Minimum battery capacity planning in wireless rechargeable sensor networks

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Abstract. This paper studies the problem of the minimum battery capacity required for the normal operation of each sensor when the charging path of the mobile charger is determined. When the parameters of the wireless rechargeable sensor network are determined, the aim is to minimize the battery capacity required by each sensor, and to ensure the permanent operation of the wireless rechargeable sensor network with the minimum sensor energy consumption. By analyzing the actual working conditions of mobile charger, a linear programming model with the goal of minimizing the battery capacity of each sensor is established, Lingo is used to solve the model, and the results are verified by computer simulation. The results show that the computer simulation results are basically consistent with the model solution results, which proved the reliability of the model.

1. Introduction

One of the hot issues studied in the wireless sensor network (WSN) is energy. Recently, the adoption of open source ideas, that is, the use of mobile charger (MC) to supplement energy for sensor nodes has attracted attention. This network is called wireless rechargeable sensor network (WRSN). Ref. [1] proves that the remaining energy of the sensor node exhibits a certain periodicity within a time period, and the necessary and sufficient condition for realizing WRSN's permanent operation is periodic charging. Ref. [2] studied the energy hunger problem of mobile charging in WRSN and proposed an online charging strategy to avoid energy starvation. This strategy effectively solves the energy hunger problem while making the mobile charger have lower charging delay and charging cost. Ref. [3] studies when the energy of MC is unlimited, it proves that MC uses the shortest Hamilton loop to charge the sensor nodes in the network, which can extend the network life cycle indefinitely. Ref. [4] studied the travel path of MC and the time to charge sensor nodes when the energy of MC is limited and proposes a charging strategy that balances the rest of the work time of each sensor node in the network aiming to greatly minimize the total energy consumption of MC, and reach the effect of extending the network running time. On the basis of Ref. [4], Ref. [5] maximizes the charging cycle while minimizing the total energy consumption of MC under the condition of ensuring the permanent operation of the network, and designs a WRSN periodic charging planning strategy with limited MC energy. Ref. [6] studies the limited energy and computing power of nodes in WSN, and proposes an energy balance algorithm optimized by PSO, which reduces the energy burden of nodes and ensures continuous network operation. In the above-mentioned research, scholars have mostly considered the energy and moving path of the
MC under the condition of ensuring the permanent work of the network, but rarely considered the energy of the sensor.

On the basis of previous studies, this paper researches how to make the network work permanently when the MC energy is large enough and driving along a certain periodic path, and the minimum battery capacity required by each sensor. Under the condition that the parameters of sensor nodes are known, this article aims to minimize the battery capacity of each sensor while ensuring the permanent operation of the network.

First, this article analyses the energy consumption rate corresponding to each sensor node. For the sake of simplifying the problem, the optimization goal is changed from minimizing the battery capacity of each sensor node to minimizing the sum of the battery capacity of all sensor nodes. This paper establishes a linear programming model and solves to get the minimum battery capacity of each sensor. Then this article simulates the actual working situation of the mobile charger via computer simulation and tests the model results. It is found that the battery capacity of each sensor converges to a stable value. The model solution results are basically consistent with the computer simulation results. This proves the reliability of the results.

2. Problem Description

Wireless sensor network (WSN) includes a data center (DC) and several sensors. The sensor is responsible for regularly collecting data and sending it to the data center. The data center is responsible for analysing the data and sending control information back to the sensor. To ensure that WSN can work continuously, energy can be provided by using environmental energy such as solar and wind energy or battery power supply.

Considering that environmental energy cannot guarantee the stable operation of the system, and it is greatly affected by regional differences, therefore, the mobile charger of wireless rechargeable sensor network (WRSN) can be used to regularly charge to provide energy, which can effectively ensure the normal operation of the system.

In this system shown in Fig. 1, only when the power of a sensor is higher than a threshold $f (mA)$, can information collection work normally. In order to make the WRSN work normally, the mobile charger needs to charge the sensor regularly. The solid arrow indicates the charging route of MC. When the distance between the data center and the sensor, and the distance between the sensor and the sensor is known, the mobile charger starts from the data center and passes through each sensor in turn at a fixed speed $v (m/s)$ according to the shortest Hamiltonian loop. The sensor is charged at a fixed charging rate $r (mA/s)$ until all the sensors are charged and then it returns to the data center. Each sensor has a specific energy consumption rate and a fixed battery capacity. Next, the minimum battery capacity of each sensor is obtained by establishing a linear programming model.
3. Model Establishment and Solution

Under the condition that the shortest Hamilton loop of the mobile charger and the energy consumption rate of each sensor are all known, combined with the analysis of the problem above, the decision variables, objective functions and constraints of the linear programming model are determined respectively.

3.1. Determination of decision variables and objective function

Taking the battery capacity $Q_i (i = 1,2,\cdots,N)$ of each sensor as the decision variable, $N$ is the total number of sensor nodes, and the battery capacity of each sensor is non-negative: $Q_i \geq 0$.

In order to simplify the problem, the optimization goal can be changed from solving a multi-objective program of the minimum battery capacity of each sensor to solving a single-objective program of the minimum battery capacity $Q$ of all sensors. The following objective function is established:

$$Q = \min \sum_{i=1}^{N} Q_i$$

(1)

3.2. Determination of constraints

The time from when the mobile charger is the $i$th sensor just fully charged to when it comes to the sensor next time is $T_i$, which is divided into two parts: one is the mobile charger's moving time $T_0$ according to the shortest Hamilton loop, and the other is the time $\sum_{j=1,j\neq i}^{N} t_j$ for charging the remaining sensors. From the uniform movement of the mobile charger:

$$T_0 = \frac{S}{V}$$

(2)

$$T_i = T_0 + \sum_{j=1,j\neq i}^{N} t_j$$

(3)

where $S$ is the shortest Hamilton loop length, $t_j$ is the time it takes for the mobile charger to charge the $j$th sensor. Since the quantity of electric charge $q_i$ of each sensor needs to be no less than $f$, in order to simplify the problem and ensure the normal operation of the sensor, it may be assumed that the charging capacity of the mobile charger for the $j$th sensor is $Q_j - f$, so $t_j$ can be expressed as:

$$t_j = \frac{Q_j - f}{r}$$

(4)

Each sensor’s quantity of electric charge $q_i$ needs to satisfy the following constraints:

$$q_i = Q_i - v_i T_i$$

(5)

$$q_i \geq f$$

(6)

where $v_i$ is the power consumption rate of the $i$th sensor.

3.3. Determination of linear programming model

Through the analysis of decision variables, objective functions and constraints, the following general linear programming model is obtained:

$$Q = \min \sum_{i=1}^{N} Q_i$$

s.t. \begin{align*}
Q_i - \frac{v_i}{r} \sum_{j=1,j\neq i}^{N} Q_j & \geq f + v_i T_0 - \frac{(N-1)v_i f}{r}, & i = 1,2,\cdots,N \\
Q_i & \geq 0, & i = 1,2,\cdots,N
\end{align*}

(8)
3.4. Solving the model

The relevant important parameters in the model are assigned according to the actual situation in real life. \( r = 0.05 \text{ mA/s}, f = 0.1 \text{ mA}, v = 5 \text{ m/s}, N = 29 \). This paper uses Lingo to solve the model, and gets the minimum battery capacity of 29 sensor nodes, as shown in the figure below:

![Lingo solution results](image)

As can be seen from Fig. 2, the battery capacity of sensor 2 is the largest, 26.31 mA. The battery capacity of sensor 21 and sensor 24 is the smallest, 12.14 mA. Since the power consumption of sensor 2 is the fastest, 7.8 mA/h, the power consumption rate of sensor 21 and sensor 24 is the slowest, 3.5 mA/h. After analysis, it is found that the total time consumed by the mobile charger during driving is much greater than the total time taken to charge each sensor, so the sensor power consumption rate directly determines its battery capacity, and then this article determines the smallest battery capacity that can keep the network working continuously. Therefore, the above results are consistent with reality.

4. Computer Simulation Test

Since it is difficult to clearly express the periodic law of the mobile charger charging the sensor, a computer simulation method is considered to simulate the process of charging each sensor by the mobile charger to verify the model results. Giving each sensor a lower initial battery capacity, so that the mobile charger will charge each sensor according to the shortest Hamiltonian circuit. If it reaches a certain sensor and finds that its power is lower than \( f \), this paper increases the battery capacity of the sensor and terminates the simulation to execute the next simulation. Until the mobile charger can continuously charge 100 million cycles without interruption and the result converges, there are sufficient reasons to believe that the battery capacity of each sensor at this time can ensure the normal operation of the entire system.

4.1. Computer simulation algorithm

The simulation algorithm is as follows:

* **Step 1** This paper initializes the energy consumption rate of each sensor, and the battery capacity is set to \( f \).

* **Step 2** According to the battery capacity of each sensor, this article initializes the current battery to full charge state, and clears the time to 0.

* **Step 3** We move the charger forward to reach the next place.

* **Step 4** We determine whether the place is a data center, if it is to execute **Step 6**, otherwise execute **Step 5**.

* **Step 5** This paper checks the remaining power of the sensor. If the remaining power is greater than \( f \), we charge the sensor and execute **Step 3**, otherwise we change the battery capacity of the sensor to the current battery capacity plus the insufficient power compared to \( f \), and then we execute **Step 2**.
Step 6 This article determines whether the current completed laps are greater than or equal to the target laps $N$. If the conditions are met, the algorithm is terminated, and the battery capacity of each sensor is output, otherwise, Step 3 is executed.

Comparing the solution results of the two methods, the values of the parameters in the computer simulation are basically consistent with the linear programming model. Due to space limitations, some of the solution results are shown in Table 1.

| Sensor | Completed laps | $10^4$ | $10^5$ | $10^6$ | $10^7$ | $10^8$ |
|--------|----------------|--------|--------|--------|--------|--------|
| 1      | 18.6587        | 18.6593| 18.6593| 18.6593| 18.6593| 18.6593|
| 7      | 21.9776        | 21.9782| 21.9782| 21.9782| 21.9782| 21.9782|
| 13     | 22.3075        | 22.3081| 22.3081| 22.3081| 22.3081| 22.3081|
| 19     | 18.9922        | 18.9928| 18.9928| 18.9928| 18.9928| 18.9928|
| 25     | 18.9922        | 18.9928| 18.9928| 18.9928| 18.9928| 18.9928|

It can be observed from Table 1 that for any sensor, when the mobile charger successfully charges the $10^5$ circle, $10^6$ circle, $10^7$ circle, and $10^8$ circle, the battery capacity required by the sensor is all equal, indicating that as the number of completed circles increases, the battery capacity of each sensor gradually converges to a specific value, and the mobile charger can successfully charge the entire system 100 million cycles in computer simulation. Therefore, it is reasonable to believe that the calculated battery capacity of each sensor can ensure the normal operation of the entire system.

Because the value of $r$ and $f$ in the problem considered in this article is small, it may not be consistent with the actual application, but by changing the value of the corresponding parameter, the minimum battery capacity of the sensor can be obtained in various situations, which has a good applicability. Considering the actual situation, this paper rounds up the required power of each sensor when successfully charging the $10^8$ circle as the minimum battery capacity of each sensor. The final result can be as shown in the Fig. 3.

![Computer simulation results](image)

Fig. 3 Computer simulation results

By consulting the data, it can be seen that the sensor generally has low energy consumption and low battery capacity. When the parameters $r$ and $f$ are both small, the required results are between 10 mA and 30 mA, which is in line with the actual situation. At the same time, considering that the moving speed of the mobile charger is 5 m/s, that is, 18 km/h, since the distance between the two sensors is several hundred meters, WCE can effectively supplement energy to the sensor in time, and the battery capacity of the sensor does not need to be too large. The computer simulation results are consistent with the above analysis.
5. Conclusion

Based on the above results and discussion, the following conclusions are drawn:

(1) Under the corresponding parameter values in this article, the minimum battery capacity of the sensor mainly depends on the power consumption rate of the sensor. The sensor with the higher power consumption rate should have a larger minimum battery capacity to ensure the permanent operation of the network.

(2) The linear programming model is basically the same as the computer simulation results, so that the sensor can ensure the permanent operation of the network with the smallest battery capacity, and effectively reduce the network energy consumption.

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References
[1] Yang, Y., Wang, C. (2015) Wireless rechargeable sensor networks. Springerbriefs in Electrical Computer Engineering, The New York.
[2] Zhu, J., Feng, Y., Sun, H., Liu, M., Zhang, Z. (2018) Energy starvation avoidance mobile charging for wireless rechargeable sensor networks. Journal of Software., 29(12): 3868-3885.
[3] Shi, Y., Xie, L., Hou, Y, et al. (2012) On renewable sensor networks with wireless energy transfer. In: IEEE International Conference on Computer Communications. San Francisco. pp. 1350-1358.
[4] Xu, J., Yuan, X., Wei, Z, et al. (2017) A wireless sensor network recharging strategy by balancing lifespan of sensor nodes. In: IEEE Wireless Communications and Networking Conference. Barcelona. pp. 1-6.
[5] Cheng, H., Wei, Z., Han, J, et al. (2017) Periodic charging strategy of energy-constrained wireless charging equipment in WRSNs. Journal of Electronic Measurement and Instrumentation, 31(7): 1031-1039.
[6] Zhu, Y., Ding, E., Hu, Y. (2015) Energy balance routing algorithm for WSNs optimized with PSO. Chinese Journal of Scientific Instrument, 36(1) : 78-86.