A Multi-node Rechargeable Algorithm via Wireless Charging Vehicle with Optimal Traveling Path in Wireless Rechargeable Sensor Networks

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***Abstract*—Recently, wireless power transfer (WPT) technology has increasingly become a promising approach to addressing the energy constraint problem in wireless sensor networks (WSNs). In this paper, we propose a multi-node rechargeable algorithm (MRA) for the WPT based wireless rechargeable sensor networks (WRSNs), which employs a mobile wireless charging vehicle (WCV) to periodically visit each specified docking site in WSNs and charge all nodes within its charging range simultaneously. Since the WCV's energy consumption includes traveling and charging, our proposed algorithm aims to reduce the number of docking sites and optimize the WCV's traveling path, thus immensely decreasing the energy consumed during the WCV's movement and improving the scalability of charging scheduling. Finally, extensive simulation results show that, compared with state-of-the-art charging schedule algorithms, our algorithm can guarantee better performance in the number of docking sites and the length of traveling path.**

Keywords-Wireless Rechargeable Sensor Networks; Wireless Power Transfer; docking sites selection; traveling path optimization; charging scheduling

I. Introduction

Owing to the small size and finite battery capacity of sensor nodes in wireless sensor networks (WSNs), the energy constraint problem has emerged as a fundamental bottleneck confronted by the practical deployment and application of WSNs. Currently, there are mainly four approaches to tackling the energy bottleneck in WSNs, namely energy conservation schemes [1], manual battery replacement schemes, energy-harvesting technologies [2] and wireless power transfer (WPT) technologies [3]. The characteristics of each approach are listed as follows.

- The energy conservation scheme can only minimize the energy consumption of sensor nodes via adopting sleep scheduling [4] or low-power MAC protocols [5], introducing mobile base stations [6], etc., whereas it cannot compensate for the energy consumed by the nodes, and may sacrifice certain network performance such as increasing communication delay and lowering transmission reliability.
- The manual battery replacement scheme is merely suitable for small-scale sensor networks where the nodes are touchable. Moreover, frequent battery replacement will induce substantial manpower and material costs.
- The energy-harvesting technology demands of the node a large energy converter, with the energy conversion efficiency fairly low, and this method is susceptible to the environment, which will inevitably incur a strong instability and uncontrollability.
- To conquer the limitations of above schemes, the WPT technology has served as a promising paradigm for providing WSNs with a sustainable and stable energy supplement. Due to the recent breakthrough in WPT based on magnetic resonant coupling [7], an energy source is no longer confined to charge only one receiver at a time. Kurs et al. [8] have proposed a single-to-many energy transfer technology that allows multiple receivers to be charged simultaneously via single source, which will thoroughly tackle the scalability problem in the WPT based wireless rechargeable sensor networks (WRSNs) and promote the overall energy transfer efficiency.

In this paper, we survey the WPT based WRSNs where a mobile wireless charging vehicle (WCV) periodically starts from the service station (SS), charges the sensor nodes wirelessly and returns to the SS to replenish energy. Inspired by the single-to-many energy transfer technology [8], we propose a multi-node rechargeable algorithm (MRA) based on the charging range of a WCV, which is suitable for large-scale WRSNs with dense or clustering nodes. Thus, we consider a scenario where a mobile WCV periodically visits each specified docking site in WSNs and charges all nodes within its charging range simultaneously. Since the WCV's energy consumption includes traveling and charging, we explore where a WCV can stop to cover more nodes (i.e., the rational selection of docking sites) and optimize the WCV's traveling path via genetic algorithm (GA) [9], [10], with the objective of saving charging time, reducing the energy consumed during the WCV's movement, enhancing charging efficiency and improving the scalability of charging scheduling.

The remainder of this paper is organized as follows. In Section II, we review the related work on WPT technologies and the classification of existing charging scheduling schemes. In Section III, we describe the mathematical models in WRSNs. In Section IV, we present our problem formulation and propose a multi-node rechargeable algorithm (MRA) to optimize the traveling path of WCV. Section V presents simulation results to evaluate our proposed algorithm performance. Section VI concludes this paper and points out our future work.

II. Related Work

A. Wireless Power Transfer

At present, wireless power transfer technologies are typically divided into three categories, among which are inductive coupling [11], electromagnetic radiation [12], and magnetic resonant coupling [7].

- Inductive coupling works by electromagnetic induction, with the advantages of simplicity and high power transfer efficiency in centimeter range. However, due to its disadvantages such as short energy transfer distance and accurate alignment in charging direction, it is not fit for charging sensor nodes.
- Electromagnetic radiation is based on radio frequency (RF) between 850–950 MHz, which can be twofold: omnidirectional radiation and unidirectional radiation. For omnidirectional radiation, the radio waves decay rapidly over distance and the energy transfer efficiency is quite low. For unidirectional radiation, it can achieve high energy transfer efficiency in kilometer range via microwaves or lasers. However, it possesses disadvantages such as sensitivity to obstructions, requirement of line-of-sight (LOS) and large scale of devices.
- Magnetic resonance coupling proposed by Kurs et al. [7] is extensively used in WRSNs due to its higher wireless power transfer efficiency in meter range, no requirement of line-of-sight (LOS) or any alignment, omnidirectional, allowing obstacles, immunity to the neighboring environment, etc. Thus, all sensor nodes can exploit magnetic resonant coupling technologies for wireless charging.

B. The Classification and Comparison of Existing Charging Scheduling Schemes

In WRSNs, the task of charging system is to guarantee a promised lifetime of global sensor nodes. To fulfill the task, a rational charging scheduling scheme remains to be designed. For one thing, the physical factors of WRSNs should be specified, such as the number, traveling speed, charging power, charging range of WCVs and the geographical position of SS. For another, the logical factors of charging scheduling should be considered, including determination of charging starting time, selection of charging nodes, optimization of charging path and individual charging period at each node over each charging cycle. Based on the physical and logical factors of charging scheduling, the existing charging scheduling schemes have been classified and compared from the following four different aspects:

1) The number of WCVs:

- Single-WCV-based scheme [13], [14]: It is fit for small-scale sensor networks with simple network topology.
- Multi-WCV-based scheme [15], [16]: It targets large-scale or ultra-large-scale sensor networks with complex network topology.

2) The charging range of WCVs:

- Single-to-single charging scheme [13]: It is appropriate for sensor networks with low node density or dispersed node distribution.
- Single-to-multiple charging scheme [14]: It applies to sensor networks with high node density or clustering node distribution.

3) The deployment scheme of service station:

- Pre-deployment scheme [13], [14]: It is suitable for sensor networks with balanced energy consumption, where the power consumption of nodes and the network topology are constant.
- Dynamic deployment scheme [17]: It is fit for sensor networks with imbalanced energy consumption and non-deterministic factors such as changes in the power consumption of nodes or the network topology.

4) The charging cycle of WCVs:

- Periodical charging scheme [13], [14]: This scheme assumes that the charging duration, traveling path and charging sequence in each round are deterministic, and the WCV charges all the nodes in every round. This scheme adapts to sensor networks with balanced energy consumption and deterministic factors such as constant power consumption of nodes and invariable network topology, where the state information of each node cannot be queried.
- On-demand charging scheme [18]: In this scheme, the WCV preferentially charges the nodes that most need to be charged in each round, hence, the charging schedule over each round dynamically changes by the behavior of sensor nodes. This scheme applies to sensor networks with imbalanced energy consumption and non-deterministic factors such as changes in the power consumption of nodes or the network topology, where the state information of each node can be queried.

5) The selection of optimized objects:

- Optimize the protocol design of sensor network [13]: This scheme can reduce the energy consumption of nodes via adopting sleep scheduling or low-power MAC protocols, optimizing routing protocol, introducing mobile base stations, etc.
- Optimize the charging scheduling of charging system [14]: This scheme decouples the protocol design

and charging scheduling, which possesses strong universality and scalability.

- Jointly optimize the protocol design and charging scheduling [19]: This scheme renders the WCV a mobile base station, thus the WCV undertook two tasks of data gathering and energy replenishment, which can maximize network utility.

III. Mathematical Modeling and Assumptions

A. System Model

Figure 1 depicts a system model of WRSNs deployed in a two-dimensional plane, including several homogeneous sensor nodes with rechargeable batteries, a mobile WCV carrying a wireless power charger, a fixed base station (BS) used as a sink node, and a fixed service station (SS), with the BS located at the center of the network. Thereinto, the sensor nodes and BS constitute a sensor network for data collection, forwarding and processing. The SS and WCV form a charging system to replenish energy for the sensor network. During each charging cycle, the WCV starts from the SS, charges each node only once and returns to SS to replenish energy. We consider a set of sensor nodes N randomly deployed over a two-dimensional area and each sensor node i is denoted as N_i, where $i = \{1, 2, \ldots, n\}$. We assume that each node has a fixed position that can be accurately located via a global position system (GPS). Besides, the SS is denoted as N_0 or N_{n+1}.

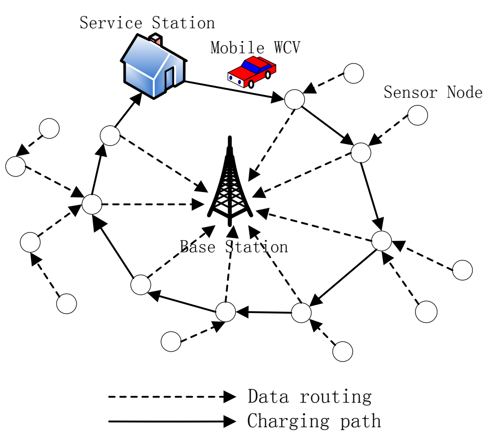


Figure 1. A system model of WRSNs with a mobile WCV.

B. Sensor Node Model

We assume that each sensor node is composed of a rechargeable module for wireless charging, a sensing module for data collection, a processing module for data processing, and a communication module for data forwarding. To prevent wireless charging from interfering with the data communication and reduce network delay, wireless charging and data communication are performed simultaneously in different frequency bands. For instance, Peng et al. [20] employed 903–927 MHz band for wireless charging and 2.4 GHz for data communication. Besides, each sensor node has a battery capacity of $E_{\max}$ and is fully charged initially. Denote $E_{\min}$ as the minimum energy for each sensor node to be operational.

We exploit the energy consumption model of nodes in [13], which only considers the energy consumed for data transmission and reception (i.e., the energy consumed for sensing data is negligible). Denote f_{ij} as the data flow rate from node i to node j (in bits/second), and f_{iB} as the data flow rate from node i to the base station (BS). Then, we denote $P_i(t)$ as the power consumption (i.e., energy consumption rate) at node i, which is

$$p_i(t) = \rho \sum_{k\in N}^{k\neq i} f_{ki} + \sum_{j\in N}^{j\neq i} C_{ij} f_{ij} + C_{iB} f_{iB} \quad (i \in N) \tag{1}$$

where ρ is the energy consumption for receiving one unit of data, and C_{ij} (or C_{iB}) is the energy consumption for transmitting one unit of data from node i to node j (or the BS), which is dependent on the distance D_{ij} (or D_{iB}) between two nodes. Then, the remaining energy of N_i (denoted as $E_{ri}(t)$) at a certain time t can be calculated according to the power consumption $P_i(t)$, as is shown in Equation (2):

$$E_{ri}(t) = E_{\max} + \int_0^t U_i(t)dt - \int_0^t p_i(t)dt \tag{2}$$

where $U_i(t)$ represents the received power of N_i from WCV.

C. Wireless Charging Vehicle Model

In this paper, we employ a mobile WCV to replenish energy to a WSN, which is made up of a charging station for wireless charging, and a communication module for data communication. Similar to the sensor nodes, wireless charging and data communication are performed simultaneously in different frequency bands. Assuming that V (in meters/second) is the WCV's traveling speed, and U_{Full} is the WCV's full output power. The WCV's charging range (denoted as R) is determined by the power attenuation model of WPT [8] and the WCV can charge multiple nodes within its charging range simultaneously. Since the energy consumption of WCV incorporates traveling and charging, the WCV's energy consumption model can be formulated as:

$$E_{WCV} = E_{mov} + E_{ch} = eL + \sum_{j\subseteq S} E_{ch}^j \tag{3}$$

where E_{mov} and E_{ch} represent the energy consumption of traveling and charging respectively, e (in Joules/meter) is the energy consumption of movement per unit of length, L is the total length of traveling path, S is the set of docking sites, and E_{ch}^j is the energy consumed for charging at docking site j.

IV. Problem Formulation and Solution

In this paper, we assume that the single WCV has sufficient energy to charge all sensor nodes during a cycle. Since the WCV's energy consumption includes traveling and charging, an optimal traveling path of WCV should be explored to minimize the energy consumed during WCV's movement. However, the single-to-single energy transfer technology [7] demands that the WCV should traverse each sensor node in WSNs, which has been proven to a NP-hard problem in combinatorial optimization and will pose higher time complexity and longer traveling path. Thus we exploit the single-to-many energy transfer technology [8] and propose a multi-node rechargeable algorithm (MRA) based on the charging range of a WCV, which transforms traveling path optimization problem into charging coverage problem. Hence, our proposed algorithm with minimal docking sites and shortest charging path will inevitably maximize the number of nodes that are charged simultaneously at each docking site, minimize charging latency, lower the energy consumed during the WCV's movement, improve energy transfer efficiency and the scalability of charging scheduling.

A. Docking Site Selection Algorithm

This algorithm aims to minimize the number of docking sites and enable the WCV to charge maximum sensor nodes simultaneously at each docking site. Thus we should group as many nodes as possible into one set. Here, we utilize intersecting circles with a radius of WCV's charging range to group nodes, as is shown below:

1) Docking site selection algorithm of intersecting circles (or tangent circles): Given a set of sensor nodes $N = \{N_1, N_2, \ldots, N_{n1}\}$, and each node N_i $(1 \le i \le n1)$ has a circle C_i with a center N_i and a radius of WCV's charging range R, which will form a corresponding set C $(|C| = |N|)$ of circles.

Definition 1 If C_i intersects (or is tangent to) another circle C_j, the two nodes N_i, N_j are in the same group. The overlapping region is denoted as ij.

Definition 2 All points in the overlapping region ij (or the tangent point) are candidate docking sites for WCV. Then put all vertexes of ij into a set $VT_{ij} = \{VT_1,\ VT_2,\ \ldots,\ VT_{n2}\}$, and a docking site SA_m should be selected from VT_{ij}, which is closer to the service station (SS). Assume that the two-dimension coordinates of the SS, SA_m, VT_m, N_i, N_j are (x_{SS}, y_{SS}), (x_{Am}, y_{Am}), (x_{Tm}, y_{Tm}), (x_{Ni}, y_{Ni}), and (x_{Nj}, y_{Nj}) respectively $(1 \le m \le n2, 1 \le i \le n1, 1 \le j \le n1)$, thus we can have

$$(x_{Am}-x_{Ni})^2+(y_{Am}-y_{Ni})^2=(x_{Am}-x_{Nj})^2+(y_{Am}-y_{Nj})^2=R^2 \quad (4)$$

$$(x_{SS}-x_{Am})^2+(y_{SS}-y_{Am})^2=\min\{(x_{SS}-x_{Tm})^2+(y_{SS}-y_{Tm})^2\} \quad (5)$$

Based on **Definition 1** and **Definition 2**, we can calculate all docking sites of intersecting circles and put them into a set $SA = \{SA_1, SA_2, \ldots, SA_{n3}\}$.

2) Docking site selection algorithm of isolated circles: The isolated circles refer to the circles that are not intersecting or tangent to other circles.

Definition 3 For a isolated circle C_k, firstly determine a docking site SA_i $(1 \le i \le n3)$ that is closest to the center N_k of C_k, then construct two tangent lines to C_k at two points SB_k, SB'_k through SA_i and select the point of tangency SB_k that is closer to the SS as the docking site of a isolated circle C_k. Assume that the two-dimension coordinates of the SS, SA_i, SA_j, SB_k, SB'_k, N_k are (x_{SS}, y_{SS}), (x_{Ai}, y_{Ai}), (x_{Aj}, y_{Aj}), (x_{Bk}, y_{Bk}), (x'_{Bk}, y'_{Bk}) and (x_{Nk}, y_{Nk}) respectively $(1 \le i \le n3, 1 \le j \le n3)$, thus we can get

$$(x_{Ai}-x_{Nk})^2+(y_{Ai}-y_{Nk})^2=\min\{(x_{Aj}-x_{Nk})^2+(y_{Aj}-y_{Nk})^2\} \quad (6)$$

$$(x_{Ai}-x'_{Bk})^2+(y_{Ai}-y'_{Bk})^2+R^2=(x_{Ai}-x_{Nk})^2+(y_{Ai}-y_{Nk})^2 \quad (7)$$

$$(x_{Ai}-x_{Bk})^2+(y_{Ai}-y_{Bk})^2+R^2=(x_{Ai}-x_{Nk})^2+(y_{Ai}-y_{Nk})^2 \quad (8)$$

$$(x_{SS}-x_{Bk})^2+(y_{SS}-y_{Bk})^2 \le (x_{SS}-x'_{Bk})^2+(y_{SS}-y'_{Bk})^2 \quad (9)$$

Based on **Definition 3**, we can determine all docking sites of isolated circles and add them to a set SB $= \{SB_1,\ SB_2,\ \ldots,\ SB_{n4}\}$. Hence, all selected docking sites of intersecting circles (or tangent circles) and isolated circles will constitute a set of docking sites $S = \{S_1,\ S_2,\ \ldots,\ S_{n3+n4}\}$.

B. Traveling Path Optimization Algorithm

Based on all selected docking sites, the optimal traveling path of WCV is the shortest Hamiltonian cycle traversing all docking sites and the service station [13], which can be found by solving the well-known Traveling Salesman Problem (TSP) that has proven to be a NP-hard combinatorial optimization problem. Here, we employ genetic algorithm (GA) [9], [10] to find the shortest Hamiltonian cycle. Figure 2 depicts the optimal traveling path of WCV determined by the above two algorithms.

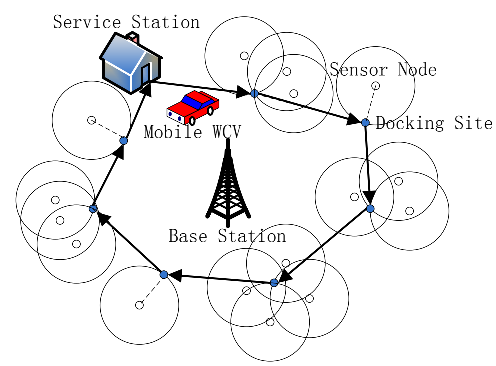


Figure 2. An optimal traveling path of WCV with our multi-node rechargeable algorithm (MRA). Solid dots represent docking sites, and empty dots represent sensor nodes.

V. Simulation Results

In this section, numerical simulations are implemented to evaluate the performance of our proposed MRA under different node density, thus we demonstrate how our algorithm can address the scalability problem in WRSNs as the node density increases and optimize the WCV's traveling path to minimize charging costs.

A. Simulation Parameters

We consider $N = 100, 500, 1000$ sensor nodes that are randomly deployed over a 100×100 m^2 two-dimensional area. The base station is placed at (50, 50) and the service station is assumed to be at the origin (0, 0). Each sensor node is equipped with a regular NiMH battery, whose nominal voltage and electricity volume are 1.2 V/2.5 Ah. Thus, the maximum battery capacity of nodes is $E_{\max} = 1.2$ V $\times$ 2.5 A $\times$ 3600 s $= 10.8$ kJ and the minimum energy threshold is $E_{\min} = 0.05 \times E_{\max} = 540$ J. For the energy consumption rate $P_i(t)$ at node i, we have $\rho = 50$ nJ/b, and $C_{ij} = 50 + 1.3 \times 10^{-6} \times D_{ij}^4$ nJ/b [13]. The traveling speed of the WCV is $V = 5$ m/s, and the charging range is $R = 2.7$ m [8]. The full output power of WCV is $U_{Full} = 5$ w.

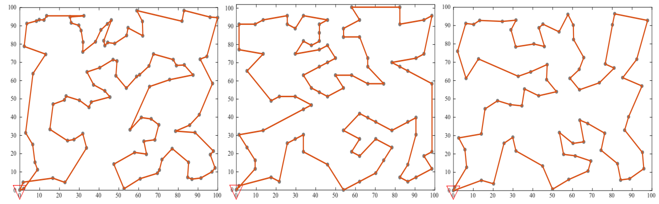
B. Performance Comparisons

In this paper, we compare our MRA with single-node renewable algorithm (SRA) [13] and multi-node charging algorithm (MCA) [14] under different node density. In [13], based on single-to-single charging scheme, a WCV periodically travels inside the sensor network and charges each node wirelessly. In [14], a hexagonal cellular structure is introduced to partition the two-dimensional plane into several hexagonal cells, assuming that the side length of each hexagonal cell was the WCV's charging range. Only by visiting the center of each cell can a WCV charge all sensor nodes within a cell simultaneously. Here, we find the shortest Hamiltonian cycle via genetic algorithm (GA) on MATLAB R2016(a). Denote L_{TSP} as the length of the shortest Hamiltonian cycle.

1) Results for a 100-node sensor network: In SRA, the WCV must traverse 100 nodes individually and $L_{TSP} = 826$ m. In MCA, the 100 nodes are distributed in 91 hexagonal cells and $L_{TSP} = 832$ m. In our proposed MRA, the number of docking sites is 65 and $L_{TSP} = 715$ m. The optimal traveling path is shown in Figure 3.

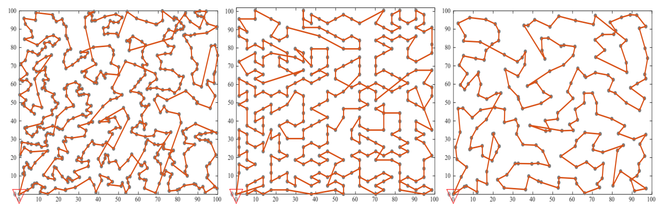
2) Results for a 500-node sensor network: In SRA, the WCV must traverse 500 nodes individually and $L_{TSP} = 1914$ m. In MCA, the 500 nodes are distributed in 341 hexagonal cells and $L_{TSP} = 1838$ m. In our proposed MRA, the number of docking sites is 196 and $L_{TSP} = 1273$ m. The optimal traveling path is shown in Figure 4.

3) Results for a 1000-node sensor network: In SRA, the WCV must traverse 1000 nodes individually and $L_{TSP} = 2655$ m. In MCA, the 1000 nodes are distributed in 459 hexagonal cells and $L_{TSP} = 2408$ m. In our proposed MRA, the number of docking sites is 281 and $L_{TSP} = 1603$ m. The optimal traveling path is shown in Figure 5.



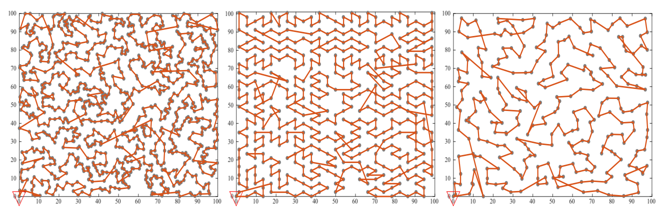
(a) (b) (c)

Figure 3. The optimal traveling path found by (a) SRA, (b) MCA, and (c) MRA respectively in 100-node sensor network.



(a) (b) (c)

Figure 4. The optimal traveling path found by (a) SRA, (b) MCA, and (c) MRA respectively in 500-node sensor network.



(a) (b) (c)

Figure 5. The optimal traveling path found by (a) SRA, (b) MCA, and (c) MRA respectively in 1000-node sensor network.

In summary, compared with SRA and MCA, the docking sites selected by our proposed MRA are sparser and more even. Figure 6 depicts performance comparisons between SRA, MCA and MRA in terms of the length of the shortest Hamiltonian cycle. We can observe that the traveling path length of MRA increases slowly as the node density increases and is much shorter than that of SRA and MCA. Hence, the MRA is especially suitable for large-scale WRSNs with dense or clustering nodes, which will

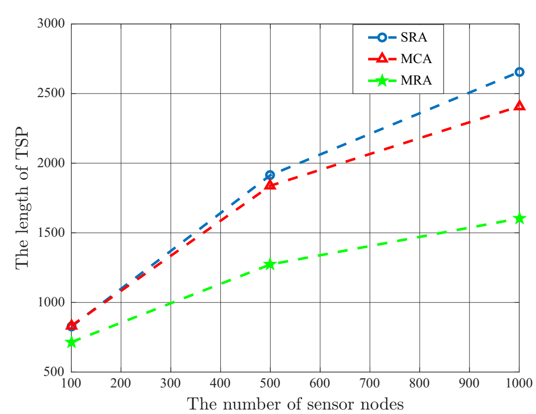


Figure 6. Performance comparisons between SRA, MCA and MRA in terms of the length of the shortest Hamiltonian cycle.

minimize charging costs, lessen charging latency and address the scalability problem in WRSNs.

VI. Conclusion

The past few years have witnessed huge advances in WPT based WRSNs, which have emerged as a paradigm for addressing the energy constraint problem in WSNs. In this paper, we propose a multi-node rechargeable algorithm (MRA) based on the charging range of a WCV, which is suitable for large-scale WRSNs with dense or clustering nodes. MRA can minimize the number of docking sites and optimize the traveling path of WCV, with the objective of reducing the energy consumed by WCV's movement, lowering charging latency and enhancing charging efficiency. Simulation results demonstrate that, compared with the existing charging scheduling algorithm SRA and MCA, our proposed algorithm can achieve better performance in terms of the number of docking sites and the length of traveling path.

Our future work will focus on the collaborate charging issue via multiple WCVs and how we can exploit the on-demand charging scheme and relevant energy consumption models to improve the performance of our algorithm.

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References

[1] W. Bin, L. Wenxin, and L. Liu, "A survey of energy conservation, routing and coverage in wireless sensor networks," in *International Conference on Active Media Technology*. Springer, 2011, pp. 59–70.

[2] F. K. Shaikh and S. Zeadally, "Energy harvesting in wireless sensor networks: A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 1041–1054, 2016.

[3] L. Xie, Y. Shi, Y. T. Hou, and A. Lou, "Wireless power transfer and applications to sensor networks," *IEEE Wireless Communications*, vol. 20, no. 4, pp. 140–145, 2013.

[4] A. Biazi, C. Marcon, F. Shubeita, L. Poehls, T. Webber, and F. Vargas, "A dynamic tdma-based sleep scheduling to minimize wsn energy consumption," in *Networking, Sensing, and Control (ICNSC), 2016 IEEE 13th International Conference on*. IEEE, 2016, pp. 1–6.

[5] K. Pattamasiriwat and C. Jaikaeo, "Evaluation of low power listening mac protocol on network monitoring in wireless sensor networks," in *Knowledge and Smart Technology (KST), 2017 9th International Conference on*. IEEE, 2017, pp. 260–265.

[6] I. Ha, M. Djuraev, and B. Ahn, "An optimal data gathering method for mobile sinks in wsns," *Wireless Personal Communications*, vol. 97, no. 1, pp. 1401–1417, 2017.

[7] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljačić, "Wireless power transfer via strongly coupled magnetic resonances," *science*, vol. 317, no. 5834, pp. 83–86, 2007.

[8] A. Kurs, R. Moffatt, and M. Soljačić, "Simultaneous mid-range power transfer to multiple devices," *Applied Physics Letters*, vol. 96, no. 4, p. 044102, 2010.

[9] D. Guo, H. Chen, and B. Wang, "An improved genetic algorithm with decision function for solving travelling salesman problem," in *Intelligent Systems and Knowledge Engineering (ISKE), 2017 12th International Conference on*. IEEE, 2017, pp. 1–7.

[10] X. Wang, P. Li, L. Wang, and L. Wang, "A novel genetic algorithm based on circles for larger-scale traveling salesman problem," in *Robotics and Automation Sciences (ICRAS), 2017 International Conference on*. IEEE, 2017, pp. 189–194.

[11] S. Ho, J. Wang, W. Fu, and M. Sun, "A comparative study between novel witricity and traditional inductive magnetic coupling in wireless charging," *IEEE Transactions on Magnetics*, vol. 47, no. 5, pp. 1522–1525, 2011.

[12] S. He, J. Chen, F. Jiang, D. K. Yau, G. Xing, and Y. Sun, "Energy provisioning in wireless rechargeable sensor networks," *IEEE transactions on mobile computing*, vol. 12, no. 10, pp. 1931–1942, 2013.

[13] L. Xie, Y. Shi, Y. T. Hou, and H. D. Sherali, "Making sensor networks immortal: An energy-renewal approach with wireless power transfer," *IEEE/ACM Transactions on networking*, vol. 20, no. 6, pp. 1748–1761, 2012.

[14] L. Xie, Y. Shi, Y. T. Hou, W. Lou, H. D. Sherali, and S. F. Midkiff, "Multi-node wireless energy charging in sensor networks," *IEEE/ACM Transactions on Networking*, vol. 23, no. 2, pp. 437–450, 2015.

[15] U. Baroudi, "Robot-assisted maintenance of wireless sensor networks using wireless energy transfer," *IEEE Sensors Journal*, vol. 17, no. 14, pp. 4661–4671, 2017.

[16] W. Liang, W. Xu, X. Ren, X. Jia, and X. Lin, "Maintaining large-scale rechargeable sensor networks perpetually via multiple mobile charging vehicles," *ACM Transactions on Sensor Networks (TOSN)*, vol. 12, no. 2, p. 14, 2016.

[17] C. Hu and Y. Wang, "Minimizing energy consumption of the mobile charger in a wireless rechargeable sensor network," *Journal of Internet Technology*, vol. 16, no. 6, pp. 1111–1119, 2015.

[18] C. Lin, J. Zhou, C. Guo, H. Song, G. Wu, and M. S. Obaidat, "Tsca: A temporal-spatial real-time charging scheduling algorithm for on-demand architecture in wireless rechargeable sensor networks," *IEEE Transactions on Mobile Computing*, vol. 17, no. 1, pp. 211–224, 2018.

[19] S. Guo, C. Wang, and Y. Yang, "Joint mobile data gathering and energy provisioning in wireless rechargeable sensor networks," *IEEE Transactions on Mobile Computing*, vol. 13, no. 12, pp. 2836–2852, 2014.

[20] Y. Peng, Z. Li, W. Zhang, and D. Qiao, "Prolonging sensor network lifetime through wireless charging," in *Real-time systems symposium (RTSS), 2010 IEEE 31st*. IEEE, 2010, pp. 129–139.