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A recharging distance analysis for wireless sensor networks☆

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A B S T R A C T

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 threshold.

1. Introduction

Recharging wireless sensor nodes has recently attracted significant research attention (see e.g., [1–3]) 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

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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 by 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. [21], Zhao et al. [22], and Xie et al. [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 [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 $\mathtt{x}(u, v) = \chi(u, v)$.

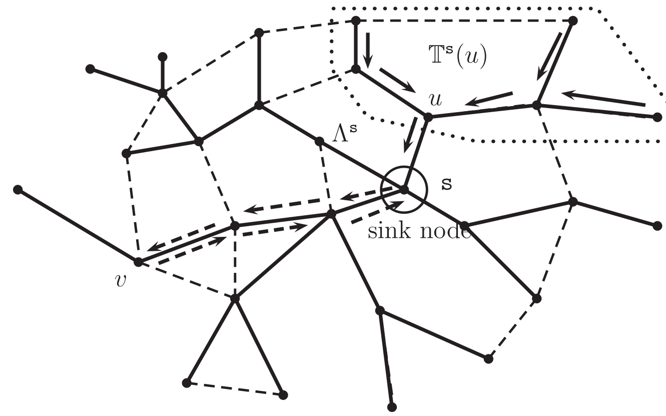

Fig. 1. For the depicted example network, dense lines correspond to the shortest path (routing) tree links when the root is the sink node $\mathtt{s}$ (within the circle), i.e., $\mathbb{T}^{\mathtt{s}}(\mathtt{s})$. Dashed lines correspond to the rest of the network links, i.e., $E \setminus E(\mathbb{T}^{\mathtt{s}}(\mathtt{s}))$. The area within the dotted shape pertain to subtree $\mathbb{T}^{\mathtt{s}}(u)$. 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.

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 $\chi(u, v) \le r_c$. 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

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

Fig. 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.