Extending network tree lifetime with mobile and rechargeable nodes

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Abstract

In this paper, we assume network trees consisting of mobile, energy constrained and rechargeable nodes as well as a static sink which collects the monitoring data and it is the root of the tree. Almost exhausted nodes can autonomously move towards a charging point to recharge their battery. However, this action leads to network disconnections and reduced lifetime since one or more predecessor nodes cannot forward their data to the sink. To alleviate this problem and extend network lifetime we examine the feasibility of replacing almost exhausted nodes using nodes with higher remaining energy. Based on this idea we propose a localized algorithm to autonomously replace nodes with high communication burden by the leaves of the tree. Both theoretical and simulation results show a big improvement in terms of network lifetime extension compared to the case where no replacement is performed and to the case where rerouting is considered.

1 Introduction

Wireless networks – such as sensor networks – are usually organized in trees or the applied routing/clustering protocols follow a tree-based scheme [18, 1, 9]. The leaves of the tree correspond to the nodes which monitor the environment and forward the data to the sink. A number of intermediate nodes act as relays if there is no direct communication between the monitoring nodes and the sink. These kind of networks are usually energy constrained since the nodes use batteries as power source.

An unavoidable problem is the loss of data when a relay node runs out of energy and, thus, the communication between its neighbors is lost. The nodes that are closer to the sink shoulder the most of the communication burden since they forward data of multiple leaves. A possible loss of a node which is close to the sink leads to the disconnection of the entire branch and, thus, to a huge loss of information.

The idea of using mobile nodes to control connectivity is not new, however, none of the previous works related to robot networks mentions the problem of lifetime extension [6, 13, 3, 22, 2]. To mitigate the aforementioned problem we assume that nodes with high energy consumption can be replaced by other tree members with high remaining energy. Since at each instance of time some nodes consume less energy than others, they will likely have much more energy after

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a certain period of time. The idea is to use part of this energy for traveling in order to replace nearly depleted nodes and keep this particular branch of the tree alive for the rest of its members.

Since all the nodes are considered mobile and energy constrained, we assume that they can move towards a recharging point to recharge their battery if there is such a need. This action may shorten the lifetime of a node in the tree, but ensures that the same node will come back with more energy to replace other exhausted nodes keeping the network alive for longer time.

Several applications can benefit from the use of the proposed scheme. Ad-hoc network applications such as the coverage of points of interest using robots [7, 14] and the area surveillance using sensors or UAVs [5, 25] consist of nodes which some of them are deployed to provide coverage and some to provide relaying. Due to the multimedia nature of the transmitted data, the relay nodes shoulder a heavy communication load which leads to a fast depletion of their battery. Moreover, wireless sensor networks are often organized in clusters, where each cluster consists of many sensing nodes. Sensing nodes can be used to replace exhausted cluster-heads in case the re-election process is either power consuming or some nodes have been isolated after a cluster-head's failure [8]. Above all, recharging and replacement can lead to autonomous networks without the need of human supervision or manual replacement. In the case where multiple nodes exist in different sites of the network, the proposed solution can be used to redeploy the network and balance the energy resources between the sites [24].

This paper contributes in the following aspects. First, we analyze the conditions under which a node replacement is feasible taking into account the energy consumption of the nodes, their distance from the recharge point, the distance between the nodes, their initial energy, and the movement cost. Second, we present "CoverMe", a localized algorithm that extends the network lifetime taking advantage of node replacement and recharge. Third, we present theoretical and simulation results and we compare against the case where no replacement is done and against the case where rerouting is chosen to connect isolated sensing nodes with the sink.

The rest of the paper is organized as follows. In Section 2, some important works on node replacement and network lifetime extension are mentioned along with their advantages and disadvantages. In Section 3, we formulate the problem and we give several conditions for a feasible node replacement, while in Section 4 we present "CoverMe". In Section 5, we discuss the theoretical and simulation results, and Section 6 concludes the paper.

2 Related Work

Many researchers have focused their works on wireless sensor networks lifetime extension problem. This section will not review the whole literature on energy management and lifetime extension of this kind of networks. Instead, this section will focus on strategies proposed in the literature to offset the negative impact of energy depletion.

The literature proposes many definitions of the "network lifetime". However, in general, the network lifetime is upper bounded by the energy of the nodes composing the network. Some nodes of the network are more prone to energy exhaustion. These critical nodes are the nodes that support a huge amount of network traffic. In the case of a network tree, where the root of the tree is the data sink, these critical nodes are located close to the sink. Whatever the definition of "network lifetime" used, these critical nodes are the bottlenecks for network lifetime extension [4, 21].

The death of a critical node in the network can lead to different levels of malfunction ranging from increased data delay to network partition and data loss [23]. To alleviate that problem, a number of solutions has been proposed in the literature. These solutions can be categorized in two common approaches: (a) the replacement of nearly exhausted nodes with new ones [19, 17, 16, 15], and (b) the data rerouting through other nodes with higher remaining energy [12, 20, 11]. Both approaches have some advantages and disadvantages. We will comment these two approaches in the following paragraphs.

The first approach can infinitely extend the network lifetime if the replacement process is well scheduled [15]. Different replacement strategies can be used depending on the application's level of criticality [19]. However, this approach assumes that an external entity or the nodes themselves can replace a dead node. This implies the mobility of the nodes. Moreover, sometimes this approach requires extra nodes which is translated to extra cost as well as to extra techniques related to network discovery and replacement.

In the second approach, the rerouting process sends the data to the sink by using the remaining nodes without any replacement. This approach is simple. It targets to balance the uneven traffic load between the relay nodes [20] and tries to avoid the appearance of holes and bottlenecks. This method does not require the use of any external entity to replace nodes nor the mobility of the nodes and works well in dense networks or in uniform networks where it is easy to find an alternative way towards the sink [11]. However, in any case, this second approach cannot extend the network lifetime indefinitely and will eventually lead to the death of the network.

We think that the first approach is more suitable for the applications described above due to network traffic intensity. Therefore, our solution is mainly based on the first approach borrowing some features from the second approach. We compare our strategy to a modified version (to have a fair comparison) of the rerouting approach proposed in [12].

3 Network Tree Lifetime

We assume that a node spends E_s energy units per time unit for sensing, E_t for transmitting, and E_r for receiving. It also spends E_m energy units per traveling meter and E_{id} energy units for the rest of the functions. All the nodes initially have the same amount of energy E_0. We also use $d(i, i')$ to refer to the Euclidean distance between nodes i and i'.

Depending on the functionality and the position of a node in the tree, it has one of the following four roles. It may be sensing node, relay node, moving node, or both sensing and relay. The energy consumption per time unit for each of these roles, when no data aggregation is used, is:

$$E_i^{cons} = \begin{cases} E_s + E_t + E_{id} & \text{if } i \text{ is sensing node,} \\ (E_r + E_t)\nu + E_{id} & \text{if } i \text{ is relay node,} \\ E_s + (E_r + E_t)\nu + E_t + E_{id} & \text{if } i \text{ is both relay \& sensing node,} \\ E_m & \text{if } i \text{ is moving,} \end{cases} \tag{1}$$

where ν is the number of predecessor sensing nodes of i. In the next paragraphs we present conditions explaining the feasibility of replacing a relay node using a sensing node. The overall extension time of the network branch is computed.

First of all, the energy consumption of the relay must be higher than the energy consumption of the sensing node. It follows that:

$$(E_r + E_t)\nu - (E_t + E_s) > 0. \tag{2}$$

Each node i leaves its current position at time t_i^r to recharge itself. The moment at which it must leave depends on its distance from the recharging point, so it will not run out of energy before reaching its target:

$$t_i^r = \frac{E_0 - E_{i,rp}^{mov}}{E_i^{cons}} \tag{3}$$

$E_{i,rp}^{mov}$ corresponds to the energy consumption for traveling from i to the recharging point rp and it is equal to $E_m d(i, rp)$.

Moreover, in order to replace a relay node p, a sensing node q must start moving t_q^{alar} time units before t_p^r, where

$$t_q^{alar} = \frac{d(q,p)}{U} \tag{4}$$

and U is the speed of the node in meters per time unit.

Using Formulas (2), (3), and (4), it follows that the sensing node will have ΔE amount of energy when it reaches the relay node. ΔE includes sensing node's energy consumption for $t_p^r - t_q^{alar}$ amount of time as well as the energy it needs to travel to the relay node:

$$\Delta E = E_0 - (t_p^r - t_q^{alar})E_q^{cons} - E_{q,p}^{mov} \tag{5}$$

The higher the ΔE, the longer the tree branch survives and the later the next replacement (if there is any) takes place. Combining all the previous equations, the extension time Xt^0 of the branch by a single replacement is given by:

$$Xt^0 = \frac{\Delta E - E_{p,rp}^{mov}}{(E_r + E_t)\nu' + E_{id}} = \frac{E_0 - (\frac{E_0 - E_m d(p,rp)}{(E_r + E_t)\nu + E_{id}} - \frac{d(q,p)}{U})(E_s + E_t + E_{id}) - E_m d(q,p) - E_m d(p,rp)}{(E_r + E_t)\nu' + E_{id}}, \tag{6}$$

where ν' is the number of predecessor sensing nodes of the new relay node after the replacement. If a node from another branch has been used for the replacement, then ν' equals ν, otherwise ν' equals $\nu - 1$. In Formula (6) is considered that i is a relay node only. In case i is a relay and a sensing node at the same time, the formula must be updated accordingly.

Since the relay node must go to the recharging point and return back to its initial position after being fully recharged, Xt^0 must be higher than the time it needs to go to the recharging point plus the time it needs to get fully recharged plus the time it needs to travel back to its position:

$$Xt^0 \geq \frac{E_0}{E_{rech}} + \frac{2d(rp, p)}{U}, \tag{7}$$

where E_{rech} is the recharge energy per time unit.

If Condition (7) holds true, the branch will stay connected, while achieving the minimum possible loss of information until another relay or sensing node dies. Apparently, as more relay nodes go to recharge, the loss of information increases, since more sensing nodes are needed to replace the relay nodes.

On the other hand, if Condition (7) does not hold true, the recharging node may leave before it gets fully recharged in order to replace the node it was previously replaced by. In this case, the node must have enough energy to support the network at least till the recharging node comes back to its previous position and returns back to the base. This condition is given by the following formula:

$$(Xt^0 - \frac{2d(p, rp)}{U})E_{rech} > 2E_m d(p, rp). \tag{8}$$

The new extension time after a partial recharge is given by:

$$Xt^1 = \frac{(Xt^0 - \frac{2d(p,rp)}{U})E_{rech} - 2E_m d(p, rp)}{(E_r + E_t)\nu' + E_{id}}. \tag{9}$$

Generalizing, the overall accumulated extension time after k replacements is:

$$Xt^k = \sum_{j=1}^{k} \frac{(Xt^{j-1} - \frac{2d(p,rp)}{U})E_{rech} - 2E_m d(p, rp)}{(E_r + E_t)\nu' + E_{id}}, \tag{10}$$

where $(Xt^{j-1} - \frac{2d(p,rp)}{U})E_{rech} > 2E_m d(p, rp), \forall\ j \in \mathbb{N}^*$.

4 CoverMe

"CoverMe" is a localized algorithm that takes into consideration the ability of nodes to move towards a recharging point. It describes the basic steps a relay node can follow to be replaced by nodes with higher remaining energy. CoverMe is not a routing protocol but a trade-off mechanism which sacrifices part of the coverage to extend network lifetime.

The replacement process is divided in three steps. During the first step all the nodes of the network compute a threshold as it has been described in Formula (3). This is a critical threshold that the nodes use to avoid running out of energy. Note that this is a time threshold but since the nodes consume energy with a constant rate, this time threshold can be easily transformed to an energy threshold.

At this moment, the relay nodes do not take into account the time of Formula (4) since they have not chosen yet a replacement node. This is done in the next step where the relay nodes communicate with non-relay nodes and select their substitutes. In case of multiple candidates, a relay node chooses the node that is placed closer to it. In case where there exist multiple relays and multiple candidates, the replacement nodes are chosen in a first-come, first-served manner and no evaluation is done between them. It is worth pointing out that depending on how long is the communication range and how many hops the messages travel away, a relay node may find one, many or no candidates.

Once the replacement node has been chosen, the nodes recompute the threshold considering the time the candidate needs to travel towards the relay node. During the last step, when the relay's energy is close to the threshold, the corresponding substitute starts moving. After the replacement the sensing node becomes the new relay node, while the old one is driven towards the recharging point. It is worth mentioning that a partially charged node is considered to be a candidate node and it can be used for future replacements unless Criterion (8) does not hold true. CoverMe prefers choosing partially recharged candidates since they are usually closer to the 1-hop relay nodes and, moreover, the remainder of the sensing nodes keep their positions prolonging the coverage time.

This three-step process continues until all the sensing nodes have depleted their energy or none of the sensing nodes can reach the sink. A relay node that cannot support any sensing node due to a network partition is considered isolated and goes recharging even if its energy threshold is placed much later. Fully recharged nodes take the initial position of the node that they were replaced by during the last replacement. This means that a relay node which was replaced by a sensing node, it will take the initial position of the sensing node.

5 Evaluation & Discussion of the Results

In this section we present theoretical results based on the analysis done in Section 3 and we discuss the feasibility of node replacement using rechargeable mobile nodes based on real values. At the same time, we simulate "CoverMe" and we compare its performance to other approaches. The results are divided in two parts. In the first part, we present results related to 2-hop networks and we compare the performance of CoverMe to theoretical results and to the approach where no replacement is performed. In the second part, we assess CoverMe in multi-hop networks and we compare its performance to the approach where no replacement is done and to the approach where rerouting is chosen to reconnect non-connected nodes to the sink. The simulations were performed on a custom simulator[1] using an ideal MAC layer. The highest density of the network was one node per 400 square meters.

For the evaluation purposes we used the following values concerning the energy consumption parameters and the speed of the nodes: $E_r = 2.5J/s$, $E_t = 5J/s$, $E_s = 2.5J/s$, $E_i = 8J/s$, $E_m = 25J$, $U = 0.9m/s$, $E_{rech} = 27J/s$. E_r, E_i, E_m and U were experimentally found using Wifibots[2]. E_t was computed

[1] http://autonomous-tree.gforge.inria.fr/
[2] Wifibots mobile robots, http://www.wifibot.com/

considering the first-order radio model [10], a communication range of 50m, a packet size of 1KB, and transmission rate of 1 packet/s.

A simple 2-hop simulation scenario was considered for the first part of the simulation with one relay node and ν sensing nodes with equal distances from the relay. The sink as well as the recharging point were located in the middle of the left side of the 10K m^2 terrain. Only the relay node had direct communication with the sink. Each simulation has been executed 50 times and the average results are presented. We must mention that using the energy consumption values presented in the previous paragraph Condition (7) cannot be achieved. It actually means that the network will die before the recharging node gets fully recharged. Partial recharge has been used in that case.

Concerning the second part of simulations, we present the average results of 50 instances per scenario as well as the 95% confidence intervals. We assume two deployment types; a random uniform and a non-uniform based on the Gaussian distribution. The sink is located in the middle of the left side of the terrain and the terrain size is enlarged to 40K m^2. For fair comparison reasons the normalized network lifetime is presented instead of the actual one. It is given by the sum, $\sum_{i=1}^{\tau} \frac{\#\_of\_sensors\_active_i}{total\_\#\_of\_sensors}$, where τ is the time where no active sensing node exists in the network.

5.1 Two-hop Networks

The first figure depicts the theoretical lifetime extension when no recharging is applied (see Figure 1). Equation (6) was used to create this figure with the previously mentioned values regarding the energy consumption model. The figure shows how lifetime changes with the increase of initial node energy for different sensor populations and distances. Concerning the distance between the nodes, we assume that $d(i', i)$ is equal to $d(i, rp)$. The theoretical results show that the higher the initial energy, the more the lifetime can be improved. However, it is worth observing that for all populations of ν the improvement converges to a maximum value which is higher when the number of successors is high. When the distance between the nodes is high, at least 4 KJ of initial energy are needed since the nodes consume more energy for the movement.

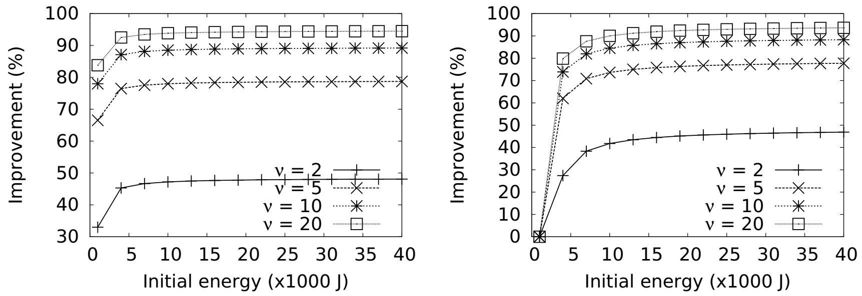

Figure 1: Theoretical lifetime improvement (%) for different values of initial energy, ν, and 10m distance (left figure) or 50m distance (right figure).

The corresponding simulation results are presented in Figure 2. It can be observed that CoverMe presents similar behavior to the theoretical measurements extending the lifetime up to 95%. For low initial energy, the trends seem to be slightly different. This happens because in CoverMe the time is divided in rounds. In each round every node checks if its remaining energy will fall below the threshold during the next round according to the current energy consumption. This process may lead to an early departure of the node, and thus to slightly different results compared to the theoretical absolute values when the initial energy is low.

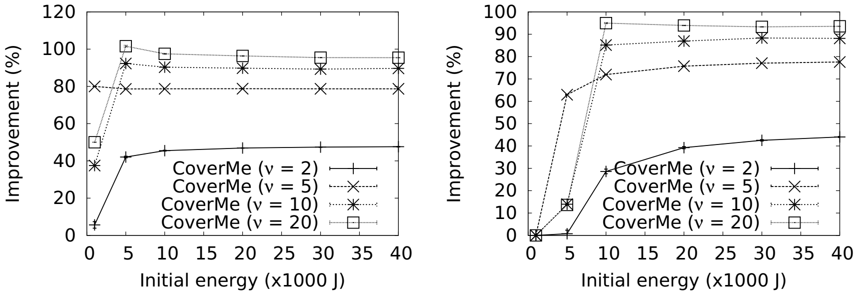

Figure 2: Simulated lifetime improvement (%) for different values of initial energy, ν, and 10m distance (left figure) or 50m distance (right figure).

Figure 3 presents the theoretical lifetime improvement that can be achieved when recharging is taken into account. Formula (10) was used for drawing the graphs. First of all, we can observe that the improvement is high even when the nodes have low initial energy (5-10 KJ for low distance), and it gradually converges to a maximum value for all values of ν. Second, the maximum improvement is achieved when the number of successor sensing nodes is 5 for both low and long distances. It is impressive that in this case the lifetime can be improved up to 200% when the initial energy is high.

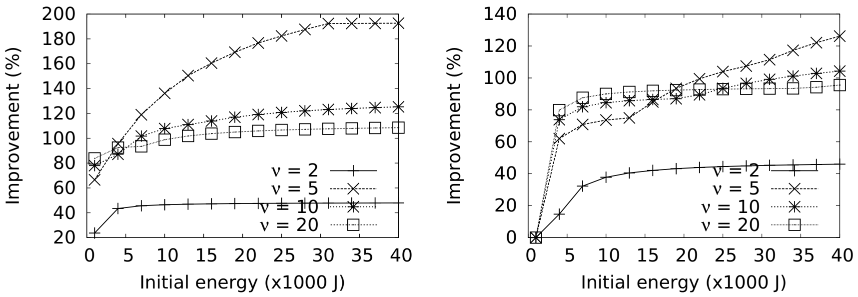

Figure 3: Theoretical lifetime improvement (%) for different values of initial energy, ν, and 10m distance (left figure) or 50m distance (right figure). Node recharging is taken into account.

Finally, Figure 4 illustrates the corresponding simulation results of the lifetime improvement over the approach where no replacements are done. The line trends are similar to those of the previous figure while the maximum absolute values are quite the same. The results are slightly different for low energy values for the same reason explained in the first simulation. The best improvement is achieved when ν is 5 and when the initial energy is above 5 KJ and 20 KJ for the low distance and the high distance case respectively.

It is important to notice here that there exists a trade-off between the value of ν and the lifetime improvement. Indeed, the higher the value of ν, the higher the quantity of data a relay node has to forward and, thus, the more its energy consumption. However, the higher the value of ν the higher the number of nodes that can replace a dying relay. This trade-off explains the fact that when $\nu = 2$, the lifetime extension is lower than the lifetime extension when $\nu = 5$. In the same way, the lifetime extension when $\nu = 10$ is higher than the lifetime extension when $\nu = 20$. Indeed, the existence of this trade-off rises the issue of a balanced network tree construction with limited leaves.

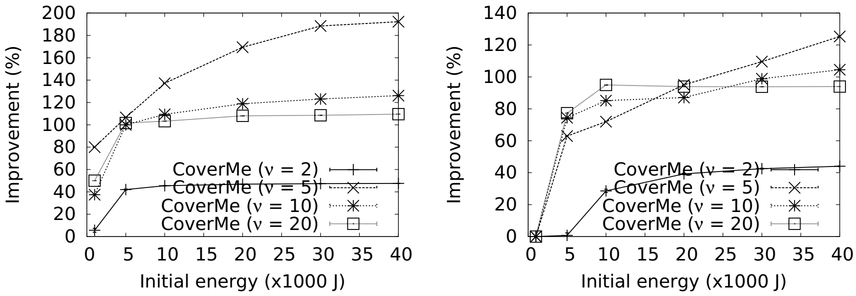

Figure 4: Simulated lifetime improvement (%) for different values of initial energy, ν, and 10m distance (left figure) or 50m distance (right figure). Node recharging is taken into account.

5.2 Multi-hop Networks

This section evaluates the use of CoverMe in multi-hop networks where branches may consist of multiple relay nodes and multiple other sub-branches. It actually means that different nodes can move or be replaced at the same time while several others may be disconnected. Due to the very large terrain size we assume that a sensing node can connect to another relay node if no substitute is selected by CoverMe. Figure 5 depicts the performance of the three approaches with uniform node positions (left figure) and non-uniform positions (right figure). The normalized network lifetime is measured for different sensing node populations, 10K Joules of energy, and when no recharging is done. The algorithms present similar performance in uniform topologies but CoverMe yields more lifetime in non-uniform topologies with a maximum improvement of 60%. “Rerouting” does not perform the same since in the non-uniform scenario the probability of finding a new path to the sink is lower than in the uniform scenario.

In Figure 6 we measure the normalized network lifetime for a similar scenario. In this case, the initial energy varies and the number of sensing nodes is fixed to 50. For both types of deployment CoverMe presents better performance which increases with the initial energy. Similarly to the previous scenario, the gap between CoverMe and the other approaches is higher for non-uniform node deployments.

An almost identical performance is achieved when recharging is taken into

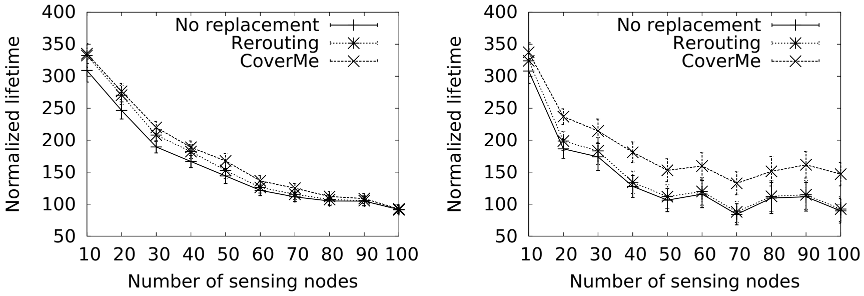

Figure 5: Normalized network lifetime for a multi-hop scenario with no recharging, variable number of sensing nodes, 10K Joules initial energy and uniform (left figure) or non-uniform (right figure) node deployment.

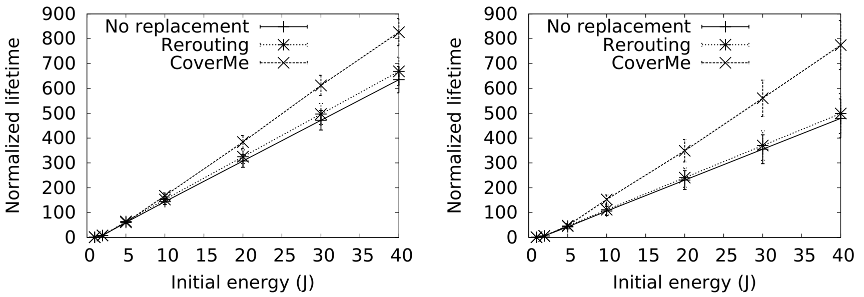

Figure 6: Normalized network lifetime for a multi-hop scenario with no recharging, variable initial energy, 50 sensing nodes and uniform (left figure) or non-uniform (right figure) node deployment.

account. The corresponding results are presented in Figures 7 and 8. This almost identical behavior appears since only a few relay nodes can take advantage of the extra recharging energy. As explained in Section 4, the relay nodes select the closest to them sensing nodes when multiple candidates exist. Since many relay nodes are far from the sink (and recharging point) they will most likely select a sensing node for the replacement than a recharging one which may be far away. An opposite strategy which prefers recharging nodes instead of the closest candidate could also be used. However, much energy would be wasted in traveling. Nevertheless, the decision of selecting the optimal strategy is an open problem.

Figure 9 depicts the number of messages sent by "CoverMe" and "Rerouting" throughout the process. The simplest (No replacement) method has been excluded from this simulation due to its negligible overhead cost. We assumed that each relay node communicates with its selected substitute every 10 iterations to ensure that it is alive. CoverMe sends less messages than Rerouting for the most of node populations since its behavior mainly depends on the activity of the relays. On the other hand, the activity of "Rerouting" depends on the number of sensing nodes. In case of a disconnection all the disconnected sensing nodes send messages to nearby relays in order to find a route towards the base station. When a few sensing nodes are placed, the number of sensing nodes is

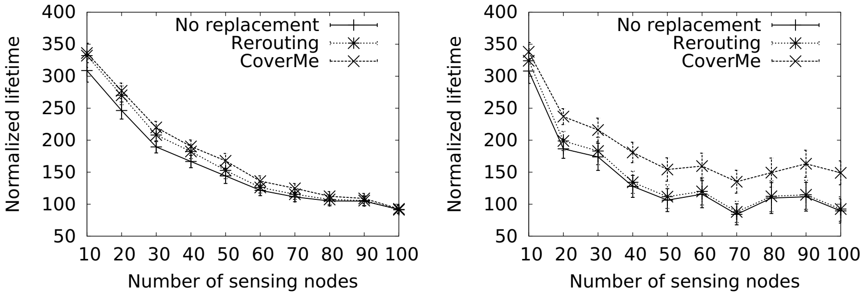

Figure 7: Normalized network lifetime for a multi-hop scenario with recharging, variable number of sensing nodes, 10K Joules initial energy and uniform (left figure) or non-uniform (right figure) node deployment.

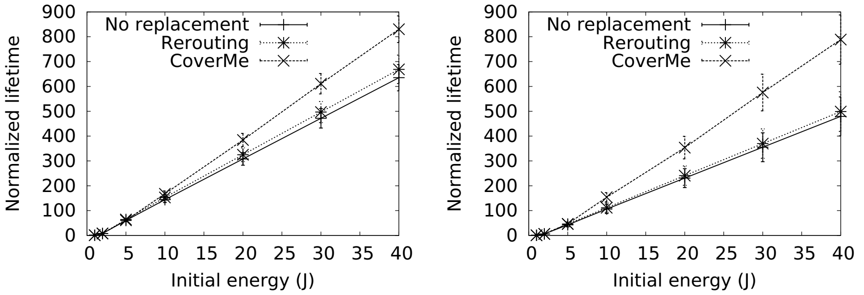

Figure 8: Normalized network lifetime for a multi-hop scenario with recharging, variable initial energy, 50 sensing nodes and uniform (left figure) or non-uniform (right figure) node deployment.

comparable to that of relays, so the two approaches produce more or less equal number of messages. We must mention that when the communication between the relays and the substitutes is done less frequently (every 30 iterations), the number of messages is reduced by 20%.

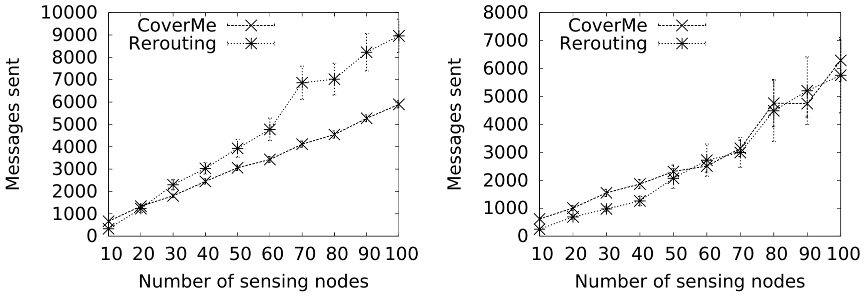

Figure 9: Number of messages sent for a scenario with variable number of nodes and uniform (left figure) or non-uniform (right figure) node deployment.

6 Conclusion & Future Work

The lifetime extension problem of energy constrained network trees was examined in this paper. In particular, we analyzed the feasibility of node replacement and recharging when nodes with high communication burden are replaced by other network members with high remaining energy. The theoretical and the simulation results showed a high performance gain in terms of lifetime for both 2-hop and multi-hop networks. The lifetime can be improved up to 200% in 2-hop networks and up to 60% for multi-hop networks, especially in the case where the nodes are not uniformly placed.

Although the proposal exhibits a high performance gain, there is room for further improvement and investigation. The selection of the best candidate and the best strategy (during the replacement process) it seems to be a critical issue since a trade-off appears between coverage time and network lifetime. On the other hand, the percentage of lifetime extension can be maximized using a certain number of predecessor nodes (sensing nodes) for each relay. This number derives from Equation (10) and can be used to construct balanced network trees with specific number of relays and leaves.

Acknowledgments

This work is partially supported by the French National Research Agency (ANR) under the VERSO RESCUE project (ANR-10-VERS-003) and by a grant from CPER Nord-Pas-de-Calais FEDER CIA .

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