Energy Harvesting Aware Relay Node Addition for Power-Efficient Coverage in Wireless Sensor Networks

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***Abstract*—This paper deals with power-efficient coverage in wireless sensor networks (WSN) by taking advantage of energy-harvesting capabilities. A general scenario is considered for deployed networks with two types of sensor nodes, harvesting enabled nodes (HNs), and none-harvesting nodes (NHNs). The aim is to use only the HNs for relaying packets, while NHNs use will be limited to sensing and transmitting their own readings. The problem is modeled using graph theory and reduced to finding the minimum weighted connected dominating set in a vertex weighted graph. A limited number of relay nodes is added at the positions close to the NHNs in the resulted set. The weight function ensures minimizing the number of NHNs in the set, and thus reducing the relay nodes to be added. Our contribution is to consider relay node placement (addition) in energy harvesting WSN, where only HNs are used to forward packets. This is to preserve the limited energy of NHNs. Extensive simulation results show that the proposed relay node addition strategy prolongs the network lifetime, from the double, to factors of several tens of times. This is at a reasonable cost in terms of the number of relay nodes added, which is compared to a lower-bound derived in the paper.**

I. Introduction and Related Work

Energy harvesting technologies (solar, wind, thermal, etc.) will play a central role to provide dependable wireless sensor network (WSN) applications in the future. With the constant increasing gap between motes complexity/energy consumption and the battery capacity on the one hand, and the limitations of power management strategies on the other hand [1], exploring new paradigms such as environment harvesting is appearing to be the key solution to the energy problem. The energy harvesting technologies are constantly evolving and maturing, and their complexity is expected to be reduced in the future to provide components that appropriate for WSN. Augmenting the sensor motes with the ambient energy harvesting capability will eliminate the problem of permanent battery drying out (dead nodes). However, the existing solutions proposed for problems in traditional WSN need to be revisited before real applications can take profit of energy harvesting technologies. In this paper, we are interested in the problem of relay node placement.

The placement of additional relay nodes upon node deployment has largely been used in traditional WSN, where the aim has been the improvement of some properties such as maximizing the network lifetime [2], survivability [3], and network connectivity [4], [5]. Such solutions do not consider node capability for energy harvesting, which adds another dimension to research in wireless networks [6]. A lot of works have been devoted to stochastic harvesting models, such as [7], [8], [9]. Duty cycle management using game theoretical models has also been investigated [10], [11]. Clustering in the context of energy harvesting has been considered in [12]. Relay node placement, the topic of this paper, has been recently addressed in the literature. Solutions for the two-tier model where only relay nodes forward the traffic has been proposed in [13], [14]. In this paper, we are interested in the one-tier model, where both sensors and dedicated relay nodes may forward traffic.

Despite the problem of relay nodes placement in the one-tier model has been considered in the literature for traditional WSN, the only excising work for energy harvesting WSN– to our knowledge– is by Misra et al. [15]. The authors consider the scenario where possible locations for relay nodes placement are limited and known a priori, and every potential location is supposed to have a constant energy harvesting potential. The authors modeled the problem with a normalized weighted graph and propose a solution based on existing Steiner-tree look-up heuristics, where the objective function was to put the minimum number of relay nodes such as to maximize harvesting. While all sensor nodes are supposed not to be harvesting-enabled, they are used to forward packets similarly to the added relay nodes. The latter are added only to improve connectivity. This does not ensure high network lifetime, as sensor batteries depletion will cause network partitioning regardless of maximizing harvesting at relay nodes. We consider a different and more realistic scenario here, where sensor nodes may be equipped with harvesting modules. Two types of sensor nodes may co-exist in the network, harvesting enabled nodes (HN), and non-harvesting nodes (NHN). The objective is to add relay nodes in a way that permit to completely eliminate NHN in data forward. This function will thus be ensured by HNs and the added relay nodes, while the use of NHN will be limited to sensing and transmitting their own readings. The remaining of the paper is organized as follow: The network model and the problem formulation are presented in Sec. II, followed by the problem resolution description in Sec. III. Numerical analysis is presented in Sec.

IV, where the a lower-bound is derived using ILP, and the proposed solution is evaluated with a comparative simulation study. Finally, Sec. V draws conclusions.

II. Network Model and Problem Formulation

A. Definitions

Definition 1 (connected dominating set): A connected dominating set for a graph, $G = (V, E)$, is a sequence of vertices, $S \in V$, that fulfils, i) $\forall u \in V \setminus S, \exists v \in S, (u, v) \in E$, ii) The subgraph induced by S is connected. The set of all sequences that satisfy this condition is denoted by $CDS(G)$.

Definition 2 (minimum connected dominating set): A minimum connected dominating set for a graph, $G = (V, E)$, is a connected dominating set with a minimum number of vertices, i.e.

$$S = \underset{\xi \in CDS(G)}{\arg\min}\ |\xi|.$$

The set of all sequences that satisfy this condition is denoted by $MCDS(G)$.

Definition 3 (minimum weighted connected dominating set): A minimum weighted connected dominating set for a vertex weighted graph $G = (V, E, W)$– where W is a function that assigns a weight to every vertex in V– is a connected dominating set with a minimum cumulative weight.

$$S = \underset{\zeta \in CDS(G)}{\arg\min} \sum_{u \in \zeta} W(u).$$

The set of all sequences that satisfy this condition is denoted by $MWCDS(G)$.

B. General Model and Principles

The network is represented by a undirected unit disk graph, $G = \{V, H, E\}$, where the set of vertices, V, represents the nodes, and E is the set of edges. $(u, v) \in E$ iff the distance between the two nodes, u and v, is no more than R, where R, the communication range of a node, is supposed to be constant. The set V is composed of two subsets, the harvesting nodes set, H, and the none-harvesting nodes set, $V \backslash H$. The harvesting nodes are supposed to have enough capacity of harvesting to keep their batteries alive all the time. This may be ensured for low data traffic applications with long inactive periods, where nodes have enough time for harvesting between cycles. V may include one or several base-stations that may or may not forward packets. This depends on the application scenario and policy, although the base-stations are generally energy unconstrained nodes. The proposed solution works in both cases. For abstraction; if base-stations can be used to forward packets, they are to be included in H. Given that nodes of the set, H, may be regarded as energy unconstrained nodes, contrary to those in $V \backslash H$ set, it is intuitively power efficient to use only the former for packet relaying to the base-station(s). The problem is thus to ensure data forwarding exclusively through nodes from H, with addition of a limited number of relay nodes for coverage.

C. Problem Formulation

The problem described in Sec. II-B can be resolved in the model represented by, $G = (V, H, E)$. This is by finding a connected dominating set, $S \in CDS(G)$, with a minimum number of nodes from $V \setminus H$ (non-harvesting nodes). Let us denote this problem by $P1$. Once $P1$ is resolved, relay nodes may be added at the positions close to none-harvesting nodes (if any) of the resulted S. These relay nodes may be regular harvesting-enabled sensor nodes (similar to those in H), or dedicated resource unconstrained relay nodes.

Theorem 1: The problem $P1$ is NP-hard.

Proof: This problem is very similar to the traditional minimum connected dominating set problem (MCDSP), which is known to be NP-hard. The only difference is to minimize the number of elements in the MCDS from a subset of V ($V \setminus H$), instead of the set V. It is easy to demonstrate the general form of this variant is also NP-hard by using the traditional MCDSP.

Lemma 1: $MCDSP <_p P1$.

To prove Lemma 1, it should be proven that the ordinary MCDSP reduces to $P1$. Searching an $MCDS(G = (V, E))$ is equivalent to $P1$, with instance $G' = (V, \emptyset, E)$. In other words, the solution of $P1$ with instance G', say S, is a solution for the the traditional MCDSP ($S \in MCDS(G)$). Therefore, $MCDSP <_p P1$.

From Lemma 1, it results that $P1 \in NP-hard$. □

III. Problem Resolution

To our knowledge, the problem $P1$ has not been treated in the operational research and graph theory literature. However, since it is very similar to the traditional MCDSP, we propose a transformation to some existing variant of MCDSP. The graph, $G = (V, H, E)$, of $P1$ is transformed into a vertex weighted graph, $G_w = (V, E, W)$, as follows.

$$\forall u \in H, W(u) = 1, \forall v \in V \setminus H, W(v) = n - 1. \quad (1)$$

Where n is the number of vertices in the graph ($n = |V|$). The sets, V and E, are unchanged. The use of $n - 1$ is motivated by the maximum number of vertices in a MCDS; that is, $n-2$. The use of a number larger than $n-2$ is helpful for the transformation, which will be explained later.

The problem $P1$ then reduces to finding a minimum-weight connected dominating set ($S \in MWCDS(G_w)$). In the following, the new problem is denoted by $P2$.

Theorem 2: If S is a solution for $P2$ (i.e, $S \in MWCDS(Gw)$), then it is a solution for $P1$.

Proof: The aforementioned theorem may be proved by reductio ad absurdum. Suppose $S \in MWCDS(Gw)$, i.e.,

$$W(S) = \sum_{u \in S} W(u) = \min_{\zeta \in CDS(G)} \sum_{u \in \zeta} W(u), \quad (2)$$

and assume it is not an optimum for $P1$. This means, there is a CDS, say S', which includes less elements from $V \setminus H$ than S. That is,

$$\exists S' \in CDS(G), |S \cap V \setminus H| - |S' \cap V \setminus H| \geq 1 \quad (3)$$

Multiplying both sides of the inequality in Eq. 3 by $n-1$ yields:

$$(n-1)|S \cap V \setminus H| - (n-1)|S' \cap V \setminus H| \geq (n-1) \quad (4)$$

Since an MCDS may not include more than $n-2$ vertices,

$$|S' \cap H| - |S \cap H| \leq n-2 \quad (5)$$

By subtracting Eq. 5 from Eq. 4 we get,

$$(n-1)|S \cap V \setminus H| + |S \cap H| - \\ ((n-1)|S' \cap V \setminus H| + |S' \cap H|) \geq 1 \quad (6)$$

It results from Eq. 1 that:

$$W(S) = |S \cap H| + (n-1)|S \cap V \setminus H| \quad (7)$$

$$W(S') = |S' \cap H| + (n-1)|S' \cap V \setminus H| \quad (8)$$

Therefore, Eq. 6 is equivalent to $W(S) - W(S') \geq 1$. This means $W(S') < W(S)$, which is contradictory with Eq. 2. □

Resolving $P1$ is thus equivalent to resolving $P2$. Given that the later is NP-hard, a heuristic is to be used. Several heuristic are proposed in the literature, such as [16], [17], [18], and they can be used in the proposed general solution framework illustrated by Algorithm 1. This algorithm has as input (line 1) the set of nodes, V, the position of each node, the communication range, denoted by R. Harvesting enabled nodes are represented by the subset H ($H \subset V$). The last input is a heuristic that calculates the minimum vertex-weighted connected dominating set, denoted by $\hbar$. The proposed algorithm makes abstraction of this heuristic, and it is flexible to employ any appropriate heuristic. The output of the algorithm (line 2) is the set of positions where the relay nodes should be placed to ensure connectivity. The algorithm starts by initiating the sets W, E, and S_0 (line 3), and then constructing the set of edges, E, as defined in Sec. II-B (lines $4-5$). The vertices' weights are then calculated by applying the formula given in Eq. 1 (line 6 throughout 8), and inserted into the set W. The resulted weighted graph, $G_w = (V, E, W)$, is passed as input to the heuristic $\hbar$ in line 9, which produces the MCDS, χ. The none-harvesting nodes from χ are denoted ξ, whose positions represent the output of the algorithm. The relay nodes are then to be put next to these positions to replace the appropriate nodes in forwarding packets. The non-harvesting nodes at those positions will be used only to collect and transmit their own data. With the addition of such relay nodes, the proposed solution ensures that the network can be connected (area covered) only though harvesting-enabled sensors, plus the new relays.

Algorithm 1: General Solution Framework Algorithm

1 **Input:** a set of nodes, V, and their positions, the communication range, R, a set of harvesting-enabled nodes $H \subset V$, and a heuristic for minimum vertex-weighted connected dominating set, $\hbar$
2 **Output:** The set of positions, S_p, where to put the relay nodes.
3 **Init:** $W = E = S_0 = S_P = \emptyset$
4 **Construct the set of edges, *E*:**
5 $\forall (u, v) \in V^2$ if($distance(u, v) \leq R$) add (u, v) to E
6 **Assign weights to vertices (construct *W*):**
7 $\forall u \in H$, add $(u, 1)$ to W,
8 $\forall v \in V \setminus H$, add $(v, n-1)$ to W.
9 Run $\hbar(V, E, W)$ to get an approximation of MWCDS(G_w), say χ.
10 $\xi = \chi \bigcap (V \setminus H)$.
11 $\forall u \in \xi$ add the position of u to S_P.
12 return S_P

IV. Numerical Analysis

A. Lower-bound Derivation

The cost of the proposed solution is proportional the number of relay nodes it adds. This depends on the MWCDS heuristic to be used. The lower bound can be obtained be determining the optimal solution to this problem. This is resolved in the following using integer linear programming. The MWCDS can be modeled by the following integer linear program:

$$\min \sum_{i=1}^{n} \omega_i X_i \quad (9)$$

S.t,

$$X_i + \sum_{j \in \mathcal{N}(i)} X_j \geq 1, \forall i \in V \quad (10)$$

$$\sum_{i \in \mathcal{N}(1)} F_{1,i} = \sum_{i \in V, i \neq 1} X_i \quad (11)$$

$$\sum_{j \in \mathcal{N}(i)} F_{j,i} - \sum_{j \in \mathcal{N}(i)} F_{i,j} = X_i, \forall i \in V, i \neq 1 \quad (12)$$

$$0 \leq F_{i,j} \leq n X_j, \forall (i,j) \in E, j \neq 1 \quad (13)$$

$$\sum_{i \in N(1)} Y_i \leq 1 + X_1(|N(1)| - 1) \quad (14)$$

$$F_{1,i} \leq n Y_i, \forall i \in N(1) \quad (15)$$

$$F_{i,j} = 0, \forall (i,j) \notin E, \text{ or } j = 1 \quad (16)$$

Where the inputs of the ILP are, i) the graph $G = (V, E, W)$; ii) ω, as the vectorial representation of the weight function (W); iii) N(1), as the set of neighboring nodes, of an arbitrary node, v_1. The outputs are: i) a vector of booleans, X, which represents the decision variables, i.e., $X_i = 1$ iff vertex, $v_i \in V$, is selected in the MCDS. ii) The flow matrix of integers, $F_{i,j}$, $(v_i, v_j) \in E$, as well as the vector Y_i, $v_i \in N(1)$, are additive variables used to model the connectivity as it will be explained hereafter.

The objective function, Eq. 9, is to minimize the total weight of vertices in the selected CDS, to achieve MWCDS. The constraint represented by Eq. 10 is to guaranty that either v_i is the CDS ($X_i = 1$), or it has some edge towards some vertex in the CDS (at least one of the terms $a_{i,j}X_j$ should equal 1). Constraints represented by Eq. 11 to Eq. 15 are for medeling the connectivity requirements. The principle is to generate a flow, only from vertex v_1. The amount of this flow is the exact amount to cover the CDS (Eq. 11), i.e., it should be $\sum X_i$ if v_1 is out of the set ($X_1 = 0$), or $\sum X_i - 1$ if it belongs to the CDS (one of the dominating vertices). In the former case, v_1 inevitably would have at least one edge towards a dominating vertex. The generated follow traverses the dominating vertices and at every one, a single unit of the flow fades (Eq. 12). Eq. 13 verifies every flow is bounded by 0 and n, and that no flow goes to dominated vertices (for which $X_j = 0$). This is as the term $f_{i,j}$ vanishes when $X_j = 0$. Note here that a more strict uper bound that would reduce the search space is $\sum Xi$ instead of n, but this would make the inequalities non-linear. Also note that the later condition, combined with Eq. 11 when $X_i = 0$, ensures no flow will be generated from vertices out of the CDS.

Constraints represented by Eq. 14 and Eq. 15 are used to limit the number of neighbors node v_1 can transfer its flow to. A binary vector, Y, is added to the outputs such that $Y_i = 1$ iff flow is permitted from node, v_1 to node, v_j. Constraint Eq. 15 ensures that a flow can only be transferred from node v_1 to v_i if $Y_i = 1$, while 14 forces Y_i to be one for only a single neighboring node in case, $v_1 \notin CDS$. Otherwise, it is bounded by the number of v_1's neighbors. Final, conditions expressed by Eq. 16 are to ensures the flow travels only through existing edges, and no flows enters v_1. Note that the latter just reduces the number of the LP variables, and does not represent constrain to be verified by the LP resolver.

This ILP is also NP-hard, but exact resolution for limited size is possible with state-o-the-art resolvers (e.g., CPLEX), which serves as the lower-bound for the proposed solution in the following analysis.

B. Comparison and Performance Evaluation

Given that no solution from the literature uses a model that is similar to the proposed solution with similar objectives, i.e., adding relay nodes to minimizing the use of non-harvesting nodes[1], it is compared to: i) a simple harvesting-aware solution, we call trivial harvesting-aware (THA), and ii) the optimum solution derived in IV-A (lower-bound). The former minimizes the use of non-harvesting nodes without relay node addition. This is simply by calculating the shortest paths on the node weighted graph, where the weights reflect node harvesting capability (Eq. 1). The comparison is in terms of network lifetime (defined as the time to first battery drain), and the cost (the number of relay nodes added). We used Network X environment to implement the network simulator, and CPLEX to resolve the ILP.

To calculate the MWCDS in the proposed solution, a simple greedy heuristic based on [18] is implemented. The MWDS (minimum weighted dominating set) is first constructed by gradually covering nodes. This is by adding at each step nodes with the lowest weight, as the first criterion, and then with the highest connectivity with uncovered nodes, until covering all the nodes. A simple clustering of the resulted CDS, along with spanning tree construction on the resulted auxiliary graph are used to connect the MWDS. Although this heuristic does not ensure the best approximation, it has the advantage of low computation complexity and thus scalability. There are some new algorithms developed by the graph theory community with theoretically proved good approximation, but at the cost of a much higher computation complexity, which prevents scalability to a high number of nodes.

We simulated different scenarios by varying the following parameters: i) number of nodes, ii) the percentage of harvesting nodes, and iii) the network degree (average number of neighboring nodes per node), to measure the performance metrics. For varying every parameter, the remaining ones have been set to values close to their mean, respectively 300 nodes, 40%, and a degree of 10 neighbors. For every generated topology, a single node is randomly picked up as a sink, and every other node periodically generates and transmits a packet to the sink every cycle. We used the parameters that features $CC2420$ radio to measure energy consumption. Every point in the following plots is the result of 40 executions (each with a different random generated graph), and the the results are presented with 95% confidence interval.

In the proposed solution (MRA), the energy consumption that affects the network lifetime is that for transmitting the nodes' own readings. This is as only harvesting nodes and dedicated relay nodes– that are energy unconstrained nodes– are used to forward traffic. Therefore, the lifetime becomes only proportional to the network traffic in the simulated scenarios, which explains its invariance in the plots of Fig. 1, Fig2, Fig3, where it was at $5.4 * 10^9$ cycles. On the contrary, Fig. 1 shows that THA's lifetime drops from $1.39 * 10^9$ for 50 nodes (more than three times lower than MRA), to $0.763 * 10^9$ for 600 nodes (more than 71 times lower). It further drops from $5.2 * 10^9$ for 10% of non-harvesting nodes, to $0.02 * 10^9$ for scenarios for 90% of non-harvesting nodes. Here, the difference with MRA also increases sharply, where it reaches the double for 30% of non-harvesting nodes, and it keeps rising to more than 274 times higher. The drop in THA is explained by the use of non-harvesting nodes as relays, to forward traffic towards the sink. This usage increases with the increase in the number of nodes (Fig. 1), as well as with the increase of the non-harvesting nodes. However, the rise in the

[1]The only solution for relay node placement in energy harvesting WSN is [15]. But it uses a completely different model with different assumptions and objectives (Sec. I)

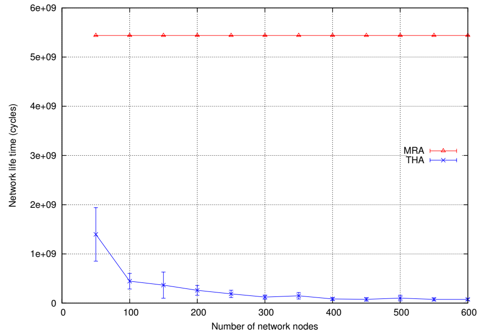

Fig. 1: Network lifetime vs. number of nodes

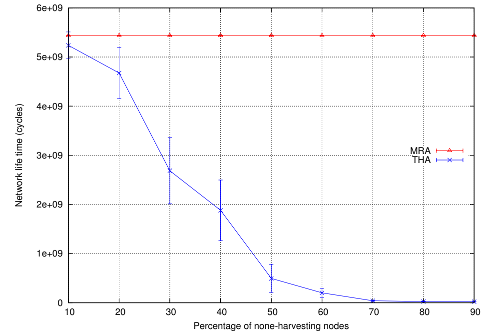

Fig. 2: Network lifetime vs. percentage of non-harvesting nodes

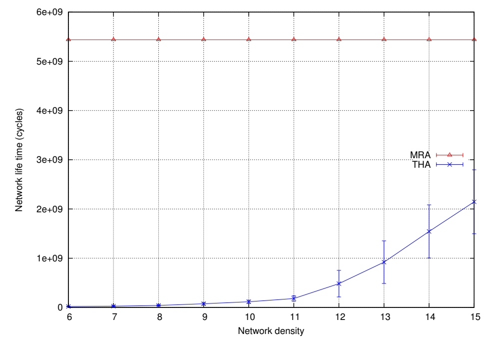

Fig. 3: Network lifetime vs. network degree

network degree improves the network lifetime of THA, as this helps finding routes with lesser non-harvesting nodes (Fig. 3). But still, the difference with MRA is very important and it is much more than the double even for very high network degree. The cost of this improvement is the addition of relay nodes. THA does not add any relay nodes and it is not represented in the cost figure as it is always null. For this metric, MRA is compared with optimum solution (ILP exact solution) that represents the lower bound (LB) of the proposed model. Given the exponential computation complexity of ILP resolver (exact solution), it was not possible to run the resolver for high number of nodes. Therefore, the comparison with LB is limited to low number of nodes (Fig. 4), but the cost of MRA is also presented separately for high number of nodes (Fig. 5). Also, note that it was not possible to simulate LB with average number of nodes (300 nodes) when varying the other metrics, given the exponential complexity of the CPLX. Hence it was fixed to 100, and plots with 300 nodes are also provided for comparison with MRA's 100 nodes, Fig. 7 and Fig. 6. These figures show that the cost of MRA is close to that of LB. The increase in the network degree helps finding dominators from the harvesting nodes, which explains the reduction of the added relays for both scenarios with 100 nodes and 300 nodes in Fig. 7. On the other hand, the increase in NHNs inevitably causes an increase in the number of added relays, but this remains reasonable even for high percentage of NHNs and does not exceed 25 nodes on average for 100 nodes scenarios, and 72 nodes for 300 nodes scenario (less than 24% from the total number of nodes).

From Fig. 5, it is clear that the difference between MRA and LB increases with the number of nodes, but MRA's cost remains reasonable, where the difference vs. LB does not exceed two nodes even for 140 nodes scenario (5.9 vs. 3.9). MRA's reasonable cost is also confirmed for higher number of nodes in Fig 4, where it remains below 20 for 600 nodes (which represents less than 3%).

V. Conclusion

Communication coverage for energy harvesting enabled wireless sensor networks (WSN) has been considered in this paper. The considered environment includes two types of

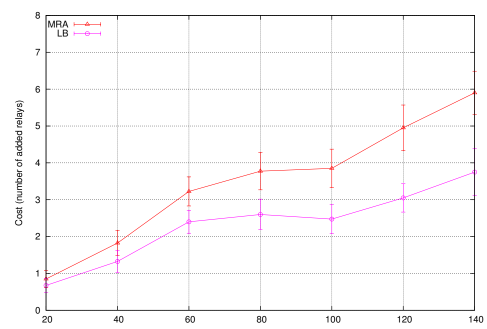

Fig. 4: Cost vs. number of nodes

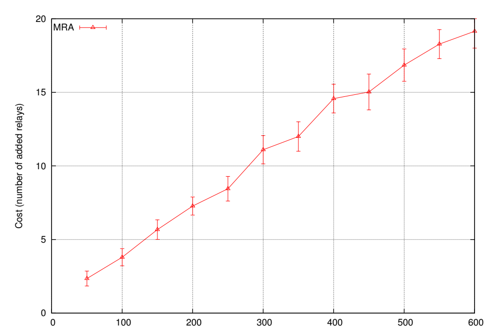

Fig. 5: Cost vs. number of nodes

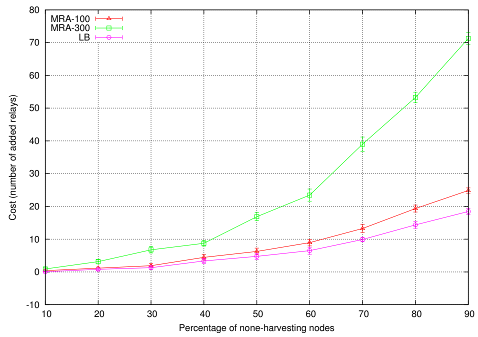

Fig. 6: Cost vs. percentage of non-harvesting nodes

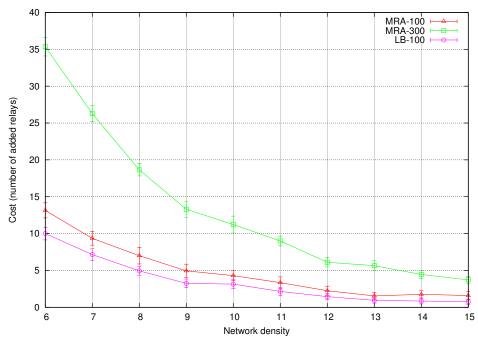

Fig. 7: Cost vs. network degree

sensor nodes, harvesting enabled nodes (HNs), and none harvesting nodes (NHNs). The proposed solution aims at limiting the use of NHNs to data reading, and ensuring coverage via HNs, with addition of relay nodes when necessary. The problem has been modeled, proved to be NP-hard, and reduced to finding the minimum weighted connected dominating set (MWCDS) in a vertex weighted graph. An integer linear program (ILP) has been derived as an optimal solution of the problem, which represents a lower bound (LB) for the number of relay nodes to be added. Given the exponential computation complexity of ILP resolvers, a heuristic should be used. In the implementation, we used a simple greedy heuristic from the literature of general MWCDS. Extensive simulations that compares the solution with the trivial power harvesting aware routing and the LB confirms effectiveness of the proposed solution. It prolongs the network lifetime, from the double, to factors of several tens of times for high number of nodes, and/or high percentage of non-harvesting nodes. This is at an inevitable cost of adding relay nodes. Results demonstrate the number of the added relay nodes is reasonable and scales with the increase in the number of nodes. However, there is still an important difference compared to the LB. This an indication as the heuristic for MWCDS calculation has an impact. Proposing a heuristic that takes into account the particularity of the problem, i.e., the use of only two wights, may helps reaching better MWCDS than those proposed for the general problem. This represents a perspective that will be treated in our future work. The solution supposes that the harvesting nodes have enough capacity of harvesting to keep their batteries alive all the time. Although harvesting technologies are evolving, it is early to fulfill this assumption for high data rate applications such as those involving video/images transmissions. Relaxing this assumption by considering limited harvesting capacities as well spatialy/temporaly variable capacities at harvesting nodes also represents a perspective.

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