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The Charging Strategy of Mobile Charging Vehicles in Wireless Rechargeable Sensor Networks With Heterogeneous Sensors

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ABSTRACT Energy shortage obstructs the applications of the wireless rechargeable sensor network (WRSN). With the development of the wireless energy transfer technology, the mobile wireless charging vehicle (WCV) becomes a promising solution to solve that problem. However, the importance of different sensor nodes in the data transmission and uneven energy consumptions are often ignored. In this paper, the charging strategy of the WCV is studied in the WRSN considering these two phenomena. According to the importance of the sensor node, which is associated with the distance to the base station, we divide sensor nodes into two types: sensor nodes in ring 0 and sensor nodes in outer ring. We propose a novel charging model, the WCV adopts different charging strategies for different sensor nodes. To make the charging more efficient, the WCV charges sensor nodes one by one in ring 0 first, and then charges multiple sensor nodes simultaneously in outer ring. To estimate the lifetime of the network, a new metric named as the normalized dead time is proposed. Maximizing the lifetime of the network is modeled as minimizing the sum normalized dead time, and an efficient algorithm is proposed to minimize the sum normalized dead time through searching the optimal charging timeslots sequences. Then, through reassigning charging timeslots of sensor nodes, the proposed minimum travel cost algorithm minimizes the travel distance of the WCV and guarantee the lifetime of the network. We further deploy a cluster head node which has larger battery capacity in each cluster and can charge other sensor nodes within a limited distance. An algorithm is proposed to pre-distribute energy of the cluster head node. At last, the performance of proposed algorithms is verified by MATLAB. The results indicate that the performance of the WRSN can be improved by our proposed algorithms.

INDEX TERMS Wireless rechargeable sensor network, wireless energy transfer technology, mobile wireless charging vehicle, charging strategy, sum normalized dead time minimization, travel cost minimization.

I. INTRODUCTION

The wireless sensor network (WSN) often consists of a mass of sensor nodes [1]–[3]. There are many applications of the WSN, like military reconnaissance, smart home, environmental monitoring, etc. [4], [5]. The conventional sensor node is battery-powered. However, the limited size of the sensor node causes the limited capacity of the battery, and the large-scale deployment of WSNs is also obstructed. To resolve this problem, many researchers have devoted their efforts to develop self-sustainable WSNs. By adopting the energy harvesting technique or the wireless energy transfer technology, the continual work can be achieved in the wireless rechargeable sensor network (WRSN).

Different from the unpredictable, time-varying and susceptible energy supply of the energy harvesting technique, which utilizes natural energy sources (e.g. heat energy and solar energy) [6], [7], stable energy can be provided by the wireless energy transfer technology. The results in [8] proved that the high efficiency of the wireless energy transfer technology. Through industry research, [9] pointed out that 60W of power can be transferred to the receiver with the limited distance

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(e.g. three feet), and the energy transfer efficiency can achieve 75%. [10] proposed the charging strategy of the wireless mobile charging vehicle (WCV) with the help of the wireless energy transfer technology, and the high and stable charging rate of the WCV is also proved.

In this paper, we study the charging strategies of the WCV to maximize the lifetime of the WRSN. Many works have studied the charging scheduling algorithms for the WCV. In [11], authors proposed the optimal charging node algorithm to minimize the waste rate of the network. Through finding the charging sequence of sensor nodes, the travel cost of the WCV is also minimized. [12] proposed a charging method based fussy logic to find the charging sequence of sensor nodes to minimize the node failure. By scheduling the WCV to charge partial sensor nodes, the lifetime of the whole network is maximized in [13]. Authors in [14] investigated the charging method for the wireless sensor network deployed in a rectangular street grid. In [15], authors proposed optimal charging strategies to minimize the recharging cycle time considering the charging distance and the angle between sensor nodes and the WCV simultaneously. However, as the node density increases, the WCV cannot charge each sensor node in time before it is expired. In [16], authors developed a multiple-node charging technology which lets the WCV charge multiple sensor nodes simultaneously. Through some experiments, the high overall efficiency of this charging method is proved.

Some works have also proposed efficient charging algorithms by using the multi-node charging technology. In [17], the whole area is divided into hexagonal cells, and the WCV provides energy to multiple sensor nodes in cells simultaneously. At the same time, an efficient algorithm was proposed by considering charging time, flowing rate and traveling path simultaneously, so that the energy consumption of the network can be minimized. Authors in [18] proposed a multi-node charging strategy based on the circular cell structure. According to k-means algorithm, an efficient policy was also proposed to minimize the number of circular cells. In [19], considering the residual energy and the energy consumption, an uneven network clustering scheme is proposed to decrease the number of dead nodes. It can be found that all of the above works sought the optimal trade-off between maximizing the lifetime of the network and minimizing the travel cost of the WCV. However, some important factors have not been considered in these works.

In the WRSN, sensor nodes relay data to the base station by multiple hops [20]. Thus, sensor nodes closed to the base station play an important role in the data transmission. If they are expired, the data relayed by these critical sensor nodes cannot reach the base station, which may result in the outage of the entire network, even if other sensor nodes still have lots of residual energy. Therefore, guaranteeing sensors node around the base station have enough energy is more important. Meanwhile, sensor nodes closed to the base station relay more data, thus they have much higher energy consumption rate. The "energy hole" problem occurs which is caused by the uneven energy consumption of sensor nodes [21]. As described above, the importance of different sensor nodes in the data transmission and the uneven energy consumption play important roles in the lifetime of the network. However, most current works did not consider them, and corresponding charging strategies without considering these two phenomena may lead to the early outage of the network.

Currently, there are two charging methods are often used: (i) The WCV charges single node individually and (ii) The WCV charges multiple nodes simultaneously. For method (i), the time spent on charging single node is short because of the high efficiency of the single-node charging. Thus, the WCV can provide energy to the next to-be-charged sensor node more quickly. However, single-charging is only suitable for the small-scale network. As the number of sensor nodes increases, the WCV cannot charge each sensor node in a timely manner [17]. Method (ii) is suitable for the large-scale network for the high overall charging efficiency [16]. However, the charging delay is longer because the charging time of a cluster is determined by the longest time of the simultaneous sensor nodes in the cluster. Then, the next to-be-charged cluster needs to wait for a long time. If there is a sensor node which has high energy consumption or very little residual energy in the next cluster, the WCV cannot charge it in a timely manner. Then, the expiration of sensor nodes and the performance degradation of the WRSN may be occurred. Therefore, method (ii) is suitable for the network which consists of lots of low-consumption sensor nodes. In the network, sensor nodes in different area have different features. Sensor nodes closed to the base station are high in energy consumption and few in number, while sensor nodes far away from the base station are low in consumption and large in number. To make charging more efficient, different charging strategies should be adopted for different sensor nodes. However, most existing works adopted only one charging method to provide energy to all sensor nodes in the network, which may cause the death of sensor nodes in a large-scale or busy network, and the lifetime of the network cannot be ensured. The comparisons of related works can also be found in Table 1.

In this paper, considering the importance of different sensor nodes in the data transmission, the uneven energy consumption and the number of different sensor nodes simultaneously, we propose a new charging scheme. That is, the WCV adopts different charging methods for different sensor nodes. Firstly, according to the distance from the base station, sensor nodes are divided into two types, sensor nodes closed to the base station are in ring 0 and other sensor nodes are in outer ring. As described above, it is obvious that sensor nodes in ring 0 play a much more important role in the connection of the whole WRSN. Thus, we schedule the WCV to charge sensor nodes in ring 0 first. Then, for the problem of uneven energy consumption, it can be easily found that sensor nodes in ring 0 have high energy consumption rate and the number of them is small, while sensor nodes in outer ring have low energy consumption rate and the number of them is large.

TABLE 1. Comparisons of related works.

Works	Charging strategy	Applicable network	Charging efficiency	Outrage probability
[11]-[15]	Single-node	Small, high-consumed	High charging efficiency	High
[16]-[19]	Multiple-node	Big, low-consumed	High overall charging efficiency	High
Our work	Both	Big, uneven consumed	Both	Low

To let the charging become more efficient, the WCV replenishes energy to sensor nodes in ring 0 one by one individually to ensure the continual operation of these critical nodes, and then charges multiple sensor nodes simultaneously in outer ring to ensure the overall charging efficiency.

Recently, wireless reverse charging technology has been a huge success [22]. It is reported that many telecoms giants, such as HuaWei and Apple, have used this technology in their latest products. Since sensor nodes in ring 0 are given more scheduling priority, sensor nodes in outer ring have less charging time. Inspired by the wireless reverse charging technology, to keep the operation of sensor nodes in outer ring, we deploy a cluster head node (CN) which has larger battery capacity in each cluster and can provide energy for other sensor nodes within a limited distance. At the same time, the use of the CN can greatly decrease the travel cost of the WCV, since the energy of all sensor nodes in the cluster can be seen as a whole and the WCV charges the cluster only when the whole residual energy of all sensor nodes in the cluster reaches "charging threshold".

Under the novel proposed charging model, we study the problem of finding an optimal charging tour to maximize the lifetime of the network which contains CNs in the outer ring. To estimate the lifetime of the network, a new metric named as the sum normalized dead time is proposed in this paper. The problem of maximizing the lifetime of the network can be modeled as minimizing the sum normalized dead time. It is obvious that the charging sequence of sensor nodes is a main factor influencing the lifetime of the WRSN and the travel cost of the WCV. Hence, if the optimal charging sequence of each sensor nodes is found, the sum normalized dead time of sensor nodes can be minimized. To simplify the model, the time is divided into timeslots. We assume that the length of each timeslot is same and each to-be-charged sensor node (or cluster) matches one timeslot. Thus, the problem of finding optimal charging sequence can be transferred into finding optimal charging timeslots sequence of sensor nodes. Through solving the problem of finding the charging timeslots sequence of sensor nodes, the sum normalized dead time of sensor nodes in the network can be minimized. At the same time, the travel cost of the WCV cannot be ignored [11]. To avoid the energy waste of the WCV, we also study the problem of finding the minimum charging tour length while the lifetime of the network can be ensured.

According to above description, we summarize the problems considered in our work as follows. (i) What is the optimal charging timeslots sequence of sensor nodes which makes the sum normalized dead time be minimized under the new charging model? (ii) What is the optimal travel tour of the WCV, which can make the travel cost be minimized? (iii) How to schedule the CN to replenish energy to sensor nodes? It is worth pointing out that problems mentioned above have not been solved by current studies. Most studies adopted only one charging method to charge all sensor nodes, while we assume the WCV adopts different charging methods for sensor nodes distributed in different area. In this paper, to solve these problems, two optimization problems and relevant efficient algorithms are proposed, respectively.

Our main contributions are described as follows.

1) Considering the importance of different sensor nodes in the data transmission, the uneven energy consumptions and the number of sensor nodes in different area simultaneously, we propose a new charging model. Different charging methods are adopted by the WCV when charges different sensor nodes. To make charging efficient, the WCV first charges sensor nodes in ring 0 by using single-charging method, and then charges multiple sensor nodes simultaneously in outer ring. Furthermore, we deploy a CN to replenish energy to sensor nodes in each cluster. The energy allocation algorithm is also proposed to pre-distribute energy of the CN to sensor nodes.
2) Under the new charging model, we formulate two optimization problems, (i) Minimizing the sum normalized dead time and (ii) Minimizing the traveling cost of the WCV while the lifetime of sensor nodes can be guaranteed, respectively. The minimum dead time algorithm is proposed to find the optimal charging timeslots sequence, and the sum normalized dead time can be minimized. We also propose the minimum travel cost algorithm to reassign the charging timeslots sequence of sensor nodes, and the travel cost of the WCV is minimized.

The remaining part is organized as follows. Section II introduces the network model, data flow routing of the network, energy consumption of sensor nodes, the recharging model, notations, and the problem formulation. Section III proposes the minimum normalized dead time algorithm while Section IV proposes the minimum travel cost algorithm. By using this algorithm, the travel distance of the WCV can be minimized and the lifetime of the sensor node can be guaranteed. Section V proposes the energy allocation algorithm to pre-distribute energy of CNs in outer ring. Section VI

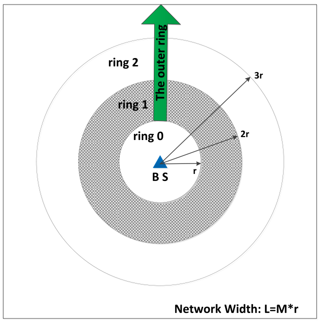


FIGURE 1. Partition Diagram of Network Area.

evaluates the performance of proposed algorithms. At last, the paper is concluded in Section VII.

II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we first introduce the system model, which includes the network model, data flow routing of the network, energy consumption of sensor nodes, and the recharging model. Then, we formulate minimizing the sum normalized dead time and minimizing the travel cost of the WCV with minimum sum normalized dead time as optimization problems, respectively.

A. NETWORK MODEL

A set $\mathbf{V}$ ($|\mathbf{V}| = n$) is used to denote all heterogeneous sensor nodes, and we assume sensor nodes are deployed in a square area (e.g. $L \times L$) randomly. The sensor node $v_i \in \mathbf{V}$ is located in (x_i, y_i). A fixed base station S is deployed in the center of the network and responsible to collect data generated by sensor nodes. The energy of S is thought to be infinite. According to the distance between sensor nodes and the base station, we divide the whole network area into several concentric bands. An example is shown in Fig.1, an $L \times L$ square area is divided into $\frac{M}{2}$ concentric bands and the width of each band is $r, L = M^*r$. We define these concentric bands as ring 0, ring 1, ring 2,..., and ring ($\frac{M}{2} - 1$), respectively. The band ring 0 which is the smallest band with radius r is assumed as ring 0. Other bands constitute the outer ring. Denote D_{is} as the distance between sensor node v_i and the base station, it can be found that for sensor nodes in ring 0, D_{is} satisfies $0 < D_{is} \leq r$, while for sensor nodes in outer ring, $r \leq D_{is} \leq \frac{L}{2}$. In this paper, The battery capacity of other common sensor nodes is $B_{\max}$. Assume sensor nodes in ring 0 and some sensor nodes in the outer ring have larger battery capacity $\Delta^* B_{\max}$ where Δ is an integer greater than 1. We use $B_{i,0}$ to represent the primary energy of common sensor node v_i, $B_{i,0} = B_{\max}$ (for some sensor nodes $B_{i,0} = \Delta^* B_{\max}$). The residual energy of sensor node v_i at some time point t is represented as $B_{i,t}$ and the energy consumption rate of sensor node v_i is denoted as ρ_i. We can get $B_{i,t} = B_{i,0} - \rho_i^* t$. We let $l_{i,t} = \frac{B_{i,t}}{\rho_i}$ denote the residual lifetime $l_{i,t}$ of sensor node v_i at some time point t. $B_{\min}$ is the minimum energy allowed for proper functioning, sensor node cannot operate properly if its residual energy is less than $B_{\min}$, and thus the data it relayed would be lost.

B. THE DATA FLOW ROUTING AND THE ENERGY CONSUMPTION

Sensor nodes transmit data to the base station by multi-hop routes. We assume the data transferred by sensor nodes traverses each ring just through a single hop transmission. f_{ij} and f_{iS} are denoted as the flow rates from sensor node v_i to sensor node v_j and the base station S, respectively. The sensing data of sensor node v_i is represented as R_i (bit/s). We use γR_i to represent the energy consumption rate of sensor node v_i for sensing, where γ is the consumed energy for sensing one unit of data. The flow balance constraint at sensor node v_i can be defined as

$$\begin{cases} \sum_{k\in V}^{k\neq i} f_{ki} + R_i = f_{iS} & i \in ring\ 0 \\ \sum_{k\in V}^{k\neq i} f_{ki} + R_i = \sum_{j\in V}^{j\neq i} f_{ij} & i \in outer\ ring. \end{cases} \tag{1}$$

The total amount data that sensor node v_i is responsible to relay is represented as $P_{i,data}$. According to (1), $P_{i,data} = f_{iS}$ when sensor node v_i is in ring 0 and $P_{i,data} = \sum_{j\in V}^{j\neq i} f_{ij}$ when sensor node v_i is in outer ring. It can be found that the data generated from all sensor nodes in outer ring reaches to the base station through sensor nodes in ring 0, which means sensor nodes in ring 0 are more important in the connection of the whole WRSN. At the same time, the problem of uneven energy consumption will be caused by this multi-hop manner.

We use C_{ij} (or C_{iS}) to denote the energy consumed by transmitting one unit of data from node v_i to v_j (or to the base station S). Define C_{ij} as follows

$$C_{ij} = \beta_1 + \beta_2 D_{ij}^{\alpha}, \tag{2}$$

where D_{ij} is defined as the distance between v_i and v_j, β_1 is a constant term which is independent of distance, β_2 is a coefficient of the distance-dependent term, and α is assumed as the path-loss index [23]. The consumed energy of sensor node v_i by the data transmission in outer ring is $C_{ij} \sum_{j\in V}^{j\neq i} f_{ij}$, while for sensor node v_i in ring 0, the energy consumed can be written as $C_{iS} f_{iS}$.

We use $\varepsilon \sum_{i\in V}^{i\neq j} f_{ji}$ to represent the energy consumption rate of sensor node v_i for reception, where ε represents energy consumed by receiving one unit of data.

Therefore, the energy consumption rate ρ_i of sensor node v_i can be expressed as

$$\rho_i = \begin{cases} \gamma R_i + C_{iS} f_{iS} + \varepsilon \sum_{i\in V}^{i\neq k} f_{ki} & i \in ring\ 0 \\ \gamma R_i + C_{ij} \sum_{j\in V}^{j\neq i} f_{ij} + \varepsilon \sum_{i\in V}^{i\neq k} f_{ki} & i \in outer\ ring \end{cases} \tag{3}$$

According to above description, it can be seen that sensor nodes in ring 0 relay more data compare with sensor nodes in outer ring. Thus, the energy consumed by relaying data at sensor nodes in ring 0 is more than sensor nodes in outer ring. Meanwhile, sensor nodes in ring 0 play important roles in the data transmission, keeping the continual operation of them is more significant than that of other nodes. As described above, the WCV will use single-node charging method to replenish energy to sensor nodes in ring 0 first, and then use the multiple-node charging method to charge sensor nodes in outer ring.

C. RECHARGING MODEL

To keep the continual operation of the network, the WCV should be scheduled to charge sensor nodes sending charging requests at some time points. Let $\mathbf{V_1}$ represent the set of to-be-charged sensor nodes. We assume the WCV charges to-be-charged sensor nodes (or clusters) at speed v_c (according to [24], $v_c = 5m/s$). After charging all sensor nodes and clusters, the WCV goes back to the base station to refuel [25]. It can be found that the path $P = \{n_0, n_1, \ldots, n_0\}$ formed by the WCV is a closed path, where n_i represents the i^{th} node (or cluster) charged by the WCV and n_0 represents the base station. We use the Euclidean distance to define the distance between two sensor nodes $v_i \in \mathbf{V_1}$ and $v_{i+1} \in \mathbf{V_1}$, which is expressed as

$$D_{i,i+1} = ||(x_i - x_{i+1}, y_i - y_{i+1})||_2. \tag{4}$$

Denote τ_{path} as the travel time, which can be expressed as

$$\tau_{path} = \sum_{i=1}^{n_c} \frac{D_{i,i+1}}{v_c}, \tag{5}$$

where n_c is equal to the number of to-be-charged sensor nodes in ring 0 plus the number of to-be-charged clusters in outer ring.

According to [17], the network we modeled is divided into hexagonal cells with a radius of $3m$, and sensor nodes in same cell are defined as one cluster. Define the sensor node v_i in ring 0 as a to-be-charged node if its residual lifetime $l_{i,t}$ reaches the charging threshold l_c. In outer ring, the CN which has lager battery is deployed to charge other sensor nodes in each cluster. When sensor nodes in outer ring need to be charged, the CN in same cluster can provide energy to them rather than the WCV, thus the travel cost of the WCV can also be reduced. Since the CN can provide energy to other sensor nodes, the total energy $\sum\limits_{v_i \in c^{th} cluster} B_{i,t}$ of all sensor nodes in c^{th} cluster can be seen as a whole. The cluster will send a charging request to the base station if the total consumed energy reaches the given critical energy E_c (e.g., $E_c = 90\% \sum\limits_{i \in c^{th} cluster} B_{i,0}$). Once receiving the charging request, the base station will send the WCV to replenish energy to these sensor node and clusters. Note that the travel time of the WCV is much shorter than the charging duration [26]. The energy consumption rate ρ_i of sensor node v_i is thought to be various at different charging tours.

In ring 0, τ_i is the charging time of sensor node $v_i \in \mathbf{V_1}$ which is expressed as

$$\tau_i = \frac{B_{i,0} - B_{i,t}}{U_i}, \tag{6}$$

where U_i is the power reception rate of v_i. $U_i = \mu(D_i) \cdot U_{Full}$, U_{Full} is the full output power from the WCV, $\mu(D_i)$ is the charging rate of the WCV, and D_i is the distance between v_i and the WCV. According to [17], the function $\mu(D_i)$ is a decreasing function of D_i, where $0 \le \mu(D_i) \le 1$.

While in outer ring, the time spent on charging the c^{th} to-be-charged cluster can be expressed as

$$\tau_c = \frac{\sum_{i=1}^{i=NC_c} B_{i,0} - \sum_{i=1}^{i=NC_c} B_{i,t}}{U_c}, \tag{7}$$

where NC_c is assumed as the number of sensor nodes in c^{th} cluster, U_c represents the charging rate of the WCV in c^{th} cluster.

Denote τ_{charge} as the total charging time in a charging cycle, and $\tau_{charge} = \sum\limits_{i=1}^{n_c} \tau_i$. Thus, the total time τ of a charging cycle spent by the WCV can be written as

$$\tau = \tau_{path} + \tau_{charge}. \tag{8}$$

The travel time of the WCV is much shorter than its charging duration, but still cannot be negligible. We assume that a constant $\Delta travel$ can represent the travel time of WCV between two adjacent to-be-charged sensor nodes. We define the travel time as the average travel time between two adjacent to-be-charged sensor nodes, that is, $\Delta travel = 60s$ [26]. Then the time can be divided into timeslots and each timeslot contains the travel time and the charging time. In ring 0, the length of the timeslot can be written as $\xi_i = \frac{B_{i,0}-B_{i,t}}{U_i} + \Delta travel$. In outer ring, the length of the timeslot can be defined as $\xi_c = \frac{\sum_{i=1}^{i=NC_c} B_{i,0}-\sum_{i=1}^{i=NC_c} B_{i,t}}{U_c} + \Delta travel$. To simplify the operation, we assume that each timeslot has the same length, which can be realized by adjusting the charging rate of the WCV according to the required energy. Hence, the length of the timeslot of each sensor node is equal, that is $\xi = \xi_1 = \xi_2 = \cdots = \xi_{n_c}$.

D. PROBLEM DEFINITION

As described above, the WCV charges sensor nodes in ring 0 first with single-node charging method. Before the WCV leaves the ring 0 area, the minimum residual lifetime of sensor nodes in ring 0 is defined as $l_{\min}$. To keep the continual operation of sensor nodes in ring 0, the WCV charges clusters in outer ring within $l_{\min}$. That is, the total charging time of the WCV in outer ring area t_{sumOut} satisfies $t_{sumOut} \le l_{\min}$.

When the residual energy of v_i is less than $B_{\min}$, we assume that sensor node v_i stops working, which means the data relayed by sensor node v_i will be lost. We define the normalized dead time $\eta_{i,k}$ of sensor node v_i in a charging tour as

$$\eta_{i,k} = \begin{cases} 0 & \text{if } \frac{l_{i,t}}{\xi} - S_k + 1 \ge 0 \\ \left| \frac{l_{i,t}}{\xi} - S_k + 1 \right| & \text{else,} \end{cases} \tag{9}$$

where $\frac{l_{i,t}}{\xi}$ represents the number of timeslots that sensor node v_i can survive, S is the set of charging timeslots and the WCV will charge sensor node v_i at k^{th} timeslots. $\frac{l_{i,t}}{\xi} - S_k + 1 \ge 0$ means sensor node v_i is still alive before the WCV replenishes energy to it and we can get the normalized dead time $\eta_{i,k}$ of

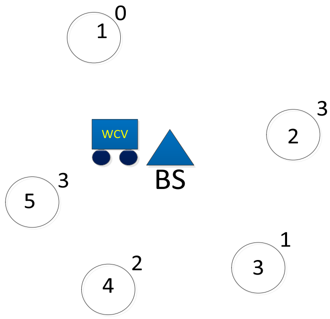


FIGURE 2. The illustration of normalized dead time.

sensor node v_i is 0, while $\frac{l_{i,t}}{\xi} - S_k + 1 < 0$ means sensor node v_i stops working before the WCV provides energy for it. We assume the sum of the normalized dead time of sensor nodes in the whole network during the charging tour as η_{sum}, which is

$$\eta_{sum} = \sum_{v_i \in \mathbf{V}} \eta_i. \tag{10}$$

We also define the traffic loss $loss_i$ of sensor node v_i in the charging tour as

$$loss_i = \eta_i \cdot P_{i,data}, \tag{11}$$

which represents the total traffic loss during the dead time η_i of sensor node v_i, the total traffic loss $loss_{sum}$ of all sensor nodes can be expressed as $loss_{sum} = \sum_{v_i \in \mathbf{V_1}} loss_i$. Fig. 2 shows an example to explain the definition of the normalized dead time.

As shown in Fig.2, we assume the charging sequence of sensor nodes is $v_1 \rightarrow v_2 \rightarrow v_3 \rightarrow v_4 \rightarrow v_5$. The residual timeslots $\frac{l_{1,t}}{\xi}$ of sensor node v_1 is assumed as 0, and its charging timeslot S_1 is 1, according to (9), we can get $\eta_{1,1} = \frac{l_{1,t}}{\xi} - S_1 + 1 = 0 - 1 + 1 = 0$, which means v_1 is unexpired before the WCV charges it. For sensor node v_2, $\frac{l_{2,t}}{\xi} - S_2 + 1 = 3 - 2 + 1 = 2 > 0$, thus $\eta_{2,2} = 0$. While for sensor node v_3, $\frac{l_3}{\xi} = 1$, $S_3 = 3$ and $\frac{l_3}{\xi} - S_3 + 1 = 1 - 3 + 1 = -1 < 0$, we can get $\eta_{3,3} = 1$, which means v_3 is expired for one timeslot before the WCV provides energy to it. Similarly, we can also achieve $\eta_{4,4} = 3$ and $\eta_{5,5} = 3$ respectively. Finally, we can achieve the sum of the normalized dead time $\eta_{sum} = \sum_{v_i \in \mathbf{V}} \eta_i = 7$ according to (10).

Under the novel charging model which is the WCV adopts different charging strategies for different sensor nodes, we model the problem of maximizing the lifetime of the network as minimizing the sum of the normalized dead time. From (11), it can be easily found that the traffic loss $loss_i$ is proportion to the normalized dead time of sensor node v_i, furthermore, the decrease of the normalized dead time of sensor node means the increase of the lifetime of sensor node. For the problem of minimizing the sum of the normalized dead time, we can deal with it through minimizing the normalized dead time of each sensor node. Choosing optimal next to-be-charged sensor node can maximize the lifetime of the network, At the same time, the time is divided into timeslots and the length of each timeslot is equal, the problem of finding optimal charging sequence can be transferred into finding optimal charging timeslots sequence of sensor nodes, so that the sum of the normalized dead time can be minimized.

At the same time, as described above, the travel cost of the WCV cannot be ignored. To minimize the energy waste of the WCV subject to that the lifetime of sensor nodes is ensured, we first assume that the sum of the normalized dead time of sensor nodes is minimized, which is η^*_{sum}. And the travel cost minimization problem can be expressed as

$$\min \ \text{travel}_{cost} \tag{12a}$$
$$s.t. \ \eta_{sum} = \eta^*_{sum} \tag{12b}$$
$$t_{sumOut} \leq l_{\min} \tag{12c}$$
$$\sum_{i=1}^{NC_c} \text{EA}_{i,c} = \Delta * B_{\max} \tag{12d}$$
$$\sum_{i \in \mathbf{V}_1} e_i = \sum_{i \in ring0} e_i + \sum_{i \in outerring} e_i \tag{12e}$$

The (12b) ensures the sum of the normalized dead time is minimized. The constraint in (12c) indicates that the total charging time t_{sumOut} of the WCV in outer ring is no more than the minimum residual lifetime $l_{\min}$ of all sensor nodes in ring 0. Since the continual operation of sensor nodes in ring 0 is more important than other nodes. (12d) implies that in each cluster, the total energy pre-distributed to each sensor node including the CN is $\Delta^* B_{\max}$, and NC_c represents the total number of sensor nodes in c^{th} cluster. When sensor node needs to be charged, the CN will replenish energy to it from the pre-distributed energy. While (12e) suggests that the total amount of energy charged to sensor node is equal to the energy demand of sensor nodes in ring 0 plus the energy demand of sensor nodes in outer ring. According to [27], it is worth pointing out that the travel cost minimization is NP-hard, and [28] gave the analogous proof process.

III. ALGORITHM FOR SENSOR NODE NORMALIZED DEAD TIME MINIMIZATION PROBLEM

In this section, we first present an efficient algorithm to solve the problem of minimizing the sum normalized dead time of sensor nodes. Then the optimality of the proposed algorithm is also proved. At last, the analysis of the complexity of the proposed algorithm is given.

A. ALGORITHM

Since sensor nodes in ring 0 are more important, the WCV is scheduled to charge these critical sensor nodes first. According to the above discussion, single-node charging has high efficiency in the small-scale network, thus the WCV charges sensor nodes in ring 0 one by one individually and charges multiple sensor nodes in outer ring simultaneously.

As described in Section 2, the set $\mathbf{V}_1$ of to-be-charged sensor nodes contains sensor nodes in ring 0 and sensor nodes in outer ring. To make charging more efficient, the WCV adopts different charging strategies for different sensor nodes. The set $\mathbf{V}_1$ is further divided into two subsets, $\mathbf{V}_{in}$ and $\mathbf{V}_{out}$. $\mathbf{V}_{in} = \{v_i | v_i \in \mathbf{V}_1, D_{is} \leq r\}$ is the set of to-be-charged sensor nodes in ring 0, and $\mathbf{V}_{out} = \{v_{i,c} | v_{i,c} \in \mathbf{V}_1, r \leq D_{is} \leq \frac{L}{2}\}$ is the set of to-be-charged sensor nodes in c^{th} cluster in outer ring. In this paper, we assume that sensor node in ring 0 also has larger capacity and only one timeslot is needed to charge a sensor node in ring 0 or a cluster in outer ring. Denote $\mathbf{S} = \{s_1, s_2, \cdots s_{n_c}\}$ as the set of the charging timeslots sequence of to-be-charged sensor nodes and clusters.

As described above, the normalized dead time minimization problem can be transformed into searching the optimal charging timeslots sequences for sensor nodes in ring 0 and outer ring. First, a bipartite graph $G = (\mathbf{V}_{in}, \mathbf{S}, E, \omega)$ is constructed. For all to-be-charged sensor nodes in ring 0, the weight $\omega(v_i, s_k)$ of each edge $(v_i, s_k) \in E$ is assumed to be the same as the normalized dead time η_i of sensor node $v_i (v_i \in \mathbf{V}_{in})$. If the WCV charges sensor node v_i which is still alive at timeslot s_k, which means $k \leq \frac{l_{i,t}}{\xi} + 1$ and we can get $\omega(v_i, s_k) = 0$. Otherwise, $\omega(v_i, s_k) = \left|\frac{l_{i,t}}{\xi} - k + 1\right|$, since v_i has stopped working before the WCV charges it. Inspired by the Hungarian algorithm and Kuhn-Munkres algorithm, a minimum weighted matching M_{in} could be found through calculating the sum normalized dead time of all to-be-charged sensor nodes with different charging timeslots matching [33], the optimal charging timeslots will be assigned to sensor nodes in ring 0. Finally we can get an optimal charging tour to schedule the WCV to charge each to-be-charged sensor node v_i in ring 0 at some timeslot s_k, which can minimize the sum normalized dead time of sensor nodes.

This solution is also feasible to to-be-charged clusters in outer ring. Since one timeslot is needed to charge each cluster, the number of clusters charged by the WCV should be no more than $\left\lfloor \frac{l_{\min}}{\xi} \right\rfloor$, where $\lfloor x \rfloor$ represents the maximum integer values less than x. When the number N' of to-be-charged clusters is more than that, which means $N' > \left\lfloor \frac{l_{\min}}{\xi} \right\rfloor$, some clusters sending charging requests have to be discarded to ensure the lifetime of each sensor node in ring 0. We define the priority level of the c^{th} to-be-charged cluster as $weight_c$, which can be written as

$$weight_c = \alpha \cdot l_{c,t} + (1 - \alpha) \cdot P_{c,data}, \tag{13}$$

where $l_{c,t}$ is the minimum residual lifetime of sensor nodes in the c^{th} cluster and $P_{c,data}$ is the total amount traffic relayed by the c^{th} cluster. Parameter α is cluster selection coefficient which satisfies $0 \leq \alpha \leq 1$. From (13), it can be found that during the optimal to-be-charged cluster selection, goals vary with the value of α. When α becomes larger, selected clusters tend to have less residual lifetime, while the total amount traffic relayed by the cluster is given more consideration if $1 - \alpha$ is larger. The detailed algorithm is shown in Algorithm 1.

Fig.3 is used to explain the execution of Algorithm 1. First, we partition the plane into ring 0 and the outer ring. In ring 0, there are two to-be-charged sensor nodes v_1 and v_2. The residual timeslots of them is $\frac{l_1}{\xi} = 0$, $\frac{l_2}{\xi} = 5$

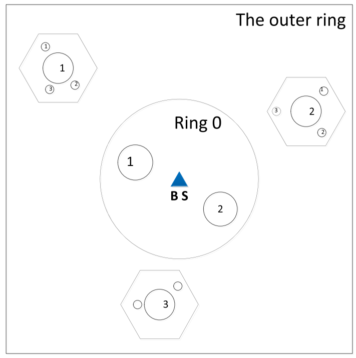


FIGURE 3. The illustration of Algorithm 1.

respectively. The weight matching of them can be written as $M_{in,1} = \{(v_1, s_1), (v_2, s_2)\}$ or $M_{in,2} = \{(v_1, s_2), (v_2, s_1)\}$. Algorithm 1 achieves the minimized normalized dead time of sensor nodes through finding the minimum matching (that is, the optimal charging timeslots sequence of sensor nodes). Then a bipartite graph $G = (\mathbf{V}_{in}, \mathbf{S}, E, \omega)$ is constructed, where the weight values $\omega(v_i, s_k)$ of sensor nodes varies according to the different assigned charging timeslots, that is $\omega(v_1, s_1) = |0 - 1 + 1| = 0,$, $\omega(v_2, s_2) = |5 - 2 + 1| = 0$ and $\omega(v_2, s_1) = |5 - 1 + 1| = 0,$, $\omega(v_1, s_2) = |0 - 2 + 1| = 1$, respectively. Then the minimum weighted matching $M_{in} = M_{in,1} = \{(v_1, s_1), (v_2, s_2)\}$ can be found through calculating the weight value of each matching. v_1 will be charged at 1^{th} timeslot and v_2 will be charged at 2^{th} timeslot, and the optimal charging sequence of sensor nodes in ring 0 is $v_1 \to v_2$. When the WCV leaves the ring 0 area, it will receive a value $l_{\min}$ (e.g. $\frac{l_{\min}}{\xi} = 2.2$) which means the number of to-be-charged clusters in outer ring should be no more than $\lfloor 2.2 \rfloor = 2$.

In outer ring, we partition this area with equal hexagonal cells and each cell is assumed as a cluster. There are three clusters sending charging requests in outer ring. However, only two clusters can be charged to ensure the lifetime of sensor nodes in ring 0. Assume that the least residual lifetime and the total traffic of these clusters are $l_1 = 2, l_2 = 5, l_3 = 6$, $P_{1,data} = 10, P_{2,data} = 1, P_{3,data} = 15$, respectively. We assume $\alpha = 0.5$, according to (13), we can get $weight_1 = 6$, $weight_2 = 3$, $weight_3 = 10.5$. Since $weight_3 > weight_1 > weight_2$, cluster 1 and cluster 3 will be charged. In outer ring, the weighted matching is $M_{out,1} = \{(c_1, s_3), (c_3, s_4)\}$ or $M_{out,2} = \{(c_1, s_4), (c_3, s_3)\}$. Similarly, we can get the weighted values $\omega(c_1, s_3) = 0$, $\omega(c_3, s_4) = 0$, and $\omega(c_3, s_3) = 0$, $\omega(c_1, s_4) = 1$ respectively. Then the minimum weighted matching $M_{out} = M_{out,1} = \{(c_1, s_3), (c_3, s_4)\}$ can be obtained and the charging sequence in the network is $v_1 \to v_2 \to c_1 \to c_3$.

B. ALGORITHM ANALYSIS

We prove that Algorithm 1 can achieve an optimal solution for our problem.

Theorem 1: An optimal solution to the sum normalized dead time minimization problem through Algorithm 1 can

Algorithm 1 The Minimum Dead Time Algorithm

Input: The coordinates $[x_i, y_i]$, the initial energy $B_{i,0}$, the residual energy $B_{i,t}$, the total amount of data traffic $P_{i,data}$, the energy consumption rate ρ_i, the charging rate U_i, the speed v_c of the WCV.

Output: The sum normalized dead time η_{sum}, the optimal charging timeslots sequence of sensor nodes, the total amount data loss $loss_{sum}$, and the total travel distance $travel_{\cos t}$ of the WCV.

The network is divided into three concentric bands, including ring 0 and outer ring area (contains ring 1 and ring 2). Sensor nodes are divided into sensor nodes in ring 0 and sensor nodes in outer ring.
for $i \leftarrow 1$ *to* $|\mathbf{V}_{in}|$ **do**
  In ring 0, construct a set $\mathbf{V}_{in}$ of to-be-charged sensor nodes in ring 0 and the corresponding bipartite graph $G = (\mathbf{V}_{in}, \mathbf{S}, E, \omega)$;
  A minimum weighted matching M_{in} is found according to $\omega(v_i, s_k)$ of each sensor node;
end for
  Find the minimum lifetime $l_{\min}$ of all sensor nodes in $\mathbf{V}_{in}$.
  In outer ring, construct a set $\mathbf{V}_{out}$ of to-be-charged clusters in outer ring and the corresponding bipartite graph $G = (\mathbf{V}_{out}, \mathbf{S}, E, \omega)$;
if $N' > \frac{l_{\min}}{\xi}$ **then**
  Choose $\left\lfloor \frac{l_{\min}}{\xi} \right\rfloor$ clusters in outer ring according to (13);
  for $i \leftarrow 1$ *to* $\frac{l_{\min}}{\xi}$ **do**
    Find a minimum weighted matching M_{out} according to $\omega(c_i, s_{k+|\mathbf{V}_{in}|})$;
  end for
else
  for $i \leftarrow 1$ *to* N' **do**
    Find a minimum weighted matching M_{out} according to $\omega(c_i, s_{k+|\mathbf{V}_{in}|})$;
  end for
end if
We then find the optimal charging timeslots sequence and the charging tour P_1 of the WCV.

be achieved. Then we prove the sensor nodes normalized dead time minimization problem in ring 0 and in outer ring respectively.

Proof: Assume that an optimal charging tour P_1 is given, η_i is the normalized dead time of sensor node v_i in ring 0 in P_1, where

$$\eta_{i,k} = \begin{cases} 0 & \text{if } (\frac{l_{i,t}}{\xi} - s_k^* + 1) \geq 0 \\ \left| \frac{l_{i,t}}{\xi} - s_k^* + 1 \right| & \text{else,} \end{cases}$$

then the minimum normalized dead time $\eta^*_{sum,in} = \sum_{v_i \in \mathbf{V}_{in}} \eta_i$ ($v_i \in \mathbf{V}_{in}$). Due to each edge E in the graph G_{in} connect two vertices, and every vertex is covered exactly once. That is, we construct a matching M_{in} in graph G_{in} from tour P_1, by assigning each to-be-charged sensor nodes to timeslots s_k^*. Note that the matching in this paper is a perfect matching. According to [29], it can be found that the lower bound of the minimum normalized dead time $\eta^*_{sum,in}$ is the weight $\omega^*(M_{in})$ of matching M_{in}, which means the matching achieved from Algorithm 1 can minimize the sum normalized dead time $\eta^*_{sum,in}$ of sensor nodes in ring 0. Similarly, the proposed algorithm is also feasible for sensor nodes in outer ring. And it also can be found that the lower bound of the minimum normalized dead time $\eta^*_{sum,in}$ is the weight the weight $\omega^*(M_{out})$ of matching M_{out}, which means this matching achieved from Algorithm 1 can minimize the sum normalized dead time $\eta^*_{sum,out}$. Thus, an optimal solution for our problem can be found through Algorithm 1.

Theorem 2: The time complexity of Algorithm 1 is $O(n^3)$, *where* $n = |\mathbf{V}_1|$.

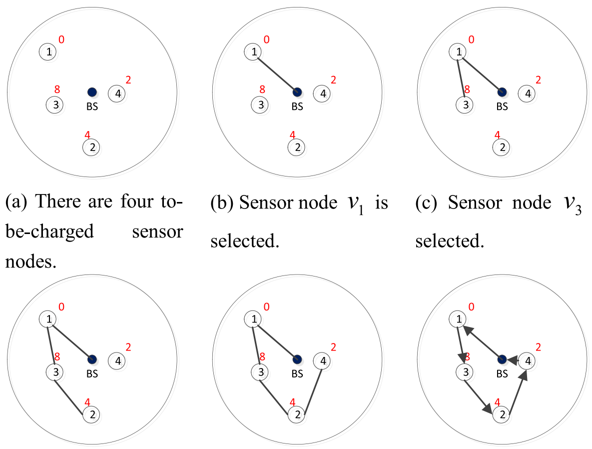
Proof: In each iteration of matching, M increases by 1, so there are at least n iterations and this happens $O(n)$ time. Then it takes $O(n)$ time to find the right vertex for the augmenting in the matching and it is $O(n)$ time to flip the matching. Improving the labeling takes $O(n)$ time. We might have to improve the labeling up to $O(n)$ time if there is no augmenting path. This makes for a total of $O(n^2)$ time. In all, there are $O(n)$ iterations each taking $O(n^2)$ work, leading to a total running time of $O(n^3)$. This completes the proof.

IV. ALGORITHM FOR THE TRAVEL COST OF THE WCV MINIMIZATION PROBLEM

In the previous section, the sum of normalized dead time is minimized. However, the travel cost of the WCV is not considered. In this section, an efficient algorithm is proposed to address the travel distance of WCV minimization problem while the lifetime of sensor nodes can be ensured.

A. ALGORITHM

In the minimum weighted matching M, each to-be-charged sensor node v_i or to-be-charged cluster is assigned to s_k^* timeslot according to Algorithm 1. In this paper, we define the to-be-charged sensor node (or cluster) v_i as an undead node when the normalized dead time $\eta_{i,k}$ of v_i satisfies $\eta_i = 0$. Inspired by the nearest neighbor algorithm in our previous work [11], the charging timeslots sequence of the undead node can be delayed from s_k^* to $s_k^\wedge$ ($s_k^* \leq s_k^\wedge$ and $\frac{l_{i,t}}{\xi} - s_k^\wedge + 1 \geq 0$) and the WCV can be scheduled to select the nearest to-be-charged sensor node as the next charging node (in same ring), so that the total distance of the WCV can be optimized. For the to-be-charged sensor node (or cluster) whose residual timeslots is less than the assigned charging timeslot s_k^*, which means $\frac{l_{i,t}}{\xi} - s_k^* + 1 < 0$, we assume its reassigned charging timeslots sequence $s_k^\wedge$ is equal to s_k^*, so that the normalized dead time $\eta_{i,k}$ of sensor node v_i remains $\left| \frac{l_{i,t}}{\xi} - s_k^* + 1 \right|$. Combine Algorithm 1 and the nearest neighbor algorithm, the travel distance of the WCV can be optimized. It is worth pointing out that the next node must



(a) There are four to-be-charged sensor nodes.
(b) Sensor node v_1 is selected.
(c) Sensor node v_3 is selected.
(d) Sensor node v_2 is selected.
(e) Sensor node v_4 is selected.
(f)The travel path P_2 of the WCV is formed.

FIGURE 4. An example of execution of Algorithm 2.

be in same ring and the WCV always charges sensor nodes in ring 0 first. Note that the proposed algorithm is feasible to sensor nodes in ring 0 and clusters in outer ring. To simplify the description, we will take sensor nodes in ring 0 as an example.

First, we reorder undead sensor nodes in ring 0 according to their residual timeslots while the charging order of other sensor nodes remains unchanged, the new set of charging timeslots sequence is represented as $\mathbf{S}^{\wedge}$ and the timeslot matched to sensor node v_i is $s_k^{\wedge}$. It is obvious that the sum normalized dead time of sensor nodes in $\mathbf{S}^{\wedge}$ is equal to that in M_{in}. As described above, there may be some undead sensor nodes in the new charging set $\mathbf{S}^{\wedge}$, which provides opportunities to optimize the distance of the WCV with the help of the nearest neighbor algorithm. Assume $s_k^{\wedge}$ contains the current charging node $v_i \in \mathbf{S}^{\wedge}$ and $s_{k+1}^{\wedge}$ contains the next to-be-charged undead sensor node $v_{i+1} \in \mathbf{S}^{\wedge}$. We assume the charging timeslots sequence of sensor node v_{i+1} is delayed from $s_{k+1}^{\wedge}$ to $s_{k+2}^{\wedge}$,if the normalized dead time $\eta_{i+1,k+2}$ of sensor node v_{i+1} satisfies $\frac{l_{i+1,t}}{\xi} - s_{k+2}^{\wedge} + 1 \geq 0$, the WCV will choose sensor node v_j (note that v_j is in ring 0) closest to node v_i as the next to-be-charged sensor node at $s_{k+1}^{\wedge}$ timeslot. Then we update the charging set $\mathbf{S}^{\wedge}$, which means sensor node v_{i+1} will be included in the timeslot $s_{k+2}^{\wedge}$ and the assigned timeslots of other undead sensor nodes are also changed. Otherwise, sensor node v_{i+1} is still matched to $s_{k+1}^{\wedge}$ timeslot. Finally, the optimal reassigned charging timeslots sequence of sensor nodes in ring 0 can be achieved. Then the optimized travel path P_2 is formed. The detailed algorithm is shown in Algorithm 2.

Fig.4 is used to present the execution of Algorithm 2. It can be found there are four sensor nodes sending charging requests in the network (here we only take the sensor nodes in ring 0 as an example and this method is also feasible to to-be-charged clusters in outer ring). Their residual timeslots and assigned timeslots in M_{in} are shown in Table 2,

Algorithm 2 The Minimum Travel Cost Algorithm

Input: The residual timeslots of sensor nodes, the minimum weighted matching M_{in}.

Output: A charging tour P_2.

Reorder sensor nodes in ring 0 according to their residual timeslots and M_{in}, the new set of charging timeslots sequence is represented as $\mathbf{S}^{\wedge}$ and each timeslot matches one node.
The charging tour P_2 contains the base station.
for $k \leftarrow 1$ *to* $|\mathbf{V}_{in}|$ **do**
  if $\frac{l_{i,t}}{\xi} - s_k^{\wedge} + 1 > 0$ **then //** Sensor node v_i is assigned to $s_k^{\wedge}$ in $\mathbf{S}^{\wedge}$.
    if $\frac{l_{i,t}}{\xi} - s_{k+1}^{\wedge} + 1 \geq 0$
      Timeslot $s_k^{\wedge}$ contains the sensor node v_j (v_j is also in ring 0) closest to the current charging node, then update the set $\mathbf{S}^{\wedge}$.
    else
      Timeslot $s_k^{\wedge}$ contains the next to-be-charged node v_i
    end if
  else
    Timeslot $s_k^{\wedge}$ contains the next to-be-charged node v_i
  end if
end for
The optimal reassigned charging timeslots sequence of sensor nodes in ring 0 can be achieved, which is $\mathbf{S}^{\wedge} = \{s_1^{\wedge}, s_2^{\wedge}, \ldots, s_{|\mathbf{V}_{in}|}^{\wedge}\}$ and the charging tour P_2 is formed.

TABLE 2. Residual timeslots and assigned timeslot of four to-be-charged sensor nodes.

Sensor nodes	v_1	v_2	v_3	v_4
Residual timeslots	0	4	8	2
Assigned timeslot	1	2	4	3

respectively. As described above, according to the residual timeslots, we reorder these sensor nodes as $\{v_1, v_4, v_2, v_3\}$, the relevant set of charging timeslots sequence $\mathbf{S}^{\wedge}$ of sensor nodes can be represented as $\mathbf{S}^{\wedge} = \{s_1^{\wedge}, s_2^{\wedge}, s_3^{\wedge}, s_4^{\wedge}\}$. Since the residual timeslot of sensor node v_1 is 0 and if its charging timeslots sequence is delayed from $s_1^{\wedge}$ to $s_2^{\wedge}$, the normalized dead time $\eta_{1,2}$ is $\left|\frac{l_{1,t}}{\xi} - s_2^{\wedge} + 1\right| > 0$ and the sum normalized dead time will increase, thus the WCV will choose it as the first charging node (see Fig.4 (b)). Sensor node v_4 is assumed to be matched to the $s_2^{\wedge}$ timeslot in $\mathbf{S}^{\wedge}$, and the normalized dead time $\eta_{4,2}$ of sensor node v_4 in Algorithm 1 satisfies $\frac{l_{4,t}}{\xi} - s_2^{\wedge} + 1 = 2 - 2 + 1 = 1 > 0$, when the charging timeslots sequence of sensor node v_4 delays, its normalized dead time $\eta_{4,3}$ is $\left|\frac{l_{4,t}}{\xi} - s_3^{\wedge} + 1\right| = 0$, which means the charging timeslots sequence of v_4 can be delayed from $s_2^\wedge$ to $s_3^\wedge$. Then sensor node v_3 which is closest to sensor node v_1 is selected as the next to-be-charged node (see Fig.4(c)). The set $\mathbf{S}^\wedge$ is updated as $\mathbf{S}^\wedge = \{s_1^\wedge(v_1), s_2^\wedge(v_3), s_3^\wedge(v_4), s_4^\wedge(v_2)\}$. For sensor node v_4 included in $s_3^\wedge$, since the normalized dead time $\eta_3 = 2 - 3 + 1 = 0$, the WCV will charge sensor node v_4 at $s_3^\wedge$ timeslot (see Fig.4(d)). Then the last to-be-charged sensor node v_2 will be charged by the WCV at $s_4^\wedge$ timeslot (see Fig.4(e)). Finally, through connecting the base station and the nearest sensor node v_4, the travel path of the WCV is formed (see Fig.4(f)). It is obvious that the length of path $P_2 = \{v_1, v_3, v_4, v_2\}$ is less than $P_1 = \{v_1, v_2, v_4, v_3\}$, and the travel cost of the WCV in Algorithm 2 can be minimized.

B. ALGORITHM ANALYSIS

Theorem 3: The proposed algorithm can minimize the travel cost of WCV while the lifetime of sensor nodes can be ensured.

Proof: For dead sensor node in ring 0, its charging timeslot $s_k^\wedge$ in tour P_2 is equal to s_k^* in tour P_1, while for undead sensor node in ring 0, though its charging sequence is delayed, the normalized dead time $\eta_{i,\hat{k}}$ is still 0. Thus the sum normalized dead time in ring 0 and the total charging delay is unchanged (which means the charging sequence of clusters is same as that in P_1). And for clusters in outer ring, similarly, the sum normalized dead time is also unchanged. Thus we can get that the sum normalized dead time of all sensor nodes in tour P_2 are equal to that in tour P_2, which proves our theorem. And the optimal travel distance of the WCV is intuitional, so the proof is omitted.

V. ALGORITHM FOR ENERGY DISTRIBUTION OF SENSOR NODES IN CLUSTERS

In previous section, since sensor nodes in ring 0 are given more scheduling priority, we deploy a CN in each cluster in outer ring which has lager battery and it could charge other sensor nodes. We also propose an algorithm to distribute energy of CN to sensor nodes in same cluster.

A. ALGORITHM

Given a set $\mathbf{V}_{out}$ of to-be-charged sensor nodes in outer ring, and the WCV charges multiple sensor nodes simultaneously. We assume sensor nodes charged by the WCV at the same time as a charging cluster, that is, the WCV provides energy to these to-be-charged clusters one by one to make the charging more efficient. According to the above description, the CN can charge other sensor nodes in cluster to ensure the lifetime of sensor nodes in outer ring and decrease the travel cost of the WCV. However, the total traffic and the energy consumption rate of each sensor node in cluster are different, if the energy of the CN is distributed to each sensor node meanly, sensor nodes which relay more traffic and have higher energy consumption will run out energy early, which will cause the "energy hole" problem in cluster. In this subsection, to ensure the lifetime of sensor nodes in cluster and decrease the traffic loss in outer ring, the problem of making full use of the energy of the head is studied. We then model this problem as maximizing the sum profit of energy distribution in cluster, the problem is then reduced to a resource allocation problem with a certain amount of energy between the CN and other sensor nodes in cluster. We also propose an efficient algorithm for that problem.

Define a set $C = \{c_1, c_2, \cdots c_{N'}\}$ of to-be-charged clusters in outer ring, where N' represents the number of to-be-charged clusters in outer ring. We assume that each cluster contains $2 \sim 3$ common sensor nodes and a CN whose battery capacity is Δ times (e.g. $\Delta = 4$) larger than other sensor

Algorithm 3 Resource Allocation Algorithm

Input: A set $C = \{c_1, c_2, \cdots c_{N'}\}$ of to-be-charged clusters in outer ring and the profit made by the pre-distributed energy $pro_{i,j,m}$.

Output: The pre-distributed energy of each sensor node in cluster

```
Partition the total energy of CN into k parts and a unit
  amount of energy pre-distributed is Ψ = Δ*B_max / k.
for m ← 1 to N' do
  for i ← 1 to NC_m do
    for k ← 1 to k_max do
      Obtain the profit pro_{i,j,m} of v_{i,m}, respectively.
    end for
  end for
end for
for m ← 1 to N' do
  for i ← 1 to NC_m do
    if Σ_{i=1}^{NC_m} j_i = k
      Find the optimal pre-distributed energy for each
      sensor node including CN in m^th cluster according
      to the pro_{i,j,m} in a greedy way, so that the sum profit
      of the energy distribution in cluster can be
      maximized.
    end if
  end for
end for
```

nodes. To use the energy of head node more efficiently, the CN will pre-distribute energy to all sensor nodes in cluster including itself according to the profit $pro_{i,j,m}$ (it will be described later), where i represents the i^{th} sensor node in m^{th} cluster and j ($j > 0$) is the units amount of pre-distributed energy of i^{th} sensor node. When sensor node $v_{i,m}$ in m^{th} cluster needs to be charged, the CN will charge it from the pre-distributed energy, if its pre-distributed energy is run out, to prolong its lifetime, $v_{i,m}$ will transfer some work to sensor node $v_{p,m}$ which has most pre-distributed energy.

In detail, we partition the total energy of CN into k (k is a large integer) parts and a unit amount of pre-distributed energy Ψ can be expressed as $\Psi = \frac{\Delta \cdot B_{\max}}{k}$, which means the amount of energy pre-distributed to each sensor node $v_{i,m}$ in m^{th} cluster is a value in $\{\Psi, 2\Psi, \cdots k\Psi\}$. According to the $pro_{i,j,m}$, sensor node $v_{i,m}$ is pre-distributed with j parts energy of the CN, and we use j_i to represent the number of parts of

TABLE 3. The profit $pro_{i,j,1}$ of sensor nodes with different pre-distributed energy.

i \ j	1	2	3	4
1	3	5	7	9
2	3	4	5	6

unit pre-distributed energy of $v_{i,m}$. Note that $\sum_{i=1}^{NC_m} j_i = k$, where NC_m is the number of sensor nodes in m^{th} cluster. The $pro_{i,j,m}$ is defined as

$$pro_{i,j,m} = \lambda \cdot j \cdot \frac{\Delta \cdot B_{\max}}{k\rho_{i,m}} + (1-\lambda) \cdot P_{i,data}, \tag{14}$$

where $\rho_{i,m}$ is the energy consumption rate of $v_{i,m}$ in m^{th} cluster, $j \cdot \frac{\Delta \cdot B_{\max}}{k\rho_{i,m}}$ represents the residual lifetime of sensor node $v_{i,m}$ with j parts pre-distributed energy and $P_{i,data}$ is the total amount of the data relayed by sensor node $v_{i,m}$. While λ is coefficient which satisfies $0 \le \lambda \le 1$. The energy of the CN will be pre-distributed to each sensor node in same cluster according to the $pro_{i,j,m}$, so that the sum profit of the m^{th} cluster is maximized. The detailed algorithm is given in Algorithm 3.

An example is used to illustrate the execution of Algorithm 3. Assume that there are two sensor nodes $v_{1,1}$ and $v_{2,1}$ in 1^{th} cluster ($NC_1 = 2$), their energy consumption rate and the total amount of to-be-sent data are $\rho_1 = 1nJ/b$, $\rho_2 = 2nJ/b$, $P_{1,data} = 2bits$, $P_{2,data} = 4bits$, respectively. We also assume $k = 4$, $B_{\max} = 4kJ$, $\lambda = 0.5$, $\Delta = 4$, which means the energy of the CN is divided into 4 parts and a unit amount of pre-distributed energy $\psi = \frac{\Delta \cdot B_{\max}}{k} = \frac{4\times 4}{4}kJ = 4kJ$. Algorithm 3 takes four iterations to find the $pro_{i,j,1}$ of sensor node $v_{1,1}$ and $v_{2,1}$, for example, $pro_{1,1,1} = \lambda \cdot j \cdot \frac{\Delta \cdot B_{\max}}{k\rho_{i,m}} + (1-\lambda)\cdot P_{i,data} = 0.5\times 1\times 4 + 0.5\times 2 = 3$(more data can be found in Table 3). At the same time, subject to $\sum_{i=1}^{NC_m} j_i = \sum_{i=1}^{2} j_i = 4$, there are three matching of energy distribution, which can be expressed as $\{(j_1 = 1, j_2 = 3), (j_1 = 2, j_2 = 2), (j_1 = 3, j_2 = 1)\}$. In a greedy way, it can be found that when $j_1 = 3, j_2 = 1$,that is, $pro_{1,3,1} = 7$, $pro_{2,1,1} = 3$, the sum profit of the 1^{th} cluster is maximum, then the optimal pre-distributed energy for each sensor node are found, and the energy pre-distributed to sensor nodes $v_{1,1}$ and $v_{2,1}$ are $3B_{\max} = 12kJ$, $B_{\max} = 4kJ$, respectively.

B. ALGORITHM ANALYSIS

Theorem 4: The time complexity of the Algorithm 3 is $O(k_{\max}^{NC_m} \cdot NC_m \cdot N')$, *where we assume that partition the total energy of CN into* $k_{\max}$ *parts,* NC_m *is the number of sensor nodes in* m^{th} *cluster,* N' *is the number of to-be-charged clusters respectively.*

Proof: We obtain the profit $pro_{i,j,m}$ of $v_{i,c}$ made by the pre-distributed energy j individually as shown in Algorithm 1 at step 2 to step 8, the time complexity of that can be written as $O(k_{\max} \cdot NC_m \cdot N')$. While in later steps, we get the optimal pre-distributed energy for each sensor node including cluster head in cluster in a greedy way, which will lead to a running time of $O(k_{\max}^{NC_m} \cdot NC_m \cdot N')$. Thus, the complexity of Algorithm 3 is bounded in $O(k_{\max}^{NC_m} \cdot NC_m \cdot N')$. This completes the proof.

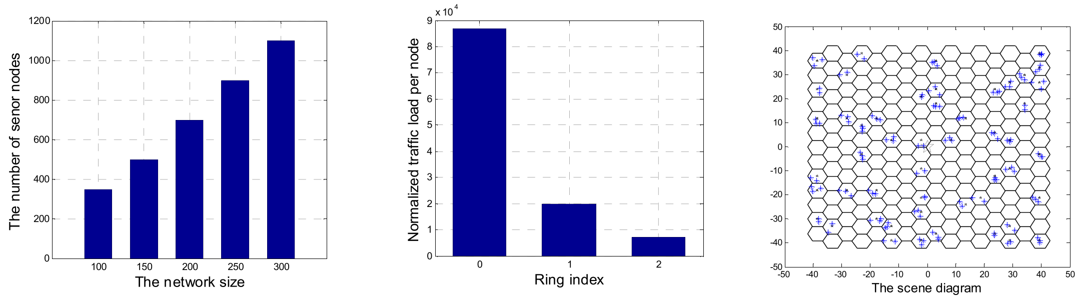
VI. PERFORMANCE EVALUATION

In this section, note that the defined scenario is a simulation based study and the performance of our proposed algorithms is verified by MATLAB. The impacts of different parameters on the performance of algorithms are studied, which contains the size of the network, the charging rate of the WCV and data rates of sensor nodes.

A. PARAMETER SETTING

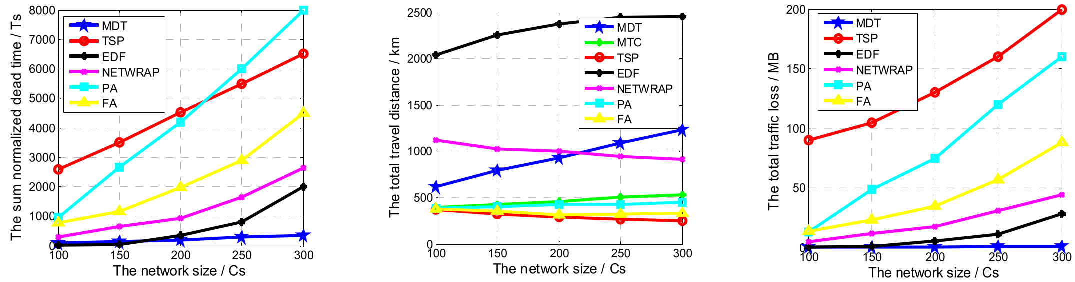
The network is divided into hexagonal cells and some cells (clusters) may contain 2 ∼ 3 sensor nodes. We use the number $N_{cluster}$ of clusters with sensor nodes in them to represent the size of the network. For example, $N_{cluster}$=200 represents that there are 200 clusters with sensor nodes in them, and the total number SN of sensor nodes is about 700 (more data can be found in Fig.5 (a)). We consider the size of the network is from 100C$_S$ to 300C_S, where $1C_S$ represents one cluster. Heterogeneous sensor nodes are deployed within a $1000m \times 1000m$ square area, the battery capacity of normal sensor nodes in outer ring is $B_i = B_{\max} = 10.8kJ$ [28], and that of sensor nodes in ring 0 and CNs in outer ring can be written as $B_i = 4 * B_{\max} = 43.2kJ$. The data sensing rate b_i of sensor node v_i is selected from an interval $[b_{\min}, b_{\max}]$, where $b_{\min}$=1$kbps$ and $b_{\min}$=10$kbps$ [30]. And we adopt the energy consumption model in [21]. The WCV travels at a speed of $v = 5m/s$ [24]. The charging rate U_i of the WCV is an integer selected from an interval $[U_{i\min}, U_{i\max}]$, where $U_{i\min} = 1Watt$ and $U_{i\max} = 10Watts$, and $5Watts$ by default [31]. In this paper, the unit of time we used in this paper is defined as T_S, where $1T_S = \frac{B_{i,0}}{U_i} + \Delta travel = \frac{43.2kJ}{5Watts} + 60s = 578.4s$. Sensor nodes will send charging requests when residual lifetime reaches the charging threshold $l_c = 70T_S$. The monitoring period is assumed as one year. The network area is divided into three concentric bands with the step size of $167m$ (ring0, ring 1 and ring 2), according to [21], in different rings, the per node traffic load is defined as $Load_{ring} = \frac{\text{total to-be-sent traffic in ring}}{\text{num of nodes in ring}}$. Fig.5 (b) shows a large difference in the $Load_{ring}$. The $Load_{ring0}$ in ring 0 is 8 times higher than $Load_{ring1}$ in ring 1 and 11 times higher than $Load_{ring2}$ in ring 2. We can get that sensor nodes in ring 0 relay much more data, which means they play a much more important role in the connection of the entire network and also consume much more energy than sensor nodes in outer ring (contains ring 1 and ring 2). Thus, the WCV is scheduled to charge sensor nodes in ring 0 first to avoid the outage of the network. Fig.5 (c) shows a diagram of the network in the simulation, which is proportionally reduced for better display.

The proposed algorithms *the minimum dead time algorithm* (*MDT*) and *the minimum travel cost algorithm* (*MTC*) are compared against algorithms *TSP*, *EDF*, *NETWRAP* [32],



(a) The illustration of the network size (b) Per node traffic load in different rings (c) The scene diagram

FIGURE 5. Some diagrams.



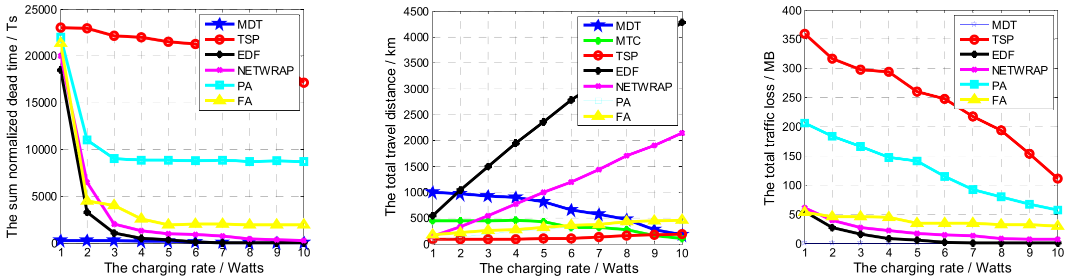
(a) The sum normalized dead time during the period (b) The total travel distance during the period (c) The total traffic loss during the period

FIGURE 6. Performance of algorithms by varying the network size $N_{cluster}$ from $100C_s$ to $300C_s$.

PA [13], *FA* [12], respectively. The *TSP* algorithm finds the charging tour just considering the travel distance of the WCV. In *EDF*, we sort to-be-charged sensor nodes by their residual lifetime, then schedule the WCV to charge them one by one. In algorithm *NETWRAP*, to-be-charged sensor nodes are sorted by the weight of travel time and residual lifetime. The *PA* algorithm chooses the next to-be-charged sensor node according to the charging probability. While the state-of-the-art algorithm FA selects the next to-be-charged node based the fussy logic, thus the performance of the network can be maximized.

B. PERFORMANCE

We study the impacts of the size of the network on the performance of all mentioned algorithms *MDT*, *MTC*, *TSP*, *EDF*, *NETWRAP*, *PA* and *FA*. The network size (which is represented by the $N_{cluster}$) varies from 100Cs to 300Cs while the charging rate U_i of the WCV is 5*Watts*. Fig.6 (a) indicates the impacts of the network size on the sum normalized dead time of sensor nodes. It can be easily found that the sum normalized dead time η_{sum} by *MDT* is shorter compared with that by other algorithms, and as the size of the network increases, the difference between mentioned algorithms becomes more enlarged. Fig.6 (b) presents the different total travel distance of the WCV by each algorithm under different network size. It can be found that the total distance by *TPS* is shortest compared with others, since *TSP* finds the shortest travel tour just considering the travel distance of the WCV. Note that the total travel distance delivered by *TSP* and *NETWARP* slightly decreases with the increase of the network size. The reason is that the increase of the network size means the increase of the number of sensor nodes, more sensor nodes or clusters will send charging requests in each charging tour, and the total time spent on per charging tour becomes larger, therefore, thus the number of charging tour during one monitoring period decreases. At the same time, sensor nodes in ring 0 consume energy faster, each charging tour maybe have more to-be-charged sensor nodes in ring 0 than that in outer ring, since *TSP* and *NETWARP* schedule the WCV considering the travel cost, sensor nodes in ring 0 will have more priority to be charged, and the total distance of the WCV in ring 0 is small. Also, since the weight of the distance in *TSP* and *NETWRAP* is different, the distance by *TSP* drops three times faster than that by *NETWRAP*. Note that the total travel distance by *MDT* is longer than that by the state-of-the-art algorithm *FA*. However, the sum normalized dead time η_{sum} of *MDT* is only 10% of *FA*. It also can be found that the total travel distance by *MTC* is only about 25% of that by *MDT*, which means *MTC* can optimize the charging tour efficiently. From Fig.6 (c), it can be found that the total traffic loss of *MDT* is much shorter compared with other algorithms. And as the network size increases, the difference between algorithms is enlarged. For example, when $N_{cluster} = 200$, the total traffic loss by *MDT* is only about 12% of that by *EDF*. The rationale

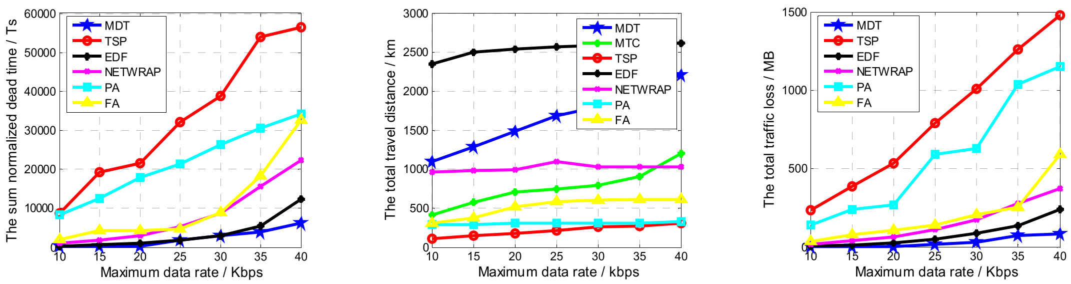


(a) The sum normalized dead time during the period

(b) The total travel distance during the period

(c) The total traffic loss during the period

FIGURE 7. Performance of algorithms by varying charging rate from 1 *Watt* to 10 *Watts* when $N_{cluster} = 200C_S$.



(a) The sum normalized dead time during the period

(b) The total travel distance during the period

(c) The total traffic loss during the period

FIGURE 8. Performance of algorithms by varying maximum data rate from 10*kbps* to 40*kbps* when $N_{cluster} = 200C_S$.

behind is that critical sensor nodes in ring 0 play a much more important role than other sensor nodes in outer ring in connection of the whole network. In our algorithm, sensor nodes in ring 0 will be charged first, so that the continual operation of whole network can be ensured, thus the total traffic loss by *MDT* is much smaller than other algorithms.

We investigate the impacts of the charging rate U_i on the performance of the mentioned algorithms. Fig.7 (a) shows that as the charging rate increases, the sum normalized dead time η_{sum} of sensor nodes by *MDT*, *EDF*, *NETWRAP*, *PA* and *FA* decreases dramatically except *TSP*. Since *TSP* algorithm does not take the residual energy of sensor nodes into consideration. It also can be found that the sum normalized dead time η_{sum} by *MDT* is shortest compared with other mentioned algorithms. Fig.7 (b) shows that the total distance of the WCV by *TSP*, *EDF*, *NETWRAP*, *PA* and *FA* becomes longer with the increase of the charging rate, while the total distance by *MDT* and *MTC* slightly decreases. The reason is that in *MDT* or *MTC*, the residual lifetime of sensor nodes is represented as $\frac{l_{i,t}}{\xi}$, where $\xi = \frac{B_{i,0}}{U_i} + \Delta travel$, as the charging rate U_i increases, ξ will become small, which means that the expiration timeslots of sensor node in our proposed algorithms becomes larger for the same sensor node. Because we assume the charging threshold is constant, the number of sensor nodes or clusters sending charging requests will decrease in each charging tour, thus the total travel distance of the WCV decreases. At the same time, the sum normalized dead time delivered by *TSP* is longest, since *TSP* only considers the travel cost of the WCV in the charging tour. Fig.7 (c) shows the impacts of the charging rate on the total traffic loss. The total traffic loss by each of the mentioned algorithms decreases with the increase of the charging rate. And it is obvious that *MDT* has the minimum total traffic loss, which is only about 15% of that by *EDF*.

The impacts of the data rate on the performance of different algorithms is also investigated, when $b_{\min} = 1kbps$, U_i=5Watts and $N_{cluster} = 200$. It is obvious that the energy consumption of sensor nodes increases with the increase of the maximum data rate $b_{\max}$, and there will be more sensor nodes and clusters sending charging requests in each charging tour. Fig.8 (a) shows that as the maximum data rate becomes larger, the sum normalized dead time by these mentioned algorithms increases, and the sum normalized dead time by *MDT* is still the minimum. For example, when $b_{\max} = 20kbps$, the sum normalized dead time by *MDT*, *TSP*, *EDF*, *NETWRAP*, *PA* and *FA* are about $250T_S$, $21600T_S$, $1040T_S$, $2980T_S$, $17880T_S$, $4310T_S$, respectively. From Fig.8 (b), it can be found that the total travel distance of the WCV by *MDT* and *MTC* become larger with the increase of the maximum data rate, while the increase of the maximum data rate has little effect on the performance of other algorithms. Fig.8 (c) shows that, with the increase of the maximum data rate, the total traffic loss of sensor nodes grows. The total traffic loss by *MDT* is the least one and only about from 1% to 20% of those by other mentioned algorithms.

VII. CONCLUSION

In this paper, we study the wireless sensor network which uses the WCV to charge sensor nodes to achieve continuous and effective working. Considering the importance of different sensor nodes in the data transmission and the uneven energy consumption, we propose a novel charging model, that is, let the WCV adopt different charging policies for different sensor nodes to prevent the early outage of the entire network. We formulate two optimal questions, which are minimizing the sum normalized dead time and minimizing the travel cost while the lifetime of the network can be ensured, we also propose efficient methods to address them. First, to minimum the sum normalized dead time of sensor nodes, we design an algorithm to obtain the optimal charging timeslots sequence of to-be-charged sensor nodes. Then, considering the travel cost of the WCV, an algorithm is proposed to minimize the travel distance of the WCV while the lifetime of sensor nodes is guaranteed, through reassigning the charging timeslots sequence of sensor nodes. To ensure the lifetime of sensor nodes and decrease the traffic loss in outer ring, we further propose the resource allocation algorithm to pre-distributed energy of the CN. Finally, proposed algorithms are verified by MATLAB and compared with various algorithms, the simulation results indicate algorithms in this paper can improve the performance of the WSN, which is useful for the application of the WSN and IoT.

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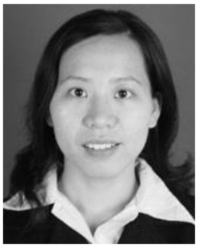

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