Deploying Fault-Tolerant Grid-Based Wireless Sensor Networks for Environmental Applications

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Abstract— **In this paper, we propose two schemes for sensor and relay node placement in environmental sensing applications. The first scheme aims at maximizing the network lifetime by reducing the total energy consumption. The second does so while maintaining fault-tolerance constraints. It guarantees a lower bound on the minimum required number of faulty nodes. Both schemes are based on a 3-D hierarchical architecture, in which nodes are placed on grid vertices to limit the search space. We divide the lifetime of the network into fixed-length rounds and find the placement which reserves more energy in each round to prolong the lifetime. These problems are formulated via Integer Linear Programs (ILPs). An ILP solver is used to find the optimal placement of nodes in addition to multi-hop routing from the sensors to the base-station in both schemes. Extensive simulations and comparisons, assuming practical considerations of signal propagation and connectivity, show that our fault-tolerant scheme introduces a significant lifetime extension as compared to the first one under the same harsh operational conditions.**

Keywords-sensor networks; fault-tolerance; lifetime; grid-deployment; environmental applications.

I. INTRODUCTION

A wireless sensor network (WSN) is composed of a number of sensor nodes limited in power, computational capacity and memory, which are densely deployed either inside the phenomenon or very close to it. Sensors come in many different types including seismic, low sampling rate, magnetic, thermal, visual, infrared and acoustic, among others, and are able to monitor a wide variety of surrounding conditions [2].

There are countless applications for wireless sensor nodes involving vehicular and personnel monitoring in offices, schools and other work settings. Sensor nodes can be applied in health disciplines, or to detect pollution hazards and control pressure and temperature actuators in industrial plants. Particularly, sensor networks have a wide range of environmental potentials. They are deployed in forests to detect fires or report wild life activities. They are distributed in water-bodies to record events concerning floods, water pollution, coral reef conditions and oil spills. Sensors are of particular importance in areas extremely rural or hazardous such as deserts, polar and volcanic terrines and battle fields. They are able to report sudden seismic activities as well as long-term changes of the chemical compositions in the soil, water and air.

Node deployment in environmental applications is a specially challenging problem due to four main reasons: Probability of Node Failure (PNF), Probability of Disconnected Nodes (PDN), cost and 3-D setups. Sensor nodes deployed outdoors face a variety of arbitrary harshness factors and natural threats, and are hence prone to high probabilities of failure and disconnectivity.

Natural harshness factors include heavy rain, hail or snowfall, sandstorms and extreme temperature variations. Nodes may also be physically destroyed by wild fauna, or may functionally fail due to hardware/software malfunctioning. Even the connectivity links between unharmed nodes are attenuated or lost due to natural causes such as dense trees and growing foliage. Cost in environmental applications is also a critical factor. Nodes in environmental monitoring are significantly more expensive due to the cost of wide-range transceivers used to cover large scale areas such as forests. The scarcity of power resources in outdoor settings is another factor in this regard. Furthermore, 3-D deployment adds to the complexity. Node deployment has to consider the multitude in horizontal and vertical paths, as well. Placement in environmental applications becomes even more intricate when nodes are placed at different vertical levels (e.g. on trees, at soil level and even under ground or water).

Accordingly, sensor networks in environmental monitoring need to overcome constraints regarding the system's lifetime, fault-tolerance and its cost. Lifetime in environmental applications is defined as the duration of the network operation time until a set of critical nodes fail as a result of battery energy depletion causing a network partition [3]. One of the most efficient techniques to prolong the lifetime is achieved by deploying Relay Nodes (RNs) which are capable of transmitting the sensed data for distances farther than those achieved by regular light sensor nodes (LNs). LNs can, hence, invest more battery power in the soul task of data collection. RNs may further be equipped with exceptional storage and processing abilities. Such nodes are very useful to overcome connectivity bottlenecks that threaten to partition the whole network and, hence, degrading the lifetime of the system.

Fault-tolerance implies that failure of any node would still allow its corresponding base station (BS) to completely recover the original data from that failed node [11]. Given the high probability of node failure in environment monitoring, redundancy is commonly applied to achieve this goal. Deploying a multitude of nodes within a specific coverage area increases the probability of message delivery under harshness threats.

Device costs' in environment applications depend on its functionality and hardware components. The more functionality the device has, the more complex and expensive it is. As nodes in environment mentoring are assume to have high functionality in terms of transmission range, sensing capabilities and energy consumption, the cost is considered here to proportional to the number of nodes placed in site. We assume the costs of individual devices of the same type to be identical.

One of the most effective and widely used deployment strategies to handle challenges in environment monitoring is grid-based deployment [4]. Grid deployment can effectively limit the 3-D search space of the candidate positions by placing the sensor nodes on well-organized vertices in regular lattice structures. These vertices can be organized in different arrangements (e.g. Cubes, Octahedrons, Pyramids, etc.) in 3-D space to provide more accurate estimates in terms of the spatial properties of the data. Moreover, grid-based deployment has several other advantages: it can isolate non-feasible positions, accurately describe possible paths to the sink node, and efficiently ensure connectivity. In addition, the grid model becomes necessary when sensor nodes are expensive and their operation is significantly affected by their positions.

In this paper, we characterize the harshness of the monitored environments by PNF and PDN measures. Our work focuses on optimizing the placement of sensor and relay nodes in 3-D space to prolong the network lifetime with constraints on fault-tolerance. To the best of our knowledge, none of the studies conducted previously have considered such circumstances with respect to grid-based placement.

The major contributions of this paper are as follows. We introduce a 3-D grid-based deployment problem, which aims at maximizing lifetime with constraints on wireless sensor network cost and fault-tolerance. The network is supposed to be fault-tolerant in terms of node failures and data recovery. We propose an optimal solution for the 3-D deployment problem, which considers practical signal propagation in harsh environments. Performance of the proposed solution is evaluated and compared to the same approach without considering fault-tolerance. The novelty of this work stems also from discretizing the infinite search space of candidate node locations and from the solid mathematical programming formulation of the 3-D deployment problem.

The remainder of this paper is organized as follows. In Section II related work is outlined. Practical system models and placement problem are presented in Section III. In Section IV our deployment schemes are described. The performance of the proposed schemes are evaluated and compared in Section V. Finally, conclusions and future work are given in Section VI.

II. RELATED WORK

Extensive work has been reported on node deployment strategies, which are mainly classified into two categories: Random and deterministic (grid-based) deployment [12]. In random deployment, nodes are arbitrarily scattered and are managed in an Ad Hoc manner. While in grid-based deployment, nodes are placed according to virtual grid vertices leading to more accuracy in data collection. Due to the interest posed by environmental applications in the exact physical positioning of sensor and relay nodes, grid-based deployment serves this purpose more appropriately, and is hence, adopted in our work. In the following, we list some previously published works that are related to those two deployment strategies. We will concentrate on grid-based deployment as it is the approach adopted in our study.

Xu et. al. [9][10] investigate the most appropriate relays random distribution in 2-D plane to maximize the network lifetime assuming relays are communicating directly with the base-station. They first show that uniform relay distribution often does not extend the network lifetime [9]. This is due to different energy consumption rates at different distances from the base-station. To overcome this shortcoming, a weighted random deployment is proposed. In this deployment, the density of relays which are far away from the base-station is increased to split the traffic load amongst more relays. Thus, the relays average lifetime is extended. However, the weighted random distribution in this approach may leave some sensor nodes disjointed from the base-station. Since, they may be placed so far which makes the base-station out of their transmission range. Therefore, a hybrid approach is introduced in [10] to balance the network lifetime and connectivity fault-tolerance goals.

In [6], the authors proposed a distributed algorithm that achieves k-connectivity in homogenous wireless sensor networks randomly deployed in 3-D space. Simply, the idea is to adapt the nodes' transmission power until either the distance separating two consecutive neighbors is greater than a specific threshold or the maximal power is reached. However, this method is not cost effective due to hardware complexity required to adapt the transmission range. Adapting the transmission range to reach farther distances would increase the power consumption and hence degrade the network lifetime.

Deterministic deployment, on the other hand, is more suitable for applications that care for exact nodal positioning. Coupling node placement with multi-path guarantees enhances lifetime and fault-tolerance chances. The work by Yang et. al. [11] focuses on node placement, and establishing a flow-based routing scheme to ensure multipath guarantees towards fault-tolerant placement while maximizing network lifetime.

The main objective of the relay placement in [5] is to achieve a fault-tolerant wireless sensor network in which there exist at least two disjoint paths between every pair of sensor nodes. A sensor is said to be covered by a relay if it can reach that relay. The authors formulate the placement problem as an optimization problem which has been shown to be NP-hard. Consequently, a polynomial time approximation algorithm is proposed. This algorithm simply identifies candidate positions for relay nodes that cover the maximum number of sensors. Such candidate positions are found at the intersections of the communication ranges of neighboring sensor nodes. Relay nodes with the widest coverage span are then placed at these candidate positions. The algorithm checks whether the relays form a 2-connected graph and every sensor can reach at least two relays. If not, more relays are added and the connectivity and coverage are rechecked. This algorithm is repeated until the objective is achieved. However, relay positions may not be true in reality due to communication range irregularity. In addition, this work becomes difficult in 3-D. Moreover, lifetime and energy constrains are not considered in this algorithm.

The approach presented in [1] counters faulty sensor nodes by repositioning pre-identified spare sensors from different parts of the network. The most appropriate candidate spare node is the one that has the lowest recovery time and overhead making the closest spares more preferable. Minimum recovery time is critical to ensure the fastest data recovery. The lowest overhead provides the most efficient solution in terms of energy consumption and message exchange complexity. In order to detect the closest spare sensor, a grid-based approach is proposed. The targeted region is divided into cells. Each cell has a head advertising available spare nodes in its cell, or requesting the spare ones for it. 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 the cell of failure without affecting the data traffic and the network topology. Even so, node mobility may not be valid when there are obstacles such as trees and buildings in the monitored site, in addition to extreme weather conditions in outdoor applications.

Our work focuses on optimizing the placement of sensor/relay nodes in 3-D space to prolong the network lifetime with constraints on fault-tolerance. Motivated by the benefits of grid deployment as well as the network heterogeneity, our research provides *k* node/link fault-tolerant deployment. We aim not only to ensure *k* disjoint paths from each sensor node to the base-station, but also to ensure that *k* sensor nodes covering a specific region in the monitored site.

III. System Models

In this section, we explain the several models we used in our approach in terms of networking, communication and lifetime. These models were specifically configured to address aspects related to WSN environmental applications as described earlier and specifically with respect to PDN and PNF.

A. Network Model

A two-layer hierarchical architecture is used in order to maximize the network lifetime. The lower layer consists of light sensor nodes (LNs) that sense the targeted phenomena and send measured data to relay nodes (RNs) in the upper layer. Usually these LNs have fixed and limited transmission ranges and do not relay traffic in order to conserve energy. The upper layer consists of relay nodes which communicate periodically with the base-station (directly or via other relay nodes) to deliver the measured data in the lower layer. Relay nodes are assumed to aggregate sensed data and coordinate medium access in addition to relaying measured data to the base-station. Unlike related work in the literature, we focus in this work on the upper and lower layer devices placement as well.

Figure 1 depicts the network architecture assumed in this paper. LNs and RNs are placed on the most appropriate grid vertices; which can serve the largest number of event centers (ECs). These ECs are assumed to represent the designated existence areas of the required phenomenon to be monitored. The base-station is placed based on the application requirements in a fixed position and it is the data sink for the system.

B. Communication Model

A probabilistic communication model is commonly used in the literature. Such a model assumes that the probability of communication between two wireless devices decays exponentially with distance [7]. In practice, wireless signals not only decay with distance, but are also attenuated and reflected by surrounding obstacles such as buildings, trees, etc. Hence, signal strength varies from one position to another based on the distance, and from one direction to another based on distribution of obstacles and the nature of the terrain. Accordingly, the communication range of each device can be represented by a 3-D arbitrary shape as depicted in Figure 2. For realistic estimation of the arbitrary shape dimensions, we need a practical signal propagation model. This model can describe the path loss[1] in the monitored environment by taking into consideration the effects of the surrounding terrain on the

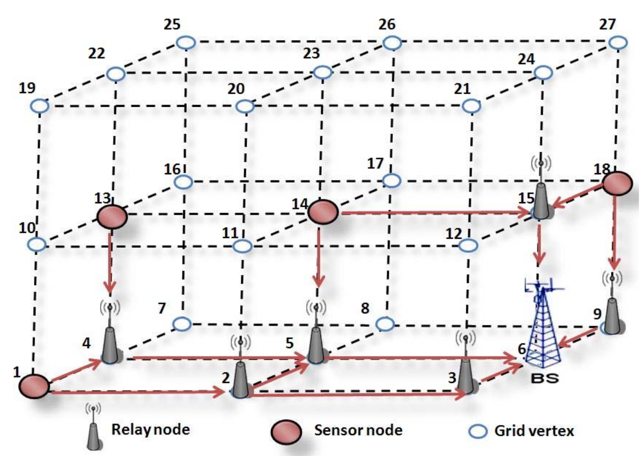

Figure 1. Sensors and relays are placed on the grid vertices to monitor specific event centers surrounded by the grid vertices in 3-D space.

[1] Path loss is the difference between the transmitted and received power of the signal.

Figure 2. An arbitrary shape of the communication range in 3D space.

power (P_r) of received signals as follows [7]

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

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 random variable describing signal attenuation effects[2] in the monitored site, and K_0 is a constant calculated based on the transmitter, receiver and field mean heights.

Assume P_r to be the minimal acceptable signal level to maintain connectivity, and γ and K_0 in Eq. (1) are also known for the specific site to be monitored. Thus, a probabilistic communication model which gives the probability that two devices separated by distance d can communicate with each other is given by

$$P_c(d, \mu) = Ke^{-\mu d^{\gamma}} \quad (2)$$

where $K_0 = 10\log(K)$.

Thus, the probabilistic connectivity P_c is not only a function of the distance separating the sensor nodes but also a function of the surrounding obstacles and terrain, which can cause shadowing and multipath effects (represented by the random variable μ).

C. Lifetime Model

Due to harshness factor in outdoor environmental settings, nodes and communication links are prone to failure. Losing some nodes and links in the network causes isolation for other nodes, which may still have significant energy effect. Thus, running out of energy is not the only reason for lifetime termination in environmental applications. Alternative (redundant) nodes and links are used in such applications to overcome the isolation problem. We also note that the effectiveness of the overall system is little affected by the death of one or a few devices. Therefore, the usability of the WSNs is not limited by the exhaustion of a few devices' power or the partitioning of some redundant devices. In order to take into consideration that node/link redundancy, the following environment-specific lifetime definition is proposed:

Definition 1 (Network Lifetime): Lifetime of a WSN is the time span from deployment to the instant when the percentage of alive and connected irredundant relay/light nodes falls below a specific threshold.

In environmental applications definition, we benefit from device redundancy by considering the network alive as long as a specific percentage of irredundant RNs/LNs, which covers the targeted data, are still alive. These RNs/LNs need not only be alive (i.e. have enough energy and not destroyed), but also must be connected to the base-station. A node is connected to BS if it can reach the base-station via a single hop or multiple hops. Note that connectivity and percentage of live nodes are both addressed in this definition. Performance of the environmental lifetime definition is evaluated by comparing it to connectivity-based and percentage of alive nodes definitions in our previous work [3]. It is worth mentioning that our results showed that our environmental lifetime definition fits more appropriately than the previously mentioned definitions in environmental applications.

Let the number of rounds be the measuring unit of WSN lifetime in this research, where in each round every irredundant RN/LN communicates with the base-station at least once. We assume number of rounds for which a wireless sensor network can stay operational to be the unit measure of the network lifetime. A *complete round* is defined in this paper as the time span t_{round} in which each EC reports at least once to the base-station. In addition, we adopt the energy consumption model proposed in [8] in which energy consumed for receiving a packet of length L is:

$$E_r = L\beta \quad (3)$$

and the energy consumed for transmitting a packet of length L for distance d is:

$$E_t = L(\varepsilon_1 + \varepsilon_2 d^{\gamma}) \quad (4)$$

where ε_1, ε_2 and β are hardware specific parameters of the utilized transceivers, and γ is the path loss exponent. Based on Eqs. (3) and (4), we can calculate the total energy E_{tot} per node after the completion of each round by

$$E_{tot} = \sum_{per\ round} E_t + \sum_{per\ round} E_r \quad (5)$$

IV. Deployment Strategy

The node placement problem proposed in this paper has infinitely large search space and finding the optimal solution is highly non-trivial. Therefore, we propose a 3-D grid model that limits the search space to a more manageable size. We assume knowledge of the 3-D terrain of the monitored site. Hence, practical candidate positions on the grid vertices can be pre-determined; none feasible positions are excluded from the search space. We use cubic grid vertices to apply two schemes for routing and placement of relay and light nodes.

The first scheme is used to maximize the lifetime of the network without any fault-tolerance considerations. The second scheme is used to maximize the lifetime of the network with a lower bound on the minimum faulty (light/relay) nodes the

[2] Wireless signals are attenuated because of shadowing and multipath effects. This refers to the fluctuation of the average received power.

network can tolerate. We expect that adding this extra constraint to the first scheme may shorten the network lifetime since the feasible solutions' space will be reduced. However, fault-tolerance constraints will have a dramatic lifetime increase under harsh operational circumstances where the probability of node failure and disconnectivity is significantly high. The two deployment schemes have been called Relay/Light Nodes Optimum Deployment (RLNOD), and Relay/Light Nodes Optimum Deployment with Fault-tolerance Constraint (RLNODwFC), respectively.

A. The RLNOD deployment strategy

In this section we describe our RLNOD scheme. We aim to solve the following problem:

The lifetime of the network is divided into equal length rounds. We aim towards finding the optimal locations of RN_{total} RNs and LN_{total} LNs together with the routing paths to deliver the generated data from all LNs to the base-station. The objective is to minimize the total consumed energy.

The problem can be formulated as an ILP. We define the following constants and variables.

Constants:

V: set of candidate grid vertices.
v: number of candidate positions on the grid vertices.
ECs: set of Event Centers to be monitored.
k_1: number of back up sensors which are sensing the same event center.
k_2: number of back up relays which are relaying from the same relay node.
LN_{total}: total available light (sensor) nodes.
RN_{total}: total available relay nodes.
f_{ij}: is the flow from node *i* to node *j* (i.e. the data units to be sent from *i* to *j*). The measuring unit of this constant is the bit per second (bps).
G_i: generated traffic by sensor node *i* and measured by (bps).
RG_i: generated traffic by relay node *i* and measured by (bps).
C_i: Capacity of traffic (BW) available for sensor node *i* and measured by (bps).
RC_i: Capacity of traffic (BW) available for relay node *i* and measured by (bps), as well.

Variables:

P_c^{ij}: The probabilistic connectivity between node *i* and *j*.
α_i: A binary variable equals to 1 when a LN is placed at vertex *i* of the 3-D grid and 0 otherwise.
β_{ij}: A binary variable equals to 1 if the vertex i of the 3-D grid is a candidate position to sense the target (event center) *j* and 0 otherwise.
R_i: A binary variable equals to 1 when a RN is placed at vertex *i* of the 3-D grid and 0 otherwise.
N(i): is a set of neighboring indices such that $j \in N(i)$ if node *j* is within the transmission range of node *i* (i.e. $P_c^{ij} \geq \tau$).
τ: is a specific connectivity threshold .
M(N(i)): is a set of indices such that $j \in M(N(i))$ if node *j* is within the transmission range of a node that can reach one of the neighboring nodes of node *i* via single or multiple hops.
E_{total}: Total energy consumed by network nodes per round and measured by (mJ).

Our policy of maximizing the lifetime is to minimize the total consumed energy by RNs and LNs in one round of data gathering. Choosing the placement that consumes the lowest energy per round can reserve an extra amount of energy for more network operational rounds, and hence prolongs the network lifetime. Unlike other placement strategies, we are considering the most appropriate routing paths to the BS in order to prolong the lifetime. We choose routes that balance the traffic load between deployed nodes, without exceeding available bandwidth for each node in the network. In order to do so, we formulate the ILP in Figure 3.

$$Minimize \quad E_{total} \qquad (6)$$

S.t.

$$\sum_{i=1}^{v} \alpha_i = LN_{total} \qquad (7)$$

$$\sum_{i=1}^{v} R_i = RN_{total} \qquad (8)$$

$$\sum_{i=1}^{v} R_j.\alpha_i \geq 1, \quad \forall j \in V \ \& \ j \in N(i) \qquad (9)$$

$$R_j. \sum_{\substack{j \in N(i) and\ (i \in N(BS) \\ or\ i \in M(N(BS)))}} R_i \geq 1, \quad \forall j \notin N(BS) \qquad (10)$$

$$\sum_{i=1}^{v} \beta_{ij}\alpha_i \geq 1, \quad \forall j \in ECs \qquad (11)$$

$$\sum_{i=1}^{v} \alpha_i \left(\sum_{j \in N(i)} E_t f_{ij} \right) + \sum_{i=1}^{v} R_i \left(\sum_{j \in N(i)} E_r f_{ij} + \sum_{j \in N(i)} E_t f_{ij} \right) = E_{total} \qquad (12)$$

$$\sum_{j \in N(i)} \alpha_i . f_{ij} \leq C_i \ , \quad \forall i \in V \qquad (13)$$

$$\sum_{j \in N(i)} R_i . f_{ij} \leq RC_i \ , \quad \forall i \in V \qquad (14)$$

$$\sum_{j \in N(i)} \alpha_i . f_{ij} = G_i, \quad \forall i \in V \qquad (15)$$

$$\sum_{j \in N(i)} R_i . f_{ij} - \sum_{k \in N(i)} R_i . f_{ki} = RG_i, \quad \forall i \in V \qquad (16)$$

Figure 3: ILP formulation for the RLNOD

In Figure 3, Eq. (6) is the objective function that is used to minimize the total energy E_{total}. Eqs. (7) and (8) satisfy the constraints that only RN_{total} relay nodes and LN_{total} light nodes are available, and thus cost constraint is satisfied. Eq. (9) ensures that each relay node is serving at least one light node to ensure connectivity between lower layer and upper layer devices. Eq. (10) determines the minimum number of relay nodes that can be used to route data towards the base-station for relay nodes which are not neighbors to the base-station. In this constraint, we assure that for each relay node *j* outside the neighborhood of the BS there exist at least one relay that is in the neighborhood of both *j* and BS. Eq. (11) guarantees that each event center EC is covered by at least one sensor node. Eq. (12) sets E_{total} to the total energy consumption. The total consumed energy per round is equal to the total energy used for data transmission from light nodes to relays, in addition to the total energy used for transmission and/or receiving at the relay nodes. Eqs. (13) and (14) satisfy the traffic capacity (bandwidth) constraints assuming that each node has a specific limit on the available bandwidth for communication. Using these two Eqs., the proposed ILP can be easily modified to handle more complex capacity constraints (by giving different weights for different links of a single node). Finally, Eqs. (15) and (16) guarantee the flow balance assuming that all nodes of the same type have to generate an equal amount of traffic to avoid overloading some nodes while others are not. Indeed, the last four constraints are required not only to reduce total energy consumed, but also due to the limited energy budget in the context of wireless sensor networks.

B. The RLNODwFC deployment strategy

Even though energy is critical resource in the context of wireless sensor networks, there should be a balance between energy saving and the provisioned fault-tolerance. Fault-tolerance is of the utmost importance in many environmental applications (e.g. forestry). In our RLNOD scheme, which was described in the previous section, a node failure might occur due to several reasons that have been mentioned above. Therefore, we propose the RLNODwFC deployment strategy which has a bound on how many faulty RNs and LNs the network can tolerate. Before introducing this strategy, we start by the following definitions.

Definition 1 (k Fault-tolerant Network): The network is *k* fault-tolerant iff *k* non-operational (relay/light) nodes are required to have network partition or data loss.

Definition 2 (Data Recovery): The lost data can be recovered as long there exist redundant nodes generating and/or relaying the same data.

Now we can define the RLNODwFC problem as follows:

The lifetime of the network is divided into equal length rounds. Find the optimal locations of RN_{total} RNs and LN_{total} LNs together with the routing paths to deliver the generated data from all LNs to the base-station, such that the deployed network is *k* fault-tolerant and data recovery is guaranteed.

In order to solve this problem, we add extra constraints on the optimization problem formulated in the previous section. These constrains guarantee the deployment that can recover lost data and destroyed nodes. As in RLNOD, the objective is again to minimize the total consumed energy per round according to Eq. (17). The optimization problem is formulated as an ILP in Figure 4.

Eq. (20) ensures that each sensor node is connected to at least k_2 relay nodes. Eq. (21) determines the minimum number ($\geq k_2$) of relay nodes that can be used to route data towards the base-station for relay nodes which are not neighbors to the base-station. Eq. (22) guarantees that each EC is covered by at least k_1 sensor node. Eq. (23) is used to ensure data recovery. It prevents the flow splitting by specifying that a relay node *j* can transmit to only one relay node *i*.

$$Minimize \quad E_{total} \qquad (17)$$

S.t.

$$\sum_{i=1}^{v} \alpha_i = \mathrm{LN_{total}} \qquad (18)$$

$$\sum_{i=1}^{v} R_i = \mathrm{RN_{total}} \qquad (19)$$

$$\sum_{i=1}^{v} R_j.\alpha_i \geq k_2, \quad \forall j \in V \;\&\; j \in N(i) \qquad (20)$$

$$R_j. \sum_{\substack{j\in N(i) and\ (i\in N(BS) \\ or\ i\in M(N(BS)))}} R_i \geq k_2, \quad \forall j \notin N(BS) \qquad (21)$$

$$\sum_{i=1}^{v} \beta_{ij}\alpha_i \geq k_1, \quad \forall j \in ECs \qquad (22)$$

$$\sum_{i=1}^{v} T_{ji} = R_j, \quad \forall j \in ECs \qquad (23)$$

$$\sum_{i=1}^{v} \alpha_i \left(\sum_{j\in N(i)} E_t f_{ij} \right) + \sum_{i=1}^{v} R_i \left(\sum_{j\in N(i)} E_r f_{ij} + \sum_{j\in N(i)} E_t f_{ij} \right) = E_{total} \qquad (24)$$

$$\sum_{j\in N(i)} \alpha_i.f_{ij} \leq C_i \;, \quad \forall i \in V \qquad (25)$$

$$\sum_{j\in N(i)} R_i.f_{ij} \leq RC_i \;, \quad \forall i \in V \qquad (26)$$

$$\sum_{j\in N(i)} \alpha_i.f_{ij} = G_i, \quad \forall i \in V \qquad (27)$$

$$\sum_{j\in N(i)} R_i.f_{ij} - \sum_{k\in N(i)} R_i.f_{ki} = RG_i, \quad \forall i \in V \qquad (28)$$

Figure 4: ILP formulation for the RLNODwFC

V. Discussion & Results

In this section, we evaluate the performance of fault-tolerant grid-based deployments in practical settings, where PNF and PDN are considered. We consider the RLNOD scheme as a baseline due to its optimality in prolonging the network lifetime and choosing the minimum number of nodes in the deployment plan.

The RLNOD and RLNODwFC schemes are evaluated and compared using three metrics: 1) the average lifetime, 2) the average energy consumed per byte, and 3) the number of LNs/RNs. The average lifetime is a measurement of the total rounds the deployed network can stay operational for. It reflects efficiency of the network as well. The average energy consumed per byte reflects the efficiency of resource (battery) utilization. Lastly, the number of LNs/RNs indicates the system's cost effectiveness. Meanwhile, two main parameters are used in this comparison: Probability of Node Failure (PNF) and Probability of Disconnected Nodes (PDN). PNF is the probability of physical damage for the deployed node. PDN is the probability of a node to be disconnected while it still has enough energy to communicate with the base-station. We chose these parameters as they are key factors in reflecting harshness of the monitored site in terms of weak signal reception and physical node damage.

The RLNOD and RLNODwFC deployment schemes are executed on virtual 3-D cubic grid vertices distributed in a 900*900*300 (m^3) monitored space. We simulate the deployment schemes while varying the total number of LNs and RNs from 50-300 and 5-30 node, respectively. We vary the PNF and PDN from 0-50%, as well. Based on experimental measurements [7], we set the communication model variables to be as follows: $\gamma = 4.8$, $P_r = -104$ (dB), $K_0 = 42.152$, and μ to be a random variable that follows a log-normal distribution function with mean 3 and variance of 10. The grid edge length is equal to 100 m. The simulator determines whether a sensor node is connected to its neighbors or not based on the aforementioned probabilistic communication model, where τ = 70%. As for the fault-tolerance constraints, we set $k_1 = k_2 = 3$. Each simulation experiment is repeated 1000 times and the average results hold a confidence interval no more than 2% of the average (over 1000 runs) at a 95% confidence level.

As shown in our simulation results, the system lifetime (measured in rounds) improves as the number of LNs is increased in a given specified terrain (Figure 5). This is also true with respect to RNs (Figure 6). The more active nodes available in a given plane the better the connectivity is and the less partitions form in the system. This, consequently, prolongs the lifetime as mentioned previously. The results in Figures 5 and 6 show only a marginal improvement of RLNOD over RLNODwFC given different node counts. This is, indeed, a very promising result. Although the introduction of the fault-tolerance constraint in RLNODwFC yields shorter lifetimes compared to systems that do not tackle that constraint, we argue that this reduction is insignificant and can be tolerated by the addition of extra redundant nodes for both LN and RN deployments. This claim is supported by the nature of the two plots in Figures 7 and 8. The graphs tend to converge as the number of deployed nodes increases. This strongly supports the optimality of our approach.

As for average energy consumed versus number of LNs and RNs in the plane, results show that the higher the number of nodes, the less energy is consumed per byte. In other words, sensed/transmitted data cost less to deliver (in terms of energy) when more sensing nodes are available in the terrain. This translates again to better connectivity of the WSN that assure more reliable delivery. Less energy consumption means longer battery life and, hence, better lifetime. This supports our previous claims. Figures 7 and 8 show, again, that RLNOD slightly over performs RLNODwFC. The same reasoning to justify the slight difference applies here as well. Considering the fault-tolerance while positioning the nodes, lead to

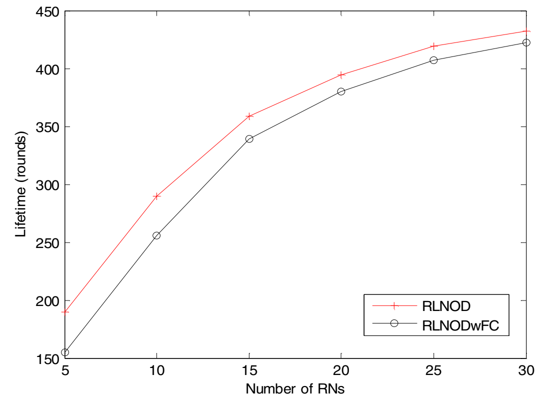

Figure 5. The average network lifetime in rounds vs. the number of relay nodes.

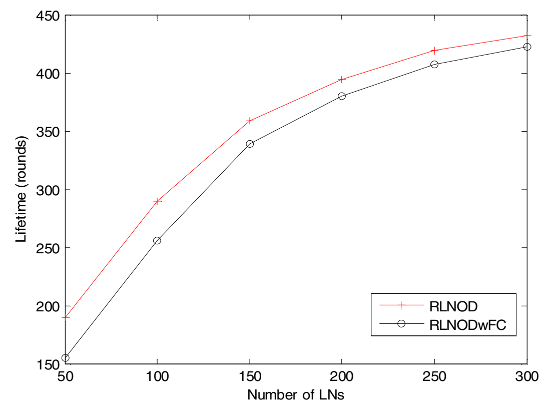

Figure 6. The average network lifetime in rounds vs. the number of light nodes.

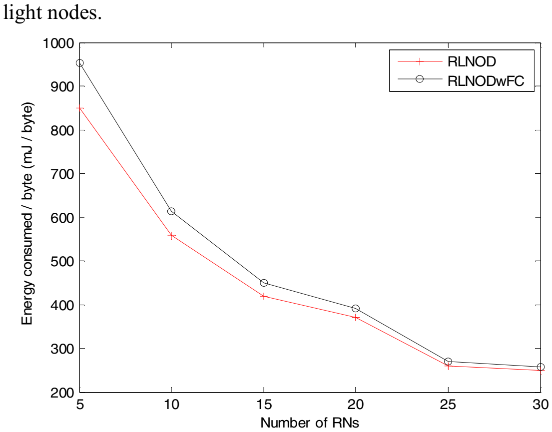

Figure 7. The average energy consumed per byte vs. the number of relay nodes.

positions that might not be optimum for lifetime. Again, having a fault-tolerant deployment is worth the small increase in energy consumption as oppose to nearly same readings for deployments that do not serve fault-tolerance constraints.

Moreover, Figure 9 compares PNF with respect to average lifetime measured in rounds assuming a total number of sensors and relays equal to 150 and 15, respectively. Here apparently, RLNODwFC scores better results than RLNOD. This is also the case when we compared PDN against average lifetime in Figure 10. A system's adoption of RLNODwFC guarantees longer lifetimes for less failure and disconnection probabilities than what is provided by RLNOD. Given the considered

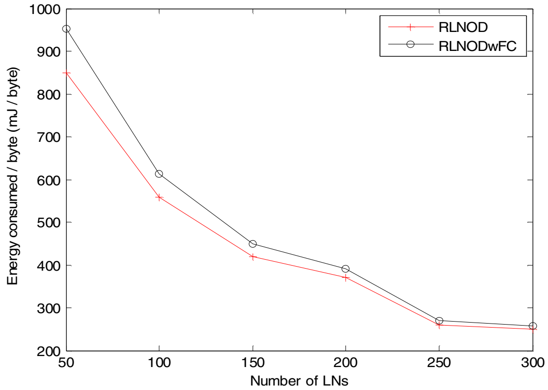

Figure 8. The average energy consumed per byte vs. the number of light nodes.

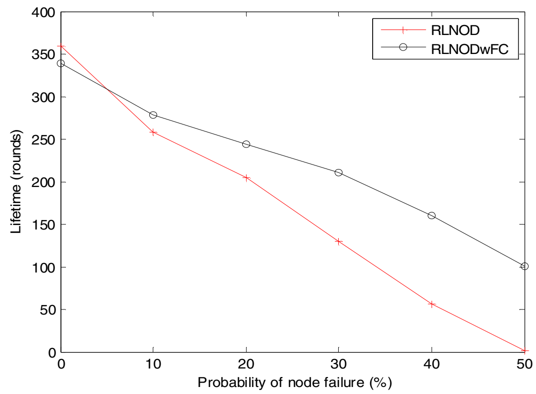

Figure 9. The average network lifetime in rounds vs. the probability of node failure in the monitored environment.

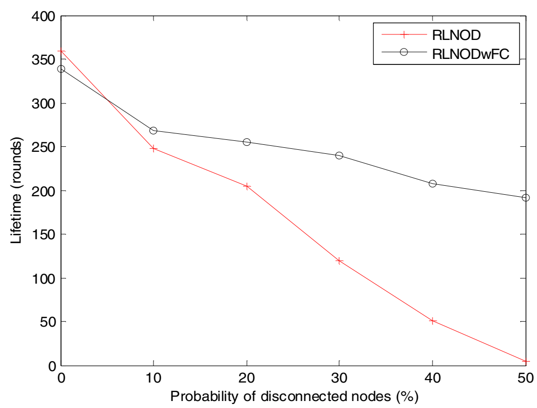

Figure 10. The average network lifetime in rounds vs. the probability of disconnected nodes in the monitored environment.

harshness factors, where failure and disconnectivity rates are expected to be extremely high, RLNODwFC proves to be much better than RLNOD, according to our simulation, and will dramatically impact the extension of the systems lifetime in a positive manner.

VI. CONCLUSION

In this paper, we have introduced a novel approach for node deployment in environmental wireless sensing applications. Our method takes into account constraints regarding harshness factors and their consequences including PNF and PND, in addition to 3-D setup. To the best of our knowledge, this is the first approach that deals with lifetime and fault-tolerance constraints in environmental grid-based deployment. We have compared two optimal node deployment schemes, with one specifically addressing fault-tolerance constraints. Our simulation results show that in terms of average nodal lifetime and average energy-consumption, there is no significant difference between the two approaches. However, in terms of lifetime with respect to probability of node failure and disconnectivity, our fault-tolerant placement scheme shows a dramatic improvement over the non fault-tolerant one. This provides a significant guideline for long-term environmental sensing applications. We remark that the proposed approach is applicable various grid shapes (e.g. Cubic, Octahedron, etc.).

Future work would investigate optimal deployment problems in other scenarios; such as when the relay nodes are mobile. Also of practical interest is the node placement within varying mediums of transmission (e.g. underwater) where signal propagation and node location face different harshness challenges.

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