A Recharging Distance Analysis for Wireless Sensor Networks

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Abstract

Efficient energy consumption is a challenging problem in wireless sensor networks especially close to the sink node, known as the energy hole problem. Various policies for recharging battery exhausted nodes have been proposed using special recharging vehicles. The focus in this paper is on a simple *recharging policy* that permits a recharging vehicle, stationed at the sink node, to move around and replenish any node's exhausted battery when a certain *recharging threshold* is violated. The minimization of the *recharging distance* covered by the recharging vehicle is shown to be a facility location problem, and particularly a 1-median one. Simulation results investigate various aspects of the recharging policy – including an enahnced version – related to the recharging threshold and the level of the energy left in the network nodes' batteries. In addition, it is shown that when the sink's positioning is set to the solution of the particular facility location problem, then the recharging distance is minimized irrespectively of the recharging

☆Part of this work was originaly published in the proceedings of the First International Balkan Conference on Communications and Networking Tirana, Albania, May 30-June 2, 2017.

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threshold.

Keywords: Battery Recharging, Energy Consumption, Facility Location Theory, Sink Positioning, Wireless Sensor Networks.

1. Introduction

Recharging wireless sensor nodes has recently attracted significant research attention (see e.g., [1], [2], [3]) as an alternative way to tackle the difficult problem of prolonging network's lifetime. This is made possible due to recent technological advances in wireless battering charging, e.g. through wireless energy transfer [4], [5]). Since their early appearance almost two decades ago [6], [7], wireless sensor networks have seen an exceptional growth and recent technological advancements have permitted the creation of small and low cost devices capable of sensing a wide range of natural phenomena and wirelessly transmitting the corresponding data.

Given that nodes of these networks are typically small devices supplied with tiny batteries and while being wireless, generally operate in the absence of an infrastructure, they depend on the energy supplied by their limited batteries. Therefore, even though energy consumption is of key importance in wireless networks, it becomes more intense in their sensor counterparts [8] mostly due to the *energy hole* problem [9]. In particular, sensor nodes also act as relays for data generated by other nodes that need to reach the *sink*, i.e., the particular node that is responsible to collect all sensed information. Consequently, nodes that are close to the sink have to relay a large amount of *traffic load*, and therefore their energy consumption is increased compared to other nodes of less intense traffic load.

In this paper, the increased energy consumption, due to the *energy hole* problem, is tackled by the implementation of a recharging vehicle able to move within the network when a request is applied by one or more sensor nodes in need for a battery replenishment. The vehicle remains stationed at the sink node when inactive, and moves according to shortest path's branches upon a energy request. A simple *recharging policy* is introduced under which a request is sent to the sink node to initiate a recharging process if the battery level of a sensor node is below a fixed *recharging threshold*. As it is shown in the paper, the *recharging distance*, i.e., the distance covered by the recharging vehicle under this recharging policy, corresponds to a facility location problem and particularly to a 1-median one [10]. This is an important contribution, since it relates battery replenishing problems in wireless networks to facility location problems.

Simulation results validate the analytical findings and show that when the sink is located at the solution of the 1-median problem formulated here, then the distance covered by the recharging vehicle is minimized. For the simulation purposes, geometric random graphs [11] are considered as suitable for representing wireless sensor network topologies [12], even though the analytical findings can be applied to any other topology type. The effect of the recharging threshold is also investigated and, particularly, how it affects the energy level of the sensor nodes' batteries and the distance covered by the recharging vehicle. It is also shown that the value of recharging threshold does not affect the optimal position of the sink, thus the minimum recharging distance remains constant as also expected by the analysis. Furthermore, this simple policy is enhanced by allowing the recharging device to replenish the nodes' battery along the trajectory towards the particular node that initiated the recharging request in the first place. As it is expected, the results are further improved and in compliance with the analysis.

The rest of this paper is organized as follows: Section 2 gives an overview of the past related work. Section 3 briefly describes the network characteristics. The recharging policy is introduced in Section 4 and is analytically investigated in Section 5 along with the formulation of the covered distance as a facility location problem. The simulation results are presented in Section 6 and the conclusions are drawn in Section 7. A list of the most used notation can be found in Appendix A.

2. Past Related Work

There is an extensive literature with respect to minimizing energy consumption (see the survey by Anastasi et al. [8]) and the need for recharging sensor network nodes (see e.g., [13] by Mathuna et al.). After the recent growth in wireless power transfer technology, the concept of recharging vehicles in wireless sensor networks was newly introduced by Kurs et al. [4] as well as Jonah and Georgakopoulos [5]. The benefit of recharging batteries in wireless networks in general, and in wireless sensor networks specifically is shown Gatzianas et al. in [14] and by Angelopoulos et al. in [1], respectively.

The problem of minimizing the number of chargers is considered by Dai et al. in [15], and an optimization problem to maximize the ratio of the wireless charging vehicle vacation time is addressed by Shi et al. in [16]. An attempt to reduce the number of chargers is described by Pang et al. in [17], while Wang et al. [18] focus on scheduling aspects. The problem of the most suitable paths selected by a recharging vehicle is studied in [19] and [20] by Han et al. and Li et al., respectively. Joint data gathering and charging techniques to prolong the wireless sensor network lifetime are proposed by Li et al. in [21], Zhao et al. in [22] and Xie et al. in [23], while in [24] by Yu et al., the possibility of recharging while moving is taken into consideration when constructing the recharging path. A collaborative mobile charging, where mobile chargers are allowed to intentionally transfer energy between themselves is proposed by Zhang and Wu in [25].

3. The Proposed System Model

The network topology is represented by a connected undirected graph, where V is the set of nodes and E the set of links among them. The size of set V, denoted by n, corresponds to the number of nodes in the network. If a link (u, v) exists among two nodes u and v (i.e., $(u, v) \in E$), then these nodes are *neighbors* and a transmission can take place between them directly. It is assumed that each node occupies a physical location determined by position coordinates (two dimensional without loss of generality). If $(u, v) \in E$, let $\chi(u, v)$ denote the corresponding *euclidean distance* between nodes u and v. If $(u, v) \notin E$ (i.e., nodes are not neighbors), there exists a shortest path among these nodes. Let $\mathtt{x}(u, v)$ denote the summation of the euclidean distances of the individual links between nodes u and v over the particular shortest path (to be referred to as the *shortest path euclidean distance*). If $(u, v) \in E$, then $\mathtt{x}(u, v) = \chi(u, v)$.

Sink nodes are responsible to collect all sensed information within the wireless sensor network and forward it outside the network. Therefore, it is reasonable to assume that each sink node is attached to some kind of infrastructure (e.g., having adequate connectivity and abundant power supply). When a node assumes the role of the sink, let $\mathtt{s}$ denote this particular node.

Regarding the network topology, (connected) geometric random graphs topologies [11], where a link exists among two nodes if their euclidean distance is less than or equal to the *connectivity radius* r_c, are considered as suitable for modeling wireless sensor networks. For this case, obviously $\chi(u, v) \leq r_c$. A commonly used model [26] for the consumed energy w during a transmission from among a pair of nodes (i.e., symmetric links), is given by $w = \mu\alpha^\gamma(u, v) + \nu$, where μ, γ and ν are constants depending on the particular environment and the device, and where α corresponds to the transmission range. For the rest of this work, the transmission range $\alpha = r_c$ (due to the geometric random graph topology), $\gamma = 3$ (common case for wireless environments) and since the dominating factor is the energy consumed for the actual transmission, ν is negligible compared to μr_c^{γ} [27], thus

$$w = \mu r_c^3. \tag{1}$$

It is assumed that data packets, from any node u in the network, arrive at the sink node $\mathtt{s}$ being forwarded over the links of a shortest path tree, created by a corresponding routing policy [28], the root being the sink node $\mathtt{s}$ (to be referred to also as *routing tree*). For sink node $\mathtt{s}$, let $\mathbb{T}^{\mathtt{s}}(u)$ denote a subtree (its root being node u) of the shortest path tree created by the previously mentioned shortest path routing policy. Under this notation, the routing tree rooted at sink node $\mathtt{s}$ is denoted by $\mathbb{T}^{\mathtt{s}}(\mathtt{s})$. When a data packet generated at some node u arrives at some other node v, then node v, in its turn, forwards the packet further towards the sink node, in addition to those data packets generated by node v itself. It is assumed that the nodes' internal memory is adequate for any queuing requirements.

Let λ_u denote the probability that a data packet is generated at some node u in any time unit, to be referred to hereafter as the *traffic load* of node u. Given a sink node $\mathtt{s}$, let $\Lambda^{\mathtt{s}}(u)$ denote the *aggregate traffic load* of node u, given by

$$\Lambda^{\mathtt{s}}(u) = \sum_{v \in \mathbb{T}^{\mathtt{s}}(u)} \lambda_v. \tag{2}$$

Figure 1 illustrates the routing tree $\mathbb{T}^{\mathtt{s}}(\mathtt{s})$, subtree $\mathbb{T}^{\mathtt{s}}(u)$ and $\Lambda^{\mathtt{s}}(u)$, for some node u of an example network.

4. A Simple Recharging Policy

As aforementioned, there is a need for recharging the nodes' batteries in order to prolong the network's operation. The use of recharging devices like vehicles, stationed at the sink node (thus, having abundant power supply) and moving to recharge nodes' exhausted batteries and then back to the sink, requires a careful study of the battery consumption process as well as the distance covered by the recharging vehicle.

Let $\mathcal{B}_u^{\mathtt{s}}(t)$ denote the amount of energy remaining at node u's battery at time t, the sink node being $\mathtt{s}$. Let $\mathcal{B}_{\max}$ denote the capacity of a node's

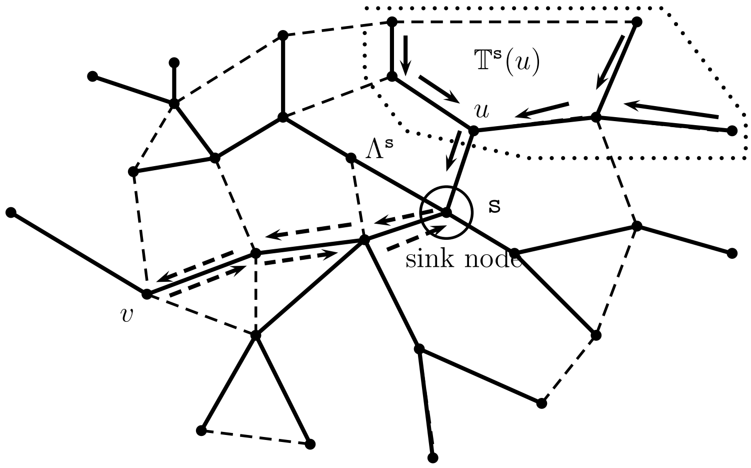


Figure 1: For the depicted example network, dense lines correspond to the shortest path (routing) tree links when the root is the sink node s (within the circle), i.e., $\mathbb{T}^{\mathsf{s}}(\mathsf{s})$. Dashed lines correspond to the rest of the network links, i.e., $E \setminus E(\mathbb{T}^{\mathsf{s}}(\mathsf{s}))$. The area within the dotted shape pertain to subtree $\mathbb{T}^{\mathsf{s}}(u)$. The dense arrows correspond to the aggregate traffic load and the dashed ones to a recharging vehicle that moves to node v and then returns to the sink node.

battery. Assuming that at the beginning of a network's life (i.e., $t = 0$) all nodes are fully charged, then $\mathcal{B}^{\mathsf{s}}_u(0) = \mathcal{B}_{\max}$, $\forall u \in V$.

Given that transmitting is the dominating energy consumption factor, if one transmission takes place from node u towards node v, it is expected that the energy level of node u's battery will be reduced by w. Assuming no transmission errors or collisions, then for a time period $[0, t]$, node u is expected to transmit (on average) $\Lambda^{\mathsf{s}}(u)t$ data packets, thus consuming (on average) $\Lambda^{\mathsf{s}}(u)wt$ energy units. Therefore, the battery's average energy level at time t is given by

$$\mathcal{B}^{\mathsf{s}}_u(t) = \mathcal{B}_{\max} - \Lambda^{\mathsf{s}}(u)wt, \tag{3}$$

where $(u, v) \in E$.

A simple recharging policy is considered in this paper, whereby there exists (i) one *recharging vehicle* hosted at the sink node, (ii) capable of moving over the routing tree's branches, (iii) to any network node that is about to exhaust its battery, (iv) recharge it, and (v) move back to the sink node. The dashed arrows in Fig. 1 illustrate the path followed by the recharging vehicle for replenishing the battery of a certain node v.

The Recharging Policy: The battery of a node $u \in V$ requires recharging, if at some time t, $\frac{\mathcal{B}_u^{\mathtt{s}}(t)}{\mathcal{B}_{\max}} \leq \rho$ is satisfied, where $0 \leq \rho \leq 1$ represents a *recharging threshold* common for all network nodes. The condition being satisfied, a *recharging process* is initiated and the recharging vehicle, stationed at sink node $\mathtt{s}$, moves to node u over the routing tree, recharges its battery and returns back to sink node $\mathtt{s}$.

Under this policy, for some node u, sink node $\mathtt{s}$ is notified whether condition $\frac{\mathcal{B}_u^{\mathtt{s}}(t)}{\mathcal{B}_{\max}} \leq \rho$ is satisfied, by control information suitably piggybacked within data packets. If the condition is satisfied, then the recharging vehicle moves a distance $\mathtt{x}(\mathtt{s}, u)$ to recharge node's u battery and then returns to sink node $\mathtt{s}$, thus having moved a total *recharging distance* of $2\mathtt{x}(\mathtt{s}, u)$. Node's battery is assumed to be recharged.

Even though the benefits of a recharging policy – like the one previously mentioned – are obvious, there is a certain cost attributed to (i) the required amount of energy for recharging purposes, and (ii) the recharging distance. Given that the recharging vehicle is normally stationed at the sink, it is reasonable to assume that it has access to power supply similarly to the sink node. Regarding the recharging distance, the purpose here is to minimize it and thus, improve certain aspects of the recharging policy considered in this paper (e.g., to minimize recharging delays). An enhancement of this recharging policy that allows the replenishment of nodes over the trajectory towards the particular node that triggered the recharging process, is also considered later in the simulation section. More sophisticated recharging policies, e.g., as in [19], are left for future work.

5. Recharging Policy Analysis

Assume that the system has started operating and some long enough time has elapsed for all nodes to have sent packets towards the sink node, i.e., the network operates at steady state mode. Let $\tau^{\mathtt{s}}(u) > 0$ denote the *recharging period* between a recharging event that took place at time t_1 and the need for a new recharging event at time t_2, or $t_2 = t_1 + \tau^{\mathtt{s}}(u)$ for node u and sink node $\mathtt{s}$.

Assuming the proposed recharging policy, $\frac{\mathcal{B}_u^{\mathtt{s}}(\tau^{\mathtt{s}}(u))}{\mathcal{B}_{\max}} = \rho$ is satisfied. Given that $\mathcal{B}_u^{\mathtt{s}}(t) \overset{\text{Equation (3)}}{=} \mathcal{B}_{\max} - \Lambda^{\mathtt{s}}(u)wt$, where v is the neighbor node of u towards the sink node $\mathtt{s}$ over the routing tree branches. Eventually, $\rho =$

$\frac{\mathcal{B}_{\max}-\Lambda^{\mathtt{s}}(u)w\tau^{\mathtt{s}}(u)}{\mathcal{B}_{\max}}$ and the recharging period for node u is given by

$$\tau^{\mathtt{s}}(u) = (1-\rho)\frac{\mathcal{B}_{\max}}{\Lambda^{\mathtt{s}}(u)w}. \tag{4}$$

Obviously, at any time instance $t \geq 0$, there would be $\lfloor t/\tau^{\mathtt{s}}(u)\rfloor$ recharges. For each one, the recharging vehicle covers a distance $2\mathtt{x}(u,\mathtt{s})$ to get to node u and then return back to its main position at the sink $\mathtt{s}$. Therefore, for node u at time t, distance $2\lfloor t/\tau^{\mathtt{s}}(u)\rfloor\mathtt{x}(u,\mathtt{s})$ is covered for recharging purposes. Consequently, for all network nodes, the *covered distance* by the charging vehicle at time t is given by $D^{\mathtt{s}}(t) = 2\sum_{u\in V}\lfloor t/\tau^{\mathtt{s}}(u)\rfloor\mathtt{x}(u,\mathtt{s})$, for sink node $\mathtt{s}$. Given Equation (4), the result is

$$D^{\mathtt{s}}(t) = 2\sum_{u\in V}\left\lfloor (1-\rho)\frac{\Lambda^{\mathtt{s}}(u)w}{\mathcal{B}_{\max}}t\right\rfloor \mathtt{x}(u,\mathtt{s}). \tag{5}$$

The requirement is to determine the particular sink node for which $D^{\mathtt{s}}(t)$ is minimized irrespectively of time t.

In order to proceed with the analysis, a more tractable form of $D^{\mathtt{s}}(t)$, as given by Equation (5), is introduced, denoted as $\mathcal{D}(\mathtt{s})$. In particular, factor $2\frac{1-\rho}{\mathcal{B}_{\max}}wt$ is omitted being a constant (the objective is minimization with respect to sink placement), and without loss of generality $\lfloor\cdot\rfloor$ is also omitted. Therefore,

$$\mathcal{D}(\mathtt{s}) = \sum_{u\in V}\Lambda^{\mathtt{s}}(u)\mathtt{x}(u,\mathtt{s}), \tag{6}$$

to be referred to as the *recharging distance*.

The objective now is to find the particular *optimal distance sink node* $\mathtt{s}_{\mathcal{D}}$ such that

$$\mathcal{D}(\mathtt{s}_{\mathcal{D}}) = \min_{\mathtt{s}}\mathcal{D}(\mathtt{s}). \tag{7}$$

This optimization problem (as given by Equation (7) and Equation (6)) is actually a facility location problem and particularly a 1-median one [10]. These are known NP-complete problems that require global information. As will be demonstrated in the sequel using simulation results, the solution of the previously mentioned median problem eventually captures the optimal position for the sink (i.e., minimization of the distance covered by the recharging vehicle).

6. Simulation Results

A simulation program is created using the omnet++ simulator [29]. Each node u generates data packets according to its traffic load λ_u and each packet is forwarded towards the sink node over the said routing tree.

6.1. Simulation Configuration

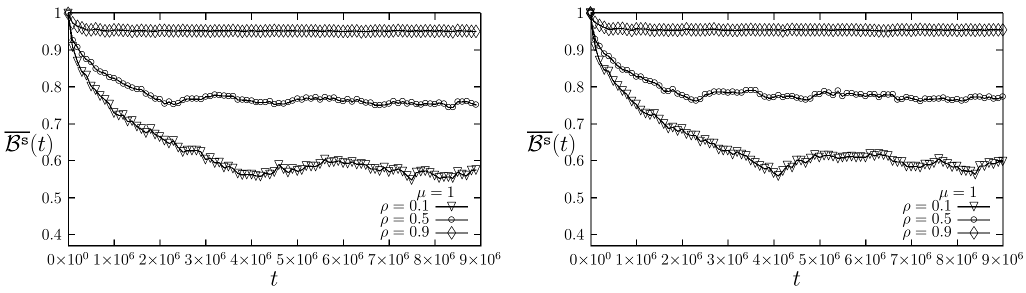
Traffic load λ_u takes random values uniformly distributed within range $[0, 1/n]$, where n is the total number of nodes. For the simulation purposes, $n = 1000$. When a transmission takes place, energy is consumed according to Equation (3) per (simulation) time unit. If a transmission is to take place from node u to node v, $(u, v) \in E$, then the battery level at node u gets reduced by $w = \mu r_c^3$ (Equation (1)), for various values of μ. The initially available energy at each node is set at $\mathcal{B}_{\max} = 1$. A uniformly distributed packet error rate of 10^{-6} is also considered for each network link (thus, corrupted packets are retransmitted).

Connected geometric random graphs topologies [11] of $n = 1000$ nodes in the $[0 \dots 1] \times [0 \dots 1]$ square area, are considered for the simulations, as the most suitable ones to capture the sensor networks' topology idiosyncrasies [30]. The connectivity radius is $r_c = 0.06$, which corresponds to a connected network topology of 10.8 (on average) number of neighbor nodes per node and 30.2 (on average) diameter, which is a typical one for wireless sensor networks. When a node runs out of battery, then the simulation stops. The maximum possible number of simulation units for the omnet++ platform [29] is close to 9×10^6.

6.2. Recharging Policy Behavior

The proposed recharging policy is implemented considering a recharging vehicle initially stationed at the sink node and then moving towards a node to recharge it upon receipt of a request for such. The time period (in time units) for the vehicle movement to take place, and consequently to return, is equal to twice the number of hops (in time units) this node is away from the sink plus one time unit for recharging. If, in the meantime, a request for replenishing the battery of another node is received, it gets queued in a first-in-first-out manner at the sink node.

Figure 2.a, depict the average battery level $\overline{\mathcal{B}^{\mathtt{s}}}(t) = 1/n \sum_{\forall u \in V} \mathcal{B}_u^{\mathtt{s}}(t)$ for some arbitrarily selected sink node $\mathtt{s}$, as a function of time t for three different values of ρ (0.1, 0.5 and 0.9) and $\mu = 1$. It is observed that the



a. b.

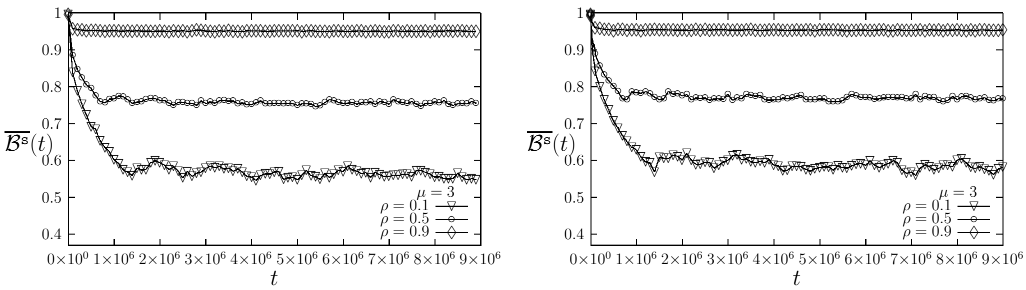
Figure 2: Simulation results regarding the average energy left at the networks nodes $\overline{\mathcal{B}^{\mathsf{s}}}(t)$, as a function of time t for three different values of the recharging threshold ρ (i.e., 0.1, 0.5 and 0.9) and energy consumption constant $\mu = 1$. The simple recharging policy is depicted (a), as well as the enhanced one (b).

average battery level decreases and eventually converges to a certain level, even for small values of ρ.

Figure 2.b depicts the same scenario considering an enhanced version of the simple recharging policy presented in Section 4. Under this *enhanced recharging policy* all nodes located en route towards the node that triggered the recharging process have their battery replenished. In particular: (i) one *recharging vehicle* is hosted at the sink node; (ii) a network node that is about to exhaust its battery makes a request for recharging; (iii) the recharging vehicle moves towards the node that has made a request over the tree's branches; (iv) it recharges all nodes located on path; (v) it recharges the particular node that initiated the process; and (vi) moves back to the sink node.

As it is observed from Figure 2.b, the average battery level $\overline{\mathcal{B}^{\mathsf{s}}}(t)$ under the enhanced recharging policy is slightly improved compared to the simple recharging policy. This is expected due to the fact that overall, the remaining energy is increased under the enhanced version of the recharging policy due to the improved replenishing process.

Figure 3 and Figure 4 depict the same simulation as in Figure 2 considering $\mu = 3$ and 5 (instead of $\mu = 1$). The same observations apply as before when comparing the simple recharging policy (a) and the enhanced one (b). When comparing figures 2, 3 and 4 (i.e., as μ increases), it is obvious that the convergence period for each case is reduced. However, the particular convergence value does not change, an indication that it depends on ρ.



a. b.

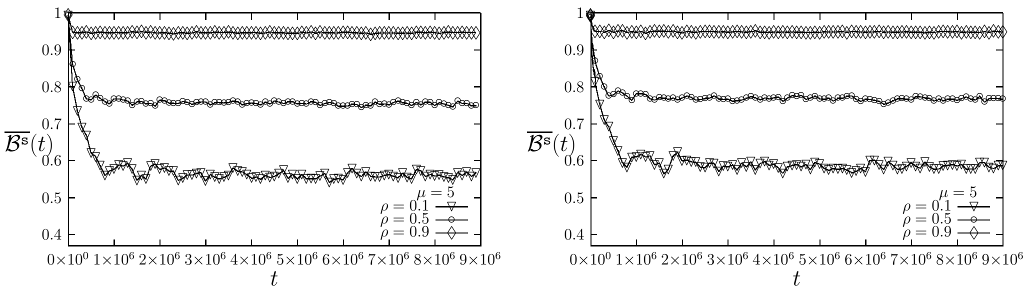
Figure 3: Simulation results regarding the average energy left at the networks nodes $\overline{\mathcal{B}^{\mathsf{s}}}(t)$, as a function of time t for three different values of the recharging threshold ρ (i.e., 0.1, 0.5 and 0.9) and energy consumption constant $\mu = 3$. The simple recharging policy is depicted (a), as well as the enhanced one (b).

Figure 5 depicts the total number of requested recharges and the total distance covered by the recharging vehicle as a function of the recharging threshold ρ after 9×10^6 time steps and $\mu = 1$. As expected, the number of recharges as well as the covered distance increase as ρ increases. Furthermore, comparing the simple recharging policy (a) and the enhanced one (b), it is obvious that the number of requested recharges and the total covered distance is reduced under the latter policy.

6.3. Evaluation of the 1*-median Problem Formulation*

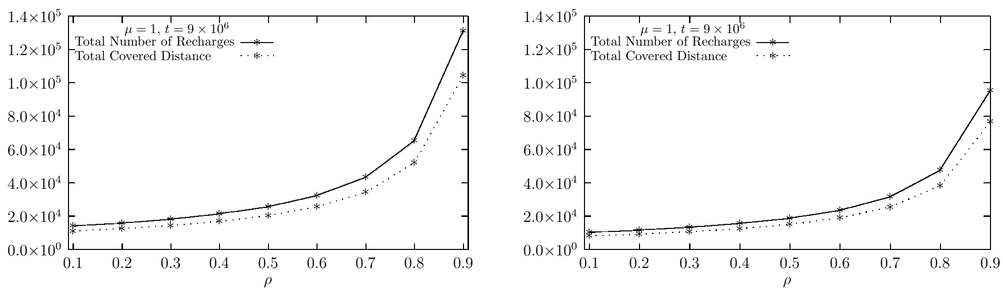
In order to evaluate the minimization of the recharging distance as a 1-median problem, it is sufficient to show that when the sink is located at the solution of the median problem, then the covered distance is minimized. Let fraction $\frac{\mathcal{D}(\mathsf{s})}{\mathcal{D}(\mathsf{s}_{\mathcal{D}})}$ denote the *distance ratio* ($\frac{\mathcal{D}(\mathsf{s})}{\mathcal{D}(\mathsf{s}_{\mathcal{D}})} \geq 1$).

Figure 6 depicts $D^{\mathsf{s}}(t)$ at time $t = 10^3$ as a function of the distance ratio $\frac{\mathcal{D}(\mathsf{s})}{\mathcal{D}(\mathsf{s}_{\mathcal{D}})}$ for $\rho = 0.9$ and $\mu = 5$ for both the simple recharging policy (a) and the enhanced one (b). Each point corresponds to the total recharging distance that took place when the sink was located at a node of the particular value regarding distance ratio. There are 1000 points that correspond to the 1000 nodes, each one being the sink. Obviously, the smaller the distance ratio, the smaller the total recharging distance, the minimum assumed at $\frac{\mathcal{D}(\mathsf{s})}{\mathcal{D}(\mathsf{s}_{\mathcal{D}})} = 1$ which is the solution of the previously formulated 1-median problem. It is clear that both the simple recharging policy and its enhanced version are in accordance with the analytical results. As observed, the recharging distance



a. b.

Figure 4: Simulation results regarding the average energy left at the networks nodes $\overline{\mathcal{B}^{\mathsf{s}}}(t)$, as a function of time t for three different values of the recharging threshold ρ (i.e., 0.1, 0.5 and 0.9) and energy consumption constant $\mu = 5$. The simple recharging policy is depicted (a), as well as the enhanced one (b).

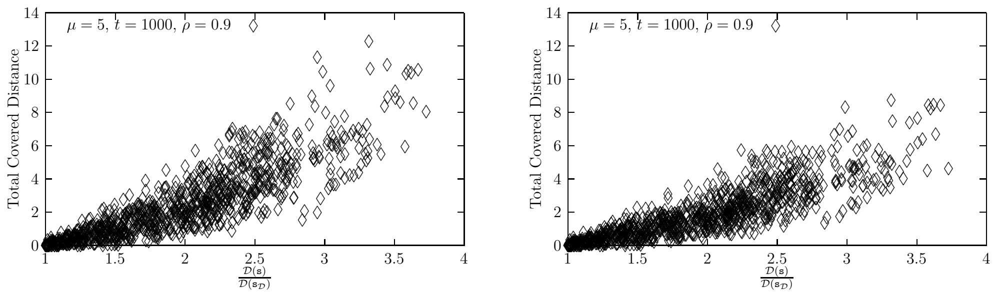


a. b.

Figure 5: Total number of requests for recharges and total distance covered by the recharging vehicle as a function of the recharging threshold ρ, at time $t = 9 \times 10^6$ and $\mu = 1$. The simple recharging policy is depicted (a), as well as the enhanced one (b).

under the enhanced version is smaller than that under the simple recharging policy.

Figure 7 depicts $D^{\mathsf{s}}(t)$ at time $t = 9 \times 10^9$ as a function of the distance ratio $\frac{\mathcal{D}(\mathsf{s})}{\mathcal{D}(\mathsf{s}_{\mathcal{D}})}$ for three different values of ρ (0.1, 0.5 and 0.9) and $\mu = 5$. The requirement for $t = 9 \times 10^9$ and the three values of ρ results in 27×10^6 more runs compared to the experiment that took place for the scenario of Figure 6.a, pushing to the limits the simulation program and thus, considering only the simple recharging policy. As before, it is observed that the minimum is assumed at $\frac{\mathcal{D}(\mathsf{s})}{\mathcal{D}(\mathsf{s}_{\mathcal{D}})} = 1$ which is the solution of the previously formulated 1-median problem, while the depicted values are more concentrated compared



a. b.

Figure 6: Total covered distance at time $t = 10^3$ as a function of the distance ratio $\frac{\mathcal{D}(\mathsf{s})}{\mathcal{D}(\mathsf{s}_{\mathcal{D}})}$, for $\rho = 0.9$) and $\mu = 5$. The simple recharging policy is depicted (a), as well as the enhanced one (b).

to those depicted in Figure 6. Moreover, the covered distance depends on the recharging threshold ρ. However, its minimization is clearly independent of ρ as it can be concluded from the analytical results (i.e., Equation (6) does not depend on ρ) and observed by the simulation results as well.

The case of $\rho = 0.9$ is interesting and requires further elucidation. As before, for $\frac{\mathcal{D}(\mathsf{s})}{\mathcal{D}(\mathsf{s}_{\mathcal{D}})} \to 1$, the total recharging distance is minimized. However, as $\frac{\mathcal{D}(\mathsf{s})}{\mathcal{D}(\mathsf{s}_{\mathcal{D}})}$ increases and more specifically when $\frac{\mathcal{D}(\mathsf{s})}{\mathcal{D}(\mathsf{s}_{\mathcal{D}})}$ is larger than 1.5, the total distance does not follow the expected pattern. The reason is that for sink nodes of these particular values, the simulation execution terminates earlier than $t = 9 \times 10^6$ due to at least one node of exhausted battery. Consequently, the obtained value corresponds to the total distance not at time $t = 9 \times 10^6$ but at an earlier time and, as expected, is smaller.

The latter observation looks like a paradox, even though it is not. For $\rho = 0.9$, after some time, a large number of nodes would require to be recharged. Consequently, their recharging requests would be queued according to the previously mentioned first-in-first-out policy. As a result, there will be some nodes (the ones close to the sink) that will be severely affected by the energy hole problem and the energy left in their batteries will be consumed before the next recharging. The fact that such a behavior is not observed for $\rho = 0.1$ or $\rho = 0.5$ is attributed to the fact that $t = 9 \times 10^6$, even thus the maximum, it is not enough to reveal this behavior. A possible improvement (left for future work) could be a replacement of the first-in-first-out policy with one considering the remaining battery level of each node that sends a recharging request. Note, however, that for all cases, when $\frac{\mathcal{D}(\mathsf{s})}{\mathcal{D}(\mathsf{s}_{\mathcal{D}})} \to 1$ there is no such

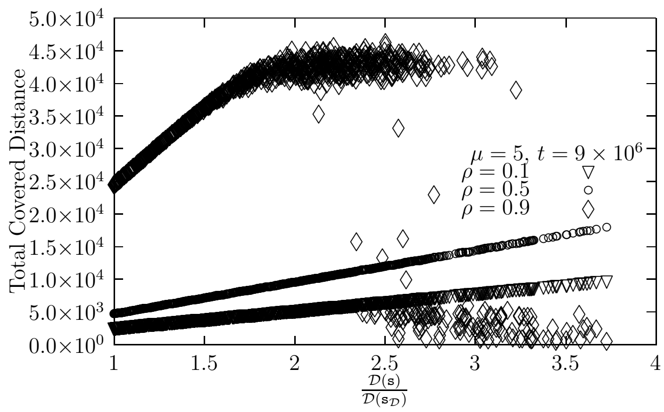


Figure 7: Total covered distance at time $t = 9 \times 10^6$ as a function of the distance ratio $\frac{\mathcal{D}(\mathbf{s})}{\mathcal{D}(\mathbf{s}_\mathcal{D})}$, for three different values of ρ (0.1, 0.5 and 0.9) and $\mu = 5$.

a problem, which is another indication that the solution of the previously formulated 1-median problem efficiently captures the minimum recharging distance for the particular simple recharging policy.

7. Conclusions

A simple recharging policy was introduced in this paper, allowing a recharging vehicle stationed at the sink node to recharge other nodes' batteries when failing under a certain recharging threshold. The objective was to minimize the distance traveled by the recharging vehicle. As it was shown here, this distance minimization problem can be formulated as a 1-median problem. The presented simulation results demonstrate the behavior of the proposed policy and reveal a significant decrement with respect to the recharging distance when the analytical results are used. An enhanced version of this policy is also employed and simulation results are derived showing an improvement in performance. Eventually, as it is clearly demonstrated, if the sink is located at the particular node that is the solution of the formulated 1-median problem, then the covered distance under the proposed recharging policy is minimized.

Acknowledgements

This work was supported in part by project "A Pilot Wireless Sensor Networks System for Synchronized Monitoring of Climate and Soil Parameters in Olive Groves," (MIS 5007309) which is partially funded by European and National Greek Funds (ESPA) under the Regional Operational Programme "Ionian Islands 2014-2020."

Appendix A. Notation Overview

$\mathcal{B}_u^{\mathtt{s}}(t)$	Remaining energy at node u's battery at time t
$\mathcal{B}_{\max}$	Initial energy (at time $t = 0$) for all nodes
$\mathcal{D}(\mathtt{s})$	Recharging distance for sink node $\mathtt{s}$
$D^{\mathtt{s}}(t)$	Covered distance for sink node $\mathtt{s}$ at time t
$\frac{\mathcal{D}(\mathtt{s})}{\mathcal{D}(\mathtt{s}_{\mathcal{D}})}$	Distance ratio
n	Number of nodes in the network
r_c	Connectivity radius
$\mathtt{s}$	Sink node
$\mathtt{s}_{\mathcal{D}}$	Optimal distance sink node
$\tau^{\mathtt{s}}(u)$	Recharging period for node u
w	Consumed transmission energy
$\mathtt{x}(u, v)$	Shortest path euclidean distances between nodes u and v
λ_u	Traffic load of node u
$\Lambda^{\mathtt{s}}(u)$	Aggregate traffic load of node u
ρ	Recharging threshold
$\chi(u, v)$	Euclidean distance for neighbor nodes u and v

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