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Research Article

TLFW: A Three-Layer Framework in Wireless Rechargeable Sensor Network with a Mobile Base Station

Anwen Wang [1] **, Xianjia Meng** [1] **, Lvju Wang,** [1] **Xiang Ji,** [1] **Hao Chen,** [2] **Baoying Liu,** [1] **Feng Chen,** [1] **Yajuan Du,** [3] **and Guangcheng Yin** [4]

[1]*School of Information Science and Technology, Northwest University, Xi'an, China*
[2]*China University of Labor Relations, Beijing, China*
[3]*Beijing Zunguan Technology Company (National Electronic Computer Quality Supervision and Inspection Center), China*
[4]*Inspur Software Group Co., Ltd., China*

Correspondence should be addressed to Xianjia Meng; xianjiam@nwu.edu.cn

Wireless sensor networks as the base support for the Internet of things have been a large number of popularity and application. Such as intelligent agriculture, we have to use the sensor network to obtain the growing environment data of crops and others. However, the difficulty of power supply of wireless nodes has seriously hindered the application and development of Internet of things. In order to solve this problem, people use low-power sleep scheduling and other energy-saving methods on the nodes. Although these methods can prolong the working time of nodes, they will eventually become invalid because of the exhaustion of energy. The use of solar energy, wind energy, and wireless signals in the environment to obtain energy is another way to solve the energy problem of nodes. However, these methods are affected by weather, environment, and other factors, and they are unstable. Thus, the discontinuity work of the node is caused. In recent years, the development of wireless power transfer (WPT) has brought another solution to this problem. In this paper, a three-layer framework is proposed for mobile station data collection in rechargeable wireless sensor networks to keep the node running forever, named TLFW which includes the sensor layer, cluster head layer, and mobile station layer. And the framework can minimize the total energy consumption of the system. The simulation results show that the scheme can reduce the energy consumption of the entire system, compared with a Mobile Station in a Rechargeable Sensor Network (MSiRSN).

1. Introduction

Internet of things (IoTs) are applied everywhere now. Wireless sensor network as the base support for the Internet of things has been a large number of popularity and application. Such as intelligent agriculture, we have to use the sensor network to obtain the growth environmental data of crops and others. However, energy supplied is the bottleneck of wireless sensor network. In the past, the method is to extend the network life through energy saving. The latest method is to combine wireless power transmission to make the wireless sensor network immortal, but the energy consumption caused by the travel time ignored in this method cannot be ignored in the sensor network with high node density. To reduce the traveling time in a period, we propose a tiered system architecture in this paper. In wireless sensor networks, finite battery capacity is a major limitation of untethered nodes. Sensor nodes will operate for a finite duration, only as long as the battery lasts. The difficulty of the power supply of wireless nodes has seriously hindered the application and development of Internet of things. In order to solve this problem, there are several solution techniques that have been proposed to maximize the lifetime of wireless sensor network, such as energy-aware routing protocols [1, 2], energy-efficient MAC protocols [3], redundant development of nodes [4], and power management strategies [5, 6]. All the above techniques can maximize the lifetime of network. But the lifetime still remains bound, and they will eventually become invalid because of the exhaustion of energy. The use of solar energy, wind energy, and wireless signals in the
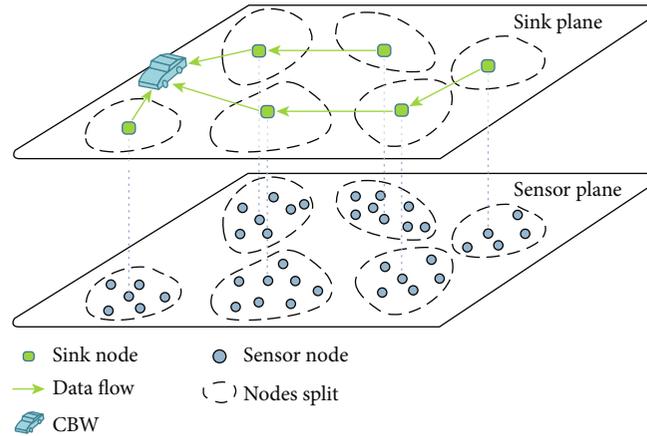
FIGURE 1: Layered system model.

environment [7, 8] to obtain energy is another way to solve the energy problem of nodes. However, these methods are affected by weather, environment, and other factors, and are unstable. Thus, the discontinuous work of the node is caused.

In recent years, the development of wireless power transfer (WPT) [9] has brought another solution to this problem. Wireless power transfer based on magnetic resonant coupling [10, 11] has been demonstrated to be a promising technology to address the problem in a wireless sensor network [12–15]. In the paper, a Mobile Station in a Rechargeable Sensor Network (MSiRSN) [12], the author shows how charging vehicle (WCV) can charge batteries of sensor nodes by wireless charging when the charging vehicle is near sensor nodes and how to carry the base station (MBS) to gather data. There is a home service station for the vehicle. The authors addressed the problem of colocating the MBS on the WCV in a WSN by studying an optimization problem with a focus on the traveling path problem of the WCV, the data flowing routing depending on where the WCV is in the network, stopping points, and charging schedule to minimize energy consumption of the entire system while ensuring none of the sensor nodes runs out of energy. In each charge period, WCV travels inside the network and charges every sensor node. In the above papers, the traveling time is a little proportion of total time consisting of traveling time, vacation time, and charging time. For example, the traveling time equals 1022 s, the vacation time equals 10.26 hours, and the charging time is 3.41 hours in the solution of simulation [13]. However, as the traveling time increases with the node density and the traveling time is a great part of the total time, traveling and charging every node in a period are improper.

To sum up, energy supplied is the bottleneck of wireless sensor network. In the past, the method is to extend the network life through energy saving. The latest method is to combine wireless power transmission to make the wireless sensor network immortal, but the energy consumption caused by the travel time ignored in this method cannot be ignored in the sensor network with high node density.

To reduce the traveling time in a period, we propose a tiered system architecture consisting of the sensor layer, cluster head layer, and mobile station layer, as illustrated in Figure 1. The CBW (a Car as Mobile bastion with Wireless power transfer) travels all cluster heads at cluster head layer and selects the cluster in which CBW travels all sensor nodes at sensor layer in a subperiod. Several subperiods form a period in which the sensor nodes in every cluster are traveling once. Compared to traveling all nodes in [12, 13], the strategy reduces the proportion of the traveling time in total time, leading to reduction of the total energy consumption in the entire system, which includes power used by the CBW and the power consumed for wireless power transfer.

1.1. Summary and Contribution

(i) In this paper, we design a three-layer framework for rechargeable wireless sensor network based on mobile base station, which reduces the energy consumption of mobile charging process

(ii) A centralized clustering algorithm is proposed, which organizes sensors into m clusters, optimizes mobile charging strategy, and shortens mobile charging time

(iii) An optimization method of joint charging plan is designed. The problem of energy supply for high-density wireless sensor network is solved

2. Related Work

The lifetime of wireless sensor networks is often limited by energy supplies. The problem of node energy supply is also a key problem in the application development of wireless sensor networks. To solve this problem, researchers have explored a wide variety of solutions.

One type of the methods is to save energy by optimizing the hardware and software [16] of the nodes. There are several solution techniques that have been proposed to allow nodes to work as long as possible in a limited amount of energy. Such as energy-aware routing protocols [1], energy-efficient MAC protocols [3], redundant development of nodes [4], and power management strategies [5]. But no

matter how energy-efficient, the battery will eventually be used up. Then, the network is invalid.

Another type of the methods is to automatically obtain energy by nodes from the natural environment, such as the wind and solar energy [17]. The energy-harvesting techniques referring to harnessing energy from the environment and converting energy to electrical energy make that a node can be powered perpetually possible, such as [7, 8]. Due to uncontrollability and unpredictability of the energy source that refers to the ambient source of energy to be harvested, the techniques cannot ensure that nodes run in every moment.

The third type of the methods is to obtain energy using ubiquitous radio signals [18]. However, this technology is still in its initial stage of research and can obtain very little energy. This is mainly caused by the far distance and the limited transmitting power of the electromagnetic wave. Recently, wireless power transfer based on magnetic resonant coupling [10] has been demonstrated to be a promising technology to address the problem in a wireless sensor network [12–14, 19, 20]. In MSiRSN, the authors showed how charging vehicle (WCV) can support wireless power transfer by bringing an energy source charge to proximity of sensor nodes and charging their batteries wirelessly. But the overall energy consumption is higher.

In this paper, we propose a tiered system architecture consisting of the sensor layer, cluster head layer, and mobile station layer to reduce the traveling time in a period. The CBW travels all cluster heads at cluster head layer and selects the cluster in which CBW travels all sensor nodes at sensor layer in a subperiod. Several subperiods form a period in which the sensor nodes in every cluster are traveling once. Compared to traveling all nodes in the above methods [12, 13], the strategy reduces the proportion of the traveling time in total time, leading to the reduction of the total energy consumption in the entire system, which includes power used by the CBW and the power consumed for wireless power transfer.

3. Overview

In order to make the nodes run forever, this paper proposes a tiered system framework for rechargeable mobile data collection wireless sensor network. The framework is divided into three layers, including sensor layer, cluster head layer, and mobile station layer. The application of this framework can reduce the traveling time in a period. In this three-layer framework, The CBW travels all cluster heads at cluster head layer and selects the cluster in which CBW travels all sensor nodes at sensor layer in a subperiod. Several subperiods form a period in which the sensor nodes in each cluster are travelled only once. Compared to other methods, this strategy reduces the proportion of the traveling time in total time, leading to reduction of the total energy consumption in the entire system, which includes power used by the CBW and the power consumed for wireless power transfer.

At the sensor layer, a centralized clustering algorithm is proposed for sensors to organize them into m clusters and the sensor nodes transmit data to the cluster head via a single hop. In contrast to existing clustering methods which balance energy consumption, our scheme generates m cluster heads to minimize the total energy consumption. The single-hop data routing reduces energy consumption through that the sensor turns off the radio when there is no data generated by themselves to transmit.

At cluster head layer, cluster heads can cooperate with each other and the cluster head information is forwarded to CBW (a Car as Mobile bastion with Wireless power transfer) via multihop. The optimal flow routing is solved for a CBW moving trajectory to save energy.

At the mobile station layer, we study an optimization problem that joints charging schedule for cluster heads and sensors, and flow routing for cluster heads.

4. Background

Wireless power transfer based on magnetic resonant coupling [10] has been demonstrated to be a promising technology to address the problem in a wireless sensor network in [12, 13]. In MSiRSN [12], the authors showed how charging vehicle (WCV) can support wireless power transfer by bringing an energy source charge to proximity of sensor nodes and charging their batteries wirelessly, and carry the base station (MBS) to gather data. There is a home service station for the vehicle. The authors addressed the problem of colocating the MBS on the WCV in a WSN by studying an optimization problem with a focus on the traveling path problem [21] of the WCV, the data flowing routing depending on where the WCV is in the network, stopping points, and charging schedule to minimize energy consumption of the entire system while ensuring none of the sensor nodes runs out of energy. In each charge period, WCV travels inside the network and charges every sensor node.

5. Layered Network Model

In this section, we give an overview of entire framework. As depicted in Figure 1, it consists of three layers: sensor layer, cluster head layer, and mobile station layer.

We consider a set of sensor nodes N^* distributed over a two-dimensional area. Each sensor node has a battery with a capacity of E_{max} and the initial energy of battery is a random value. E_{min} is denoted as the minimum level of energy at a battery for it to be operational. Each sensor node i generates sensing data with a rate r_i (in b/s), $i \in N^*$. Within the sensor network, there is a mobile CBW to charge sensor nodes and gather the entire network information.

In the paper [12, 13], the authors proposed strategies to keep all nodes running forever using the wireless power transfer. In MSiRSN, the authors studied the problem of colocating the MBS on the WCV in a WSN to minimize energy consumption of the entire system. The WCV follows a periodic schedule to travel inside the network for charging every sensor node.

However, as the traveling path increases with the number of sensor nodes, the time of traveling all sensor nodes is a large proportion of a period with large sensor nodes in a

wireless network. So, traveling all sensor nodes in a period is an unwise strategy.

To address the issue, we introduce a three-layer model, consisting of the sensor layer, cluster head layer, and mobile station layer, as illustrated in Figure 1. The CBW travels all cluster heads N at cluster head layer and selects a cluster in which CBW travels all sensor nodes at sensor layer in a sub-period. Several subperiods form a period in which the sensor nodes in every cluster are traveling once. The schedule shows the cluster heads with higher energy consumption have higher charging frequency than normal sensor nodes.

6. Cluster Selection Algorithm

Since sensor nodes are energy-constrained, the network's lifetime is a major concern, especially for applications of WSNs in harsh environments. There are several solution techniques proposed, such as energy-aware routing protocols [1], energy-efficient MAC protocols [3], redundant development of nodes [4], and power management strategies [5]. To support scalability of large WSN, nodes are often grouped into disjoint and mostly nonoverlapping cluster. The most well-known hierarchical routing protocols are LEACH, HEED, TEEN, PEGASIS [22], etc. Other clustering algorithms in the literature vary in their objectives, such as load balancing [23], fault-tolerance [24], increased connectivity and reduced delay [25–27], and minimal cluster count [28]. However, the above clustering algorithms are all proposed to prolong the lifetime of the network. In this paper, a cluster selection algorithm is proposed to minimize the energy consumption of the whole network, and it can be combined with wireless power transmission technology to make the nodes run forever. Then, let the wireless network achieve immortality instead of maximizing the network life.

We propose an algorithm to minimize the total communication energy consumption $C_s = \sum_{i=1}^{m} \sum_{t \in S_i} C_{ti} \cdot r_t (i \in N)$ in sensor layer. In order to clearly describe the algorithm, denote $\bar{N}$ as the number of elements in set N. The inputs of the algorithm are all node N^* locations, communication consumption model parameters β_1, β_2, and ω, and the number of cluster head m. The output of the algorithm is the m cluster in which there are several normal nodes and a cluster head to minimize the within-cluster sum of communication energy consumption. The algorithm has four steps:

Step 1. Randomly give initial cluster head set N and $\bar{N} = m$

Step 2. We assign each node to a cluster that the node's communication energy consumption to the cluster head is minimum. The strategy yields the least within-cluster sum of communication energy consumption

Step 3. We update the cluster head in a cluster through calculating the new mean to be the centroid of the sensor nodes in a cluster and setting the sensor nodes closest to the centroid as new cluster head in the cluster

Step 4. Alternate Step 2 and Step 3 until the centroids of all clusters do not change in range

7. Layer 1: Normal Sensor Nodes

7.1. Static Routing. We suppose every node's location is known in the network. By a clustering algorithm in Section 6, we can get m clusters and two type sensor nodes (normal nodes and cluster head nodes). To conserve the energy, we suppose the normal sensor nodes have no collaboration capability, only send data to the cluster head via a single hop, and do not forward packets coming from other sensor nodes.

The total data rate in cluster i (denoted as R_i) contains two parts: the first is data received from normal sensor nodes in cluster i and the second is the data generated by cluster head node i. Hence,

$$R_i = \sum_{t \in S_i} r_t + r_i, \tag{1}$$

where S_i is the set of the type 0 nodes in cluster i, r_i and r_t is the data generation rate of nodes i and t respectively. Given that cluster results, we have that R_i is constant.

7.2. Energy Consumption in a Cluster. Denote C_{ti} as the energy consumption rate for transmitting one unit of data flow from normal sensor node t to cluster head i. Then, C_{ti} (in Joule/bit) can be modeled as [29]: $C_{ti} = \beta_1 + \beta_2 D_{ti}^{\omega}$, where D_{ti} is the physical distance between node t and node i, β_1 and β_2 are constant terms, and ω is the path loss index and typically between $2 \le \omega \le 4$ [30].

$$D_{ti} = \sqrt{(x_t + x_i)^2 + (y_t + y_i)^2}, \tag{2}$$

where (x_t, y_t) and (x_i, y_i) are the coordinates of cluster head i and normal sensor node t. Given that all nodes are stationary and the cluster result is stationary, we have D_{ti} and C_{ti} that are all constants.

Denote α (in Joule/bit) as the energy consumption rate for sensing one unit of data. The power consumption of the CPU is not taken into account.

For a normal sensor node t, the total energy consumption rate c_t is as follows:

$$\alpha \cdot r_t + C_{ti} \cdot r_t = c_t, \quad (t \in S_i), \tag{3}$$

where S_i is the set of normal nodes within the cluster i. Denote C_i^* as the total energy consumption of all normal sensor nodes in a cluster i. Because the normal sensor nodes at a cluster only send data to the cluster head, there is no receiving energy consumption. Then, we have the following:

$$C_i^* = \sum_{t \in S_i} c_t = \sum_{t \in S_i} (\alpha \cdot r_t + C_{ti} \cdot r_t), \quad (i \in N). \tag{4}$$

Given a cluster solution, C_i^* is constant. C_s is denoted as the total energy consumption in the sensor layer, and then we have the following:
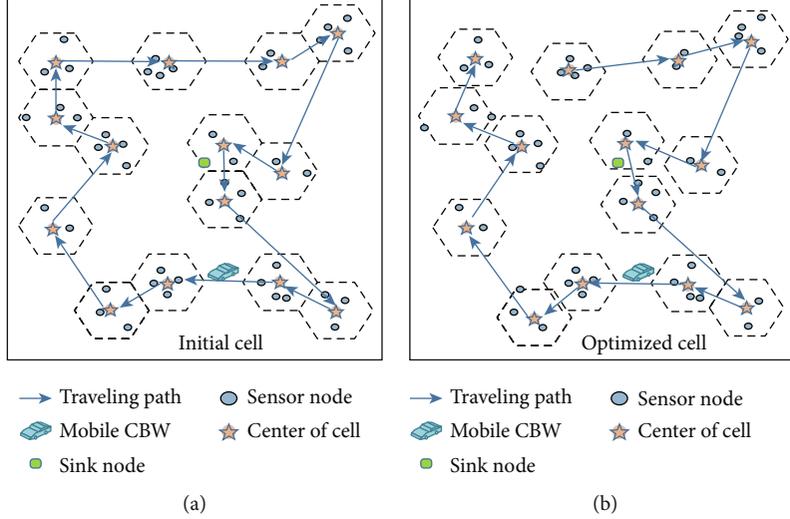
FIGURE 2: Cell charging model at a cluster.

$$C_s = \sum_{i=1}^{m} C_i^* = \sum_{i=1}^{m} \sum_{t \in S_i} (\alpha \bullet r_t + C_{ti} \bullet r_t), \quad (i \in N), \quad (5)$$

where m is the number of cluster.

7.3. Charging Model and Charging Behavior. In this section, we give a charging model and a charging behavior for normal sensor nodes in a cluster.

7.3.1. Charging Model. Based on the charging technology [31], the vehicle with a wireless power transfer can charge neighboring nodes as long as they are within its charging range. We denote $U_{tB}(p)$ as the power reception rate at normal sensor node t when the vehicle position is p. Denote the efficiency of wireless charging by $\mu(D_{tB}(p))$ when the node is in charge range. $U_{\max}$ is denoted as the maximum output power for a node and D_δ is denoted as the charging range of wireless power transfer. We assume power reception rate is too low to make magnetic resonant coupling work properly at the node battery, when the distance between the node and the mobile CBW wireless charging model is as follows [13]:

$$U_{tB}(p) = \begin{cases} \mu(D_{tB}(p)) \bullet U_{\max}, & \text{if} \quad D_{tB}(p) \le D_\delta, \\ 0, & \text{if} \quad D_{tB}(p) > D_\delta, \end{cases} \quad (6)$$

where $\mu(D_{tB}(p))$ is a decreasing function of $D_{tB}(p)$, and $0 \le \mu(D_{tB}(p)) \le 1$.

7.3.2. Cellular Structure and Energy Charging Behavior. We consider all normal sensor nodes in a cluster. We employ the partition strategy in [13]. The two-dimensional plane of a cluster is partitioned into hexagonal cells with side length of D, as illustrated in Figure 2. We optionally optimize the cell partition solution by the algorithm which the solution is illustrated in Figure 2. To charge normal sensor nodes in a cell, the mobile CBW only needs to visit the center of a cell. All normal sensor nodes within a hexagonal cell are within a distance of D from the cell center. Denote Q_i as the set of all

cell centers and $q^*(q \in Q_i)$ as a cell. So, the power reception rate of t in a cell with a center q is $U_{tB}(q) = \mu(D_{tB}(q)) \bullet U_{\max}$ $(q \in Q_i, t \in q^*)$, where $D_{tB}(q)$ is the distance between t and the center q. Note that given the cell deployment and the t' position, the $D_{tB}(q)$ is constant. So we simply convert $D_{tB}(q)$ into D_t and $U_{tB}(q)$ into U_t.

We employ the so-called logical energy consumption rate $\gamma_t = c_t/U_t$ at a normal sensor node. Denote Γ_i^* as the logical energy consumption rate at a cluster.

$$\gamma_t = \frac{c_t}{U_t} = \frac{\alpha \bullet r_t + C_{ti} \bullet r_t}{U_t}, \quad (t \in S_i), \quad (7)$$

$$\Gamma_i^* = \sum_{t \in S_i} \gamma_t = \sum_{t \in S_i} \frac{c_t}{U_t} = \sum_{t \in S_i} \frac{\alpha \bullet r_t + C_{ti} \bullet r_t}{U_t}, \quad (i \in N). \quad (8)$$

7.4. Traveling Period in a Cluster. Denote $\mathscr{P}_i$ as the traveling path and τ_i as the amount of time for each cycle. Then, τ_i includes three components:

(i) The total traveling time along path $\mathscr{P}_i$ is $\mathscr{D}_{\mathscr{P}_i}/V$, where $\mathscr{D}_{\mathscr{P}_i}$ is the distance along path P_i and V is the traveling speed of the vehicle

(ii) The total sojourn time along path $\mathscr{P}_i$, which is defined as the sum of all stopping times of the vehicle when it travels on $\mathscr{P}_i$

(iii) The vacation time for the vehicle in a cluster i, τ_{vac_i}, which starts when the vehicle leaves the cluster i and ends when the vehicle travels the path $\mathscr{P}_i$ for charge all normal nodes in the cluster i

Then, we have the following:

$$\tau_i = \frac{\mathscr{D}_{\mathscr{P}_i}}{V} = \sum_{p \in \mathscr{P}_i}^{\omega_i(p) > 0} \omega_i(p) + \tau_{\text{vac}_i}, \quad (p \in \mathscr{P}_i), \quad (9)$$

where $\omega_i(p)$ denotes the aggregate amount of time when the vehicle stays at point $p \in \mathscr{P}_i$, and τ_{vac_i} denotes the vehicle leaves the cluster i and is out of cluster i charging period.

Note the mobile CBW only visits the cell center. To minimize the traveling time in a cluster, the mobile CBW must move along the shortest Hamiltonian cycle that connects the cluster head and the centers of cells in which there is at least one normal sensor node. The shortest Hamiltonian cycle can be obtained by solving the well-known Traveling Salesman Problem (TSP) [32]. D_{Pi} is denoted as the solution of the TSP.

7.5. Energy Constraints for Normal Sensor Node. We offer two conditions of energy renewable and show that once they are met, the energy level at normal sensor node never falls below

$E_{\min}$ that means the normal sensor can run forever. First, we split energy consumption at normal sensor node t in cluster i into three parts:

(i) Energy is consumed when the CBW does not select the cluster i to charge battery: $\gamma_t \bullet \tau_{\mathrm{vac}_i}$

(ii) Energy is consumed when the CBW makes stops at all centers of cell in which there is at least one normal sensor node: $\sum_{p \in \mathscr{P}_i}^{\omega_i(p)>0, D_{tB}(p)>D_\delta} \gamma_t \bullet \omega(p)$

(iii) Energy is consumed when the CBW is moving along $\mathscr{P}_i$ that is Hamiltonian cycle that connects the cluster head and the centers of cells in which there is at least one normal sensor node, $\gamma_t \bullet (\mathscr{D}_{\mathscr{P}_i}/V)$

$$E_{\max} - \left[\gamma_t \bullet \tau_{\mathrm{vac}_i} + \sum_{p \in \mathscr{P}_i}^{\omega_i(p)>0, D_{tB}(p)>D_\delta} \gamma_t \bullet \omega(p) + \gamma_t \bullet \frac{\mathscr{D}_{\mathscr{P}_i}}{V}\right] \geq E_{\min}, \quad (i \in N, t \in S_i), \tag{10}$$

$$\gamma_t \bullet \tau_{\mathrm{vac}_i} + \sum_{p \in \mathscr{P}_i}^{\omega_i(p)>0, D_{tB}(p)>D_\delta} \gamma_t \bullet \omega(p) + \gamma_t \bullet \frac{\mathscr{D}_{\mathscr{P}_i}}{V} \leq \sum_{p \in \mathscr{P}_i}^{\omega_i(p)>0, D_{tB}(p)>D_\delta} U_{tB}(p) \bullet \omega(p), \quad (i \in N, t \in S_i). \tag{11}$$

We employ a cellular structure for normal sensor nodes (in Section 7.2). From Equations (10) and (11), we obtain the following:

$$E_{\max} - \left[\gamma_t \bullet \tau_{\mathrm{vac}_i} + \sum_{q \in Q_i} \gamma_t \bullet \omega(p) + \gamma_t \bullet \frac{\mathscr{D}_{\mathscr{P}_i}}{V}\right] \geq E_{\min}, \quad (i \in N, t \in S_i), \tag{12}$$

$$\gamma_t \bullet \tau_{\mathrm{vac}_i} + \sum_{q \in Q_i} \gamma_t \bullet \omega(p) + \gamma_t \bullet \frac{\mathscr{D}_{\mathscr{P}_i}}{V}$$
$$\leq \sum_{p \in \mathscr{P}_i}^{\omega_i(p)>0, D_{tB}(p)>D_\delta} U_{tB}(p) \bullet \omega(p), \quad (i \in N, t \in S_i), \tag{13}$$

where Q_i is the set of all cell centers in cluster i.

8. Layer 2: Cluster Head Nodes

8.1. Dynamic Routing. With a clustering algorithm in Section 6 to minimize the total energy of all sensor nodes, we can get some specific nodes and denote them as cluster heads. Different from normal nodes, the cluster head has collaboration capability.

8.2. Dynamic Flow Balance. Due to the mobility of the vehicle, data flow routing is dynamic with routing topology changing over time. Denote $f_{ij}(p)$ and $f_{iB}(p)$ as flow rates from cluster head i to cluster head j and to the base station when the vehicle is at location $p \in P$, respectively. Then, we

have the following flow balance constraint at each cluster head i.

$$\sum_{k \in N}^{k \neq i} f_{ki}(p) + R_i = \sum_{j \in N}^{j \neq i} f_{ij}(p) + f_{iB}(p), \quad (i \in N), \tag{14}$$

where N is the set of cluster heads gotten by cluster selection algorithm in Section 6, and R_i is determined by Equation (1).

8.3. Energy Consumption. Like the energy consumption model for normal sensor nodes, the communication energy consumption between two cluster nodes i and j can be modeled as follows:

$$C_{ij} = \beta_1 + \beta_2 D_{ij}^\omega, \tag{15}$$

where $D_{ij} = \sqrt{(x_i + x_j)^2 + (y_i + y_j)^2}$, and (x_i, y_i) and (x_j, y_j) are the coordinates of cluster heads i and j. $D_{iB}(p) = \sqrt{(x_i + x_B)^2 + (y_i + y_B)^2}$, and (x_j, y_j) and (x_B, y_B) are the coordinates of type 1 node i and vehicle B at $(p \in \mathscr{P})$. Given that the cluster result and all cluster heads are stationary, we have D_{ij} and C_{ij} that are all constants. However, $D_{iB}(p)$ and $C_{iB}(p)$ varied with vehicle position p. Denote γ (in Joule/bit) as the energy consumption rate for receiving one unit of data. Then, the total energy consumption rate for transmission, reception, and sense at cluster head i when the

vehicle is at $p \in \mathscr{P}$, denoted as $c_i(p)$, is as follows:

$$
\alpha \bullet r_i + \rho \bullet \sum_{t \in S_i} r_t + \rho \bullet \sum_{k \in N}^{k \neq i} f_{ki}(p) + \sum_{k \in N}^{j \neq i} C_{ij} \bullet f_{ij}(p)
$$
$$
+ C_{iB}(p) \bullet f_{iB}(p) = c_i(p), \quad (i \in \mathscr{P}), \tag{16}
$$

where $\alpha \bullet r_i$ is denoted as the sensing consumption, $\rho \bullet \sum_{t \in S_i} r_t$ is denoted as the consumption for receiving data from all normal sensor nodes at cluster i, $\rho \bullet \sum_{k \in N}^{k \neq i} f_{ki}(p)$ is denoted as the consumption for receiving data from other cluster heads, $\sum_{k \in N}^{j \neq i} C_{ij} \bullet f_{ij}(p)$ is denoted as the consumption for transmitting data to other clusters, and $C_{iB}(p) \bullet f_{iB}(p)$ is denoted as the consumption for transmitting data to the mobile CBW. Note that the cluster head consumption $c_i(p)$ dynamically changes with the position p.

8.4. Charging Model. Like the energy charging model for normal sensor nodes in Section 7.3, we use wireless power transfer [31] to charge the rechargeable battery of cluster heads. Different from normal sensor nodes charging schedule, the charging point for every cluster head is located in cluster head, taking into account of the distance between any two cluster heads is longer than the charging range of wireless power transfer D_δ, which means it is impossible to charge two cluster heads simultaneously.

$$
U_{iB}(p) = \begin{cases} U_{\max}, & \text{if } p = i, \\ 0, & \text{if } p \neq i, \end{cases} \tag{17}
$$

where p is the mobile CBW position, $p = i$ denotes the mobile CBW and cluster head i are at the same position, and $p \neq i$ denotes the mobile CBW and cluster head i are at two different positions. Equation (17) shows the mobile CBW just charges a cluster head while they are at the same position and do not charge battery when it is moving.

8.5. Traveling Period for Cluster Layer. Like Section 7.4, the charge time for cluster heads is $\tau = \mathscr{D}_{\mathscr{P}} / V = \sum_{p \in \mathscr{P}}^{\omega(p) > 0} \omega(p) + \tau_{\mathrm{vac}}$, $(p \in \mathscr{P})$, where $\omega(p)$ denotes the aggregate amount of time the vehicle stays at point $p \in \mathscr{P}$ and p_{vac} denotes the location of the home service station. To minimize the traveling time of all cluster heads, the mobile CBW must move along the shortest Hamiltonian cycle that connects the server station and all cluster heads. Like traveling time at a cluster $D_{\mathscr{P}}$, $D_{\mathscr{P}}$ is denoted as the solution of the TSP.

Based on the distance between two type 1 nodes that is longer than charging range of wireless power transfer D_δ, the points where the vehicle stops for charge cluster heads are in cluster head position. Then, Equation (9) can be written as follows:

$$
\tau = \frac{\mathscr{D}_{\mathscr{P}}}{V} = \sum_{p \in \mathscr{P}}^{\omega(p) > 0} \omega(p) + \tau_{\mathrm{vac}}, \quad (p \in N_i). \tag{18}
$$

8.6. Energy Consumption in a Subperiod. We offer two energy renewable conditions and show that once they are met, the energy level at clusters head will never fall below $E_{\min}$, which means the cluster head can run forever. First, we split energy consumption at normal sensor node t into three parts:

(i) Energy is consumed when the CBW makes a stop at the service station: $c_i(p_{\mathrm{vac}}) \bullet \tau_{\mathrm{vac}}$

(ii) Energy is consumed when the CBW makes stops at all cluster heads: $\sum_{p \in N, p \neq i} c_i(p) \bullet \omega(p)$

(iii) Energy is consumed when the CBW is moving along $\mathscr{P}$ that is Hamiltonian cycle that connects all cluster heads and the service station: $\int_{s \in [0, D_P]}^{\omega(p(s)) = 0} (1/V) \bullet c_i(p(s)) ds$

$$
E_{\max} - \left[c_i(p_{\mathrm{vac}}) \bullet \tau_{\mathrm{vac}} + \sum_{p \in N, p \neq i} c_i(p) \bullet \omega(p) + \int_{s \in [0, D_P]}^{\omega(p(s)) = 0} \frac{1}{V} \bullet c_i(p(s)) ds \right] \geq E_{\min}, \quad (i \in N), \tag{19}
$$

$$
c_i(p_{\mathrm{vac}}) \bullet \tau_{\mathrm{vac}} + \sum_{p \in N, p \neq i} c_i(p) \bullet \omega(p) + \int_{s \in [0, D_P]}^{\omega(p(s)) = 0} \frac{1}{V} \bullet c_i(p(s)) ds \leq \sum_{p \in \mathscr{P}}^{\omega(p) > 0, D_{iB}(p) \leq D_\delta} U_{iB}(p) \bullet \omega(p), \quad (i \in N). \tag{20}
$$

9. Layer 3: Charging Schedule at CBW

We consider minimizing energy consumption of the entire system which includes normal sensor nodes and cluster heads. Firstly, we minimize the total transmission energy consumption of all normal nodes in a cluster through a cluster selection strategy and give an optional charge strategy including an approximative optional path and charge time. Secondly, for cluster head layer, we formulate the problem including mobile CBW traveling path, dynamic flow routing, and charge time, and solve the problem by CPLEX solver [33].

9.1. Formulation for Normal Sensor Nodes in a Cluster. We develop a travel schedule for the mobile CBW and charging schedule among normal sensor nodes so that no normal node

never runs out of energy. For the objective function, we consider minimizing energy consumption in sensor layer. We have followed optimization problem (OPT-normal) (time constraints (9), energy consumption model ((7), (8)), and energy renewable constraints ((12), (13)())):

$$\max \frac{\tau_{\mathrm{vac}_i}}{\tau_i}$$

$$\text{s.t. Time constraints}$$

$$\text{Energy consumption model}$$ (21)

$$\text{Energy renewable constraints}$$

$$\tau_i, \tau_{\mathrm{vac}_i}, \omega_i(p) \geq 0, (p \in \mathscr{P}_i).$$

To minimize the traveling time in a cluster, the mobile CBW must move along the shortest Hamiltonian cycle that connects the cluster head and the centers of cells in which there is at least one normal sensor node. So, $\mathscr{P}_i$ is denoted as the solution of this TSP.

9.2. Formulation for Cluster Nodes. We develop a travel schedule for the mobile CBW, charging schedule, and data flow routing among cluster heads so that no cluster head never runs out of energy. For the objective function, we consider minimizing energy consumption in cluster head layer. We have followed optimization problem (OPT-cluster) (time constraints (18), energy consumption model (16), and energy renewable constraints ((19), (20))):

$$\max \frac{\tau_{\mathrm{vac}}}{\tau}$$

$$\text{s.t. Time constraints}$$

$$\text{Energy consumption model}$$ (22)

$$\text{Energy renewable constraints}$$

$$\tau, \tau_{\mathrm{vac}}, \omega(p) \geq 0, (p \in \mathscr{P})$$

$$f_{ij}(p), f_{iB}(p), r_i(p) \geq 0, (i, j \in N, i \neq j, p \in P).$$

To minimize the traveling time of all cluster heads, the mobile CBW must move along the shortest Hamiltonian cycle that connects the server station and all cluster heads. So, P is denoted as the solution of the TSP.

9.3. Joint Solution. We find solutions to D_{tps_i}, rate$_i$, and $t_{\max\,i}$ for a cluster i and τ_{vac}, τ, and τ_{tsp} for cluster head by CPLEX [33]. Denote the $t_{\max}$ as the min $(t_{\max_i}, i \in N)$.

Denote h as the number of subperiod during which the mobile CBW charges all cluster heads once, in an entire period. Denote T as the total time of a period. Then, we have $h \bullet \tau = T$. Denote T_{vac} as the vacation time in the entire period. T_{vac} equals the total time of a period minus the sum of the traveling time of cluster heads and normal sensor nodes, and the charging time of all nodes in the wireless network. T_{vac} equals the total vacation time of cluster head traveling in h subperiod minus the sum of charging time and traveling

TABLE 1: Location and data rate R_i for each node in a 50-node network.

Node index	Location	R_i	Node index	Location	R_i
1	(0.547, 0.644)	0.1	26	(0.833, 0.115)	0.2
2	(0.662, 0.757)	0.7	27	(0.639, 0.658)	0.1
3	(0.037, 0.859)	0.4	28	(0.704, 0.930)	0.6
4	(0.723, 0.741)	1.0	29	(0.977, 0.306)	0.8
5	(0.529, 0.778)	0.9	30	(0.673, 0.386)	0.5
6	(0.316, 0.035)	0.4	31	(0.021, 0.745)	0.7
7	(0.190, 0.842)	0.8	32	(0.924, 0.072)	0.6
8	(0.288, 0.106)	0.8	33	(0.270, 0.829)	0.1
9	(0.040, 0.942)	0.2	34	(0.777, 0.573)	0.8
10	(0.264, 0.648)	0.4	35	(0.097, 0.512)	0.9
11	(0.446, 0.805)	0.5	36	(0.986, 0.290)	0.2
12	(0.890, 0.729)	0.5	37	(0.161, 0.636)	0.7
13	(0.370, 0.350)	0.1	38	(0.355, 0.767)	0.9
14	(0.006, 0.101)	0.7	39	(0.655, 0.574)	0.5
15	(0.393, 0.548)	0.1	40	(0.031, 0.052)	0.4
16	(0.629, 0.623)	0.1	41	(0.350, 0.150)	0.3
17	(0.084, 0.954)	0.5	42	(0.941, 0.724)	0.1
18	(0.756, 0.840)	0.2	43	(0.966, 0.430)	0.2
19	(0.966, 0.376)	0.7	44	(0.107, 0.191)	0.3
20	(0.931, 0.308)	0.6	45	(0.007, 0.337)	0.3
21	(0.944, 0.439)	0.1	46	(0.457, 0.287)	0.4
22	(0.626, 0.323)	0.4	47	(0.753, 0.383)	0.1
23	(0.537, 0.538)	0.2	48	(0.945, 0.909)	0.1
24	(0.118, 0.082)	0.3	49	(0.209, 0.758)	0.3
25	(0.929, 0.541)	0.2	50	(0.221, 0.588)	0.8

path time of normal sensor nodes at all clusters. Then, we have $h \bullet \tau - \sum_{i \in N} \Gamma_i^* \bullet T + D_{tps_i}/V = T_{\mathrm{vac}.}$

To minimize the entire system consumption jointing sensor layer, cluster head layer, and mobile bastion station, we study the following problem (OPT-joint).

$$\max \frac{T_{\mathrm{vac}}}{T}$$

$$\text{s.t. } h \cdot \tau = T$$

$$T \leq t_{\max}$$

$$h \bullet T_{\mathrm{vac}} - \sum_{i \in N} \Gamma_i^* \bullet T + \frac{D_{tps_i}}{V} = T_{\mathrm{vac}}$$ (23)

$$\text{rate}_i \bullet T + \leq T_{\mathrm{vac}}, (i \in N)$$

$$h > k.$$

Constraint $T \leq t_{\max}$ shows the entire period is no greater than the minimum value of maximum lifetime for a cluster in all clusters, which ensures every normal sensor node is not out of energy. rate$_i \bullet T + D_{tps_i}/V \leq T_{\mathrm{vac}}$ $(i \in N)$ shows the time that the mobile CBW is into a cluster and charges normal sensor nodes is no longer than the T_{vac} that ensures in a
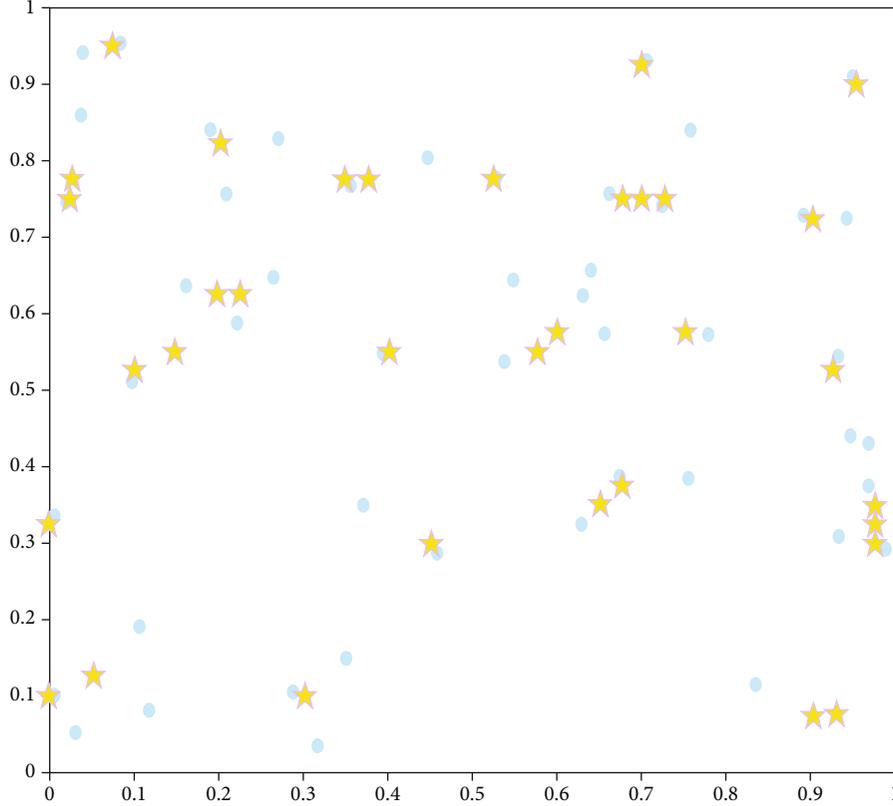
FIGURE 3: The solution in MSiRSN. The yellow star represents the stopping points, and the blue circle represents the sensor node.

subperiod; the mobile CBW can charge all normal sensor nodes. For the fractional objective function T_{vac}/T, we define $\eta_{\text{vac}} = T_{\text{vac}}/T$. Then, we can reformulate the above problem as follows:

$$
\begin{aligned}
& \max \ \eta_{\text{vac}} \\
& s.t \ h \cdot \tau = T \\
& T \le t_{\max} \\
& h \bullet \eta_{\text{vac}} - \sum_{i \in N} \left(\Gamma_i^* \bullet T + \frac{D_{tps_i}/V}{T} \right) = \eta_{\text{vac}} \\
& \text{rate}_i \bullet T + \le \eta_{\text{vac}}, \quad (i \in N) \\
& h > k.
\end{aligned} \tag{24}
$$

The equation $h \bullet \eta_{\text{vac}} - \sum_{i \in N} (\Gamma_i^* \bullet T + (D_{tps_i}/V)/T) = \eta_{\text{vac}}$ shows the η_{vac} increases with T. So, we can maximize the η_{vac} via maximizing T with two constraints $T \le t_{\max}$ and $\Gamma_i^* \bullet T + (D_{tps_i}/V)/T \le \tau_{\text{vac}}/T$, where $t_{\max}$ and τ_{vac}/T can be calculated in Section 9.1 and Section 9.2, respectively. So, the joint problem can be solved.

10. Performance Evaluations

In this section, we present some numerical results to demonstrate how our solution works to achieve wireless energy

transfer and evaluate the performance of the system compared to MSiRSN.

10.1. Simulation Settings. In this section, we evaluate the performance of the system and compared it with the strategy in MSiRSN. The network parameters are set like in MSiRSN. We assume sensor nodes are deployed over a 1×1 square area. The service station is at (0.5, 0.5). The traveling speed of the mobile CBW is $V = 0.1$. The data rate r_t, $t \in N^*$, from each node is randomly generated within [0.1, 1]. Power consumption coefficients are $\beta_1 = 1, \beta_2 = 1, \rho = 1, \alpha = 0$. The path loss index is $\omega = 4$. Suppose that a sensor node uses a rechargeable battery with $E_{\max} = 10,000$ and $E_{\min} = 500$. For the charging efficiency function, $\mu(D_{tB}(p)) = -40D_{tB}(p)^2 - 4D_{tB}(p)^2 + 1$. Let $U_{\max} = 50$ and $D_\delta = 0.1$ for a maximum distance of effective charing. We consider a 50-node network. The normalized location of each node and its data rate are given in Table 1 in MSiRSN.

10.2. Solution with Strategy in MSiRSN. The simulation results in MSiRSN are given as follows. The traveling path in a period is $D_{P_{OPT-lb}} = 4.89$ and the traveling time is $D_{P_{OPT-lb}}/V = 48.9$. The cycle time is $\tau = 9414$, the vacation time is $\tau_{\text{vac}} = 6410$, and the objective value is 68%. The traveling path is shown in Figure 3.

10.3. Solution with Our Strategy. With our strategy, we can get a layer framework of the network, shown in Figure 4. We solve optimization problems (OPT-normal and OPT-
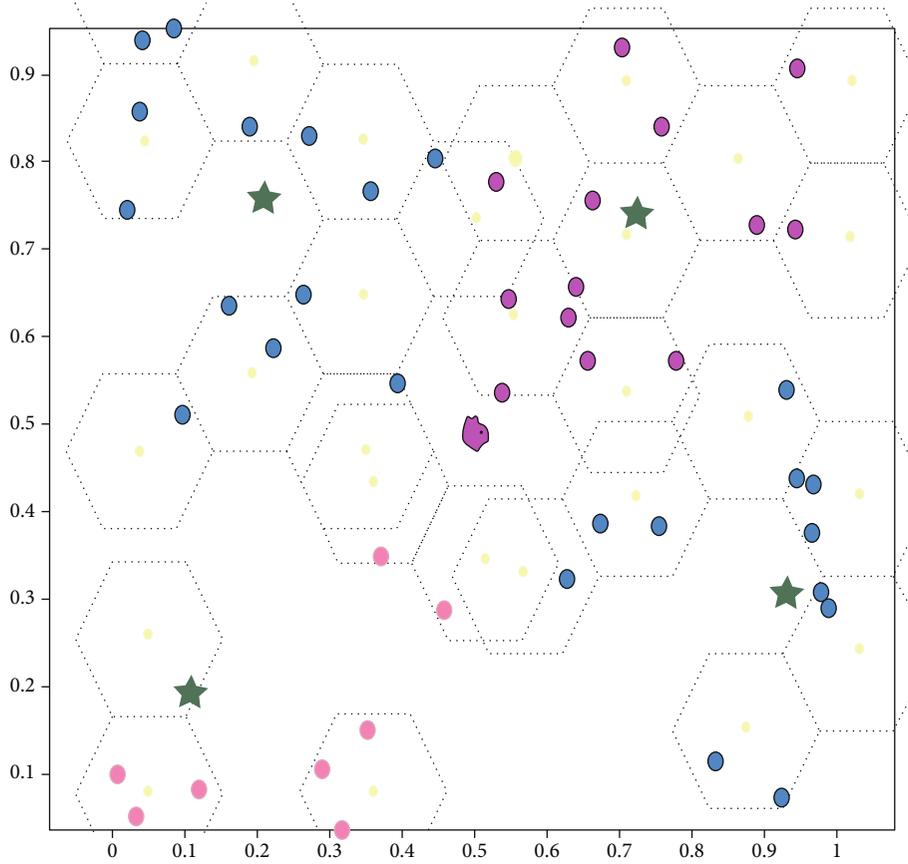
FIGURE 4: The layer framework of a network in Section 9. The green star represents the cluster head, the yellow ellipse represents the cell center that is the stopping point for charging normal nodes in the cell, and other four colored circles represent four types of normal nodes.

cluster) by CPLEX [33] and get the following solutions. Denote τ_c as the total charging time for cluster heads in a subperiod, τ_{c_i} as the total charging time for normal sensor nodes at cluster i.

$$D_{tps} = 2.5425, \tau_{vac} = 209.1, \tau_c = 52.3, \tau = 286.8$$

$$D_{tps_1} = 1.3196, \tau_{vac_1} = 10674, \tau_{c_1} = 30, \tau_1 = 10717$$

$$D_{tps_2} = 1.239, \tau_{vac_2} = 8703, \tau_{c_2} = 56, \tau_2 = 8771.3 \qquad (25)$$

$$D_{tps_3} = 1.5124, \tau_{vac_3} = 8416.7, \tau_{c_3} = 89, \tau_3 = 8520$$

$$D_{tps_4} = 1.732, \tau_{vac_4} = 5946.57, \tau_{c_4} = 171, \tau_4 = 6134$$

We set a period $T = \tau_4 = 6134$. We can get charging time for normal nodes $\sum_{\tau_{c_i}} 17 + 39 + 64 + 171 = 291$, charing time for cluster heads $\tau_c \cdot T/\tau = 1115$, traveling time for normal nodes $\sum D_{tps_i}/V = 84$, and traveling time for cluster heads $(D_{tps}/V) \cdot (T/\tau) = 543$ in this period. Then, we can get $\tau_{vac}/T = (6134 - (291 + 1115 + 84 + 543))/6134 = 0.71$. Our objective solution of 71% is greater than 68% in MSiRSN.

11. Conclusion

Wireless sensor network is the main part of IoTs. With the high developing time of IoTs, the difficulty of the power sup-ply of wireless nodes has seriously hindered the application and development of IoTs. In this paper, we proposed a three-layer framework consisting of the sensor layer, cluster head layer, and mobile station layer in a rechargeable wireless sensor network. We studied the problem of charge schedule and traveling path of a mobile CBW and a cluster selection algorithm in order to minimize the energy consumption of entire system. The simulation result shows that the scheme can get a smaller energy consumption of the entire system, compared with MSiRSN.

Data Availability

The data used in this paper can be obtained directly in the sentences and tables of the paper or generated by combining them with the algorithm. The core steps and algorithms of data processing method are introduced in the paper in detail, too.

Disclosure

Anwen Wang and Xianjia Meng are co-first authors.

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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