MSR : Minimum-Stop Recharging Scheme for Wireless Rechargeable Sensor Networks

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***Abstract*—This paper deals with simultaneous energy transfer to multiple nodes for scalable wireless recharging in wireless sensor networks. All existing recharging schemes rely on the use of a mobile charger that roves the network and drops by some locations for nodes recharging. However, they focus on the efficiency of energy transfer and neglect the energy engendered by the charger movement. This is tackled in this paper, where the wireless charging is modeled as a path optimization problem for the mobile charger, with objective function to minimizing the number of stop locations in the path. Due to the NP-harness of the problem, we propose a simple but efficient heuristic. It is based on clique partitioning to find the minimum number of locations allowing the mobile charger to replenish all the node's batteries in the network. Evaluation results demonstrate that the proposed approach significantly reduces the total energy consumption of the mobile charger, while using a low-complexity techniques that permit scalability to a higher number of nodes.**

***Keywords*-Sensor networks, wireless energy transfer, mobile recharger, tour planning**

I. Introduction

Wireless sensor networks are composed of nodes that are powered by onboard batteries or super capacitors. This limited energy resource highly constrains the lifetime of the network and makes energy efficiency as fundamental design objective. To address this issue, a plethora of energy conservation solutions have been proposed in the literature [1]. These solutions can only slow down the energy dissipation of the network operations in order to extend the network lifetime, but they cannot guarantee a perpetual functioning. For this purpose, energy harvesting techniques have been proposed [2]. They permit to recharge sensor nodes with ambient environmental energy such as solar or wind energy. However, this kind of solutions suffer from the high uncertainty in the power supply which is subject to variations of environmental conditions. For example, in solar harvesting system, the energy output of the charger depends on the amount of solar radiations received at the panel which varies with the time of the day and weather conditions. This major shortcoming limited the success of environmental energy harvesting in wireless sensor networks.

Recently, a breakthrough in the domain of wireless energy transfer has opened up a revolutionary paradigm for energy renewal in wireless sensor networks. Kurs et al. [3] developed a new technique called magnetic resonant coupling that enables efficient and stable energy transfer between two devices through mid-range distances (for example 2m). Furthermore, such wireless energy transfer is immune to the neighboring environment and does not require a line of sight between the charging and receiving nodes (omnidirectional). It is expected in the near future the emergence of a new class of *wireless rechargeable sensor networks* that have the potential to bring perpetual sensing, communication and computation capabilities to our daily life. Many existing works propose to use mobile chargers in wireless rechargeable sensor networks [4]. The mobile charger periodically travels around the network and stops by some locations to replenish node's batteries. However, most of these solutions are limited to charge one node at a time, which poses a real scalability problem as network size increases.

Interestingly, Kurs et al. discovered in [5] that by properly tuning the magnetic resonance coupling, it is possible to perform a wireless energy transfer to multiple receivers simultaneously. In addition, it has been demonstrated through experiment results that the overall output efficiency of charging multiple devices was better than the output efficiency of charging each device individually.
Inspired by these new findings, we propose a novel wireless recharging scheme based on simultaneous energy transfers to multiple nodes. In contrast to [6], the goal in this paper is to optimize the energy consumption for both wireless charging of sensor nodes and the movement of the mobile charger. In addition, we consider a scenario where no assumptions are made on the possible locations of stopping points as well as on other network parameters such as the node's data transmission rate, contrary to the work in [7].

For this purpose, we model the wireless charging problem as a path optimization problem of the mobile charger with the objective of minimizing the number of stop points in the planned path. The advantage of minimizing of the number of stop locations in the charging path is twofold. First , it allows to optimize the charging time of the sensor nodes by maximizing the number of nodes that are charged simultaneously at each stop position. This reduces the overall energy amount necessary for charging all nodes in the networks. Second, stoping points minimization helps in reducing the length of the charging path, as well as the energy and time needed to stop and resume movement after each stoping point. Consequently it optimizes the energy expenditure related to the mobile charger movement as well as charging energy.

The main contributions of our work are as follows:

- We propose a new modeling approach for the problem of wireless charging based on simultaneous energy transfer to multiple nodes. The minimum-stop recharging model (MSR) optimizes both the wireless charging operation and the mobile charger path by minimizing the number of stop locations in the charging tour.
- We prove that the problem, as modeled is NP-hard.
- The model is then approximated to the clique partitioning problem and a simple but efficient heuristic is proposed. It allows to find a charging path with a minimal number of stoping points.
- The proposed charging schemes is compared to a recently proposed solution that uses simultaneous energy transfer to multiple nodes. Results indicate a considerable gain in the total energy consumption, as well as a scalability to higher number of nodes.

The remainder of the paper is as follows: Section II briefly reviews the related works on wireless recharging schemes in sensor networks using a mobile charger. Section III describes the network and energy models that we considered. Section IV formulates the Minimum-Stop Recharging (MSR) problem and proves its NP-hardness. In Section V, we reformulate the MSR problem using clique partitioning, and propose a heuristic to find the stop locations that form the charging path. Performance evaluations are discussed in Section VI, and Section VII concludes the paper.

II. Related Work

Li et al. [8] proposed a joint routing and charging scheme to prolong the sensor network lifetime. The key idea is to develop a routing protocol that actively coordinates with the mobile charger in order to fully exploit the potential benefits of the adopted recharging strategy. In [9], the authors study the feasibility of bundling the wireless charger and the base station into a single mobile entity that collects data and charges sensor nodes at the same time. For this purpose they presented a model that jointly optimizes traveling path, stoping points, charging schedule, and flow routing. The work in [10] considers the scenario where individual sensors request charging from the mobile charger when their energy runs low. In order to satisfy the requesting nodes, authors propose an on-demand charging strategy based on nearest next job with preemption. They showed through analytical results that the adopted strategy allows a good performance in terms of system throughput and charging latency. In contrast to the aforemention works, our approach is independent from routing or data collection operations. Also, the charging operation is performed proactively and not in on-demand manner. Furthermore, all these works are based on recharging a single node at once, and suffer from the scalability problem, contrary to the proposed solution.

Xi et al.[7] is the first work that investigated the use of simultaneous multi-node wireless recharging to tackle the scalability problem noticed in state-of-the-art works. However, the authors focused on optimizing the charging time - and consequently the charging energy - while neglecting energy consumed by the charger movement. In fact, the stoping points that form the charging path are fixed a priori as the centers of the hexagonal cells that partition the deployment field. The optimization is performed only on the stop durations spent by the mobile charger in each cell center. Moreover, the authors assume some static parameters in the sensor networks which do not meet with the dynamic and unpredictable nature of the wireless sensor networks application. For example, a unique data transmission rate is assumed for all the sensor nodes in the network, as well as a static flow routing.

The work described in [6] is the most closely related to our context as it is based on multi-node charging and no prior assumption is made on the stoping points of the charging path or other parameters in the network. Still, the authors's goal was to minimize the overall charging time spent by the mobile charger to recharge all the nodes and no attention was paid to the energy spent by the mobile charger for traveling along the charging tour.

III. Model and assumptions

We consider a network containing a mobile charger (*MC*) and n static sensor nodes that are randomly scattered over a two-dimensional deployment area. Each sensor i, located at the position of coordinates (x_i, y_i), is equipped with an onboard battery of capacity σ_i. To recharge the network nodes, the *MC* computes a charging tour that consists in a set of stop locations and their corresponding stop durations. For each charging tour, the *MC* must start from an energy station (called depot) and return back to it. Without loss of generality, the depot is supposed to be located at the reference position, say $s_0(0,0)$, in the deployment area. Let $\Pi = \{s_1, s_1, ..., s_p\}$ be the ordered set of stoping locations that define the charging path. The length of this path is given by the following expression :

$$L = \sum_{j=0}^{p-1} d(s_j, s_{j+1}) + d(s_p, s_0) \quad (1)$$

where $d(a,b)$ denotes the Euclidean distance between the two arbitrary positions a and b.

In order to be able to charge a given node in the network, the stop location of the mobile charger needs to be within the node's *power reception disk*. We define this latter as the disk centered at the node position, with a radius equal to the maximum energy transfer distance of the mobile charger, denoted as R_c. A node i can be charged when the *MC* stops by the position s_j iff, $d(i, s_j) \leq R_c$. For a given stop point

s_j, the *MC* charges simultaneously all the nodes that verify the aforementioned inequality. The received power $p_i(s_j)$ by a sensor node i located at a distance d from this stopping point is given by the following equation:

$$p_i(s_j) = \mu(d)p_t \quad (2)$$

Where p_t denotes the *MC* transmission power for wireless recharging, and $\mu(d)$ reflects the efficiency of the wireless energy transfer operation. The value of this efficiency is always inferior to 1 and polynomially decreases with higher distances between the charging node and the mobile charger.

To fully charge a node battery of capacity σ_i, the received power at this node needs to be accumulated during a charging time t_i such that:

$$t_i = \frac{\sigma_i}{p_i(s_j)} \quad (3)$$

The energy dissipated by the mobile charger to perform this charging operation is $E_{charg}(i) = p_t t_i$. Since the mobile charger may recharge multiple nodes simultaneously in each stop position, the stop duration needed to charge all nodes covered by this stop location is : $t(s_j) = \max_i(t_i)$, and the *MC* energy expenditure for that stoping location is given by, $E_{charg}(s_j) = p_t t(s_j)$. Consequently, the overall energy that consumes the *MC* to charge all the nodes of the network depends on the number of stops p on the charging path :

$$E_{charg} = \sum_{j=1}^{p} E_{charg}(s_j) \quad (4)$$

In addition to the charging energy, the *MC* consumes mechanical energy, denoted by E_{travel}, for movement along the charging path. In fact, for a tour of length L, $E_{travel} = aL$, where a is the value of the *MC* propulsion force that depends on the *MC* velocity [11]. Finally, the total energy consumed by the mobile charger is : $E = E_{charg} + E_{travel}$

IV. Problem formulation

The aim is to plan a charging strategy that allows the mobile charger to recharge all the nodes in the network with an optimized energy expenditure. Specifically, the objective is to find optimal stop locations and the corresponding stop durations that minimize the total energy consumed by the mobile charger. The energy optimization must take into account the two aspects of energy expenditure; charging energy and the traveling energy. For this purpose, the problem is formulated as a minimum stop recharging (MSR) problem that computes a charging path allowing to recharge all the nodes in the network, with a small number of stops. In fact, minimizing the number of stops has two advantages. First, it maximizes the number of nodes that are charged simultaneously, which allows to decrease the charging energy needed to replenish all the nodes. Second, planing a charging path with a reduced number of stops helps in lowering the distance traveled by the mobile charger, and it optimizes the traveling energy.

The MSR problem is formulated as follows. Let N be the set of n nodes in the network, i.e.,$|N| = n$. Each node, i, is represented by its *power reception disk*, D_i, as defined in the previous section. We consider R the set of all potential stop regions, R_j, from where the mobile charger can charge one or multiple nodes in the network. Geometrically, (R_j) is either delimited by the intersection of several node's power reception disks, or just by a single region of a power reception disk that do not intersect with any other region. In our model, each region R_j is represented by the set of nodes that can be charged from the region, say, NR_j. Hence:

$$NR_j = \bigcup_{i=1}^{n} \{i | R_j \cap D_i \neq \emptyset\} \quad (5)$$

Obviously, if we have m regions, the union of all regions' representative sets (NR_j is equal to the set of nodes in the network:

$$N = \bigcup_{j=1}^{m} NR_j \quad (6)$$

Since the number of nodes that can be charged from a given region, R_j, is unrelated to the *MC* position (provided it is inside the region), the region's centroid is chosen to be the stop location s_j of the mobile charger when R_j belongs to the charging path. For the ease of presentation, the terms stop region and stop location are used interchangeably.

Given the calculated sets NR_j of possible stop regions, we define $n \times m$ a matrix $A = \| a_{ij} \|$ by:

$$a_{ij} = \begin{cases} 1 & \text{if node } i \in NR_j \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

Minimizing the number of stop locations allowing to recharge all the n nodes in the network is equivalent to the following optimization problem :

$$\begin{aligned} \text{Min} \quad & \sum_{j=1}^{m} x_j \\ \text{s.t.} \quad & \sum_{j=1}^{m} a_{ij} x_j \geq 1 \qquad i = 1, ..., n \\ & x_j \in \{0, 1\} \end{aligned} \quad (8)$$

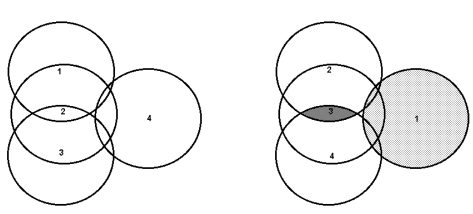
Where x_j is a binary variable that is equal to 1 if the region R_j belongs to the minimum stop path and 0 otherwise. Also, the n inequality constraints ensures that every node must belong to at least one stop region in the minimum stop path. The problem as defined is Integer Linear Programming (ILP) problem and it is NP-hard. This problem is resolved in the next section by a simple heuristic allowing to find a charging path with a small number of stop locations.

V. MSR Algorithm

Finding the optimal solution by resolving the ILP defined in (8) is NP-hard, and thus cannot be achieved with an acceptable computing time performance for a high number of nodes. To deal with this problem, we propose, in the following a Minimum Stop Recharging (MSR) algorithm. The objective is to compute a charging path with a reduced number of stop locations, using low complexity mechanisms that scale with the augmenting number of nodes, as well as with higher network densities.

The main idea is to transform the MSR problem into a clique partitioning problem, and take advantages of a simple but efficient related heuristic to find a reduced number of stop locations in the charging path. To this end, the problem is reformulated as follows: Let $G(V, E)$ be the undirected graph where each node in the network is represented by a vertex in V. An edge between two vertices exists iff. the power reception disks of the corresponding nodes intersect. The clique partition problem applied to $G(V, E)$ consists in finding the minimal number of cliques that partition the graph, where each clique represents a subset of V, such that every two vertices in this subset are connected by an edge. Although the graph portioning is NP-hard, we can find in the literature several heuristics that achieve a near-optimal result in polynomial time. In the proposed algorithm, we use the well known heuristic proposed by Tseng et al. in [12]

The intuition behind partitioning the graph G into a number of cliques is that when a set of nodes form a clique, it is highly probable that a single intersection region exists between their power reception disks. Thus, the algorithm considers this region as stop region from where the mobile charger can charge all the nodes belonging to the clique. However, it is possible that a set of nodes form a clique but their power reception disks do not intersect in a single common region. Fig. 1(a) illustrates an example of four nodes represented by their power reception disks. These nodes form a clique but no common intersection region exist between their power reception disks. When such special case is met, MSR proceeds iteratively to find a minimal set of stop regions from which the nodes of this this clique can be charged. It starts by isolating a single node from the clique and checks if the resulting new clique has a common intersection region. If this is the case, the algorithm considers two stop regions; namely the intersection region of the new clique and the power reception disk of the isolated node. Otherwise, if no common intersection is found in the new clique, the algorithm proceeds to the next iteration by isolating higher number of nodes. Fig. 1(b) shows that by isolating the node 1 from the clique, a common intersection region can be found for the remaining nodes (dark grey region). The algorithm considers, for this case, two stop regions (grey regions).



(a) (b)

Figure 1. An example of a 4-nodes clique. (a) No common intersection region exist for all nodes. (b) Two stop regions are identified after isolating the node 1

The minimum stop recharging path produced by the algorithm is consequently defined by the set, Π, that includes all stop regions related to each clique of the graph G. Upon determination of the set Π, the MSR algorithm calculates the stop durations necessary for the *MC* to charge the nodes covered by each stop region, using the equations provided in Section III. Finally, the last step consists in finding the best strategy allowing the *MC* to travel around the calculated stop positions in order to charge all nodes. For this, we apply a Traveling Salesman Problem (TSP) subroutine on the set Π to produce a minimum-length charging path that includes all the calculated stop positions. The Algorithm 1 summarizes the important steps of our minimum stop recharging algorithm.

Algorithm 1 Minimum Stop Recharging Algorithm

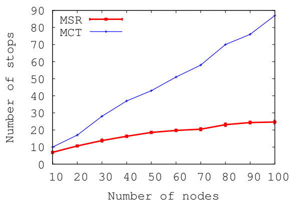
Input: $N = \{i(x_i, y_i, \sigma_i)\}, i = \{1, .., n\}$
Output: $\Pi = \{s_j(x_j, y_j, t_j)\}, j = \{1, .., m\}$
$\Pi = \emptyset$
for $i = 1$ to n **do**
  $D = \emptyset$
  define D_i of node $i(x_i, y_i, \sigma_i)$
  $D = D \cup D_i$
end for
Calculate the graph $G(V, E)$ given D
Find minimum number p of cliques in G(V,E) using heuristic in [12]
for Every clique C_j, $j = 1$ to p **do**
  Find the set P_j of k stop regions using iterative routine, $k \geq 1$
  Calculate the stop duration for each stop region in P_j using formula (2),(3)
  $\Pi = \Pi \cup P_j$
end for
Apply TSP subroutine on Π

VI. Performance Evaluation

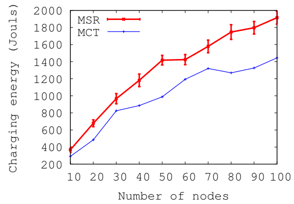
In this section, extensive simulations are conducted to evaluate the proposed solution under different network settings. In the current literature, there is no existing work that uses simultaneous charging of multiple nodes with the objective to optimize both charging and traveling energy. The most related and recent work is by Fu et al. [6], termed the minimum charging time solution (MCT), to which we compare in the following.

A. Simulation Settings

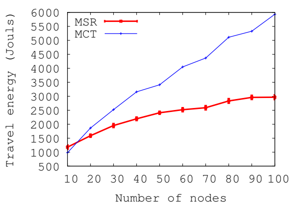
A network of heterogenous sensor nodes that have different battery capacities ($\sigma_i \in [25, 50]J$) is considered. To measure the energy consumed in charging operations, we refer to the experimental data on the efficiency of simultaneous wireless energy transfer, described in [5]. By undertaking a curve fitting on the experiment results, the equation that computes the energy efficiency transfer $\mu(d)$ as a function of the distance between the mobile charger and charged node is found to be : $\mu(d) = -0.0958d^2 - 0.0377d + 1.0$. Assuming, the mobile charger power transmission, $P_t = 5W$, and a minimum received power threshold allowing to a sensor node to be charged, $P_{min} = 1W$, a charging range for the mobile charger would be, $R_c = 2.7m$. Also, and in order to better reflect a realistic environment, the motion characteristics of the Pioneer 3DX robot are considered for the mobile charger *MC* [13]. Hence, to travel from a



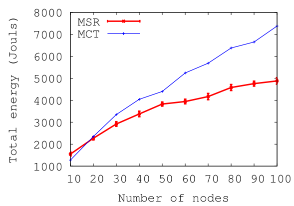
(a) Number of stop locations vs network size



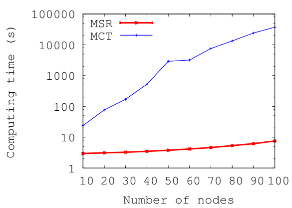
(b) Charging energy vs network size



(c) Travel energy vs network size



(d) Total energy vs network size



(e) Computing time vs network size

Figure 2. MSR performance in low and medium scale networks

charging position to another, the mobile charger increases its traveling speed with an acceleration of $a = 0.3m/s^2$. If the maximum velocity $v_{max} = 2m/s$ is reached, the *MC* keeps traveling with this constant speed before decelerating to stop at the destination. To measure the energy consumed by the mobile charger for traveling along the charging path, we refer to the study presented in [11] on the Pioneer 3DX robot. In fact, it has been shown through real experiments that the traveling energy consumption varies linearly with the robot speed following the equation: $P_{travel} = 7.4v + 0.29$. Finally, all the results are measured with a 0.95 confidence interval.

B. Results of low and medium scale networks

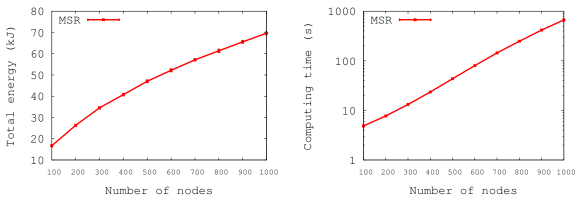
In the first part of our simulation experiments, we evaluate the performance of MSR and compare it with MCT by varying the network size from 10 to 100 nodes. For each simulation scenario, the nodes are randomly deployed over a square surface of $25 \times 25m$.

Figure 2(a) shows the number of stop locations on the charging paths in MSR and MCT. As shown, the number of stop locations in MSR increases slowly with higher number of nodes. Also, it remains low compared to the number of charged nodes in the network (25 stops for 100 nodes). In contrast, the number of stops in MCT augments linearly and reaches high values for highe number of charged nodes. In fact, since MCT scheme focuses on optimizing the charging energy only, the mobile charger tends to visit each node individually to perform the charging operations from shorter distances and enhance the charging efficiency. This explains the high number of stop points in MCT. In MSR, minimizing the number of stop points allows to optimize the charging energy, but in different way than MCT. In fact, rather than minimizing the charging energy by enhancing the efficiency of energy transfer, MSR tends to maximize the number of nodes that can be charged simultaneously in order to take benefit from the simultaneous multi-node charging technology. This is shown in figure 2(b) where MSR consumes more energy for charging the nodes, but the measured values stay relatively close to MCT that consumes a near-optimal charging energy as demonstrated in [6]. In addition, the plots show a similar rise shape vs. the number, for MSR and MST.

Contrary to charging energy expenditure, we notice a considerable optimization in the traveling energy consumed by MSR, compared to MCT (Fig 2(c)). This is due to the low number of stops in MSR which helps in reducing the length of charging path and thus, the energy needed for traveling around this path. Also, minimizing the number of nodes in the charging path optimizes the motion of the mobile charger that consumes more energy when the charging path contains lot of stops due to repetitive accelerations and decelerations, and high dynamics in traveling speed.

Figure 2(d) illustrates the total energy consumed by the mobile charger for both charging nodes and traveling around the path. We remark that for a relatively low number of nodes ($n \leq 20$), MSR and MCT consumes almost the same amount of energy. However, this amount becomes higher for MCT then for MSR as the number of nodes increases. This is explained by the fact that the optimization on charging energy in MCT cannot compensate the high traveling energy expenditure when the number of nodes to be charged is high. Consequently, we conclude that for large-scale network, and when using simultaneous multi-node recharging, optimizing the total energy expenditure of the mobile charger inevitably requires minimizing the traveling energy.

The scalability of a wireless recharging scheme with respect to high number of nodes should not be measured only in terms of its energy efficiency. It is important to consider also the complexity of the techniques used to compute the charging path and stop durations. The entity responsible of undertaking these calculations in wireless rechargeable sensor networks is the mobile charger. Even that the latter is assumed to be more powerful in terms of computing and memory capacity, compared to the sensor nodes, the computing overhead of the charging path and stop durations needs to stay within a feasible performance interval, in order to allow the recharging scheme to be practical. In Fig. 2(e), the time to compute the charging path and stop durations is represented. The experiments are performed on a desktop computer with an Intel®Core i3 CPU and $4GB$ of RAM, running Windows8 operating system. As it can



(a) Total energy vs network size (b) Computing time vs network size

Figure 3. MSR performance in large scale networks

be noted, the MCT approach is very consuming in terms of computing time. For example, calculating the charging path for 100 nodes took more than 7000 seconds, while the MSR calculation time did not exceed 10 seconds. This considerable gap is caused by the difference in pursued approaches to compute the charging path. MCT adopts a linear programming optimization approach where the number of optimization variables in the modeled problem exponentially increases with number of node. However, MSR adopts a low-complexity heuristics that are known to scale well with the size of optimization problem.

C. Results for large-scale networks

To better demonstrate the scalability of MSR in large-scale networks, we vary the number of charged nodes from 100 to 1000 nodes. The nodes are randomly deployed in a square area of $100 \times 100m$. However, and because of the high complexity of MCT, we have been unable to execute this approach within an acceptable computing time. Hence, the second part of our simulation study is limited on providing an insight about MSR behaviour in large-scale networks. As shown in Fig. 3(a) and 3(b), both the total energy consumption and execution time increase in smoothly with respect to higher number of charged nodes, which demonstrates the good scalability of MSR in large-scale sensor networks.

VII. Conclusion

In this paper, recent advances in simultaneous multi-node energy transfer are exploited to devise an energy efficient and scalable recharging scheme for wireless rechargeable sensor network. Our approach was to formulate the problem as a minimum stop recharging path calculation, that jointly optimizes charging and traveling energy. After proving the NP-hardness of the model, a simple algorithm based on clique-partitioning was proposed to find a charging path with a reduced number of stop locations. The proposed approach (MSR) has been compared to MCT, where the simulation results show a superiority of MSR in reducing the number of stops and thus, the mechanical energy that consumes the mobile charger (travel energy). Further, MSR has a low computation complexity, and the difference compared to MCT is exponential with this respect. The simulation results demonstrated that optimizing the number of stops in the charging path reduces considerably the total energy consumed by the mobile charger. In addition, the low-complexity mechanisms integrated in MSR allowed it to have a good scalability in large-scale networks.

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