# Energy Harvesting Aware Minimum Spanning Tree for Survivable WSN with Minimum Relay Node Addition

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*Abstract*—**Survivable wireless sensor networks that take advantage of green energy resources from the environment is considered in this paper. The particular problem of constrained relay nodes (RNs) placement to ensure communication coverage in the single-tiered topology while taking advantage of the energy harvesting potentials of sensor nodes (SNs) is dealt with. The contribution is to consider a realistic energy harvesting model where harvesting potentials may vary from one node to another. Without loss of generality, the energy model used in this paper is appropriate to wireless charging, but the proposed solution can be extended to the use of any energy harvesting technology. Based on this model, we propose a heuristic based on spanning tree calculation in an edge weighted graph model where the traffic routed at every node is proportional to its effective energy. RNs are added to help non-leaf nodes in the tree that cannot meet the defined survivability condition. A lower-bound of the proposed model is derived using integer linear programming. The proposed solution is compared by simulation to the single solution from the literature that treats the problem of RNs placement while considering energy harvesting capacity of SNs. A simplified model is used in the simulation to allow comparison. The performance results show that the proposed solution ensures survivability by adding a lower number of RNs.**

## I. INTRODUCTION

Green communication is not anymore an option but becomes an inevitable choice to preserve our environment, and to enable large scale deployments of future communication networks. For example, energy harvesting from the environmental resources such as electro magnetic waves (wireless charging), solar, wind, etc., is appearing to be the key solution for power-constrained wireless networks in the future. Today, real applications of such networks, e.g., of wireless sensor networks (WSN), face a big challenge to achieve long term deployment without battery replacement (long network lifetime). Power-management policies and protocols (e.g., duty-cycling scheduling and medium access protocols, routing protocols, etc.) help prolonging the network lifetime, but they remain insufficient. Augmenting the sensor motes with ambient energy harvesting technologies 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 these technologies. In this paper, we are interested in the particular problem of relay nodes (RNs) addition for efficient data gathering. Periodic traffic is considered, where every node periodically reports its reading to the base station (BS). The single-tiered model is used, where both sensors and dedicated RNs may forward traffic. Nodes are supposed to be powered by green energy and enabled with energy harvesting capability (with different capacities). The difference in harvesting capacity may be due to the node hardware, or to its location. We use a simple yet realistic physical layer energy transfer model that is appropriate for wireless energy harvesting. The remaining of the solution is more general and does not depend upon the harvesting technology. This makes extensible to other harvesting technologies by simply updating the energy model.

In a deployed network, the aim is to add a minimum number of RNs within the sensing area to assure energy-efficient data gathering. Both energy-harvesting capability and the traffic load handled by every node are taken into account. Nodes with high capacity tend to be more solicited to forward traffic for other nodes, while those with limited capacity are less solicited. Addition of RNs close to strategic nodes is performed if necessary. The problem is solved by calculating a minimum spanning tree on an edge weighted communication graph. The weights are calculated using the nodes' harvesting capacity. Then the data traffic model is used, along with the energy model to identify nodes that are unable to handle traffic and that should be endowed with RNs to satisfy the survivability condition. The latter is defined as the energy consumed in a time slot should not exceed the generated one. The contribution is to consider the difference of nodes' energy harvesting capacity in the single-tier model for RNs addition. This aspect has been ignored in the literature of RNs deployment in WSN. A lower-bound in the proposed model is derived using integer linear programming (ILP). The proposed solution is evaluated by simulation, and compared with available solution from the literature.

The remaining of the paper is organized as follow: The related work is presented in Sec. II, then the network model in Sec.III. The proposed solution is introduced in Sec. IV, followed by a simulation study in Sec.V. Finally, Sec. VI concludes the paper.

## II. RELATED WORK

RNs placement in WSN has been largely treated in the literature. Existing solutions can be classified into two main categories, single-tiered RNP vs. two-tiered RNP [1]. For the first category, a SN can be used by other nodes in the network for data forwarding, whereas for the second one, every SN sends its own data to dedicated RNs that forward the data to the BSs. Hand et al. [2] investigated the survivability problem in single-tiered and two-tiered topology, by ensuring that each sensor is connected to the BS through two disjoint paths. A 16-approximation algorithm is provided for single-tiered topology, and a $(20 + \epsilon)$-approximation algorithm is provided for the two-tiered one. The connectivity problem in single-tiered and two-tiered topology is addressed in [3], where the authors proposed a 7-approximation algorithm for the single-tiered problem and a $(5+\epsilon)$-approximation algorithm for the two-tiered problem. Another example of solutions dealing with connectivity is [4]. Network lifetime has been considered by Wang et al. [5] and a solution to accommodate the heterogeneous traffic that flows from different sources has been proposed. The problem of two-tiered constrained RNP is investigated in [1], while addressing both the connectivity and the survivability requirements. Approximation algorithms with small ratios are proposed to solve these problems. Experimental results in [1] show that the number of RNs that are used does not exceed twice of that used in the optimal solution. Other examples of papers dealing with the two-tiered model include [6], [1], [7]. All the previous solution are proposed for traditional battery-operated WSN and do not consider node capability for energy harvesting, which adds another dimension to research in wireless networks [8].

Many problems in energy harvesting WSN (EHWSN) have been treated such as optimal duty cycling [9], optimal access [10], and clustering [11]. But to our knowledge, the existing works on RNP in EHWSN are limited to the work of Misra et al. [12], and Djenouri et al. [13]. Misra et al. [12] consider the scenario where possible locations for RNs placement have different energy harvesting potentials. The aim was to deploy a minimum number of harvesting enabled RNs in the network while increasing the harvesting capability. The authors modelled 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 RNs such as to maximize harvesting potentials. While all sensor nodes are supposed not to be harvesting-enabled, they are used to forward packets similarly to the added RNs. The latter are added only to improve connectivity in locations that maximize the harvesting potentials. This does not ensure high network lifetime, as the use of battery-operated sensors to relay traffic will cause fast depletion of their batteries. This problem has been considered in [13], where energy harvesting capability of SNs is considered. The model supposes two categories of nodes, i) energy harvesting enabled nodes, and ii) non-harvesting nodes. The use of the latter is limited to data collection and first-mile transmission of the collected data to forwarders, while the former are responsible to forward data. A minimum number of RNs is added when the harvesting nodes cannot assure coverage. A formulation based on minimum connected dominating set has been used to solve the problem.

Although energy harvesting capability of sensor nodes is considered in [13], the model used is very simple and assume all harvesting nodes to have the same capability. However, in practice nodes have different harvesting capability. For example, when using wireless charging, nodes close to the wireless charger have more capacity than those that far, or when using solar energy, nodes that are directly reached by sun light have more capacity than those located in shadowy areas. Therefore, this black and white model does not reflect the reality, and SNs should not be simply divided into harvesting enabled vs. non-harvesting nodes, but those with harvesting capability have different potentials, and if a harvesting enabled node is used to forward traffic, the amount of traffic it might forward depends on its harvesting potential, and should not be assumed unlimited. Considering this problem represents the main contribution of the present paper.

## III. NETWORK MODEL AND ASSUMPTIONS

The network topology is represented by an undirected graph, $G = (V, E)$, where the set of vertices, $V$, represents the nodes, and $E$ is the set of edges. Links are supposed bi-directional, and an edge is set between two nodes iff the two nodes can reach each other. The graph is supposed to be connected. Periodic traffic is considered, where every node periodically sends its readings to a base station (BS). The format of sensor readings is supposed to be known a priori, and thus the traffic rate. Nodes are supposed endowed with different energy harvesting capabilities. The minimum harvesting capacity should be high enough for a node to run sensing tasks and handle its own traffic. The sensors are supposed to be already deployed in the sensing area, and the topology graph is available as an input to our model. The aim is to add a minimum number of RNs within the sensing region to assure permanent[1] connectivity. That is, to help nodes with low energy capacity to relay traffic. We consider the scenario where the placement of RNs is constrained and only possible close to the SNs, and RNs are supposed to be energy unconstrained nodes.

### A. Traffic Model

Cyclic traffic sampling applications are considered, where every SN periodically reports its sensed data to the BS. Let us denote by $\zeta_i$ the number of nodes of the branch where node, $i$, is the root (its children and grand children), and by, $C_i$, the number of its direct children. Every node is supposed

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[1] Permanent with respect to energy, i.e., without considering permanent node failures due to other issues (only failure due to battery drain out failure is considered).

to generate $\lambda$ bits in each sampling period, $T$. Therefore, the traffic received by the SN, $i$, is given by,

$$Rec_i = \lambda\zeta_i, where \tag{1}$$

$$\zeta_i = \sum_{j\in C_i} (\zeta_j + 1) \tag{2}$$

Every SN will transmit,

$$Tr_i = \lambda(\zeta_i + 1) \tag{3}$$

The previous model is appropriate when sensors transmit raw data without any aggregation. If an aggregation function is applied, then every SN will transmit $\lambda$ bits in every cycle, i.e.,

$$Tr_i = \lambda, \forall i \in S \tag{4}$$

and it receives,

$$Rec_i = \lambda C_i \tag{5}$$

### *B. Energy Model*

We consider a simple energy model without storage, where the amount of energy harvested in a cycle should be used immediately in the next cycle. Let $h_i$ be the harvesting rate of node $i$. Note that different nodes have different harvesting capacities. There are various ambient energy sources, such as solar energy, thermal energy, and wind energy. Solar energy harvesting is one of the most commonly used way to replace battery power supplies. Photovoltaic solar cells are used to convert sunlight into electrical current. The intensity of this current depends mainly intensity of the light irradiating the cell [14]. The level of solar irradiation varies depending on the location of the harvesting nodes and consequently the harvesting rate changes from one node to another. The solar energy harvesting process is uncontrollable. Absence of sunlight makes the RN unable to forward the traffic from the sensors. The inability of several RNs to achieve their mission in data transfer can damage the functioning of the whole wireless sensor network. To avoid the aforementioned problems, a controllable source of energy need to be utilized. Without loss of generality and following this line of thought, we consider wireless energy harvesting where the nodes (energy harvesting enables SNs, and RNs) harvest energy from the radio signals sent from the BS. The solution proposed in the forthcoming sections applies for other energy models, including those for solar energy. The only aspect to consider at the application level in this case (for example) is energy availability, and traffic generation during dark periods should be avoided. Wireless energy transfer to RN results in perpetual network connectivity. The practical feasibility of the far-field wireless power transfer has been reported in the literature (see [15], [16], and references therein). Beamforming techniques can be used at the BS to form sharp energy beams toward the harvesting nodes, which improves the energy transfer efficiency. We consider that the BS broadcast energy on a different band than that used for information exchange. This allows avoiding interference problems that might occur if the same band is used for energy transfer and for data transfer. The energy harvested at a node $i$, $E_{h_i}$, is defined as the product of its received power and the time during which the power is harvested, i.e.,

$$E_{h_i} = \eta_i P_t(d_i)^{-\beta}\xi_i T, \tag{6}$$

where $\eta_i$ represents the receiver harvesting efficiency at node $i$, $P_t$ stands for the transmit power at the BS. The distance between node $i$ and the BS is denoted by $d_i$, while $\beta$ and $T$ refer to the path-loss exponent and the harvesting time duration, respectively. The symbol $\xi_i$ stands for the composite fading channel which accounts for the fast fading and the shadowing. The fast fading follows generally a Nakagami distribution while the shadowing has a log-normal distribution. Due to the random nature of $\xi_i$, the harvested energy $E_{h_i}$ is also a random variable.

The mean value of harvested energy can be written as [17],

$$\bar{E}_{h_i} = \eta_i P_t(d_i)^{-\beta}\bar{\xi}_i T = h_i T, \tag{7}$$

where $h_i$ represents the harvesting rate, i.e. expectation of $\eta_i P_t(d_i)^{-\beta}\xi_i$. Note that $h_i$ is deterministic but varies from one node to another. The variation of the value of $h_i$ is mainly due to the distance change between the BS and different nodes in the network, as well as the change in the mean value of the composite fading $\bar{\xi}_i$ and the receiver harvesting efficiency $\eta_i$. The forthcoming analysis will be based on the harvesting rate $h_i$ rather than on the random harvested energy $E_{h_i}$. This will allow us solving the RNs addition problem using graph theory tools.

We denote by $E_p$ the consumed energy for processing (sensing and computation) per cycle, and $E_t$ (resp. $E_r$) the energy consumed to transmit (res. receive) one bit. The total consumed energy is given by,

$$E_i = Rec_i E_r + Tr_i E_t + E_p \tag{8}$$

The survivability condition is thus,

$$h_i T \geq E_i, \forall i \in S \tag{9}$$

The problem is thus to construct a data gathering tree that assures previous survivability condition, with the addition of a minimum number of RNs to replace SNs that are unable to forward traffic. We assume that the harvesting rate of every node is at least sufficient enough to make the required processing and transmit local traffic, i.e., $h_i T \geq E_p + \lambda E_t \forall i$.

## IV. PROPOSED SOLUTION

### *A. Solution Overview*

First, a weight function that reflects the harvesting capability of the SNs is defined. The following simple normalized function is used. Let $h_{max} = \max_{v\in V} h_v$. The weight of a SN is given by,

$$\omega_i = (h_{max} - h_i)/h_{max}. \tag{10}$$

This gives a vertex weighted graph, where the weights are in the interval $[0, 1]$, and thus low weights reflect high harvesting capability, and vice versa. The vertex-weighted graph is then transformed into an edge-weighted graph, where the weight of

**Algorithm 1:** Solution Overview

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 1: Input: $(V, E, \mathcal{B}, h)$, Minimum Spanning Tree Algorithm $\mathcal{MST}$
    Output: $R$: The set of nodes for which to add the RNs.
 2: $R = \emptyset$
    Calculate the vertices weights
 3: $\forall i \in V$, calculate $\omega_i$ using Eq.10
    Obtain the edge weighted graph
 4: $\forall (u, v) \in E$, calculate $W_{u,v}$ using Eq. 11
 5: $(V, \mathcal{E}, \mathcal{B}) = MST(E, V, W')$
 6: $\forall i \in V$, calculate $\zeta_i$ in the resulted tree $(V, \mathcal{E}, \mathcal{B})$
 7: if $\zeta_i \neq 0$ then
 8:     calculate $E_i$ using Eq. 8
 9:     if the constrained represented by 9 is not satisfied for $i$ then
10:         $R = R \cup \{i\}$
11:     end if
12: end if
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an edge is simply the sum of the weights of its two vertices, i.e,

$$W_{u,v} = \omega_u + \omega_v \tag{11}$$

From the resulted edge-weighted graph, a minimum spanning tree (MST) is calculated. The intuition behind this is to construct a tree where edges with low weights are more likely to be selected, i.e, vertices forming these edges have high harvesting capability, whereas those with low energy harvesting are likely to be pushed down to the leaves. Then using the resulted MST, the survivability condition (Eq. 9) is checked out for every non-leaf SN, and a RN is put near the position of every SN that is unable to fulfil the condition.

### *B. Algorithm Description and Illustration*

The proposed solution is described in Algorithm 1. The algorithm has as input the communication graph $(V, E)$, the base station, $\mathcal{B}$, the vector $h$ representing the harvesting capacity of nodes, and a polynomial time algorithm that calculates the minimum spanning tree, $MST$. Any algorithm can be used, such as Prim's algorithm, or Kruskal's algorithm. The output is a set of vertices (nodes) to be augmented with RNs, say $R$. The later is initiated to $\emptyset$, then the weight of every node is calculated using Eq.10. Then the edge weighted graph is obtained by calculating the matrix $W'$ using Eq. 11. In line 5, the MST algorithm is called to calculate the MST from the resulted edge weighted graph. The output of the algorithm is an MST rooted at $\mathcal{B}$, with a reduced set of vertices $\mathcal{E}$. $\zeta_i$, the number of descendent vertices from every vertices, $i$, is calculated (line 6). If the vertex $i$ has descendent vertices (it is not a leaf in the MST), the survivability condition is checked (Eq. 9). If the condition is not fulfilled, then the vertex is added to $R$ (line 10).

Figure 1 gives an illustrative example for the use of the algorithm on a simplified topology. Fig. 1 (a) shows the network topology with the harvesting capacities of every node (arbitrary values have been used just for illustration). Fig. 1 (b) shows the resulted vertex-weighted graph upon applying Eq. 10. Fig. 1 (c) shows the transformation of the vertex-weighted graph to the edge-weighted graph. Finally, by calculating the spanning tree, the resulted tree is represented by Fig. 1 (d). In this figure, the harvesting capabilities of nodes are shown again as they are used to decide about the positions of RNs. The survivability condition is checked for all the non-leaf nodes in the tree that are represented with the dark vertices (i.e., nodes 2, 6, 5, 9, 11, 15). For example, node 6 should be able to handle (in addition to its task) all the traffic transmitted in the sampling period (T) by nodes 8, 10, 11, 14, 15, [2]. This is possible iff the energy it generates in the period $T$, i.e., $h_iT$, is higher than that it would consume in that period (right side of Eq. 9). That is, it is higher than

If this not fulfilled a RNs will placed next to node 6 to route the traffic of nodes, 8, 10, 11, 14, 15, and that of node 6 as well towards node 2. The role of node 6 will be limited to submitting its traffic to the added RN. The same process is repeated for every non-leaf node.

### *C. Lower-Bound*

The lower-bound is given by the following ILP:

$$\max \sum_{u \in V} X_u \tag{12}$$

S.t.,

$$\forall u \in \mathcal{S} : \lambda \sum_{v \in C_u} (F_{u,v} E_{rec} + E_{tr}) + E_p$$
$$\leq X_u h_u T + (1 - X_u)(E_{rec} + E_{tr} + E_p)|\mathcal{S}| \tag{13}$$

$$\forall u \in \mathcal{S} : \sum_{v \in C_u} Y_{u,v} = 1 \tag{14}$$

$$\forall u \in \mathcal{S} : \sum_{v \in C_u} F_{u,v} - \sum_{u \in C_v} F_{u,v} = 1 \tag{15}$$

$$\sum_{v \in C_u} F_{v,\mathcal{B}} = |\mathcal{S}|. \tag{16}$$

$$\forall u, v \in V : 0 \leq F_{u,v} \leq Y_{u,v}|\mathcal{S}| \tag{17}$$

The vector $X$ represents decision variables for the fluffiness of the survivability condition (Eq. 9), $X_u = 1$ if node $u$ fulfills the condition, and 0 otherwise. Entries of the matrix $Y$ are also decision variables representing the tree, i.e. $Y_{u,v} = 1$ iff $v$ is parent of $u$ in the MST. The objective function of the ILP is to maximize the sum of the vector $X$ entries, Eq. 12. Constrains represented by Eq. (13) are to check survivability condition (Eq. 9). The left side of the equation represents the energy consumed by the SN, where $\sum_{v \in C_u} F_{u,v}$ reflects the number of nodes of the branch rooted at node $u$, i.e $\zeta_u$. Note that $F_{u,v} = \zeta_v + 1$ if $v$ is a child of $u$ in the tree (otherwise $F_{u,v} = 0$). To set $X_u$ to 1, the constraint requires the fluffiness of the survivability condition (consumed energy is less than the generated one), as the remaining term of the right side vanishes ($(E_{rec} + E_{tr} + E_p)|\mathcal{S}|$). Otherwise, the latter is always higher than the left side.

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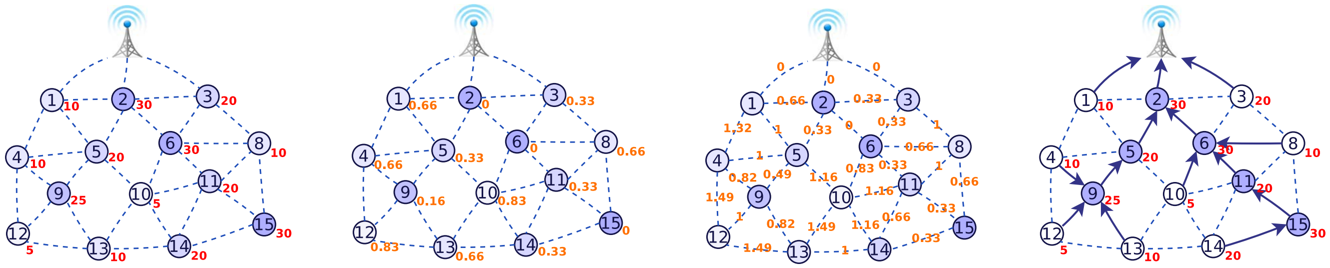
[2] Traffic of nodes 14, 15 are received via node 11, and if data aggregation is used, their traffic is reduced to a single node traffic along with that of node 11.



(a) (b) (c) (d)

Fig. 1: Illustrative Example

The following constraints are used to ensure the construction of spanning tree. Constraints presented by Eq. (14) ensure that each SN in $S$ has only one parent. The constraints (15), (16), (17) are used for modelling the network connectivity and to ensure that all SNs can transmit their data to the BS, $\mathcal{B}$. To guarantee that the formed topology connects all the SNs to $\mathcal{B}$, the packet flow principle is used, where a packet is generated and routed from every SN to $\mathcal{B}$. Constraints represented by Eq. (15) assure that a single packet is generated by every SN, i.e. the difference between the incoming and outgoing flow is one. Constraints of Eq. (16) assure the whole traffic is received at the BS. Constraints represented by (17) force the generated flow to be routed only within the constructed topology,i.e., each constraint forces $F_{u,v} = 0$, if $Y_{u,v} = 0$.

## V. SIMULATION ANALYSIS

The proposed solution is evaluated in this section by simulation. Recall that the only solution that deals with RNs placement in EHWSN while considering energy harvesting capability of sensors is [13], which is thus the only available candidate to compare with. However, that solution uses as a simplified harvesting model where nodes are supposed to be either capable of harvesting energy or incapable of that, without any distinction between the harvesting capabilities at nodes. While the solution proposed in this paper uses a more general model, this $(0, 1)$ model can be viewed a very particular case for which the solution is still valid. Therefore, we use this simplified model where the survivability condition becomes fulfilled for energy harvesting nodes (HNs), and not for the other harvesting nodes (NHNs). The main difference between the two solutions is the way to determine the RN positions. [13] uses a vertex weighted graph and calculates approximation of the minimum weighted dominating set, while the one proposed herein uses a heuristic based on the MST calculation. The study presented in this section compares, in terms of the number of added RNs, the proposed solution (SPT) with that presented in [13] (MRA), as well as the lower-bound (LB) which is obtained by resolving the ILP. NetworkX environment has been used to implement the network simulator, and CPLEX to resolve the ILP. The number of added relays (cost) has been measured in different scenarios, where for every generated topology, a single node is randomly picked up as a BS, and every other node periodically generates and transmits a packet to the BS in every cycle. Every point in the following plots represents the average of extensive repetitions with different random generated graphs, and the error bars are presented with $95\%$ confidence interval. In each figure, a single parameter has been varied while setting the other parameters to their mean values, and then accordingly generating random graphs. The variable parameters are i) the number of nodes, ii) the network density (average number of edges per vertex in the graph), and iii) the percentage of NHNs.

The results depicted in Fig. 2, Fig. 3, and Fig. 4 clearly show the improvement of the proposed solution vs. MRA. It can be noted from the figures that for all algorithms, the number of added RNs increases with the increase of the number of nodes, as well as the percentage of NHNs, and it decreases with the networks density. This is explained by the fact that the increase of the number of nodes while keeping the other parameters (likewise the increase of NHN) requires more RNs to be added to ensure reliable coverage, while the increase of the network density gives more connectivity through HNs, which reduces the need for additional RNs. It is to note from Fig. 3 that for large values of the network density, the performance of SPT is very close to the LB. The results confirm the effectiveness of the SPT solution in terms of RNs calculation, and superiority over MRA. In this simplified $(0, 1)$ model, results related to network lifetime of all solutions are the same (assuming infinite energy potential at the HNs, which makes the lifetime proportional to the traffic generated by NHNs), thus they are omitted.

## VI. CONCLUSION

We have considered in the work presented in this paper one of the challenges related to green communications and proposed a solution for the particular problem of constrained relay nodes (RNs) placement in wireless sensor networks (WSN). The solution ensures communication coverage in the single-tiered topology, while taking advantage of the energy harvesting potentials of sensor nodes (SNs) for the purpose of assuring survivability. The survivability constraint is defined using a simplified, yet realistic energy model, and then fulfilled by mapping the traffic load at every SN to its harvesting

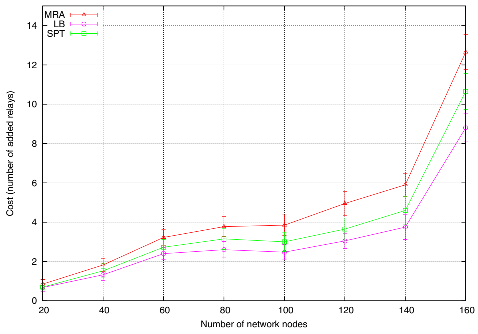


Fig. 2: Number of added RNs vs. number of SNs

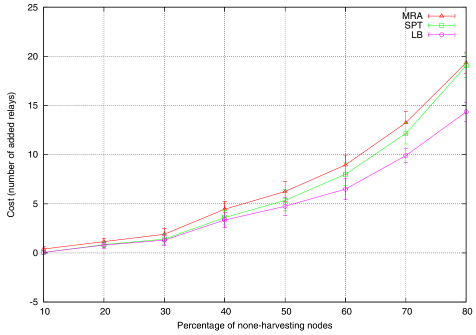


Fig. 4: Number of added RNs vs.Percentage of NHN

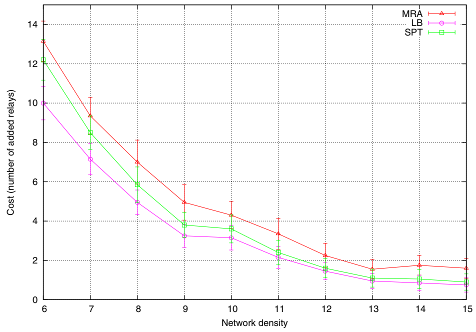


Fig. 3: Number of added RNs vs. Network Degree

potential. The contribution is to consider a more realistic energy harvesting model where harvesting potentials may vary from a node to another. According to this model, we proposed a heuristic based on spanning tree calculation in an edge weighted graph model, where the traffic routed by every node is proportional to its effective energy. SNs in the tree that cannot meet the defined survivability condition are endowed with RNs that replace those nodes in data forwarding. A lower-bound of the number of RNs in the proposed model is derived using integer linear programming, and the proposed solution is compared by simulation to the available candidate solution from the literature. A simplified model is used in the simulation to allow comparison, where every node is either able or unable to harvest energy, i.e., $(0, 1)$ model. The performance results demonstrate superiority of the proposed solution and show that it ensures survivability by adding a lower number of RNs. While comparison with existing works was possible only by using this $(0, 1)$ model, running simulations with more realistic energy harvesting scenarios where nodes have different harvesting potentials is in our agenda.

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