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Speed control of mobile chargers serving wireless rechargeable networks

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HIGHLIGHTS

- We identify the key limitations of the existing works caused by overlooking the charging opportunity on the movement of the charger.
- We formalize the problem as Traveling Salesman Problem with Speed Variations, which jointly considers path planning and speed control.
- We propose a heuristic to the problem and conduct simulation experiments to investigate its performance. The evaluation results demonstrate that the charging delay is greatly reduced compared to the state-of-the-art works.

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ABSTRACT

Wireless rechargeable networks have attracted increasing research attention in recent years. For charging service, a mobile charger is often employed to move across the network and charge all network nodes. To reduce the charging completion time, most existing works have used the "move-then-charge" model where the charger first moves to specific spots and then starts charging nodes nearby. As a result, these works often aim to reduce the moving delay or charging delay at the spots. However, the charging opportunity *on the move* is largely overlooked because the charger can charge network nodes *while* moving, which as we analyze in this paper, has the potential to greatly reduce the charging completion time. The major challenge to exploit the charging opportunity is the setting of the moving speed of the charger. When the charger moves slow, the charging delay will be reduced (more energy will be charged during the movement) but the moving delay will increase. To deal with this challenge, we formulate the problem of delay minimization as a Traveling Salesman Problem with Speed Variations (TSP-SV) which jointly considers both charging and moving delay. We further solve the problem using linear programming to generate (1) the moving path of the charger, (2) the moving speed variations on the path and (3) the stay time at each charging spot. We also discuss possible ways to reduce the calculation complexity. Extensive simulation experiments are conducted to study the delay performance under various scenarios. The results demonstrate that our proposed method achieves much less completion time compared to the state-of-the-art work.

1. Introduction

Energy has always been a major obstacle for practical deployment of wireless sensor networks [1–3]. The network lifetime is strictly limited by the battery capacity [4,5]. While many works focus on the duty cycling to reduce the energy consumption [6,7], another trend is energy provisioning [8–11]. The recent advances in wireless energy transfer technology [8] have enabled the development of Wireless Rechargeable Sensor Networks (WRSNs), where sensor nodes can be recharged via magnetically resonant objects before energy drain happens. Different from traditional energy harvesting sensor networks, WRSN is more reliable and can provide stable and sufficient energy supply services for the sensing tasks.

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Since the charging range of a charger is limited, a mobile wireless charger is often required to move and charge the network nodes. A typical rechargeable sensor node has to be charged above a threshold before it can perform sensing, communication and computation tasks [12]. Due to the limited wireless charging speed, the charging is often time consuming. For example, it requires about 155 s to fully charge a WISP node [12] in a 10 m distance. This will greatly affect the network performance especially in large scale networks.

As a result, the charging completion time plays a critical role for overall performance of WRSNs and has attracted increasing research attention in recent years [9,13,10]. Most existing works follow the "move-then-charge" model: a mobile charger moves to each charging spot and then charges the nodes nearby the spot. The process goes until all networks nodes are fully charged. However, the charging opportunity on the movement is overlooked in the "move-then-charge" model, because a charger can charge considerable amount of energy to the network nodes on its movement, which could be used for better charging scheduling to further reduce the charging completion time. To exploit the charging opportunity on the movement, the speed control of the charger is of great significance. The paradox of speed control is as follows. For charging the network nodes, the speed is required to be low such that more energy can be charged and the charging time is expected to be reduced. On the other hand, the speed is required to be high to reduce the moving delay. We will analyze the impact of the charging opportunity and moving speed in Section 2.

In this paper, we investigate the problem of speed control of the mobile charger in WRSNs. Aiming to minimize the completion time, we propose a speed optimization scheme for the mobile charger which jointly considers both the moving and charging delay. We first cluster the network nodes into a certain number of spots and then calculate the route and speed variations of the charger on visiting the charging spots. The problem is formulated as a Traveling Salesman Problem with Speed Variations (TSP-SV), which is NP-hard. We propose a heuristic solution which finds a good tradeoff between the moving delay and charging delay, and the charger is expected to achieve the minimum charging completion time. Our scheme has two distinct features compared to the existing works: (1) Instead of minimizing the moving distance or the charging time at specific spots, the optimization goal is the end-to-end metric, completion time; (2) The speed can vary during the charging process, which allows the charger to fully exploit the charging opportunity during the movement.

We implement the approach and conduct extensive simulation experiments. The evaluation results show that by exploiting the charging opportunity on the movement of the charger and allowing speed variations for the charger, the proposed approach outperforms the state-of-the-art work in terms of charging completion time (23.8%). The major contributions of this paper are listed as follows.

- We identify the key limitations of the existing works caused by overlooking the charging opportunity on the movement of the charger.
- We formalize the problem as Traveling Salesman Problem with Speed Variations, which jointly considers path planning and speed control.
- We propose a heuristic algorithm to the problem and conduct simulation experiments to investigate its performance. The results show that the charging delay is greatly reduced compared to the state-of-the-art works.

The remainder of this paper is organized as follows. Section 2 presents the network model and preliminaries. Section 3 presents the proposed model for delay optimization and the heuristic algorithm. Section 4 evaluates the algorithm using simulation experiments. Section 5 presents the related works. Finally, Section 6 concludes this paper and points future directions.

2. Preliminaries and motivation

In this section, we present the preliminaries and the motivation of this work.

2.1. Preliminaries

Wireless rechargeable nodes Wireless rechargeable nodes are capable of sensing, computing and energy harvesting with wireless chargers. For example, Wireless Identification and Sensing Platform (WISP) [12] is a typical wireless rechargeable low power node developed by Intel Research. Compared to the traditional RFID tags, A WISP node can be charged by the nearby RFID readers (denoted as chargers in this paper).

Energy charging model: In this paper, we use the charging model proposed in [11] as follows:

$$P_r = \frac{G_s G_r \eta}{L_p} \left(\frac{\lambda}{4\pi (d + \beta)} \right)^2 P_0 \tag{1}$$

where d denotes the distance between the node and the charger, P_0 denotes the charging power of the charger, G_s denotes the source antenna gain, G_r denotes the receive antenna gain, L_p denotes the polarization loss, λ denotes the wavelength, η denotes the rectifier efficiency and β denotes the parameter to adjust the *Friis′* free space equation for short distance transmission. d is the only variable in the equation. The above model is based on the *Friis′* free space equation and has been tested empirically by [14,11].

The network charging model: In the existing works, some specific charging spots are selected for charging the nearby network nodes. The spots can be obtained by clustering algorithms [14]. The mobile charger moves to charging spots and then charges the nodes nearby the spots. When all nodes near one charging spot are fully charged, the charger moves to the next spot for charging. This process continues until all network nodes are fully charged.

Charging completion time: In this paper, we focus on optimizing the charging completion time, which is the time period elapsed from the time when the charger starts charging to the time when it returns back to the starting spot. Apparently the completion time consists of two parts: the moving time and the charging time at each charging spot.

1. **Moving time**. The moving time denotes the time duration of the charger's movement, which equals the sum of the moving delay on each edge in the path.
2. **Charging time** The charging time denotes the sum of the stay time at each charging spot.

It is worth noting that, as we will analyze in this paper, there exists an overlap between the moving time and the charging time considering the charging opportunity during the movement of the charger.

In this work, we focus on the speed control of the case of a single charger and jointly consider the moving time and the charging time optimization.

2.2. Motivation

In this subsection, we use two typical examples to illustrate the motivation of our work.

Charging opportunity on the movement: In the aforementioned works, the charging opportunity during the movement of the charger is widely overlooked, which may greatly reduce the completion time. Fig. 1 shows an example where one charger is used to charge a network with one node. The charger spot is exactly the same as the node's position. With the existing works, the charger first moves to the charging spot and then starts charging the node. The distance between the charger and the node is

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