Minimizing the Longest Charge Delay of Multiple Mobile Chargers for Wireless Rechargeable Sensor Networks by Charging Multiple Sensors Simultaneously

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***Abstract*—Wireless energy charging has emerged as a very promising technology for prolonging sensor lifetime in Wireless Rechargeable Sensor Networks (WRSNs). Existing studies focused mainly on the 'one-to-one' charging scheme that a sensor can be charged by a single mobile charger at each time, this charging scheme however suffers from poor charging scalability and inefficiency. Recently, another charging scheme - the 'multiple-to-one' charging scheme that allows multiple sensors to be charged simultaneously by a single charger, becomes dominant and can mitigate charging scalability and improve the charging efficiency. Most research studies on this latter scheme focused on the use of a mobile charger to charge multiple sensors simultaneously. However, for large scale WRSNs, it is insufficient to deploy just a single mobile charger to charge many lifetime-critical sensors, and consequently sensor expiration durations will increase dramatically. Instead, in order to charge as many as lifetime-critical sensors, the use of multiple mobile chargers for charging sensors can speed up sensor charging significantly, thereby reducing their expiration durations and improving the monitoring quality of WRSNs. However, this poses great challenges to schedule multiple mobile chargers for sensor charging at the same time such that the longest delay among the chargers is minimized due to multiple critical constraints. One such an important constraint in multiple mobile chargers is that each sensor cannot be charged by more than one mobile charger at each time, otherwise, the sensor cannot receive any energy from either of the chargers. In this paper we address this challenge by first formulating a novel longest delay minimization problem that is NP-hard. We then devise the very first approximation algorithm with a provable approximation ratio for the problem. We finally evaluate the performance of the proposed algorithm through experimental simulations. Simulation results demonstrate that the proposed algorithm is very promising, which outperforms the other heuristics in various settings.**

***Index Terms*—Wireless rechargeable sensor networks; multi-node energy charging; multiple mobile chargers; multiple charging tour scheduling; charging delay minimization; approximation algorithms; maximal independent set.**

I. Introduction

Wireless Sensor Networks (WSNs) have been widely applied in various domains, from military surveillance, disaster forecasting to cutting-edge smart homes, and smart cities [4], [16]. They all rely on ubiquitous sensors to capture multi-dimensional data from surrounding objects for various purposes. However, a sensor is usually powered by an on-board battery with limited energy capacity, sensor lifetime prolongation remains a critical issue [14]. Although energy harvesting technologies [6], [21], [23] have been proposed to accumulate energy from ambience, such as solar and wind energy, these methods are sensitive to environments, thus they cannot provide stable energy to sensors.

Wireless energy charging was proposed to address energy issues in WSNs [8], [17], [22], [31]. It can be achieved by charging a nearby sensor with a *Mobile Charging Vehicle (MCV)*. This technology possesses many advantages as it does not require direct contact between the mobile charger and the sensor, or even it does not require line-of-sight (LOS) as long as the charging device is within the wireless energy transmission range of the mobile charger. Also, compared to renewable energy harvesting, wireless energy transfer can provide stable energy to sensors. This charging process can be applied in an on-demand manner when devices request to be charged. The powerfulness of wireless energy charging technology brings about broad commercial applications [3], [19], [25], [32].

Despite wireless energy transfer is a promising technique to prolong sensor lifetime, the energy charging efficiency and scalability of this technique has been explored in the past. For example, Kurs *et al.* [9] proposed a *multi-node wireless energy charging* scheme, where multiple sensors can be charged simultaneously by properly tuning operation frequencies of both the sender and the receiver coils.

Most research studies on the multi-node charging scheme focused on the use of a single mobile charger to charge multiple sensors simultaneously [7], [15], [18], [20], [28]. However, for a large scale WRSN, it is insufficient to deploy only a single mobile charger to charge many lifetime-critical sensors, as it still takes a long time (e.g., 30-90 minutes) to

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fully charge a commercial sensor battery, and consequently sensor expiration durations will increase dramatically [24], [31]. Instead, in order to charge many lifetime-critical sensors as early as possible, the use of multiple mobile chargers can speed up sensor charging and reduce the expiration durations of sensors, thus improve the monitoring quality of the sensor network.

The adoption of multiple mobile chargers with each charging multiple sensors simultaneously in WRSNs poses great challenges. (i) How to schedule the charging tours of multiple mobile chargers to ensure that all lifetime-critical sensors can be charged as soon as possible? (ii) How to ensure in such scheduling that each sensor will not be charged by more than one MCV at any time? A sensor may be in the coverage ranges of multiple MCVs located at different locations, but the sensor cannot be charged by two or more mobile chargers at the same time, due to the facts that (1) the sensor cannot receive any energy from either of the chargers; or (2) overcharging a sensor will damage its recharging battery. For example, Fig. 1 shows that sensor u will be charged by two chargers simultaneously if they stay at locations v_1 and v_2, respectively, at the same time. (iii) What is the charging duration of each MCV at each of its charging locations to ensure that all sensors in its charging coverage range will be fully charged? As a sensor could be in the coverage ranges of multiple MCVs at different charging locations, some sensors have been already charged when an MCV moves to a location in which the sensor is in its charging coverage range. In this paper, we will address these three challenges by developing efficient solutions for them.

The novelty of this paper focuses on efficient charging multiple sensors simultaneously in a WRSN, by deploying multiple mobile chargers instead of only a single charger. To the best of our knowledge, we are the first to formulate a novel scheduling problem of the longest delay minimization problem that aims to charge multiple sensors simultaneously, by employing $K \geq 1$ mobile chargers and finding a closed charging tour for each of the K mobile chargers, while meeting an important constraint that each sensor cannot be charged by two or more mobile chargers at the same time. We develop the very first approximation algorithm for the problem through exploring the combinatorial property of the problem, and design and analysis technique in the development of the approximation algorithm may have independent interest in other approximation algorithms developments.

The main contributions of this paper are as follows. We first formulate a novel longest charge delay minimization problem by adopting $K \geq 1$ mobile chargers with each enabling to charge multi-node simultaneously while ensuring that no sensor can be charged by more than one MCV at each time. We aim to minimize the longest delay among the K MCVs, by finding a charging tour for each of the K mobile chargers, where the total delay of an MCV is the sum of the charging duration at each location and the travel delay in its charging tour. We then devise an approximation algorithm with a constant approximation ratio for the problem. We finally evaluate the performance of the proposed algorithm through experimental simulations. Simulation results show that the proposed algorithm is promising. Especially, the longest charging delay among the K MCVs by the proposed algorithm is at least 65% shorter than those by existing algorithms.

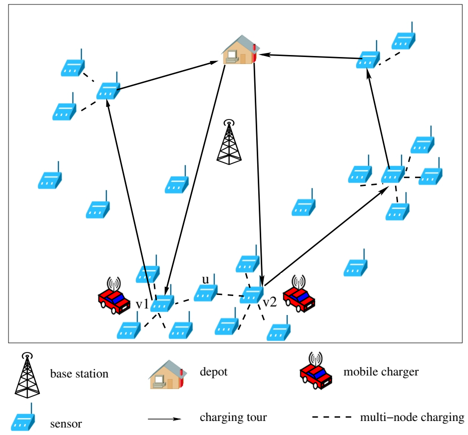


Fig. 1. An example of multi-node energy charging by two mobile chargers, where sensor u will be charged by the two chargers simultaneously if they stay at locations v_1 and v_2, respectively, at the same time.

The rest of the paper is organized as follows. Section II reviews related work. Section III introduces notions, notations, and the problem definition. The NP-hardness of the defined problem is also shown in this section. Section IV deals with the longest charging delay minimization problem. Section V analyzes the proposed algorithm. Section VI evaluates the performance of the proposed approximation algorithm empirically, and Section VII concludes the paper.

II. RELATED WORK

Wireless energy transfer technology based on strongly magnetic resonances [8] has been regarded as a breakthrough technology for lifetime prolongation of sensors in wireless rechargeable sensor networks (WRSNs) in literature [2], [18], [22]. Several studies on wireless energy charging have been conducted, by applying a mobile charger to charge sensors one by one in WRSNs [5], [15], [18], [24]. For example, Shi *et al.* [22] theoretically studied applying this technique to charge sensors in WSNs by periodically dispatching a mobile charging vehicle such that the network can operate perpetually. Liang and Luo [11] studied multiple mobile chargers for sensor charging under the one-to-one charging scheme, for which they proposed a heuristic by a reduction to a series of minimum maximum matching problems. However, that algorithm cannot be extended for the problem under one-to-many charging scheme, as the constraint that a sensor cannot be charged by more than one MCV at any time does not exist in the one-to-one charging scheme. There is not any guarantee on the solution delivered by their algorithm, this implies that the solution may be far from the optimal one. Wu *et al.* [26] formulated a cooperative charging problem by using multiple mobile chargers to charge sensors such that none of the sensors will run out of energy. They aimed to minimize energy consumption of mobile chargers by leveraging genetic algorithms. Xu *et al.* [30] considered sensor charging by employing multiple mobile chargers, and proposed an approximation algorithm for finding a charging tour for each mobile charger such that all sensors are charged and their total expiration duration is minimized, assuming that different sensors have different energy depletion rates. Liang *et al.* [13], [14] considered an optimization problem of minimizing the number of mobile chargers to charge a set of sensors, assuming that the energy capacity of each mobile charger is limited. They developed an approximation algorithm for the problem. Also, Liang *et al.* [15] studied the charging utility maximization problem, and proposed efficient approximation algorithms for the problem under both full charging and partial charging models.

All mentioned studies so far is under one-to-one charging scheme, i.e., each mobile charger can only charging one sensor, and this charging does not affect the other sensor. However, this scheme is neither energy-efficient nor scalable. There is another charging scheme refereed as the multi-node charge scheme, or one-to-many charge scheme where a single mobile charger can charge all sensors within its charging range. Under this later scheme, Xie *et al.* [28] were the first to study multi-node wireless energy charging in WRSNs by periodically dispatching a mobile charger. They aimed to minimize energy consumption of the mobile charger by minimizing sojourn time at each stopping point. They [29] later further considered the use of a mobile charger for both sensor charging and data collection with the aim of minimizing the energy consumption of the whole network under the constraints that none of the sensors will not run out of energy and all collected data can be relayed to the base station. For both mentioned studies, they assumed that the traveling path of the mobile charger is given in advance. However, planning a the traveling path by choosing sojourn locations for the mobile charger is non-trivial in multi-node charging scenarios. Ma *et al.* [18] recently considered the multi-node charging scheme for a single MCV, by proposing a framework to measure the charging utility gain of each charged sensor, and proposed heuristic and approximation algorithms for maximizing the charging utility gain, subject to the energy capacity of the mobile charger. They studied the finding of a charging closed tour for a single MCV with different optimization objectives under different assumptions, including the energy capacity of the mobile charger, not all requesting charging sensors will be charged in the end due to the energy constraint on the mobile charger. In addition, Khelladi *et al.* [7] investigated an on-demand multi-node charging problem. They aimed at minimizing the number of stopping points and energy consumption for a mobile charger in its charging tour. Different from the optimization objectives and assumptions in [7], [18], in this paper we will investigate multiple MCVs for sensor charging. We aim to charge all sensors while the longest charge delay among the MCVs is minimized. The key challenge to tackle this multiple mobile chargers scheduling problem lies in an important constraint. That is, each sensor cannot be charged by more than one MCV at any time; otherwise, the sensor will be damaged due to overdose energy on it simultaneously or it cannot be charged at all due to receiving different charge energy frequencies from multiple MCVs at the same time.

III. Preliminaries

In this section, we first introduce the system model, notions and notations. We then define the problem precisely.

A. Network model

We consider a Wireless Rechargeable Sensor Network $G_s = (V, E)$ consisting of a set V of stationary sensors distributed over a two-dimensional space, E is the set of edges, there is an edge between two sensors if they are within the transmission range of each other. There is a fixed base station, which is the sink node for sensor data collection. Each sensor $v \in V$ is powered by an on-board rechargeable battery with energy capacity C_v, sensors consume their energy on sensing, data processing, and data transmission. Denote by RE_v the residual energy of sensor v when it requests for charging. Without loss of generality, we assume that there is sufficient energy supply to the base station, it thus has no energy constraint.

We assume that there is a depot for mobile charging vehicles (MCVs), this depot may or may not be co-located with the base station, and there are K (≥ 1) MCVs located at the depot. Each MCV has a charging rate η and constant travel speed s. Each sensor sends a charging request to the base station when its residual energy falls below a threshold, and the base station then identifies a set $V_s \subseteq V$ of lifetime-critical sensors for energy charging [31]. The base station starts scheduling the MCVs by finding a charging closed tour for each of them and dispatches them for sensor charging along their planned tours. The MCVs will return the depot for recharging themselves when they finish their charging tasks.

B. Multi-node wireless energy charging, mobile chargers and their charging tours

The technique of wireless energy transfer to multiple sensors simultaneously was invented by Kurs *et al.* [9]. They showed that the overall energy efficiency can be significantly improved by proper tuning of the coupled resonators when multiple receivers instead of a single receiver are charged simultaneously. This multi-node wireless energy charging technique is a promising technique that can address both charging efficiency and scalability for large-scale wireless rechargeable sensor networks. In this paper, we will adopt this *multi-node energy charging* scheme, where multiple sensors can be charged simultaneously if they are within the energy transmission range of a mobile charger.

To maintain long-term operations of WRSNs and minimize the expiration durations of sensors, multiple MCVs usually are employed to charge the sensors in V_s, where each mobile charger is equipped with a wireless charger that can charge multiple sensors simultaneously. We assume that all mobile chargers are located at a depot v_0 initially, which may or may not be co-located with the base station. The mobile chargers are dispatched from the depot v_0 by the base station for sensor charging through travelling along the scheduled closed tours for them. Ideally, a mobile charger can stop at any location in the monitoring area for sensor charging, and each stop location is referred to as a *sojourn location* of the mobile charger. However, this introduces infinite numbers of potential sojourn locations for mobile chargers. For the sake of problem tractability, we assume that mobile chargers can only stop at the locations co-located with sensors.

As we consider multi-node charge simultaneously, once an MCV stops at a location, it can charge all sensors within its energy transmission range. However, one very critical constraint in the scheduling of the K MCVs for their charging tours is that if there is a sensor within the charging ranges of two or more MCVs, the sensor cannot be charged by these MCVs at the same time. Fig. 1 is an illustrative example of multi-node energy charging by two mobile chargers. It can be seen that sensor u will be charged by two mobile chargers simultaneously, if the two chargers replenish sensor energy at v_1 and v_2 at the same time. This constraint makes the charging tour scheduling of MCVs become very difficult.

When a mobile charger stops at a sensor node $v \in V_s$, sensor v and its neighbors in $N_c(v)$ within its energy charging range γ can be simultaneously charged, where $N_c(v) = \{u \mid d(u, v) \leq \gamma,\ u \in V_s, u \neq v\}$, $d(u, v)$ is the Euclidean distance between sensor nodes u and v, and γ is the mobile charger's charging radius, e.g., $\gamma = 2.7\ m$ [9]. Denote by $N_c^+(v) = \{v\} \cup N_c(v)$, only all sensors in $N_c^+(v)$ have been fully charged, the mobile charger can move to the next sojourn location for its sensor charging. For the sake of convenience, we assume that energy leaking of sensors during this multi-node charging process is negligible, and a mobile charger has sufficient energy for traveling and sensor charging per charging tour as we employ enough number of MCVs for sensor charging as needed. The base station serves as not only the data collector of the network but also the scheduler of mobile chargers. When one mobile charger finishes its charging tour, it will return the depot to replenish energy for its next charging tour. Each charging tour C_k of a mobile charger k is a *closed tour* including the depot.

C. Problem definition

In this paper, we formulate the following multiple mobile chargers tour scheduling problem, by leveraging the multi-node charging technique. Given a set V_s of on-demand charging sensors, each sensor $v \in V_s$ has a energy capacity C_v and its current residual energy RE_v, let t_v be the charging duration for charging sensor v to its full capacity by a mobile charger vehicle, then t_v is defined as follows.

$$t_v = \frac{C_v - RE_v}{\eta}, \tag{1}$$

where η is the charging rate of a mobile charger.

Assume that an MCV located at v can charge all sensors within its transmission range. To ensure that all sensors in the range will be fully charged, the longest charge duration of the MCV at v is upper bounded by

$$\tau(v) = \max_{u \in N_c^+(v)} \{t_u\}. \tag{2}$$

We assume that there are K mobile chargers located at a depot initially. Each mobile charger at its sojourn location can charge multiple sensors simultaneously as long as these sensors are within its charging radius γ.

Let u and v be the two sojourn locations that two MCVs are currently located respectively, assuming that two MCVs arrive at their sojourn locations u and v at time points s_u and s_v respectively, then their charging finish time are $f_u = s_u + \tau'(u)$ and $f_v = s_v + \tau'(v)$. We say that these two MCVs are *overlapping* with each other at u and v if there is a sensor $w \in N_c^+(u) \cap N_c^+(v)$ in their charging overlapping area and their charging time intervals $[s_u, f_u]$ and $[s_v, f_v]$ overlap with each other, i.e., $[s_u, f_u] \cap [s_v, f_v] \neq \emptyset$, or sensor s will be charged by the both MCVs at any time point of $[s_u, f_u] \cap [s_v, f_v]$. This implies that it is prohibited that two MCVs at u and v can charge sensors at the mentioned time intervals.

Definition 1: Given a set of sensors V_s to be charged with each sensor $v \in V_s$ having its residual energy RE_v, there are K mobile chargers (MCVs) to charge the sensors, the *longest charge delay minimization problem* in the wireless sensor network $G = (V_s, E_s)$ then is to find a closed charging tour $C_k = \langle v_{k,i_0}, v_{k,i_1}, v_{k,i_2}, \ldots, v_{k,i_k} \rangle$ including the depot $v_{k,0}$ for each mobile charger k such that the longest charging delay among the K mobile chargers is minimized, subject to that no sensor can be charged by two mobile chargers simultaneously, assuming that v_{k,i_0} is the depot with $1 \leq k \leq K$.

Let $V(C_k) = \{v_{k,i_j} \mid 1 \leq j \leq k\}$ be the set of node locations in the closed tour C_k. Then, $\cup_{k=1}^{K} V(C_k) \subseteq V_s$, $\cup_{k=1}^{K} \cup_{v \in V(C_k)} N_c^+(v) = V_s$ and $V(C_i) \cap V(C_j) = \{v_{k,i_0}\}$ if $i \neq j$, where $v_{1,i_0} = v_{2,i_0} = \ldots = v_{K,i_0}$ is the depot of the K MCVs.

Let $\tau'(v_{k,i_l})$ be the actual charge time of mobile charger k at a sojourn location v_{k,i_l} in its closed tour C_k. Then

$$\tau'(v_{k,i_l}) = \max_{u \in N_c^+(v_{k,i_l}) \setminus \cup_{j=1}^{l-1} N_c^+(v_{k,i_j})} \{t_u\}. \tag{3}$$

It can be seen that $\tau'(v_{k,i_l}) \leq \tau((v_{k,i_l})$, as some sensors in the charging range of MCV k at its sojourn location v_{k,i_l} may have been charged by the mobile charger itself or other mobile chargers prior to arriving its current sojourn location. The *charge delay* of mobile charger k along C_k thus is

$$T'(k) = \sum_{l=0}^{i_k - 1} (\tau'(v_{k,l}) + d(v_{k,l}, v_{k,l+1})/s) + d(v_{k,i_k}, v_{k,0})/s, \tag{4}$$

Let $T(k)$ be the upper bound on the delay $T'(k)$ of mobile charger k on its charging tour $C_k = \langle v_{k,i_0}, v_{k,i_1}, v_{k,i_2}, \ldots, v_{k,i_k} \rangle$. Then,

$$T(k) = \sum_{l=0}^{i_k - 1} (\tau(v_{k,i_l}) + d(v_{k,i_l}, v_{k,i_{l+1}})/s) + d(v_{k,i_k}, v_{k,0})/s, \tag{5}$$

where $d(v_{k,l}, v_{k,i_{l+1}})/s$ is the travel time of mobile charger k from its current sojourn location v_{k,i_l} to its next sojourn location $v_{k,i_{l+1}}$ with a constant speed s.

Clearly, $T'(k) \leq T(k)$. The longest charge delay minimization problem then is to find K node-disjoint closed tours for the K MCVs (all sojourn locations form the set of nodes for

k-node-disjoint closed tours) to cover all sensor nodes $v \in V_s$ such that the longest delay $\max_{1 \leq k \leq K}\{T'(k)\}$ among the K closed tours is minimized, subject to that no sensor can be charged by two or more mobile chargers at the same time, i.e., no two MCVs at their sojourn locations are overlapping at any time during their charging periods. The rationale behind the problem definition is that we aim to make each requested sensor to be charged as soon as possible to reduce its potential expiration time.

Notice that the longest delay minimization problem is NP-hard, since the well-known NP-hard TSP problem can be reduced to it. Due to limited space, the proof of the NP-hardness of the problem is omitted.

IV. Approximation Algorithm for the Longest Delay Minimization Problem

In this section we consider K MCVs employed, we have the following algorithm.

We construct a charging graph $G_c = (V_s, E)$, where V_s is the set of to-be-charged sensors, and there is an edge between two sensors in E if their distance is no greater than the charging range γ.

A. Find a partial solution without overlapping

In the proposed algorithm, in order to charge all sensors, we first find a maximal independent set (MIS) S_I in charging graph G_c, $S_I \subseteq V_s$. Then, the distance between any nodes u and v in S_I is strictly larger than the charging range γ. Also, each node in S_I is a potential sojourn location of one MCV among the K MCVs for charging unless all sensors covered by the node (or it represents the sojourn location) have been charged by other MCVs already.

We then construct another graph $H = (S_I, E_H)$, where S_I is the set of nodes and there is an edge $(u, v) \in E_H$ between two nodes if $N_c^+(u) \cap N_c^+(v) \neq \emptyset$. Thus, each edge in E_H indicates that the distance between its two endpoints is strictly larger than γ but less than 2γ. Let V'_H be a maximal independent set of graph H, then we observe that for any two nodes in V'_H, there will be no overlapping between any MCVs at these two locations at any time.

We finally find K node-disjoint closed tours in the set V'_H such that the longest delay among the K closed tours is minimized. However, even for this special case of the problem where only a subset $\cup_{v \in V'_H} N_c^+(v) \subset V_s$ of sensors, it is NP-hard. We instead can find an approximate solution to this special problem [14]. Denote by $C_1, C_2, \ldots, C_K$ the initial K closed tour, where $C_k = \langle v_{k,i_0}, v_{k,i_1}, \ldots, v_{k,i_k} \rangle$ and $\cup_{k=1}^{k} V(C_k) = V'_H$.

Now, given the current setting $\{C_1, C_2, \ldots, C_K\}$, *the charging finish time* $f(v_{k,i_l})$ of each node v_{k,i_l} in a closed tour C_k is defined as

$$f(v_{k,i_l}) = \sum_{j=0}^{l-1} (d(v_{k,i_j}, v_{k,i_{j+1}})/s + \tau'(v_{k,i_j})) + \tau'(v_{k,i_l}), \quad (6)$$

where s is the travel speed of MCV k.

B. Extend the partial solution

The rest is to determine whether each node $u \in S_I \setminus V'_H$ should be inserted into one of the K closed tours. Node u can be either removed from the consideration if its coverage area (or an MCV located at it for sensor charging) $N_c^+(u)$ has been covered by the nodes in $\cup_{k=1}^{K} \cup_{v \in V(C_k)} N_c^+(v)$ already, or inserted to one of the K closed tours. However, inserting a node in to one of the closed tours is challenging as we need to consider two critical issues.

One is that node u cannot be arbitrarily inserted to any closed tour; otherwise, assuming that u is inserted to a closed tour in a position between two neighboring nodes v_1 and v_2 of the closed tour, then the travel distance between v_1 and u and the travel distance between u and v_2 may become very large, implying that it will take a long time for an MCV traveling from v_1 to v_2 through node u. Instead, u should be inserted to one of its neighbors v_i in H, and the distance between u and v_i is strictly less than 2γ by the construction of graph H.

Another is that the insertion of node u into a closed tour should still maintain the sensor charging property for all charging tours, ensuring the charging scheduling still to be feasible. That is, no sensor will be charged by two MCVs at the same time. Otherwise, this important constraint might be violated.

In the following we deal with the insertion of node $u \in S_I \setminus V'_H$ into a closed tour while maintaining the solution obtained is feasible.

For a node $u \in S_I \setminus V'_H$, if $N_c^+(u) \subseteq \cup_{k=1}^{K} \cup_{l=1}^{k} N_c^+(v_{k,i_l})$, then all sensors covered by an MCV at u will be charged by the K MCVs along their closed tours built so far. Node u thus will not be considered as a sojourn location of any mobile charger. Otherwise, the neighboring set of node u in graph H can be expressed as follows.

$$N_H(u) = N'_H(u) \cup N''_H(u), \quad (7)$$

where $N'_H(u) \subset \cup_{k=1}^{K} V(C_k)$, and $N''_H(u)$ is the set of nodes that have not been assigned to any of the K closed tours.

We claim that $N'_H(u) \neq \emptyset$; otherwise, node u should have been included in V'_H already. Thus, without loss of generality, in the rest of our discussion, we assume that $N'_H(u) \neq \emptyset$.

For each sensor $u \in S_I \setminus V'_H$, we consider the latest charging finish time $f_N(u)$ of its neighbors in $N'_H(u)$, i.e.,

$$f_N(u) = \max_{v_{k,j} \in N'_H(u)} \{f(v_{k,j})\}, \quad (8)$$

where sensor $v_{k,j}$ is charged in tour C_k and $f(v_{k,j})$ is its charging finish time.

We sort the nodes in $S_I \setminus V'_H$ in increasing order of their latest neighbor charging finish times. Assume that the sorted sequence is $u_1, u_2, \ldots, u_{n_I}$, then
$f_N(u_1) \leq f_N(u_2) \leq \cdots \leq f_N(u_{n_I})$, where $n_I = |S_I \setminus V'_H|$.

We deal with the potential insertions of nodes $u_1, u_2, \ldots, u_{n_I}$ into the K closed tours one by one. Assume that u is the next to-be inserted node. We distinguish our discussion into two cases.

Case (i). $\exists k$ such that $N'_H(u) \subset V(C_k)$ with $1 \le k \le K$, i.e., all the neighbors of u in H are in a single closed tour C_k.

Case (ii). The nodes in $N'_H(u)$ are in at least two or more closed tours among the K the closed tours.

We now consider Case (i). Recall that each node v_{k,i_j} in closed tour C_k has its charging finish time $f(v_{k,i_l})$ with $1 \le k \le K$ and $0 \le j \le k$. Assume that $N'_H(u) \subset V(C_{k_0})$, where

$$k_0, j_0 = \arg\max_{k,j}\{f(v_{k,i_j}) \mid v_{k,i_j} \in N'_H(u)\}. \quad (9)$$

We first insert node u just after node (location) $v_{k_0,i_{j_0}}$ in closed tour C_{k_0}, and calculate the charging duration of MCV k_0 at location u as follows.

$$\tau'(u) = \max_{v \in N_c^+(u) \setminus \cup_{v' \in \cup_{k=1}^K V(C_k)} N_c^+(v')} \{\frac{C_v - RE_v}{\eta}\}. \quad (10)$$

We then recalculate the charging finish time of all nodes in C_{k_0}, i.e., the charging finish time of each node in C_{k_0} will be updated, due to the insertion of node u. In other words, we only update the charging finish time of each node after node $v_{k_0,i_{j_0}}$. That is, the charging finish time of the newly inserted node u in C_{k_0} is

$$f(u) = f(v_{k_0,i_{j_0}}) + d(v_{k_0,i_{j_0}}, u)/s + \tau'(u). \quad (11)$$

For every other node v_{k_0,i_l} in C_{k_0} with $j_0 < l \le k$, we have

$$f(v_{k_0,i_l}) = f(v_{k_0,i_l}) + d(v_{k_0,i_{j_0}}, u)/s + d(u, v_{k_0,i_{j_0+1}})/s - d(v_{k_0,i_{j_0}}, v_{k_0,i_{j_0+1}})/s + \tau'(u). \quad (12)$$

The rationale behind the handling of Case (i) is that MCV k_0 at location u is only overlapping with itself at the other locations $v' \in N'_H(u)$ in closed tour C_{k_0}, and some sensors in $N_c^+(u)$ have already been charged by MCV k_0 or the other MCVs prior to MCV k_0 moving to the location u, and the charging duration of MCV k_0 at location u is $\tau'(u)$. Notice that location u in C_{k_0} has the largest charging finish time, compared with the charging finish time of any other neighbor $v' \in N'_H(u)$ of u in C_{k_0}. Thus, no sensor will be charged by two MCVs at the same time.

The rest is to deal with Case (ii) nodes as follows. Consider a being considered node u in Case (ii). Let

$$k_0, j_0 = \arg\max_{k,j}\{f(v_{k,i_j}) \mid v_{k,i_j} \in N'_H(u)\}. \quad (13)$$

We first insert node u to closed tour C_{k_0} just after node (the location) $v_{k_0,i_{j_0}}$ in closed tour C_{k_0}. The charging duration of MCV k_0 at location u is $\tau'(u)$ can be calculated by Eq. (11). We then recalculate the charging finish time of all nodes in closed tour C_{k_0} by Eq. (12), which is almost identical to Case (i), omitted.

The rationale of node insertion in Eq. (13) is that if it is inserted into a location which is a neighbor of u in H a closed tour that the charging finish time is not the maximum one among its neighbors, then it is very likely that there will be overlapping between MCV k_0 at location $v_{k_0,i_{j_0}}$ and another MCV located at its neighbor in H in another closed tour. In other words, the charging intervals of these two MCVs will be overlapping and if a sensor is within their overlapping area, it will be charged by both of them at the same time.

Notice that once node u is inserted to a closed tour C_{k_0} after node $v_{k_0,i_{j_0}}$, we update not only the charging finish time of each of the nodes after node $v_{k_0,i_{j_0}}$ in the closed tour C_{k_0}, but also the latest neighbor charging finish time of the nodes in $S_I \setminus V'_H$ that have not been inserted.

The proposed algorithm is given in `Algorithm` 1.

V. Algorithm analysis

In this section, we analyze the approximation ratio of the proposed algorithm, `Algorithm` 1. We observe that the value of an optimal solution of the longest delay minimization problem in a subset $V' \subseteq V_s$ of sensors is no greater than the value of the optimal solution of the longest delay minimization problem in a set V_s. We thus make use of the optimal solution of the problem in a special subset $\cup_{u \in V'_H} N_c^+(u)$ of V_s as the approximate estimation on the optimal solution of the problem in set V_s, and then derive the approximation ratio of the proposed approximation algorithm for the longest delay minimization problem in V_s as follows.

Recall that V'_H is a maximal independent set of graph H. Each node v in V'_H thus covers a set of sensors, and the coverage areas of any two nodes in V'_H are not overlapping with each other. We define the following optimization problem.

Definition 2: Given a set V'_H of nodes and a depot v_0 in a 2-D metric space, each node $v \in V'_H$ has a charging duration $\tau(v)$, assume that there are K MCVs at the depot initially, the travelling time of a mobile charger between two nodes u and v with constant traveling speed s is $d(u,v)/s$, i.e., each edge (u,v) has a travel delay weight $d(u,v)/s$, *the K-optimal closed tour problem* is to find K (≥ 1) node-disjoint closed tours except that the depot will be contained by all K closed tours such that the longest delay among the K closed tours is minimized, subject to that the union of nodes in the K closed tour is V'_H, where the total delay of a closed tour is the weighted sum of nodes and edges in the tour.

Notice that the k-optimal closed tour problem is NP-hard, and there is a 5-approximation algorithm for the K-optimal closed tour problem due to Liang *et al.* [14]. The solution to the K-optimal closed tour problem is exactly an optimal solution to the longest delay minimization problem in a set V' ($= \cup_{u \in V'_H} N_c^+(u)$) of sensors, and for any two nodes u and v in V'_H, $N_c^+(u) \cap N_c^+(v) = \emptyset$ and $d(u,v) \ge 2\gamma$, i.e., there is no overlapping between any two MCVs located at any two nodes in V'_H at any time.

Denote by L'_{OPT} and L_{OPT} the optimal solutions of the longest delay minimization problem in sets $\cup_{u \in V'_H} N_c^+(u)$ and V_s, respectively. It can be seen that $L'_{OPT} \le L_{OPT}$. Let L be the solution delivered by an approximation algorithm for the K-optimal closed tour problem in V'_H. Then,

$$L \le 5 \cdot L'_{OPT} \le 5 \cdot L_{OPT}. \quad (14)$$

Algorithm 1 Algorithm Appro

Input: A set of sensors V_s to be charged, a depot v_0, K mobile charging vehicles with each having an energy charging range γ and a traveling speed s.

Output: K closed charging tours $C_1, C_2, \ldots, C_K$ with each including the depot v_0 such that the longest delay closed tour among the K closed tour is minimized.

Construct a charging graph $G_c = (V_s, E)$, where there is an edge between two vertices in E if their distance is no greater than the charging radius γ;
Find a Maximal Independent Set S_I in G_c. Thus, if there is an MCV at each vertex $v \in S_I$ to charge all sensors in $N_c^+(v) = \{u \mid u \in V, \& \ d(u,v) \leq \gamma\}$ for a duration $\tau'(v)$ which is defined in Eq.(3). Thus, all sensors in $N_c^+(v)$ will be charged;
Construct another auxiliary graph $H = (S_I, E_H)$ where S_I is an MIS of G_c, and there is an edge $(u, v) \in E_H$ if there $N_c^+(v) \cap N_c^+(u) \neq \emptyset$, i.e., if there are two MCVs located at u and v, they are overlapping with each other when they charge at the same time;
Find an MIS V'_H of graph H;
Find K node-disjoint closed tours with each tour containing the depot of MCVs and the union of the nodes in these tours is V'_H. Let $C_1, C_2, \ldots, C_K$ be the K node-disjoint closed tours delivered by an approximation algorithm for K-optimal closed tour problem due to Liang *et al.* [14];
Calculate the charging duration at each node v in C_k; i.e., $\tau'(v) \leftarrow \tau(v)$; and its charging finish time $f(v)$ by formulas (11) or (12);
$U \leftarrow S_I \setminus V'_H$; /* the set of potential sojourn locations of the K mobile chargers */
for $U \neq \emptyset$ **do**
    Pick a node $u \in U$ with the smallest latest neighbor charging finish time, i.e., $u = \arg\min_{u \in U}\{f_N(u)\}$;
    if $N_c^+(v) \subseteq \cup_{k=1}^{K} \cup_{l=1}^{k} N_c^+(v_{k,i_l})$ **then**
        /* location u will not be considered */;
    else
        if all neighbors of u in H are in a single C_{k_0} for some k_0 with $1 \leq k_0 \leq K$ **then**
            /* Case (i) */
            Identify the location of u in closed tour C_{k_0} by Eq (9), calculate the charging duration $\tau'(u)$ of MCV k_0 at u and insert u just after node $v_{k_0,i_{j_0}}$ in C_{k_0};
            Recalculate the charging finish time of all the nodes after node $v_{k_0,i_{j_0}}$ in C_{k_0}, and the latest neighbor charging finishing time of nodes in $U \setminus \{u\}$;
        else
            /* Case (ii): the neighbors of u in H are in at least two closed tours */
            Identify the location of u in closed tour C_{k_0} by Eq. (13), calculate the charging duration $\tau'(u)$ of MCV k_0 at location u, and insert node u just after node $v_{k_0,i_{j_0}}$ in C_{k_0};
            Recalculate the charging finish time of each node in C_{k_0}, and the latest neighbor charging finishing time of nodes in $U \setminus \{u\}$;
        end if
    end if
    $U \leftarrow U \setminus \{u\}$;
end for
return The K charging tours $C_1, C_2, \ldots, C_K$.

Denote by Δ_H the maximum degree of graph $H = (S_I, E')$. Let C_k be any charging closed tour obtained after considering the nodes in V'_H initially by applying the approximation algorithm due to Liang *et al.* [14]. We then add nodes $u \in S_I \setminus V'_H$ in cases (i) and (ii) to the K closed tours. We finally estimate the length (delay) of each closed tour in the end by showing that the length (delay) of each C_k is no greater than constant times of the initial delay of C_k as follows.

Consider a node v in the initial closed tour of C_k, then the cardinality of its neighborhood in H is $|N_H(v)| \leq \Delta_H$ and the distance of each its neighbor from v is strictly less than 2γ; otherwise, there will be no overlapping between their coverage areas, following the definition of graph H.

The analysis on the length of the final closed tour C_k, compared with its initial length L_k^0 is given by the following lemma.

Lemma 1: The length of C_k is upper bounded by $(\Delta_H + 1) \cdot L_k^0$.

Proof: As the initial length L_k^0 of C_k is no less than $2\gamma \cdot |V(C_k)|$, the traveling time of MCV k on C_k is no less than $2\gamma \cdot |V(C_k)|/s$. The traveling time of MCV k on the final closed tour C_k after inserting nodes in cases (i) and (ii) to the closed tour thus is upper bounded by

$$\sum_{v \in V(C_k)} 2\gamma \cdot (|N_H(v)| + 1) \leq 2\gamma \cdot (\Delta_H + 1) \cdot |V(C_k)| \leq (\Delta_H + 1) \cdot L_k^0, \quad (15)$$

i.e, the traveling time of MCV k along its tour C_k is $(\Delta_H + 1)$ times the traveling time on the initial closed tour C_k. ■

We then analyze the total charging time in C_k. The initial total charging time of MCV k in C_k is $TC_k^0 = \sum_{v \in V(C_k)} \tau(v)$, as the coverage area by each node in C_k are not overlapping with each other.

The total charge time of MCV k after inserting nodes of cases (i) and (ii) in the closed tour C_k is

$$\begin{aligned} & \sum_{v \in V(C_k)} \sum_{u \in N_H(v)} \tau'(u) + \sum_{v \in V(C_k)} \tau'(v) \\ \leq & \sum_{v \in V(C_k)} \tau(v) + \sum_{v \in V(C_k)} \sum_{u \in N_H(v)} \tau'(u) \\ \leq & \sum_{v \in V(C_k)} \tau(v) + |V(C_k)| \cdot \Delta_H \cdot \tau_{max} \\ \leq & TC_k^0 + TC_k^0 \cdot \Delta_H \cdot \frac{\tau_{max}}{\tau_{min}} \quad \text{since } TC_k^0 \geq |V(C_k)| \cdot \tau_{min} \\ \leq & TC_k^0 \cdot (1 + \Delta_H \cdot \frac{\tau_{max}}{\tau_{min}}), \end{aligned} \quad (16)$$

where $\tau_{max} = \max_{v \in V_s}\{\tau(v)\}$ and $\tau_{min} = \min_{v \in V_s}\{\tau(v)\}$ are the longest and shortest charging durations of any mobile charger at any sojourn locations.

The total charge delay of MCV k along the closed tour C_k thus is

$$TC_k^0 \cdot (1 + \Delta_H \cdot \frac{\tau_{max}}{\tau_{min}}) + (\Delta_H + 1) \cdot L_k^0/s \quad (17)$$

$$\leq (1 + \Delta_H \cdot \frac{\tau_{max}}{\tau_{min}}) \cdot (TC_k^0 + L_k^0/s). \quad (18)$$

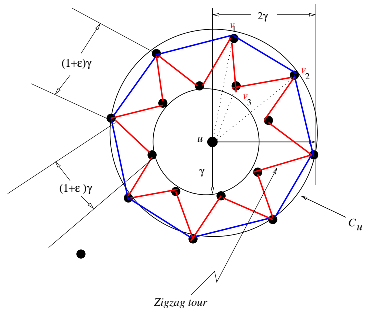


Fig. 2. An illustration of a disk $R(u, 2\gamma)$ and all nodes (locations in S_I with radius γ (black dots) that each coverage area is overlapping with the one by node u, where C_u is the circumference of a cycle centered at u with radius of 2γ, while the red zigzag tour consists of all nodes in the band area between the internal and outside circumferences of center u.

Let D_k^0 be the longest delay in the initial K closed tour C_k. Recall that L'_{OPT} and L_{OPT} are the optimal solutions to the longest delay minimization problem in sets V_s and $\cup_{u \in V'_H} N_c^+(u)$, respectively. Then, $D_k^0 \le 5 \cdot L'_{OPT}$ by the approximation algorithm for the K-optimal closed tour problem [14]. We also know that $L'_{OPT} \le L_{OPT}$. Thus, $D_k^0 \le 5 \cdot L_{OPT}$, while the longest delay of MCV k on the final closed tour C_k is no greater than $(1 + \Delta_H \cdot \frac{\tau_{max}}{\tau_{min}}) \cdot D_k^0$. Therefore, the value of the approximate solution delivered by the proposed approximation algorithm is

$$(1+\Delta_H \cdot \frac{\tau_{max}}{\tau_{min}}) \cdot D_k^0 \quad \le \quad (1+\Delta_H \cdot \frac{\tau_{max}}{\tau_{min}}) \cdot 5 \cdot L_{OPT}. \quad (19)$$

The rest is to show that $\Delta_H \cdot \frac{\tau_{max}}{\tau_{min}}$ is a constant. Thus, the approximation ratio ρ of the proposed approximation algorithm is constant, by the following lemma.

Lemma 2: $\Delta_H \le \lceil 2 \cdot \frac{4\pi\gamma}{\gamma} \rceil = \lceil 8\pi \rceil$.

Proof: Following the construction of graph H, the distance between any neighbor $v \in N_H(u)$ of node $u \in S_I$ in H and node u is no less than $(1+\epsilon)\gamma$ but less than 2γ, where ϵ is a value no less than zero.

Consider nodes v_1, v_2 and v_3 which are the three neighbors of u in H, and the coverage area of each of them is overlapping with the coverage area of node u, as illustrated in Fig. 2.

Then, nodes v_1, v_2, and v_3 must be located in the band area of con-centered at u with radii γ and 2γ, respectively. Assuming that both v_1 and v_2 are nearby the circumference C_u of the cycle centered at u with radius 2γ, and they are two neighbors in the *blue* zigzag line. The distance between any of two nodes among u, v_1, v_2, and v_3 is at least $(1+\epsilon)\gamma$ with $\epsilon > 0$ as they all are in S_I, while S_I is an independent set of graph G_c. Thus, all neighbors of node u in H must be in the band area, and the maximum number of neighbors of u in H is bounded by a constant $2 \cdot \frac{4\pi\gamma}{\gamma} \le 8\pi$, i.e., the number of nodes in the *red* zigzag line. In other words, the maximum degree Δ_H of any node u in H is upper bounded by the number of neighbors in the band area of node u, i.e., $\Delta_H \le \lceil 8\pi \rceil$. ∎

Theorem 1: Given a wireless rechargeable sensor network in a plane and a set V_s of sensors required to be charged, assume that each sensor $v \in V_s$ with energy capacity C_v and residual energy RE_v when the sensor sent out its charging request. There are K homogeneous mobile charging vehicles with $K \ge 1$ with constant speed s, each mobile charger has a wireless energy transmission range γ with charging efficiency η, and charge all sensors within his energy transmission range. It is also assumed that it is not allowed that a sensor can be charged by two MCVs at the same time. There is an approximation algorithm with a constant approximation ratio ρ for the longest delay minimization problem, and the algorithm takes $O(|V_s|^3)$ time, where $\rho = 40\pi \cdot \frac{\tau_{max}}{\tau_{min}} + 1 = O(1)$, τ_{max} and τ_{min} are the longest and shortest charging durations of a mobile charger at a sojourn location.

Proof: We have shown that the longest delay among the K closed tours is no more than $(1 + \Delta_H \cdot \frac{\tau_{max}}{\tau_{min}}) \cdot L$ by Inequality (18), where L is the longest delay closed tour among the K closed tours. The approximation ratio of the proposed approximation algorithm thus is ρ $(= 1 + \Delta_H \cdot \frac{\tau_{max}}{\tau_{min}} \cdot 5 = 40\pi \cdot \frac{\tau_{max}}{\tau_{min}} + 1)$, which is a constant if the ratio of the longest charging duration τ_{max} to the shortest charging durations τ_{min} of MCVs at any locations is a constant, this assumption is true in a real setting where each to-be-charged sensor has consumed a significant amount of its energy. For example, assume that each sensor sends a charging request if its residual energy falls below 20% of its energy capacity, then the ratio of τ_{max} to τ_{min} is no more than $\frac{1}{1-20\%} = 1.25$.

The analysis of the time complexity of the approximation algorithm is omitted, due to the limited space. ∎

VI. Performance Evaluation

In this section, we evaluate the performance of the proposed algorithm through experimental simulations.

A. Experimental environment settings

We consider a wireless rechargeable sensor network with size from 200 to 1,200 sensors randomly distributed in a 100×100 m^2 square. Assume that the base station and the depot of MCVs are co-located at the center of the monitoring area. The energy capacity of the battery of each sensor is set as 10.8 kJ [22]. The data sensing rate b_i of each sensor v_i is randomly chosen from an interval $[b_{min}, b_{max}]$ with $b_{min} = 1$ $kbps$ and $b_{max} = 50$ $kbps$, respectively. We adopt a real sensor energy consumption model from [12]. The wireless energy transfer range γ of each MCV is set at 2.7 m [7]. The number of MCVs K in the network is set from 1 to 5. Each MCV travels at a speed of $s = 1$ m/s and its energy charging rate η is set at 2 W. The charging duration of an energy-empty sensor then is $\frac{10.8\ kJ}{2\ W} = \frac{10.8\ kJ}{2\ J/s} = 1.5$ hours. We consider the monitoring of the sensor network for a period T_M of one year. To evaluate the performance of the proposed algorithm `Appro` for the longest charge delay minimization problem, we adopt the following four benchmarks.

(i) In algorithm Earliest Deadline First with K MCVs (K-`EDF`), it first sorts to-be-charged sensors by their residual lifetimes in increasing order, then partitions the sensors into multiple groups with each group having K sensors (except that the last group may have less K sensors), finally assigns the K sensors in each group to the K MCVs such that the sum of the traveling distances of the K MCVs from their current locations to the K sensors are minimized.

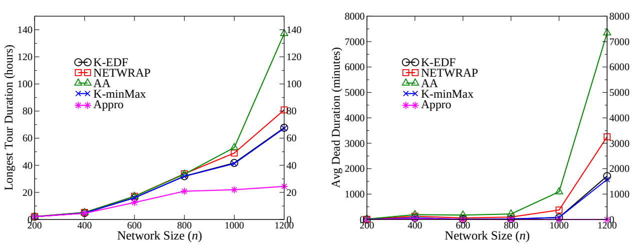
(ii) In algorithm `NETWRAP` [24], each MCV selects the next to-be-charged sensor that has the minimum weighted sum of the travel time from the MCV to the sensor and the residual lifetime of the sensor, a tie is broken arbitrarily if a sensor is selected by multiple MCVs.

(iii) In algorithm K-`minMax` [14], it finds K node-disjoint closed tours to visit to-be-charged sensors, such that the longest delay among the K tours is minimized. Algorithm K-`minMax` delivers a 5-approximate solution.

(iv) In algorithm `AA` [24], it first partitions the to-be-charged sensors into K groups by applying the K-means algorithm, and each MCV charges the sensors in one group. Each MCV charges a proportion of sensors in its assigned group before their energy expirations, so as to maximize the total amount of energy charged to sensors minus the total traveling energy cost of the charger.

The value in each figure is the mean of the results out of 100 WRSN instances with the same network size.

B. Experimental results

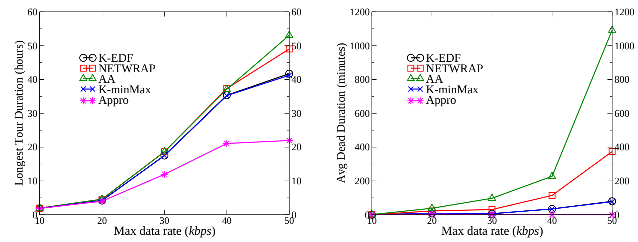


(a) Average longest tour duration (b) Average dead duration per sensor during T_M

Fig. 3. Performance of algorithms `Appro`, K-`EDF`, `NETWRAP`, `AA`, K-`minMax` by varying the network size n from 200 to 1,200, and there are $K = 2$ mobile chargers.

We first evaluate the performance of algorithms `Appro`, K-`EDF`, `NETWRAP`, `AA`, and K-`minMax`, by varying the network size n from 200 to $1,200$ and there are $K = 2$ mobile chargers in the sensor network. Fig. 3(a) shows that longest tour duration of the $K = 2$ charging tours delivered by the proposed approximation algorithm `Appro` is much shorter than those delivered by the existing four algorithms. For example, the longest tour durations of algorithms `Appro`, K-`EDF`, `NETWRAP`, `AA`, and K-`minMax` are around 24, 68, 80, 137, 67 hours, respectively, when there are $n = 1,200$ sensors in the network. Then, the longest tour duration by algorithm `Appro` is at least $1 - \frac{24}{67} = 65\%$ shorter than those by the other four mentioned algorithms. Fig. 3(a) also demonstrates that the longest tour duration by each of the five algorithm increases with the growth of the network size n. The rationale behind is that more sensors are needed to be charged in a larger network, and the charging duration of each charging tour will be prolonged.

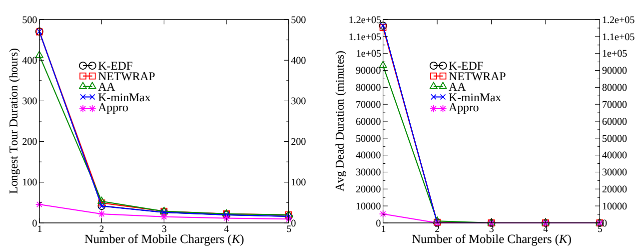
Fig. 3(b) plots the average dead duration per sensor by different algorithms in the monitoring period T_M (i.e., one year) of the sensor network, when the network size n increases from 200 to 1,200. It can be seen from Fig. 3(b) that the average sensor dead duration by algorithm `Appro` is no more than 40 minutes when there are $n = 1,200$ sensors, while the average sensor dead durations by algorithms K-`EDF`, `NETWRAP`, `AA`, and K-`minMax` are 1,700, 3,200, 7,300, and 1,500 minutes, respectively, which are significantly higher than the proposed algorithm.



(a) Average longest tour duration (b) Average dead duration per sensor during T_M

Fig. 4. Performance of algorithms `Appro`, K-`EDF`, `NETWRAP`, `AA`, K-`minMax` by varying the maximum data rate b_{max} from 10 $kbps$ to 50 $kbps$ in a network with $n = 1,000$ sensors and $K = 2$ mobile chargers, while $b_{min} = 1$ $kbps$.

We then study the algorithm performance by varying the maximum data rate b_{max} from 10 $kbps$ to 50 $kbps$ in a network with $n = 1,000$ sensors and $K = 2$ mobile chargers, while $b_{min} = 1$ $kbps$. It can be seen that sensor energy consumption rates grow with a larger data rate, and thus there will be more to-be-charged sensors in each charging tour. Fig. 4(a) shows that the longest tour duration by algorithm `Appro` is no more than 22 hours, while the longest tour durations by the other four algorithms are at least 40 hours when $b_{max} = 50$ $kbps$. Fig. 4(b) demonstrates that the average sensor dead duration by algorithm `Appro` is only 5 minutes, whereas the average sensor dead durations by algorithms K-`EDF`, `NETWRAP`, `AA`, and K-`minMax` are 80, 370, 1,100, 77 minutes, respectively, when $b_{max} = 50$ $kbps$.



(a) Average longest tour duration (b) Average dead duration per sensor during T_M

Fig. 5. Performance of algorithms `Appro`, K-`EDF`, `NETWRAP`, `AA`, K-`minMax` by varying the number of mobile chargers K from 1 to 5, in a network with $n = 1,000$ sensors.

We finally investigate the performance of the five algorithms, by increasing the number of mobile chargers K from 1 to 5, in a network with $n = 1,000$ sensors. Fig. 5(a) demonstrates that the longest tour duration by each of the algorithms decreases significantly when K increases from 1 to 2, but the decease becomes slower for more chargers, i.e., a larger value of K. Also, it can be seen from Fig. 5 that both the longest tour duration and average sensor dead duration by algorithm `Appro` are much shorter than those by the other existing algorithms.

VII. Conclusion

In this paper we studied the use of multiple mobile chargers, instead of only a single charger, to charge sensors, thereby speeding up sensor charging and reducing their expiration durations, where each charger can replenish multiple sensors simultaneously within its energy charging range. We formulated a novel longest charge delay minimization problem through finding charging tours for K mobile charging vehicles such that the longest total time spent among the tours is minimized, subject to that no sensors can be charged by two or more mobile chargers at the same time. Since the problem is NP-hard, we then devised the very first approximation algorithm with a provable approximation ratio for it. We finally evaluated the performance of the proposed algorithm through experimental simulations. Simulation results demonstrate that the proposed algorithm is very promising, and outperforms the other heuristics in various settings.

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