Direction Based Charging in Rechargeable Wireless Sensor Network

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Abstract. One of the main issues in rechargeable wireless sensor networks (RWSNs) is the stainability of network operation. Recently, wireless power transmission technology has been applied in RWSNs to transmit wireless power from chargers to sensor nodes. In this paper, we focus on how a charger changes its direction to cover different nodes for energy provisioning and, how to sense maximum data from the area of network. We intend to tackle the challenge that how to cover different nodes from each direction so that the charger can provide maximum power to maintain network performance. In this regard, a direction scheduling algorithm is proposed to fill the charging demand. Furthermore, a proposed Linear Programming based solution is proposed to determine maximum data sensing rate. The simulation results show that the proposed method performs better compared with existing methods.

Keywords: Rechargeable wireless sensor networks · Energy provisioning · Wireless power transmission · Direction scheduling

1 Introduction

Wireless sensor networks are widely deployed in remote or dangerous areas to sense ambient environment and generate data to reflect the real-world scenarios [1]. In these applications, prolonging the network lifetime and throughput is critical for achieving acceptable quality of services. Recently, researchers consider energy harvesting from different sources [2,3] such as solar power [4], thermal power [5], radio frequency (RF), and wind [6]. Especially, RF power transfer becomes the most popular one because of its reliability, safety and efficiency.

To transmit charging power in RWSN, we use directional charger. A directional charger changes its orientation at different time slot to different nodes to transmit energy according to their energy demands. Different directional chargers are deployed at different positions In RWSN. After fulfilling energy demand, sensor nodes start their sensing tasks. The objective of this study is to transmit

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maximum power and sense maximum data from different sensor nodes. How to improve the throughput performance in RWSNs is a significant topic.

In most of the existing works, the covering area of a charger is assumed to be omnidirectional, which is not practical for many RF wireless charging platforms, such as WISP and Powercast. The key idea of this study is to maximize an RWSN's throughput by scheduling the directions of chargers optimally. Then, a charger directional scheduling algorithm is help full to provide near-optimal coverage of sensor nodes in each time slot. The Existing algorithm is also helpfull to obtain optimal sensing rate of each sensor node. Extensive simulations are conducted to verify the effectiveness of our design network.

Wireless charger deployment problem has attracted plenty of attention in recent years. In [7], it demonstrated how to minimize charging cost by reducing energy consumption rate and improving recharging efficiency. In [8], it verified the effectiveness of Friis' Free space equation in wireless charging and first investigated the minimum static charger deployment problem. In [9], the authors optimized the basic station deployment in order to improve data collection rate. In [10], the authors divided the sensing areas into grids and placed omnidirectional wireless charger on various grid points. All these studies did not consider a directional charging method to transmit energy.

The main contributions of this paper can be summarized as follows:

- We notice that chargers provide directional charging service in practical systems, which lead to a new problem of optimally scheduling chargers direction, so that the throughput of an RWSN can be maximized.
- We design a near-optimal charger direction scheduling algorithm, and further propose a solution based on linear programming to maximize the network throughput.
- Extensive simulations are conducted to show that our design is effective and robust under different network settings.

The rest of the paper is organized as follows. Section 2 describes the Problem Statement. Section 3 shows the proposed Charging Orientation Scheduling scheme for an RWSN. Simulation results of the proposed scheme are shown in Sect. 4, which are then compared with those of the other schemes in Sect. 5. Finally, Sect. 6 concludes the paper.

2 Problem Statement

In practical hardware settings, antennas of chargers can be directional, which leads to a new design challenge of scheduling orientation of chargers optimally, so that the network throughput is maximized. In this work, we consider an optimization problem as follows. Given a network area, where a set of $N = \{1...n\}$ rechargeable sensor nodes, a set of $P = \{1...p\}$ sink stations and a set of $M = \{1...m\}$ chargers are randomly deployed. Each node is required to sense data and forward it to the sink station. Chargers are deployed to transmit wireless power to sensor nodes. A Charger is directional and the covering area is a

Table 1. Notation definition

Symbol	Definition
r_{it}	Sensing rate of node i in time t
N	Total nodes which are deployed in the area of network
M	Chargers which are deployed in the area of network
$f_{it}^{(in)}$	Data in-flow in node i
$f_{it}^{(out)}$	Data out-flow of node i
$p_o(i)$	Parameter energy consumption for node to sense one bit of data
$p_r(i)$	Parameter energy consumption for node to receive one bit of data
$p_t(i)$	Parameter energy consumption for node to transmit one bit of data
$p_c(ij)$	Charging power that comes from charger j to node i
X_{ij}	Node i coverage area where charger j provide energy at each direction of the node
C_{ij}	Relationship between direction of charger and state of the node
Y_j	Direction of the node where charger j provide energy to the node i
$P_c(i)$	Direction of the node where charger j provide energy to the node i

90 degree sector to transmit charging power to the sensor node and the charger can change its orientation to provide power from different directions. We need to schedule each charger's orientation optimally, so that the network throughput is maximized. To simplify this problem, we divide the time series into slots $T = \{1...t\}$ and suppose that in each slot, the charger can only select one of the four sectors to cover the nodes in the area of RWSNs. In our work we apply a tree topology with single-path routing, where each node has only one link to its next hop, and routing table is fixed. Thus, we have the following model:

$$max \quad \Sigma_{t=1}^{T} \Sigma_{i=1}^{N} r_{it} \tag{1}$$

$$s.t. \quad r_i + f_{it}^{(in)} = f_{it}^{(out)} \tag{2}$$

$$p_o(i) r_i + p_r(i) f_{it}^{(in)} + p_t(i) f_{it}^{(out)} \geq P_c(i) \tag{3}$$

$$P_c(i) = \Sigma_{i=1}^{M} X_{ij} p_c(ij) \tag{4}$$

$$X_{ij} = C_{ij} \times Y_j \tag{5}$$

The notations used in this paper are summarized in Table 1. Equation (1) shows the sensing rate of node i. Equation (2) shows the data conservation constraint, i.e., for each sensor node, the aggregated incoming data flow is equal to the aggregated outgoing data flow. Equation (3) calculates the available power of every sensor node. Equation (4) is the charging power, showing that the consumption power should never exceed the total charging power. Equation (5) shows the sensor node coverage area, where a charger provides energy at each direction (Figs. 1 and 2).

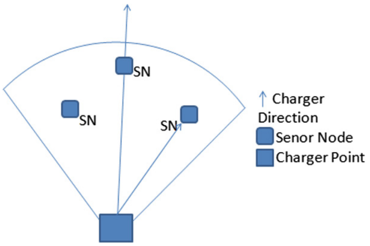

Fig. 1. Coverage area of directional based charger, which changes its orientation at different time slot to cover different nodes.

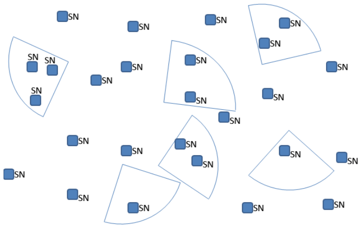

Fig. 2. Rechargeable wireless sensor network with different sensor nodes and directional chargers.

2.1 Energy Charging Model

We first specify our energy charging model based on the Frii's free space equation:

$$p_r = \frac{GsGr\eta}{Lp}\left(\frac{\lambda}{4\pi(d+b)^2}\right)p_o, \tag{6}$$

where d is the Euclidean distance between sensor node and charger, p_o is the source power, G_s is the source antenna gain, G_r is the receive antenna gain, Lp is polarization loss, η is a parameter to adjust the model for short distance transmission, and b is the parameter to set the rectifier efficiency. For the ease of the presentation, we simplify the energy charging model as:

$$p_r = \frac{a}{(d+b)^2}. \tag{7}$$

This has been proved experimentally to be a valid approximation of energy charging in [8]. We use the powercast wireless charging sensor nodes fabricated in our lab and the $XT91501$ powercast transmission. We fit experimental parameters for energy charging model. Based on the experimental results, we choose $a = 7.593$ and $b = 0.3154$ in our simulation.

2.2 Energy Consumption Model

The energy consumption model for wireless communication in our work is shown as follows:

$$p_t(k,d) = (p_r + \epsilon d^2) \times k, \quad p_r(k) = p_r \times k. \tag{8}$$

The model describes the communication energy, where d is the Euclidean distance between transmitter and receiver, k is the number of transmitted data bits, and p_t, p_r, and ϵ are the constant parameters concerned with the communication environment. Equation (8) shows the power consumption for data transmission and the power consumption of data reception. To obtain feasible values of these parameters, we perform communication experiments with Zigbee. Based on the results, we choose $p_t = p_r = 558\ nJ/bit$, and $\epsilon = 44.66\ pJ/bit/m^2$.

3 Solution of the Problem

To tackle the problem, we propose the following solution. The only constraint comes from the limited energy that in each time slot, the total energy used by sensing and communication should never exceed the sum of remaining energy and charged energy. The consumed energy should be expressed as follows:

$$\phi_i^{(t)} = p_o r_i + p_r f_i^{(t)} + (p_t + \varepsilon d_i^2) g_i^{(t)}, \tag{9}$$

where $f_i^{(t)}$ is the income flow of node i in timeslot t and $g_i^{(t)}$ is outcome flow. The charged energy of node i in timeslot t is as below:

$$\Psi_i^{(t)} = \Sigma_{j=1}^{M} \frac{a}{d_{ij} + b^2} x_{ij}^{(t)}, \tag{10}$$

where $x_{ij}^{(t)}$ is index denoting whether node i can be charged by charger j in time slot t. For charger j, it has four sectors to select in each timeslot. Thus, we use a vector $y_j^{(t)}$, to denote its directions. For instance, if charger j selects the second sector to cover, then we have $y_j^{(t)} = [0, 1, 1, 1]$, we use coefficient vector a_{ij}, to denote whether node i can be charged by charger j, if charger j selects current sector to cover. For instance, if node i can be charged by charger j when it turns to the first sector, then we have $a_{ij} = [1, 0, 0, 0]$. Therefore, we can build up the relationship between $x_{ij}^{(t)}$ and $y_i^{(t)}$, as follows:

$$x_{ij}^{(t)} = a_{ij} y_j^{(t)}. \tag{11}$$

Then the energy constraint can be expressed as:

$$e_i^t = e_i^{(t-1)} - \Phi_i^{(t)} + \Psi_i^{(t)},\ 0 \le e_i^t \le B \tag{12}$$

Our optimization objective is to maximize the network throughput. e_i^t is the total energy that node i consumes in time t, $\Phi_i^{(t)}$ is the consumed energy in node i at time t, and $\Psi_i^{(t)}$ is the energy consumed to charge node i at time t. Thus, the optimization problem is as follows:

$$max \quad \sum_{t=1}^{T} \sum_{i=1}^{N} r_{it} \tag{13}$$

We set score for each node in each iteration to evaluate its demand of being charged. Intuitively, those nodes with low energy should have the charging priority. On the other hand, we adopt a tree based routing protocol in our design. Then node in the upper layer should obtain more energy, since they will take on more relay task.

Therefore, we design such scoring mechanism based on $\frac{g}{e+p+\varepsilon}$, where g is related to the number of node layer (a node close to sink is in a top layer), e denotes the remaining energy after the previous time slot, p is the charging power that node has received in current time slot, and ε is a factor to avoid the denominator being zero. Thus, in each time slot, we run the following mechanism to obtain chargers' orientation scheduling. In each iteration, we update each node's score, then we can calculate each sector's total score, and we select the sector with highest score greedily. This process continues until every charger has decided its covering sector. After the charger's orientation has been decided, it is easy to obtain each node energy level in current time slot. After that we adopt the tree based routing protocol to transmit data. The network throughput is recorded and the nodes energy is updated from time to time.

4 Simulation Results

According to the system model, we conduct simulation using MATLAB to evaluate the performance of the proposed method.

4.1 Simulation Setup

We consider a $100 \times 100\ m^2$ network area, where 50 sensor nodes are randomly deployed and a sink station is used for data collection. Operation time is divided into different slots to sense data from the network area. One bit of data is sensed in each time slot. We set the data sensing power p_o as 0.00024 mW/bit, data transmission power p_t as 0.00024 mW/bit, and data receiving power p_r as 0.000558 mW/bit. The simulation results have been obtained by running extensive simulations. After providing energy to each sector, the maximum data collection rate of different nodes in different time can be tested.

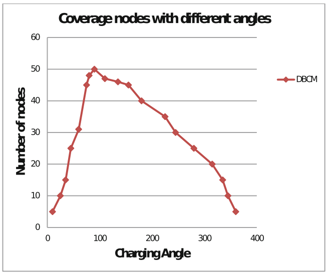

Fig. 3. Covered nodes with different angles.

4.2 Experimental Results

We demonstrate the results using different number of chargers which provide energy to different nodes at different time slot with 90 degree angle. Data sensing rate of different node can increase on the base of charging power. In Fig. 3, different number of nodes are covered by a charger with an orientation angle ranging from 0 to 360 degree. It is observed that maximum nodes coverage is achieved at 90 degree.

5 Performance Comparison

In this section, we compare our results with other methods. The performance evaluation of our proposed Directional Based Charging Method (DBCM) and existing Moveable Charging Based Method (MCBM) [11] is presented in Fig. 4. Both methods cover more than 60 present of the network nodes. Our main purpose is to satisfy charging demand of different nodes in RWSNs. We can see that in DBCM, a charger covers more nodes with a charging angle of 90 degree. Then the charger number is fixed to one, and its charging angle varies from 0 to 360 degree. We compare DBCM with two existing methods, i.e., Power Balance Aware Deployment (PBAD) [12] and Random Position Random Orientation (RPRO) [12]. The results are shown in Fig. 5. As shown in the figure, when the charging angle is around 90 degree, all three methods can reach the largest coverage. Still, DBCM performs better than the other two methods.

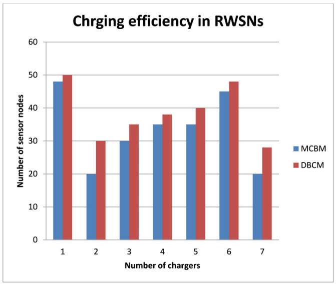

Fig. 4. Coverage *vs.* number of chargers (with charging angle of 90 degree).

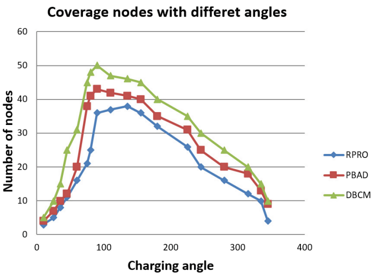

Fig. 5. Coverage *vs.* charging angle (only one charger).

6 Conclusion

In this paper, we consider an RWSN's throughput maximization problem by scheduling the directions of different chargers optimally. We design a charger direction scheduling algorithm to provide near-optimal coverage of sensor nodes in each time slot. It is helpful for obtaining optimal sensing rate of each sensor nodes from routing table. Extensive simulations are conducted to verify the effectiveness of our design.

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