST algorithm.*
2. *Optimize locations of extra RNs that maximize connectivity of the constructed B by solving (5).*
   - 2.1. *Pre-calculate the coefficients matrices (A_1, A_2, …, A_{nc}) associated with each α_i.*
   - 2.2. *Evaluate L(α) using (4).*
   - 2.3. *Calculate (N_{RN} – N_{MST}).*
   - 2.4. *Find the non-Boolean solution of the SDP problem in (5) using SDPA-M Matlab Package for example.*
3. *Heuristically determine the Boolean solution of the deployment problem (i.e. which RNs are allocated on the grid vertices).*

V. Performance Evaluation

In this section, the proposed O3D strategy is evaluated and compared to two possible random deployment strategies, Random 3D Grid Deployment (R3D) and Random 3D Grid Deployment with Optimal Backbone (R3DwOB). In R3D strategy, we consider a uniform random allocation of the RNs on the 3D grid vertices. So we do not compute the MST to connect SNs (or CHs) with the BS. However, In R3DwOB strategy, we consider a uniform random allocation of the RNs on the 3D grid vertices that are not used by the MST. So we compute the MST to connect SNs (or CHs) with the BS and then we start randomly allocate extra RNs to maximize the connectivity of the generated MST graph (i.e. the B). These strategies are evaluated under different node/edge failure probabilities. The influence of the estimated value of the required RNs on the connectivity of the WSN is also addressed.

A. Simulation Model

We simulate a WSN of 14 data aggregation centers (CHs), one BS and 60 RN candidate positions on a 400*400*200 (m^3) cubic sensing site in the forest. Each CH is connected to 10

SNs (a total of 140 SNs). Based on measurements taken in a forestry site in [10], we set our signal propagation model variables to be as follows: γ=4.8, δ=10, P_{min}= -104 (dB), h_t=14 (m), h_r=1 (m), and h_f=30 (m), and χ to be a random variable that follows a log-normal distribution function with mean 3. Thus, using equation (1) and based on our binary disk sensing model, $l = 100(m)$. A mesh topology is used in our simulation.

We assume CHs and BS are pre-positioned as shown in Fig. 2 (a). Then, we try to optimize the number and locations of RNs that maximize the algebraic connectivity between CHs and BS using the O3D strategy. For comparison purposes, we simulate the connectivity of the deployed CHs and BS using R3D and R3DwOB strategies. Finally, we compare between the performance of the O3D and the R3DwOB in harsh environment by simulating them under 6 different node/edge failure probabilities varies from 0-50%. Each simulation experiment is repeated 100 times and average results are reported.

B. Simulation Results

The main metric used to evaluate the performance of the O3D strategy in harsh environment is the connectivity (λ_2). λ_2 is the second smallest eigenvalue of the simulated WSN Laplacian. Three main simulation parameters are used: number of RNs (extra RNs in case of O3D and R3D), PEF and PNF. PEF is the probability of edge failure, and uniformly affects any of the network edges. PNF is the probability of node failure, and uniformly affects any of the network nodes (devices).

The O3D and R3DwOB strategies are conducted on the same network while the PEF and PNF varies from 0 to 50%. Both strategies are conducted on the connected network which is produced by applying the MST algorithm on the CHs and BS shown in Fig. 2 (a). The MST algorithm allocates 11 RNs as the minimum number of RNs that are required to establish a connected graph for the scattered CHs and BS in the forest as shown in Fig. 2 (b).

While the O3D strategy optimizes the locations of extra RNs in order to achieve the maximum connectivity, R3DwOB attempts to find the locations of the extra RNs randomly. Fig. 3 presents the average λ_2 variations under different PEF in the forest environment using 10 extra RNs in addition to the 11 RNs of the network Backbone. Not surprisingly, using R3DwOB, WSN becomes disconnected when PEF exceeds 20%. On the other hand, O3D strategy stays connected for PEF values up to 50% – a relatively high edge failure rate. Furthermore, by repeating the same simulation with different extra RNs, we find that the O3D strategy always outperforms other deployment strategies. Similarly we show the effect of the PNF on the connectivity of the same two strategies in Fig. 4.

Fig. 3 and Fig. 4 show that the O3D can achieve high reliability. This is because we have an operational path from all CHs to the BS even in the presence of 40% & 50% of edge and node failure, respectively [1]. In addition, using the O3D strategy we can set a threshold on the minimum number of required RNs to maintain the connectivity of WSN in environment of a specific PNF or PEF. For example, we run our simulator for several values of extra RNs varies from 0 to 10. We conclude that we need at least 10 extra RNs (E-RNs) to stay connected in environment with 50% PNF as shown in Fig. 5.

We also investigate how the number of RNs affects the optimal and random deployments. We test the O3D, R3D, and R3DwOB strategies for different values of (N_{RN} – N_{MST}). For the case of R3D, N_{MST} = 0. The connectivity results are compared in Fig. 6 and demonstrate how the O3D strategy can reach the highest connectivity using the least number of RNs. This is because we select the optimal locations for the used RNs.

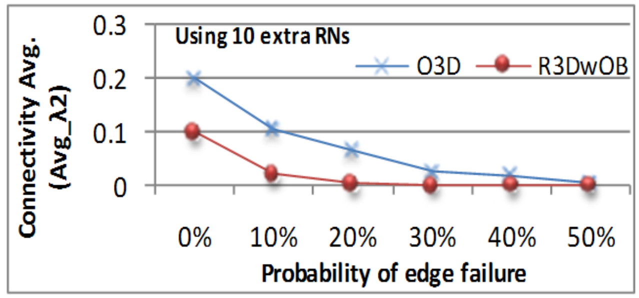


Fig. 3. Comparison of two strategies by PEF.

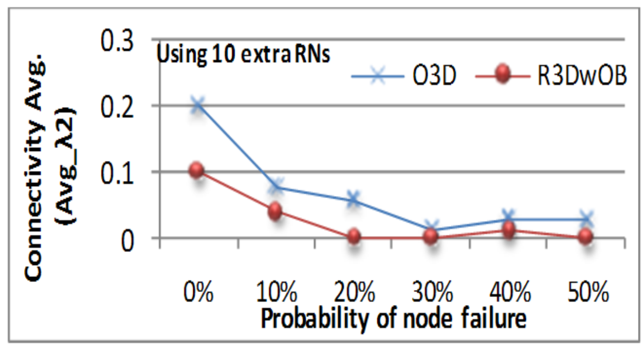


Fig. 4. Comparison of two strategies by PNF.

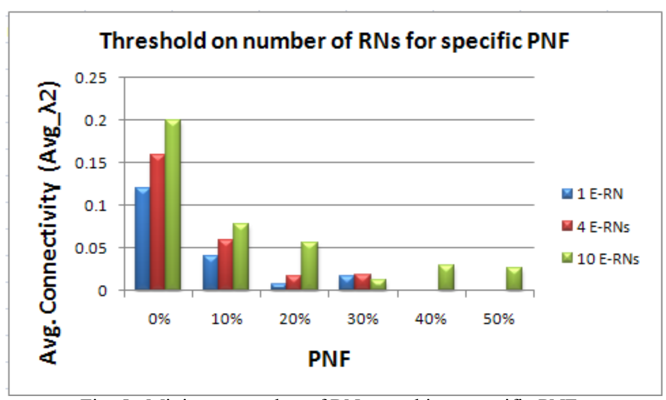


Fig. 5. Minimum number of RNs to achieve specific PNF.

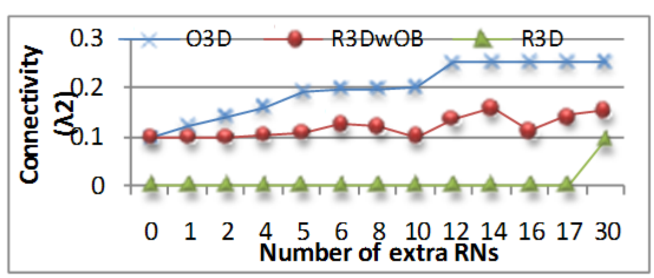


Fig. 6. Comparison of 3 deployment strategies by required number of RNs.

VI. Conclusion

In this paper, we explore the problem of relay node placement in 3D forestry space, aiming at maximizing the connectivity with constraints on the maximum number of nodes. The proposed optimal placement was examined under different probabilities of node/edge failure and compared to other random deployment strategies. The proposed scheme shows robustness and reliability in addition to optimality in terms of connectivity and required relay nodes.

We remark that the deployment process is done offline at the early stages per application requirements; hence time complexity should not be a major issue. Future work includes investigating optimal WSN forestry deployment problem under further constraints, such as lifetime, coverage, energy consumption, and data fidelity. Furthermore, the work can be extended to include adaptive transmission range at RNs and/or SNs.

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