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Clustering and splitting charging algorithms for large scaled wireless rechargeable sensor networks

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ABSTRACT

As the interdiscipline of wireless communication and control engineering, the periodical charging issue in Wireless Rechargeable Sensor Networks (WRSNs) is a popular research problem. However, existing techniques for periodical charging neglect to focus on the location relationship and topological feature, leading to large charging times and long traveling time. In this paper, we develop a hybrid clustering charging algorithm (HCCA), which firstly constructs a network backbone based on a minimum connected dominating set built from the given network. Next, a hierarchical clustering algorithm which takes advantage of location relationship, is proposed to group nodes into clusters. Afterward, a K-means clustering algorithm is implemented to calculate the energy core set for realizing energy awareness. To further optimize the performance of HCCA, HCCA-TS is proposed to transform the energy charging process into a task splitting model. Tasks generated from HCCA are split into small tasks, which aim at reducing the charging time to enhance the charging efficiency. At last, simulations are carried out to demonstrate the merit of the schemes. Simulation results indicate that HCCA can enhance the performance in terms of reducing charging times, journey time and average charging time simultaneously. Moreover, HCCA-TS can further improve the performance of HCCA.

1. Introduction

Wireless sensor networks (WSNs) are massively composed of tiny nodes, which are deployed in specific areas for monitoring events. By implementing wireless communication protocols, a multi-hop and self-organization network is constructed in which sensors cooperatively sense, collect and deal with the information obtained for monitoring purposes. Potential applications of WSNs include industrial control and monitoring, intelligent transportation management and intelligent medical care and so on, which have flourishing and extensive application prospects (Akyildiz et al., 2002; Ye et al., 2002).

Sensors in WSNs are powered by batteries, which have constrained energy capacity, leading to limited network lifetime. This has been a long-lasting, fundamental problem existing in sensor networks. To resolve this problem, more and more researchers have devoted their efforts to developing energy efficient protocols, such as energy harvesting protocols (Kansal et al., 2007; Vigorito et al., 2007; Sharma et al., 2010), data aggregation protocols (Luo et al., 2011; Tan et al., 2012; Lin et al., 2012), energy preserving MAC protocols (Tang et al., 2011; Ren et al., 2014), energy saving framework (Gomez et al., 2012; Riggio et al., 2011; Sicari et al., 2013) and so on. Although energy efficiency is improved, problem of the limited energy constraints has not been resolved. The finite network lifetime is still acting as a bottleneck, which is regarded as the main reason that prevents the widespread deployment of WSNs.

Recent breakthrough in wireless power transfer (WPT) technique (Kurs et al., 2007) provides a new alternative for solving the limited power capacity problem, which makes it promising to charge energy for prolonging network lifetime. Different from energy harvesting, WPT together with more and more mature and inexpensive mobile robots, such as mobile wireless charging vehicles (WCVs), creates a controllable and perpetual energy source, with which power can be replenished proactively to meet application requirements rather than being passively adapted to the environmental resources. Nowadays, the WPT technique has been used

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for charging mobile devices, electric vehicles, implantable devices and WSNs (Xie et al., 2013a). Based on these applications, Xie et al. (2012b) have proposed the definition of the wireless rechargeable sensor networks (WSRNs) (Yang and Wang, 2015).

A WRSN is made up of three components: a base station, wireless charging vehicles and rechargeable sensors. The base station collects, aggregates data from sensor nodes. In the meanwhile, to avoid the exhaustion of sensors, a WCV, which guarantees the network can work regularly, is responsible for providing the energy supply for the rechargeable sensors. Network lifetime of WRSN directly depends on the charging efficiency, especially in the large scale WRSN. Due to the large number of the sensors, only a slight deterioration in performance will lead to considerable extra resource and time expenditure. For instance, *when the average delay increases 1%, more than 3% energy will be consumed* (see Section 5). Therefore, to enhance the charging performance, it is necessary to promote the performance from the perspective of charging location determinations and charging behaviors.

One of the most common ways to design the charging path planning solution is to convert the wireless charging problem into the Traveling Salesman Problem (TSP) (Xie et al., 2012a, 2012b, 2013c). The Hamiltonian cycle is constructed, which is regarded as a feasible solution to TSP as well as the charging path for WCV. Although the Hamiltonian cycles are regarded as feasible solutions for both single-node charging scheme (Xie et al., 2012b) and multi-node charging scheme (Xie et al., 2013b, 2013c; Wu et al., 2015), unfortunately, to the best of our knowledge, less work has been conducted on (1) location relationships (Lin et al., 2015) between nodes and (2) determination of charging points from the view of charging tasks. The problems for these issues are three folds as follows:

1. For the single-node charging scheme (Xie et al., 2012b), each time only one node can be charged, which thus reduces the charging efficiency and wastes charging resources.
2. For the multi-node charging scheme (Xie et al., 2013b, 2013c), although the charging efficiency has been improved, the location relationships (Lin et al., 2015) between sensor nodes are overlooked.
3. The charging tasks are considered to be non-preemptive, deterministic and periodical, which lacks of dynamical adaption to topology changing. Therefore, preemptive techniques are required to be used to fit the dynamicity.

When developing path planning for WCV, it is essential to determine the charging locations and path planning problem simultaneously. The charging locations have a great impact on the charging efficiency. For instance, in the multiple-node charging case (Xie et al., 2013c), feasible charging scheme will reduce charging times, shorten charging time, and reduce charging path length to enhance the charging efficiency. However, in the on-demand charging scheme (Jiang et al., 2014; Lin et al., 2015), the location information of the nodes is identified as non-deterministic factor. Hence, the WCV gathers the needs, and frequently re-calculates the charging path, so as to meet the time limitation of all the charging requests to maintain the availability of the network, which puts more burden to the WCV. Therefore, when designing the charging algorithm, the primary issue should be finding optimal charging locations.

Motivated by the need to overcome the existing problems and enhancing the charging efficiency. In this work, clustering and splitting charging schemes for solving the charging problems in WRSN are devised. Firstly, we proposed a hybrid clustering charging algorithm (HCCA) for solving the path planning problem for WCV. Nodes in a WRSN are grouped into clusters in which multiple nodes can be simultaneously charged by WCVs. In HCCA, hierarchical clustering and *K*-means clustering algorithms are combined which respectively pay close attention to the issues of location relationship and energy awareness. Comprehensive simulations are carried out to show advantages of HCCA. Simulation results show that our scheme can improve the performance of energy replenishing in terms of fewer charging times, shorter traveling time and so on. To further optimize the performance of HCCA, HCCA-TS is proposed, which transforms the energy charging process into a task splitting model. A number of tasks generated from HCCA are split into small tasks, which shortens the charging time to enhance the charging efficiency.

The contributions of this work are summarized as follows:

1. To decrease charging times, shorten traveling time and reduce average charging delay in a global manner, we propose a hybrid clustering charging algorithm (HCCA). HCCA combines hierarchical clustering and *K*-means clustering. Hierarchical clustering is applied to group neighboring nodes into the same cluster to realize location awareness. *K*-means clustering is utilized to construct energy core set of each cluster, so as to achieve energy awareness.
2. To further optimize the performance of wireless charging in a local way, a task splitting algorithm HCCA-TS is introduced. Charging actions in HCCA are formalized as tasks. Then tasks are split into subtasks, and the charging path will be rescheduled. This approach will lead to improvement of charging efficiency.
3. To show the merits of the proposed schemes, we implemented sophisticated simulations to compare the performance of HCCA, HCCA-TS, a state-of-the-art scheme HTSP (Xie et al., 2012a) and NTSP (Xie et al., 2012b), which are designed for periodic charging. Then salient features of the proposed schemes are demonstrated.

The rest of this paper is organized as follows: Section 2 gives a brief overview of wireless charging problems. Section 3 introduces the preliminaries of the proposed schemes. In Section 4, HCCA is described in detail. Simulations and analysis are given in Section 5. In Section 6, we develop a task splitting algorithm HCCA-TS for further enhancing the performance of HCCA. At last, Section 7 concludes this work.

2. Literature review

In literature, energy charging approaches for WSRNs can be categorized into three kinds: periodical charging (Xie et al., 2012b, 2013a, 2013c), cooperating charging (He et al., 2013, 2014) and optimizations for wireless charging (Zhang et al., 2013; Jiang et al., 2011; Zhang et al., 2012).

Periodical charging schemes Xie et al. (2012b, 2013a, 2013c) converted the energy charging problem into a TSP problem (Lin and Kernighan, 1973) based on the energy distribution model and the energy consumption model, where the Hamiltonian cycle is calculated as the solution. Periodical charging schemes can be divided into two categories: single-node charging scheme (Xie et al., 2012b) and multi-node charging scheme (Xie et al., 2013b, 2013c). In single-node charging scheme, at one time, a WCV is responsible for replenishing for one sensor, therefore, the charging efficiency is relatively low. A straightforward method is to simultaneously charge several neighboring nodes, which is called multiple-node charging scheme (Xie et al., 2012a; Shi et al., 2011). In the multiple-node charging scheme (Xie et al., 2012a; Shi et al., 2011), a WCV is able to charge multiple neighboring nodes within its charging range simultaneously, which greatly improves the charging efficiency (Xie et al., 2012a; Shi et al., 2011). Based on the multiple-node charging solution, Xie et al. explored the path planning problem when WCVs are regarded as the mobile base stations (Xie et al., 2013b, 2013c) by establishing the smallest enclosing disk (SED) (Fu et al., 2013; Welzl, 1991). Then they