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Impacts of traveling paths on energy provisioning for industrial wireless rechargeable sensor networks

Guangjie Han [a,b,*], Aihua Qian [a], Li Liu [a], Jinfang Jiang [a], Chuan Zhu [a]

[a] Department of Information & Communication Engineering, Hohai University, China
[b] Changzhou Key Laboratory of Special Robot and Intelligent Technology, Changzhou, China

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ABSTRACT

Traditional Industrial Wireless Sensor Networks (IWSNs) are constrained by limited battery energy. Recent breakthroughs in wireless power transfer have inspired the emergence of Industrial Wireless Rechargeable Sensor Networks (IWRSNs). IWRSNs usually contain one or more mobile chargers which can traverse the network to replenish energy supply for sensor nodes. The essential problem in mobile energy provisioning is to find the optimum path along which the mobile chargers travel to improve charging performance, prolong the battery lifespan of nodes and reduce the charging latency as much as possible. In this paper, we introduce and analyze the impacts of four traveling paths, namely, SCAN, HILBERT, S-CURVES(ad) and Z-curve on energy provisioning for IWRSNs. This evaluation aims to embody effective and essential properties that a superior traveling path should possess. Our simulations show that S-CURVES(ad) outperforms the other traveling paths in the lifetime of nodes and traveling efficiency. And at the same time, it has relatively small charging latency.

1. Introduction

Nowadays, WSNs have been widely applied in many fields such as smart home, disaster aid, environment monitoring and so on [1,2]. Applying WSNs to industrial systems overcomes the deficiency that traditional industrial wired automation systems require expensive communication cables, which need to be installed and maintained regularly [3–5]. Meanwhile, it as well brings about many technical challenges due to the unique characteristics of IWSNs, one of which is energy constraints of nodes [6–8]. As is universally known, energy is the foundation and premise to ensure various operation of sensor nodes. In practical applications, plenty of tiny sensor nodes are always deployed in complicated scenarios which are powered by batteries, which makes it impossible to replace all the dead nodes with new ones especially in large scale sensing area.

Researchers attempt to solve the energy problem from the following two aspects: “increasing income”and “reducing expenditure”. “Increasing income” means enabling nodes to harvest energy from environment by converting mechanical, thermal, photovoltaic energy into electrical energy [9,10]. But the strength acquired by this method is typically low and unsteady because it highly relies on the environment [11]. “Reducing expenditure” usually means adopting efficient routing protocols to reduce the energy consumption as much as possible [12,13]. Although energy-efficient routing protocols can prolong the network lifetime to some extent, the energy constraints problem cannot be solved at its most fundamental by this way.

Recent advances of wireless energy transfer technology have inspired the appearance of IWRSNs, in which the mobile chargers can travel around the network and replenish energy for nodes without interconnecting wires [14,15]. Since the traveling paths of mobile chargers certainly have significant impacts on energy provisioning, in this paper we focus on the impacts of different traveling paths on energy provisioning for IWRSNs. Specifically, we compare four traveling paths including SCAN, HILBERT, S-CURVES(ad) and Z-curve in terms of the number of charging stop locations, the length of traveling path, energy provisioning distribution, alive nodes over time, charging latency and traveling efficiency.

The main contribution of this paper is that we introduce and compare the performance of four traveling paths in charging performance comprehensively, analyze and conclude the characteristics that an effective traveling path should possess from the simulation results. The purpose of this work is to establish a solid

* Corresponding author at: Department of Information & Communication Engineering, Hohai University, China.

E-mail addresses: hanguangjie@gmail.com (G. Han), bettyhhuc@gmail.com (A. Qian), liulihhuc@gmail.com (L. Liu), jiangjinfang1989@gmail.com (J. Jiang), dr.river.zhu@gmail.com (C. Zhu).

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foundation for traveling path planning of mobile chargers and provide guidance on designing more advanced charging traveling paths.

The remainder of the paper is organized as follows. Section 2 summarizes the state-of-the-art in charging algorithms of WRSNs. Section 3 describes the characteristics of SCAN, HILBERT, S-CURVES(ad) and Z-curve in detail. Section 4 presents detailed analysises of simulation and evaluation results. Section 5 draws conclusions and summarizes contributions.

2. Related work

Recent breakthroughs of wireless charging technologies have made great contributions to the emergence of IWRSNs. In this paper, we study a IWRSN built from the industrial wireless identification and sensing platform (WISP) and commercial RFID readers. The RFID readers serve as wireless chargers and can transmit RF signals to sensors [14]. In the following, we refer to RFID readers as chargers for simplicity. According to the wireless charging model which is based on Friis' free space equation [14], the relationship between the transmission power of transmitter P_t and the received power of receiver P_r can be formulized as follows:

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

where G_s and G_r denote the antenna gain of the transmitter and the receiver, respectively. η is rectifier efficiency, L_p refers to polarization loss, λ is the wavelength of the signal, β is a parameter to adjust the Friis' free space equation for short distance transmission, and d is the distance between the transmitter and the receiver. In this case, the transmitter is a charger and the receiver is a sensor node. To ease the description of the equation, we formulate formulation (1) by $P_r = \frac{\alpha}{(d+\beta)^2}$, where $\alpha = \frac{G_s G_r \eta P_t}{L_p}\left(\frac{\lambda}{4\pi}\right)^2$. According to the hardware and environment parameters set and experiments conducted in [12], $\alpha = 4.32 \times 10^{-4}, \beta = 0.2316$. We can see from this formulation that the received power of nodes decreases rapidly with the increase of distance between the transmitter and the receiver. That is, if the charger is too far away from the sensor node, the wireless charging power would be too low to be harvested. Therefore, we assume that there exists a threshold of distance, denoted by charging range R, beyond which the nodes cannot be charged. We set R be 5 m in this paper, that is, only the nodes within 5 m of the charger can be replenished energy.

So far there have been a certain number of researches on charging strategies in WRSNs [15–21]. Since there has no uniform standard of classification for these charging algorithms, here we classify the existing charging algorithms with respect to the mobility state of chargers into two groups: (1) static chargers such as methods proposed in [15,16], (2) mobile chargers such as methods proposed in [17–20]. In consideration of the fact that the available charging area of each charger is very limited, multiple static chargers are needed to replenish energy for all nodes, which is costly especially when it comes to large scale sensor networks. Hence we only focus on algorithms under the scenario of one mobile charger.

Constantinos Marios Angelopoulos et al. proposed three novel, alternative protocols for wireless charging in [17]: Global Knowledge Protocol (GKP), Limited Reporting Protocol (LRP) and Reactive Trajectory Protocol (RTP). The authors introduced "criticality" to capture a node's importance in the network, which relies on the traffic served by the node and the energy consumed by the node. GKP is an on-line and centralized protocol which requires a global knowledge of the state of the network, such as the criticality of all nodes to decide the charging sequence. LRP is a distributed protocol which selects some representative nodes in the network to report their criticality and provide guidance for mobile charger. LRP only uses limited network information. RTP reactively adapts to energy shortage alerts by forming trees rooted at nodes. GKP outperforms the other two strategies but also introduces great communication overhead. Various simulation results demonstrated that the three charging protocols proposed in this paper have better performance than existing charging strategies in most cases.

Zi Li et al. presented a set of heuristics to determine the wireless charging strategies under various routing schemes in [18]. In consideration of the fact that there exists mutual dependency between wireless charging and routing protocols, the authors formulated the problem of maximizing the sensor network lifetime as ML-JRC by combining the aspects of routing and charging. Then they proved the NP-hardness nature of the problem and derived the theoretical maximum sensor network lifetime that could be achieved with ML-JRC. But it is computationally complicated to find an optimal solution as the network scale increases. Hence, the authors proposed low-complexity heuristic solutions to determine the energy charging strategies for the mobile charger under different routing schemes, Least Residual Energy First (LRE), Least Estimated Lifetime First assuming Fixed Routes (LEL) and Adaptive Energy Allocation with Dynamic Routes (AEA), which give priority to residual energy, estimated lifetime and adaptive energy allocation respectively. The heuristics were proved to be superior in prolonging the sensor network lifetime.

Liguang Xie et al. proposed an energy-renewal approach with wireless charging technology in [19]. The authors firstly introduced a new concept called renewable energy cycle and studied how to maximize the ratio of the charger's vacation time over the whole cycle time. Through the mathematical deduction, this paper proved that the optimal traveling path for the mobile charger in each renewable cycle is the shortest Hamiltonian cycle. In addition, this paper took permanent operation of wireless sensor networks into consideration and the solution proposed can make sensor networks immoral. While exploiting this traveling path could be inefficient and lead to high computational complexity when the node density increases.

In [20], Liang He et al. proposed an on-line path planning scheme for the mobile charger, which laid theoretical foundation for the on-demand mobile charging problem. Specifically, in this work the authors analyzed the on-demand mobile charging problem using a Nearest-Job-Next with Preemption (NJNP) discipline for the mobile charger where individual sensor nodes would send charging requests to the charger when their energy run low. NJNP takes both spatial and temporal properties of charging requests from nodes into account, on which that the mobile charger will select the next to-be-charged node is based. While NJNP is an on-line protocol which poses considerable communication costs of the nodes and it is not suitable for large-scale and dense sensor networks.

While pioneering works on the mobile charging problem mainly focus on dynamic path planning of the mobile charger, which have high requirements on the network information and may cause great communication overhead during the energy provisioning procedure, especially for those on-line charging algorithms. Such charging algorithms could be inefficient in relatively dense IWRSNs because moving back and forth frequently in the network brings about long traveling length. We note that energy provisioning using a mobile charger in WRSNs shares something in common with localizing ordinary nodes with the help of a mobile beacon node, in that they both require a mobile object to traverse the whole network and stop at certain locations to serve the sensor nodes (replenish energy/localize nodes). In addition, they maintain the same goal: serve more sensor nodes in the