Optimized Relay Repositioning for Wireless Sensor Networks Applied in Environmental Applications

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***Abstract*— Nowadays Wireless Sensor Networks (WSNs) are used to provide vast coverage areas in environmental applications, and thus relay nodes with wide transmission ranges are employed. However, these relays usually operate under harsh conditions with a very limited energy resources, making the network very prone to severe node failures and disconnectivities. In this paper, we propose a proactive Optimized Relay Repositioning (ORR) approach in which relays are regularly repositioned to maintain a specific level of fault-tolerance in addition to minimize the total network energy consumption. ORR is a grid-based approach, in which nodes are placed on grid vertices to limit the huge search space in large–scale environmental applications. This approach is formulated as a Mixed Integer Linear Program (MILP) for solid mathematical solutions. Extensive simulations and comparisons, assuming practical considerations of signal propagation and connectivity, show that our fault-tolerant approach can introduce a significant lifetime extension as compared to other heuristic and MILP-based approaches.**

***Keywords*-Wireles Sensor Network (WSN); fault-tolerance; lifetime; grid-deployment; environmental applications.**

I. Introduction

Wireless Sensor Networks (WSNs) are composed of Sensor Nodes (SNs) used to sense certain properties of the surrounding environment and send the measured data back to a central system sink, called a Base-Station (BS) [1]. Due to their potential significance in remote data gathering, WSNs have been applied widely in Outdoor Environment Monitoring (OEM) applications such as forest fires and air pollution detection [2][3]. WSNs in OEM are supposed to provide vast coverage areas, and thus Relay Nodes (RNs) with wide transmission ranges are utilized. Nevertheless, these relays are expensive, energy constrained, and face a variety of harsh natural threats, and hence are prone to extensive Probabilities of Node Failure (PNF) and Probabilities of Disconnected Nodes (PDN). Consequently, several relay repositioning schemes have been proposed recently in the literature to overcome these probabilities [4][5]. These schemes are common in performing a relay repositioning only at the occurrence of the network damage. Nonetheless, performing a regular relay repositioning regardless of the damage event can prolong the network lifetime, in addition to maintaining a healthy and functional WSN.

In this paper, we divide the network lifetime into equal rounds, and focus on optimizing the relay repositioning at the beginning of each round to prolong the network lifetime with constraints on the network fault-tolerance. The major contributions of this work are as follows: 1) We limit the huge search space of the relay candidate positions in OEM applications by considering a grid-based deployment (Fig. 1); where RNs are placed only on the grid vertices, 2) We introduce a generic relay repositioning problem, which aims at maximizing lifetime with constraints on the WSN cost and fault-tolerance, 3) We mathematically formulate this problem as an MILP, which considers practical signal propagation in harsh environments, and 4) Effectiveness of the proposed solution considering the relay repositioning per round is evaluated and compared to other related approaches in the literature.

The remainder of this paper is organized as follows. In Section II, related work is outlined. Practical system models and problem definition are presented in Section III. In Section IV, our relay repositioning scheme is described. The performance of the proposed scheme is evaluated and compared in Section V. Conclusions and future works are outlined in Section VI.

II. Related Work

Approaches in relay repositioning can be classified into two categories: 1) Proactive repositioning and 2) Reactive repositioning. In proactive repositioning, relays' positions are changed on a regular basis to achieve a specific goal. Contrary, in reactive repositioning, relays' positions are changed only if a node failure occurs and they do not change otherwise. For example, the approach presented in [6] is to reposition pre-identified spare nodes in the network once it experiences a node failure. The most appropriate candidate spare node is the one that has the lowest recovery time and overhead, and thus, the closest spares are more preferable. In order to detect the closest spare sensor, a grid-based approach is proposed. The grid is divided into cells. Each cell has a head that advertises the available spare nodes in its cell or requests the spares for its cell. A quorum-based solution is proposed to detect the intersection of the requests within the grid. Once the spares are located, they are moved to a cell with failed nodes. Similarly, a reactive approach, called DARA [4], is utilized to replace the failed node with one of its neighbors. The approach requires 2-hop neighbor information at each node so that the effect of the node loss can be assessed, i.e., whether a network partition occurs or not. The candidate among the neighbors of the failed node is picked based on its distance from the failed node. Nevertheless, the authors in [4] and [6] focused on repairing the network connectivity rather than maintaining a specific fault-tolerance level in the generated WSN which is very desirable in harsh OEM applications.

Accordingly, a heuristic repositioning approach is proposed in [7] to re-establish a particular level of fault-tolerance, where each node in the WSN is connected to at least k neighboring nodes. The authors in [8] formulate the repositioning 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 connected to the maximum number of sensors, and thus providing at least two disjoint paths between every pair of sensor nodes. Such candidate positions are found at the intersections of the communication ranges of the neighboring nodes. Relay nodes are then placed at these candidate positions. The algorithm checks whether the relays form a 2-connected graph and that every sensor can reach at least two relays. If not, more relays are added and the connectivity is rechecked. This algorithm is repeated until the objective is achieved. Nonetheless, adding more relays violates the network cost-effectiveness in OEM. And the discovered relay positions may not be accurate in reality due to the ignored communication range irregularity. Moreover, lifetime and energy constrains are not considered in this algorithm.

In contrast to the previous work in [4], [6], [7], and [8], we are interested in providing a proactive relay repositioning approach which not only ensures k disjoint paths from each node to the base-station, but also aims at minimizing the total energy consumed per round, in addition to repairing connectivity problems (if any). This approach is utilizing a MILP model to achieve more optimized solutions. Based on an earlier work [2], our approach considers an OEM-specific lifetime definition, and irregular communication ranges with the deployed nodes for more practical contributions.

III. System Models & Problem Definition

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

A. Network Model

A two-layer hierarchical architecture is used in order to maximize the network lifetime. The lower layer consists of Sensor Nodes (SNs) that sense the targeted phenomena and send measured data to Relay Nodes (RNs) in the upper layer. Usually these SNs have fixed and limited transmission ranges and do not relay traffic in order to conserve energy. The upper layer consists of RNs which communicate periodically with the Base-Station (BS) to deliver the measured data in the lower layer. Relay nodes are assumed to coordinate the medium access, in addition to relaying measured data to the BS. In this work, we focus on the upper layer devices (i.e., RNs) placement. Fig. 1 depicts the two-layer network architecture assumed in this paper. Given a pre-deployed WSN, we are interested in solving the following problem:

Definition 1. *(Problem Statement Definition): Given a specific sensing task with pre-specified SNs, RNs, and BS locations, determine the re-positioning strategy of the RNs so that the network lifetime is maximized while cost and fault-tolerance constraints are satisfied.*

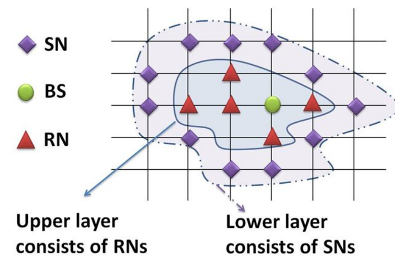

Fig. 1. Grid-based network architecture.

B. Communication Model

In practice, the signal level at distance d from a transmitter varies depending on the surrounding environment. These variations cause an irregular communication range and are captured through the so called log-normal shadowing model [9]. According to this model, the signal level at distance d from a transmitter follows a log-normal distribution centered around the average power value at that point. Mathematically speaking, this can be written as

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

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 normally distributed random variable with zero mean and variance σ^2, i.e. $\mu \sim \mathcal{N}(0, \sigma^2)$, and K_0 is a constant calculated based on the mean heights of the transmitter and receiver.

Using the model in (1), the probability of successful a communication between two nodes separated with a distance d can be calculated as follows. Assume $P_{\min}$ be the minimum acceptable signal level for successful communication between a transmitter and a receiver separated by the distance d. The probability of successful communication is $P_c = \Pr[P_r(d) \geq P_{\min}]$. After some mathematical manipulations, P_c can be written as

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

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

Thus, the probabilistic connectivity P_c is not only a function of the distance separating the deployed nodes but also a function of the surrounding obstacles and terrain, which can cause shadowing and multipath effects (μ). Thus, the ability to communicate between two wireless devices in this work is defined as follows:

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

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 this into consideration, we consider the following OEM-specific lifetime definition [2].

Definition 3. *(Network Lifetime): Lifetime of a WSN is the time span from deployment to the instant when the percentage of alive and connected irredundant relays/sensors falls below a specific threshold β.*

IV. Optimized Relay Repositioning

The relay repositioning problem investigated in this paper has infinitely large search space and finding the optimal solution is highly intricate. Therefore, we propose a grid model that limits the search space to a more manageable size. We use the grid vertices as candidate positions to reallocate the deployed RNs.

Optimized Relay Repositioning (ORR) scheme is used to maximize the network lifetime while maintaining a lower bound on the minimum faulty relay nodes the network can tolerate. We expect that maintaining this constraint may shorten the network lifetime a bit since the feasible solutions' space will be reduced. However, this constraint will have a dramatic lifetime increase under harsh operational circumstances where the probability of node failure and disconnectivity is significantly high.

The ORR scheme divides the network lifetime into equal length rounds. At the beginning of each round, it aims to find the optimal locations of Q_{RN} relays that reserve more energy for the next round. Towards this end, we minimize the total consumed energy per round while considering k fault-tolerant network. Fault-tolerance of the WSN can be quantified by the number or the percentage of the tolerated faulty nodes. Hence, a k fault-tolerant network can be defined as:

Definition 4. (k *Fault-tolerant Network): The network is k fault-tolerant if it can tolerate a maximum of k non-operational nodes before experiencing a network partition.*

The relay repositioning problem defined in the previous section can be formulated as an MILP by defining the following *constants* and *variables*.

Constants:

V: A set of candidate grid vertices.
v: The count of candidate positions on the grid vertices.
k: The count of backup nodes for every single sensor/relay.
Q_{SN}: The total available (pre-deployed) sensor nodes.
Q_{RN}: The total available (pre-deployed) relay nodes.
f_{ij}: The data flow from node i to node j. The measuring unit of this constant is the bit per second (bps).
g_i^{SN}: Generated traffic by sensor node i and measured by bps.
g_i^{RN}: Generated traffic by relay node i and measured by bps.
C_i^{SN}: Capacity of traffic (or bandwidth) available for sensor node i and measured by bps.
C_i^{RN}: Capacity of traffic available for relay node i and measured by bps, as well.

Variables:

P_c^{ij}: The probabilistic connectivity between two nodes i and j.
α_i^{SN}: A binary variable equals to 1 when a sensor is placed at vertex i of the grid and 0 otherwise.
α_i^{RN}: A binary variable equals to 1 when a relay is placed at vertex i of the grid and 0 otherwise.
$N(i)$: A set of neighboring indices such that $j \in N(i)$ if node j is probabilistically connected to node i, (see Definition 2).
$M(N(i))$: A set of indices such that $j \in M(N(i))$ if node j is probabilistically connected to a node that can reach one of the neighboring nodes of node i via single or multiple hops.
E_t: Energy consumed for transmitting a single data packet.
E_r: Energy consumed for receiving a single data packet.
E_{cons}^{tot}: Total energy consumed by the network nodes per round and measured in mJ.

Thereby, we formulate the MILP optimization problem as

$\mathbb{P}_1$:

$$\text{Minimize} \quad E_{\text{cons}}^{\text{tot}} \quad \text{Subject to,} \tag{3}$$

$$\sum_{i=1}^{v} \alpha_i^{RN} = Q_{RN}, \tag{4}$$

$$\sum_{i=1}^{v} \alpha_i^{SN} \cdot \alpha_i^{RN} \geq 1, \quad \forall j \in V \quad \& \quad j \in N(i), \tag{5}$$

$$\alpha_j^{RN} \cdot \Big(\sum_{i \in \{N(BS), M(N(BS))\}} \alpha_i^{RN} \Big) \geq 1, \quad \forall j \notin N(BS), \tag{6}$$

$$\sum_{i=1}^{v} \alpha_i^{RN} \Big(\sum_{j \in N(i)} E_r f_{ij} + \sum_{j \in N(i)} E_t f_{ij} \Big) + \sum_{i=1}^{v} \alpha_i^{SN} \Big(\sum_{j \in N(i)} E_t f_{ij} \Big) = E_{\text{cons}}^{\text{tot}}, \tag{7}$$

$$\sum_{j \in N(i)} \alpha_i^{SN} \cdot f_{ij} \leq g_i^{SN}, \quad \forall i \in V \tag{8}$$

$$\sum_{j \in N(i)} \alpha_i^{RN} \cdot f_{ij} - \sum_{k \in N(i)} \alpha_i^{SN} \cdot f_{ki} = g_i^{RN}, \quad \forall i \in V \tag{9}$$

$$\sum_{j\in N(i)} \alpha_i^{SN} \cdot f_{ij} \le C_i^{SN}, \qquad \forall i \in V \tag{10}$$

$$\sum_{j\in N(i)} \alpha_i^{RN} \cdot f_{ij} \le C_i^{RN}, \qquad \forall i \in V \tag{11}$$

$$\sum_{i=1}^{v} \alpha_i^{SN} \cdot \alpha_j^{RN} \ge k, \qquad \forall j \in V \quad \& \quad j \in N(i), \tag{12}$$

$$\alpha_j^{RN} \cdot \Big(\sum_{i\in\{N(BS), M(N(BS))\}} \alpha_i^{RN} \Big) \ge k, \quad \forall j \notin N(BS) \tag{13}$$

In $\mathbb{P}_1$, Eq. (3) is the objective function that is used to minimize the total energy E_{cons}^{tot}. Eq. (4) satisfies the relay count constraint that only Q_{RN} relay nodes are available, and thus cost constraint is satisfied. Eq. (5) ensures that each relay node is serving at least one sensor node to ensure connectivity between lower layer and upper layer devices. Eq. (6) guarantees that every relay can reach the BS either directly (one hop) or indirectly (multiple hops). 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. (7) sets $E_{cons}^{\text{tot}}$to the total energy consumption. The total consumed energy per round is equal to the total energy used for data transmission from sensors to relays, in addition to the total energy used for transmitting and/or receiving at the relay nodes. Eqs. (8) and (9) fairly divide the traffic between deployed relays such that no single node is overloaded. Furthermore, Eqs. (10) and (11) maintain the limit of the available bandwidth for every node. Using these two Eqs., the proposed MILP can be easily modified to handle more complex capacity constraints (by giving different weights for different links of a single node). Finally, Eqs. (12) and (13) satisfy the fault-tolerance constraints according to Definition 4. Where Eq. (12) ensures that each sensor node is connected to at least k relay nodes. And Eq. (13) determines the least number (=k) of relay nodes that should be used as a backup for the relays outside the BS neighborhood.

V. DISCUSSION & RESULTS

In this section, we validate the effectiveness of our ORR approach under practical OEM settings, where considerable PNF and PDN values are assumed, by simulation and in comparison to related work in the literature. The simulation environment, performance metrics, baseline approaches, and simulation results are described as follows.

A. *Simulation Environment*

Using MATLAB, we simulate randomly[1] generated WSNs which have a graph topology and consist of varying number of nodes. To solve the previously modeled MILP optimization problem, we used MATLAB *lp-solver v5.5* with a timeout of 10 minutes [10].

B. *Performance Metrics & Parameters*

To evaluate the ORR approach, we tracked the following performance metrics:

1. Average WSN lifetime: is a measurement of the total rounds the deployed network can stay operational for, and is measured in *rounds*.
2. Average relay lifetime: is a measurement of the total rounds a deployed relay can stay operational for, and is measured in *rounds*, as well.

Three main parameters are used in this work: 1) PNF, 2) PDN, and 3) the RN count. The PNF is the probability of physical damage for the deployed node. The PDN is the probability of a node to be disconnected while it still has enough energy to communicate with the BS. We chose these two parameters as they are key factors in reflecting harshness of the monitored site in terms of weak signal reception and physical node damage. Finally, the RN count indicates the WSN cost effectiveness.

C. *Baseline Approaches*

The performance of ORR is compared to the following two approaches; DARA [4], and Unconstrained ORR (UORR) [5]. DARA is a heuristic approach in which each node keeps a table of its 1 and 2-hop neighbors. If a node does not receive from its 1-hop neighbor for a specific time period, it assumes that the neighbor has failed and a selection scheme is executed in which the node with the shortest distance to the failed one is moved to cover it. We consider DARA because it is a distributed approach and therefore it is different from the Linear Program (LP) approaches which solve the relay repositioning problem based on a centralized global knowledge. To investigate the effect of the fault-tolerance constraint on the above metrics, we compare our LP-based approach used in ORR with a similar LP-based approach, called UORR [5]. The UORR opts to reposition the network relays exactly like the ORR approach except that it has no fault-tolerance constraints (i.e., without Eqs. (12) and (13) in $\mathbb{P}_1$).

In summary, both DARA and UORR deployment approaches are used as a baseline in this research due to their efficiency in repositioning the RNs, which prolong the network lifetime and provide sustainable WSNs in harsh outdoor environments.

D. *Simulation Setup and Results*

The three deployment schemes: DARA, UORR, and ORR, are executed on 500 randomly generated WSNs in order to get statistically stable results. The average results hold confidence intervals of no more than 2% of the average values at a 95% confidence level. For each topology, we apply a random node/link failure based on a pre-specified PNF and PDN values, and performance metrics are computed accordingly. A Linear Congruential random number generator is used. Dimensions of the deployment area is 900×900 (m^2). We assume a predefined fixed time schedule for traffic generation at the deployed WSN nodes. We assume that each WSN is required to be operational for the maximum number of rounds using a maximum of 50 RNs and 150 SNs (cost constraints).

[1] Random in terms of node positions and network size.

Based on experimental measurements [9], the communication model and simulator parameters are set as in Table 1 below. We point out that the simulator determines whether or not a SN is connected to its neighbors according to the probabilistic communication model described earlier.

Table 1. Parameters of the simulated WSNs.

Parameter	Value	*Parameter*	Value
$\tau = \beta$	70%	r	100 (m)
σ^2	10	PNF=PDN	20%
P_{min}	-104(dB)	Q_{RN}	50
k	3	C_i^{SN}	1000 (byte/hr)
K_0	42.152	C_i^{RN}	2000 (byte/hr)
γ	4.8	$E_{init}^{SN} = E_{init}^{RN}$	3000 (J)
g_i^{SN}	10 (byte/round)	g_i^{RN}	100 (byte/round)

Fig. 2 (a) compares the ORR approach with DARA and UORR. As expected, centralized approaches based on LP models have the highest lifetime rounds since they have global information compared to DARA which is based on 2-hop information, only. However, considering the average lifetime per relay, we notice that DARA shows a better performance than the UORR approach due to involving more nodes in the relay repositioning than those involved by the UORR, as depicted in Fig. 2 (b).

In Fig. 2 (c), ORR shows a significant performance gain in terms of the average WSN lifetime under harsh operational conditions. It outperforms both DARA and UORR by at least 100 rounds. This is due to the considered global information and fault-tolerance constraints.

VI. Conclusion

In this paper, we have introduced a novel approach for the relay repositioning in environmental wireless sensing applications. Our method takes into account constraints regarding harshness factors and their consequences including PNF and PDN, in addition to irregular communication ranges. We have compared two relay repositioning schemes (heuristic and LP-based), with one specifically addressing the fault-tolerance constraints. Simulation results show that in terms of the average nodal and/or network lifetime, the fault-tolerant approach is dominating the other heuristic and LP approaches. Moreover, in terms of the network lifetime with respect to the probability of node failure and disconnectivity, this approach shows a dramatic improvement over the non fault-tolerant ones. This in turn provides a significant guideline for long-term environmental sensing applications. We remark that the proposed fault-tolerant approach is applied on a square grid model in 2D plane. Therefore, in the future, we would investigate it on further 2D/3D grid models (*e.g.,* Cubic, Triangular, Pyramidal, etc.).

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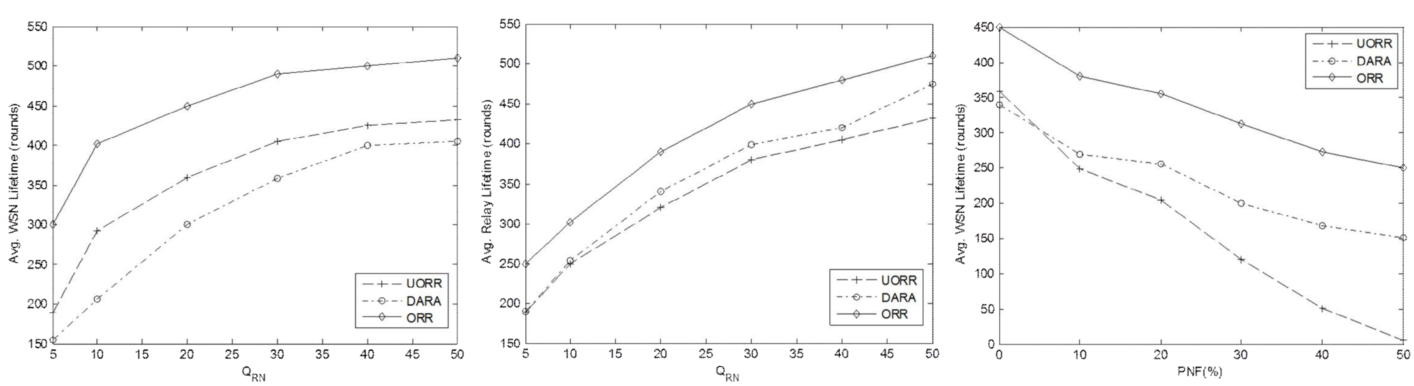

(a) (b) (c)

Fig. 2. Simulation results, where (a) shows the WSN lifetime as a function of the RNs count, (b) shows the relay lifetime as a function of the RNs count, and (c) shows the WSN lifetime as a function of the PNF/PDN.