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An Opportunistic Charger Recollection Algorithm for Wireless Rechargeable Sensor Networks

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ABSTRACT

Wireless rechargeable sensor networks (WRSNs) have received a lot of attention due to the development of wireless charging technology. Recently, a new solution of wireless charging vehicle (WCV) for WRSNs with separable charger array equipped with multiple chargers was suggested. By this method, each charger can be unloaded to serve one sensor, while the WCV can work in a very efficient way because it needs not to stay on site and can continue to perform its assigned task. But this solution created a new problem that is how to recollect these chargers for reusing when their charging services are finished. In previous research, however, the recollecting strategy has seldom been considered. In this work, an effectively opportunistic charger recollection algorithm (OCRA) are proposed. Simulation results indicate that OCRA has outperformed previous algorithms in many aspects.

KEYWORDS

Opportunistic Charger Recollection Algorithm, Recycling Schedules, Separable Chargers, Wireless Rechargeable Sensor Networks

1. INTRODUCTION

Efficient wireless energy transmission technology in wireless rechargeable sensor networks (WRSNs) has developed rapidly for many years (Clerckx et al., 2019; Mudulia, L., Mishrab, D. P., & Jana, K., 2018; Liu, X., Guo, Y., Li, W., Hua, M., & Ding, E., 2018; Yao, K. H., Jiang, J. R., Tsai, C. H., & Wu, Z. S., 2017), which addresses the problems of charging, lifetime extension, and energy renewal between different devices. Recently, current research on WRSNs has focused mainly on the design and scheduling of wireless charging vehicles (WCVs) (Xu, C. J., Cheng, R. H., & Wu, T. K., 2018; Zhong et al., 2017; Lin et al., 2018).

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Using a WCV to replenish energy for WRSNs requires addressing the problem of the energy limitation (Xie et al., 2015). In most current charging solutions, the WCV with wireless chargers must wait on site until the sensor is fully charged, which will result in long-term waiting and will increase the risk of sensor failure due to power exhaustion. Therefore, a partial charging mode was suggested so that the WCV can move to the next charging location without completing the current sensor's charging (Xu, W., Liang, W., Jia, X., & Xu, Z., 2016). This partial charging mode can also extend the WCV's running time as a result of less energy consumption on driving the WCV's own motion. As an improvement, Cheng, R.-H. (2019) proposed another cooperative charging scheme with multiple WCVs to extend the whole lifetime of WRSNs, but it will lead to an increase in the costs of devices. However, the method using one or more WCVs still suffers from unbearably long waiting times of charging.

To further extend the lifetime of sensors, Xu et al. (2018) designed a novel type of WCV with a separable charger array, which can carry multiple chargers to replenish energy to adjacent sensors at the same time. As there is no need to stay on site, the WCV can continue to perform assigned charging tasks. This new concept of a separable charger array can greatly improve the rescue efficiency for sensors and can successfully extend the lifetime of entire WRSNs. Even so, the number of chargers that can be used in the array is limited, and the chargers need to be recollected when their charging services are finished.

Xu et al. (2018) proposed a backward recollection algorithm (BRA) to fulfill the charger array again for the next charging mission. According to the BRA, during its back way toward the base station (BS), the WCV will recollect chargers near the WCV's moving line. However, according to the BRA, as the backward charger recollection method is a straightforward strategy, the effectiveness of recollection is low. There is an upper limit on the number of chargers that can be recollected. The recollection rate of chargers is lower than 30%.

However, consider that the WCV can pick up the chargers to be recollected, not only on the back way but also on its charging tour toward sensors. In this work, we propose a new recollection algorithm called the opportunistic charger recollection algorithm (OCRA). Unlike the BRA, which recollects chargers only on the back way of the WCV's charging mission, in the OCRA, the WCV will perform recollection actions in the whole charging route to recollect chargers as many as possible.

The OCRA algorithm mainly includes four steps: (1) Segmenting the WCV's charging route to restrict the scheduling computation range in the length direction. (2) Calculating the range of recollection in the width direction according to the lifetime of sensors, the speed of the WCV and other parameters. (3) Optimizing the order of chargers to be recollected in each segment of the WCV's charging route. (4) Combining the results of all segments to merge into a whole scheduling route. Through the above four steps, the overall rate of recollected chargers is between 40% - 60%, which has greatly outperformed the previous achievements.

The rest of this paper is organized as follows. Section 2 is the review of previous work. Section 3 presents the proposed new recollection algorithm in detail, followed by a comparison and evaluation of simulation results in Section 4. Finally, Section 5 concludes this paper with further work.

2. BACKGROUND

In recent years, with the improvement of wireless charging technology (Li, X., Tang, Q., & Sun, C., 2018; Yang, X., Han, G., Liu, L., Qian, A., & Zhang, W., 2019), wireless rechargeable sensor networks have been greatly developed. In WRSNs, rechargeable batteries still cannot be replaced easily and inexpensively. To conveniently replenish sensors, many constructive solutions have been proposed, such as building a power-saving data collection tree (Wang, C., Li, J., & Yang, Y. Y., 2015), improving wireless charging efficiency (Wei, Y., Ma, X., Yang, N., & Chen, Y., 2017), and balancing power consumption load (Jia, J., Chen, J., Deng, Y., Wang, X., & Aghvami, 2017). However, the above methods can only temporarily slow down the energy consumption of the battery. Due to the different functions and performance of different sensors, the energy consumption speed of these batteries is different. Therefore, for large-scale WRSNs, the on-demand charging scheme is better than the regular energy replenishment scheme (Lin, C., Han, D., Deng, J., & Wu, G., 2017; Zhu, J., Feng, Y., Liu, M., Chen, G., & Huang, Y., 2018; Rao et al., 2018; Tomar, A., Muduli, L., & Jana, P. K., 2019).

2.1 WCV in WRSNs

When the coverage area of the WRSN is very large, authors considered that only one WCV cannot meet the demands for charging sensors. Therefore, Zhang et al. (2015) proposed a collaborative mobile charging concept of a WCV, in which energy can be transmitted between these individual WCVs. They suggested the Push-Wait algorithm, which is proven to be optimal and can cover a one-dimensional wireless sensor network (WSN) of inðnite length. They demonstrate its advantages in energy usage effectiveness and charging coverage. A similar mobile charging concept was also advised in (Zhao, J., Dai, X., & Wang, X., 2015).

Different from the collaborative mobile charging concept of WCVs proposed by Zhang et al. (2015). Madhja et al. (2016) considered that the energy limitation of WCVs could be solved by using two types of vehicles. One is the mobile charger (MCs) for charging sensors, and another type is a special charger (SC) for replenishing MCs. As an alternative solution, Liu et al. (2017) proposed a push-shuttle-back (PSB) method. Furthermore, when considering the energy loss in a real application scenario, that group proposed exploiting a detachable battery pack (DBP) and proposed a DBP-PSB algorithm to address this problem. Wei et al. (2019) proposed a multi-MC charging schedule algorithm with time windows based on a genetic algorithm. When the average energy of all the sensor nodes falls below the upper energy threshold, each MC begins to charge the sensor nodes simultaneously.

To extend the lifecycle of the WRSNs as long as possible, the scheduling of the charging route is very important in addition to the energy saving measures of WCVs (Hu, C., & Wang, Y., 2014; He, L., Kong, L., Gu, Y., Pan, J., & Zhu, T., 2015). In WRSNs, not all sensors can be replenished in time. If the key sensor runs out of energy, it will have a great impact on the system (Zhu, J., Feng, Y., Liu, M., Chen, G., & Huang, Y., 2018; Pal, A., & Nasipuri, A., 2019;). Lin et al. (2016) proposed a temporal and distention priority (TADP) algorithm for solving the energy replenishment problem. They merged temporal priority and distantial priority into a mixed priority. The WCV sequentially replenishes the sensors according to the mixed-priority queue formed by the TADP. Chen et al. (2018) concluded that the goal of prolonging the lifecycle of WRSNs can also be achieved by controlling the speed of the WCV.

Recently, Lin et al. (2018) proposed a new algorithm called the temporal-spatial charging scheduling algorithm (TSCA). Compared with the TADP in (2016), the TSCA focuses on scheduling optimization to minimize the number of dead nodes while maximizing energy efðciency to prolong network lifetime in a global scope. Ma et al. (2018) studied how to use a WCV to charge multiple sensors simultaneously under energy-limited conditions. Upon this, they discussed the method of minimizing the length of the charging route.

Although these approaches try to charge sensors as many as possible within a limited remaining lifetime of the sensor battery and shorten the length of the charging tour of the WCV, this fully charged mode wastes a great deal of rescue time. In this mode, if multiple sensors send charging requests at the same time; before executing the next charging task, the WCV must wait until the sensor is fully charged. However, an excessive waiting time may cause sensor failure and affect the work of the WRSNs.

2.2 Separable Chargers in WRSNs

To recharge sensors more effectively, Xu et al. (2018) proposed a novel algorithm framework based on a separable charger array for wireless rechargeable sensor networks, and four scheduling algorithms are demonstrated based on this separable strategy. Xu's method not only satisfies the demand that one WCV can charge multiple adjacent sensors within a short time but also shortens the travelling distance of the WCV.

The WCV in WRSNs has two kinds of battery modules (Xu et al., 2018). One is used for supporting its own motion, while the other is the separable charger module, which can be used for charging of the sensors. Upon receiving a charging request, the WCV will move to the side of the sensor, which is waiting to be recharged. Then, the arms of the WCV will unload a charger near that sensor. Subsequently, the WCV will immediately move to the next sensor until the end of the charging list. After completing these tasks, the WCV will return to the BS, where some other chargers with full power will be reloaded up to the WCV. Thus, the WCV is ready for the next mission.

However, in this framework, because the chargers are separable and the quantity is limited, to reuse these chargers, it is necessary to solve the problem of recollecting them effectively and inexpensively. To deal with this new problem, a simple strategy called the backward recollection algorithm was advised by Xu et al. (2018). It recollects the chargers in the back way of the charging tour, as shown in Figure 1. Some chargers can be recollected by this method, but the recollection rate of chargers is very low. Therefore, more attention is still needed for the recollection of chargers for wireless rechargeable sensor networks.

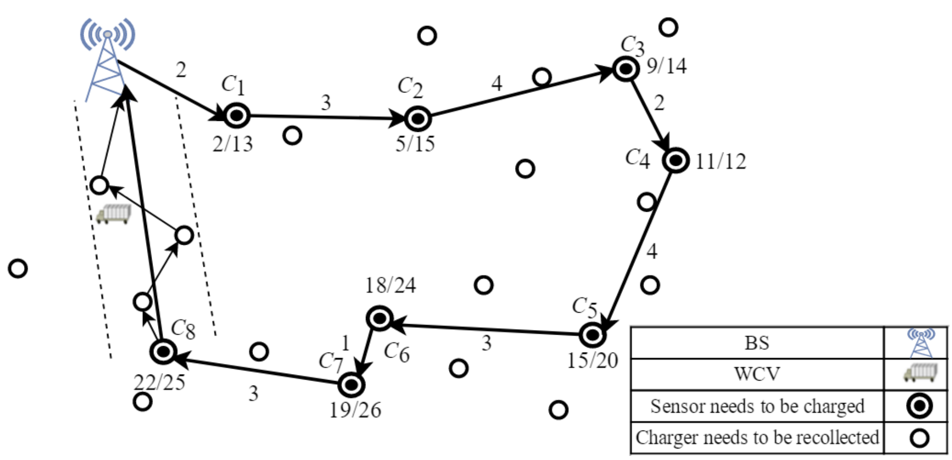
3. OPPORTUNISTIC CHARGER RECOLLECTION ALGORITHM

In this paper, we proposed a charger recollection algorithm, which can recover the charger in the charging process without affecting the timely completion of the charging task. In this section, we introduce the problem definition, the method, the framework of the OCRA and the case illustration of the OCRA.

3.1 Problem Definition

In this work, sensors are randomly deployed in an open environment, as shown in Figure 2. In WRSNs, a charging request from the sensor will be triggered when its remaining power is lower than the given predefined threshold K_r. Then, it will be sent hop by hop to the BS. According to the requesting time, distance from the WCV and remaining power, the BS will assign a charging mission for the WCV to carry some separable chargers to rescue those sensors that lack energy. When the WCV comes to the requested sensor, the WCV will unload a charger and put it near that sensor to perform the charging task. On the other hand, when a charger has finished its charging task, it will be added

Figure 1. Recollect the chargers using the BRA



in the recollection list to be picked up. Therefore, it is important to find an effective policy to make the WCV recollect chargers as much as possible in its charging tour, while those sensors waiting to be charged could be served in time. In this paper, we try to take into account both the charging and recollection of the scheduling algorithm for the WCV.

As shown in Figure 3, define $S_c(i)$ as the state of the charger. If $S_c(i)$=1, the charger needs to be recollected, and if $S_c(i)$=0, the charger is serving the sensor, as shown in Equation (1). K represents the remaining power of the charger. K_r is the power threshold of the charger. The number of chargers waiting to be recollected is represented by N_c, which is calculated using Equation (2), where N is the total number of chargers in the system.

$$S_c\left(i\right) = \begin{cases} 0 & K \geq K_r \\ 1 & K < K_r \end{cases} \quad (1)$$

$$N_c = \sum_{i=0}^{N} S_c\left(i\right) \quad (2)$$

If there are N_c chargers to be recollected, by exhausting all possible options for scheduling the charging route of the WCV, it is necessary to select an optimal choice from N_c! options. Often, N_c is a large number that will lead to incomputable selection. Therefore, if the range of chargers listed to be recollected could be reduced, e.g., by segmenting the travelling tour, the selection could be limited to only one segment as a local optimal strategy. Then, the number of chargers that need to be recollected in one segment could be reduced to m. Generally, $m<N_c$, so $m!<<N_c!$.

For easy reference, all symbols and notations used in this article are summarized in Table 1.

3.2 Method

The method is composed of three parts: computation strategy, segmenting and restricting the recollection width in the moving line.

Figure 2. Charging route of the WCV

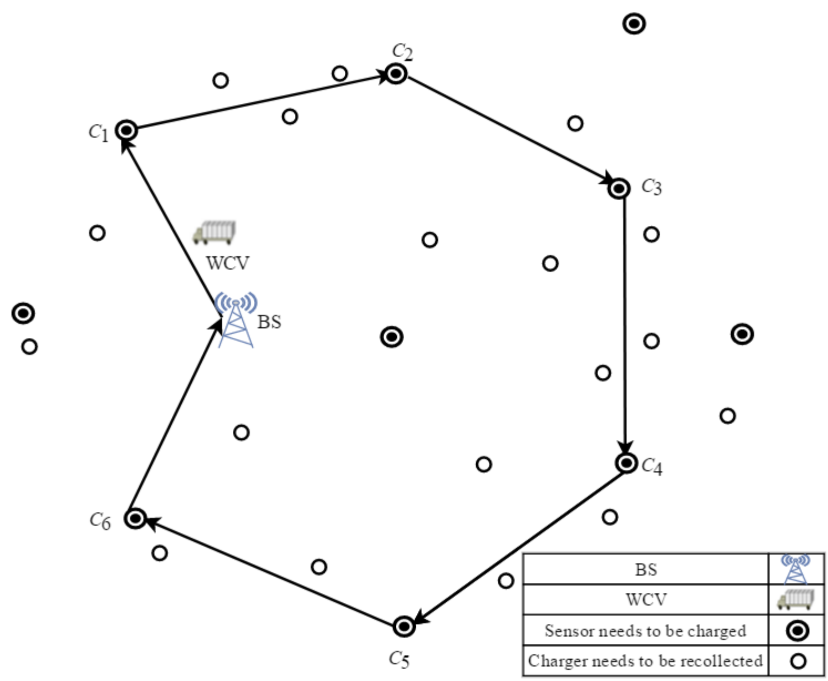


Figure 3. Reduce the charger's range of recollection

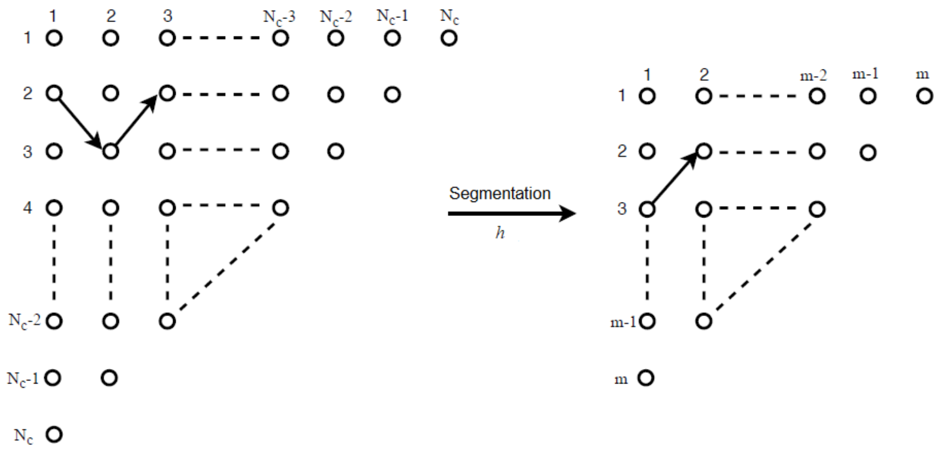


Table 1. Symbols and definitions

Symbol	Definitions
N	Total number of chargers in the sensor networks.
Et	The range of the sensor power level threshold.
Rr	Center of the rectangular area.
N_r	Number of sensors requested for charging.
N_{sec}	Number of segments.
C_i	The i^{th} charger.
N_c	Number of chargers that need to be recycled.
N_{seg}	Number of segments allowed for segmentation.
$S_c(i)$	State of the i^{th} charger.
D_r	Recycled charger set.
h	Recycling vertical distance.
d_i	Vertical distance from the i^{th} charger to the charging route.
N_s	Number of charging segments.
n_i	Number of recycling nodes in the i^{th} charging segments, iÎ{1, 2,..., N_s}.
S_{ij}	Charging path from sensor i to sensor j.
S_{max}	Maximum charging path.
T_d	Deadline (or exhaustion time) of sensor i.
v	Speed of the WCV.
x_i	Abscissa of the i^{th} charger position.
y_i	Ordinate of the i^{th} charger position.
T_{ij}	Time required for the WCV to reach from sensor i to sensor j.
$t_{node}(k)$	Time spent on the k^{th} charger recollection.
T_{total}	Total time of charger recollection.
$t_r(i)$	Minimum recollection time in the set.
$T_{dmax}(i)$	Maximum time of the i^{th} charging node that can be used for recollection.
K_c	Threshold for a sensor to issue a charging request.
K_r	Threshold for a charger to issue a recycle request.

3.2.1 Strategy of Computation

To make the scheduling more computable, the strategy is to replace global optimization with local optimization by segmenting the charging tour of the WCV and to try to find a tradeoff between the rate of recollected chargers and the time consumed in recollection. Four different charging schemes are applied to verify the effectiveness of the OCRA, EDF, REDF_A, REDF_L and REDF_AL (Xu et al., 2018). For the purpose of reducing computation, the first step to divide the charging route into several segments according to the limitations of the remaining lifetime of sensors and the speed of the WCV in order to restrict the range of recollection in the length direction. Then, by setting the width of the charging path, the range of recollection is reduced once more. Finally, the chargers that can be recollected in the whole route are selected and scheduled.

Set the object function $W_\theta(x)$ of each segment, where 1£θ£N_{sec} and xÎD_r is the charger number to be recollected.

$$W_\theta(x_0) = \max\left\{W_\theta(x)\right\},\ x_0 \in D_{rn},\ T_{total} < t_r(x),\ D_{rn} \subseteq D_r \tag{3}$$

Subject to:

$$T_{total} = \sum_{x=1}^{N_{ni}} t_{node}(x) \tag{4}$$

$$t_r\left(x\right) = min\left\{T_{dmax}\left(x\right)\right\} \tag{5}$$

$$W(x)=\sum_{\theta=1}^{N_{sec}} W_\theta(x),\ x \in D_r \tag{6}$$

where D_{rn} is the set of the chargers to be recollected in each segment and $t_{node}(x)$ represents the time required for the charger moving to the nearest charging line. N_{sec} is the number of segments, and the total number of chargers to be recollected in each segment is denoted by N_{ni}. Performing the recollection task during the charging tour will inevitably increase the time consumption of WCV motion. To ensure that all sensors could be rescued in time, the total recollection time T_{total} in each segment must be less than the maximum permissible time $t_r(x)$ of the recollection operation. Therefore, the condition of $T_{total} < t_r(x)$ must be met. The local optimal recollection scheme for each segment is integrated by Equation (6) to obtain the final recollection scheme W(x).

3.2.2 Segmenting

Assume a charging schedule as shown in Figure 4. Here, r_1 to r_{15} are all chargers waiting to be recollected, C_1 to C_6 are sensors that need to be charged, and S_{ij} is a charging route from C_i to C_j. To choose a sensor as the segmenting point, the shortest $t_r(i)$ is determined from C_1 to C_6. For example, if $t_r(4)$ is the shortest lifetime remaining of the sensors in the entire charging route, the first segmenting point of the schedule is C_4. Subsequently, as described above, $t_r(i)$ of C_5 and C_6 are compared. If $t_r(5)>$ $t_r(6)$, C_6 is selected as the segmenting point, while the whole schedule can be divided into two segments. Otherwise, if $t_r(5)< t_r(6)$, C_5 is also the segmenting point, and the number of segments is three.

As shown in Figure 5, there are 14 chargers waiting to be recollected. If the first segmenting point of the schedule is C_4, all possible choices of scheduling of recollection will be reduced from 14!to 9!+5!. Thus, the selection area in the length direction of the charging route has been greatly reduced.

3.2.3 Restricting the Recollection Width in a Moving Line

Considering the time consumed in the movement of a WCV, the candidate chargers should be as close to the charging path as possible. Therefore, the recollection range in the width direction can be the vertical distance limitation for the WCV to recollect chargers, as shown in Figure 6. Here, d represents the vertical distance from the charger to the moving line of the WCV. By the limit of h, most of the chargers waiting for recollection are temporarily excluded from the recollection list.

To schedule the recollection task, the chargers r_i is sorted in the order of d, as shown in Figure 7. Through Equation (7), the number of all possible recollection options Q can be calculated and is reduced by segmentation and limitation of the size of h. Here, N_s is the number of the segments,

Figure 4. Scheduling the charging tour

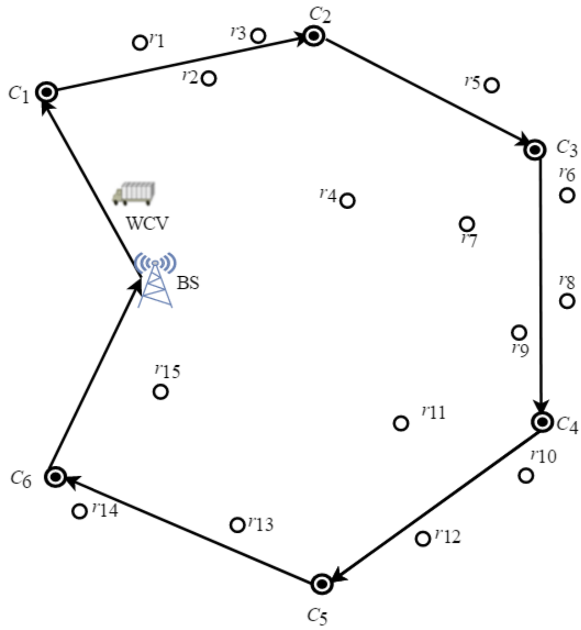


Figure 5. Possible choices after segmenting the charging route

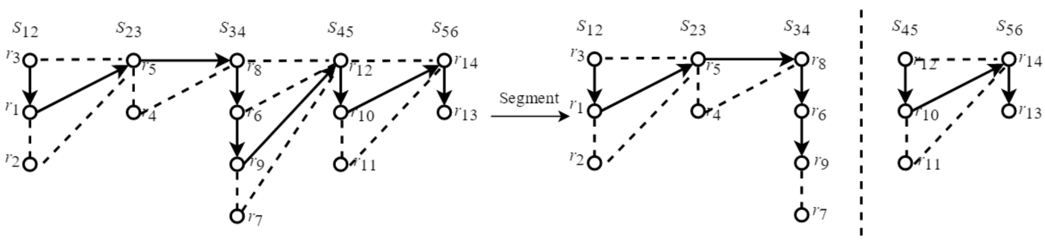
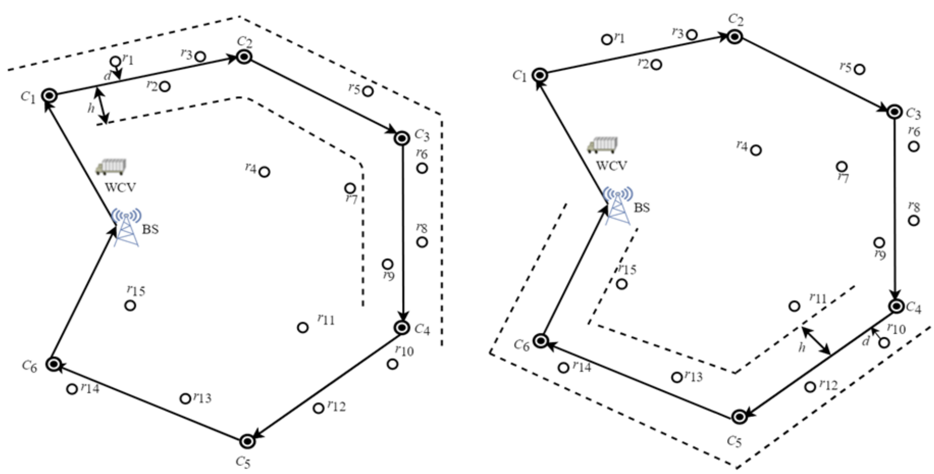


Figure 6. Restricting the recollection width by h



while n_i means the number of sensors in each segment that satisfy the condition of the recollection. Q reflects the number of all possible options after the above reduction in calculation.

$$Q = \sum_{i=1}^{N_i} n_i + \sum_{i=1}^{N_i - 1} \left(n_i \times n_{(i+1)} \right) \tag{7}$$

According to Figure 7, Q in S_{14} and S_{46} is 22 and 8, respectively, which can be obtained by Equation (7). Through the above two steps, the range of the charger recollection area in the length direction and width direction has been reduced greatly, resulting in a reduction in the number of chargers that the WCV can choose to recollect in its charging path, so the computation of scheduling the route of the WCV in its charging path becomes simplified.

3.3 Framework of the OCRA

The following four parts explain the framework of the OCRA.

3.3.1 Mapping the Charging Route into a Straight Line

The charging scenario of the WCV is shown in Figure 8. To analyze and explain the recollection problem of the charging clearly, the route of the WCV is mapped into a straight line from BS to BS, as shown in Figure 9.

Figure 7. Possible choices after restricting the recollection width

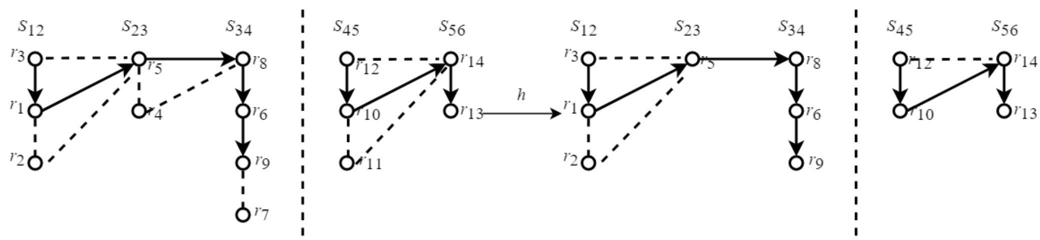


Figure 8. Charging simulation scenario

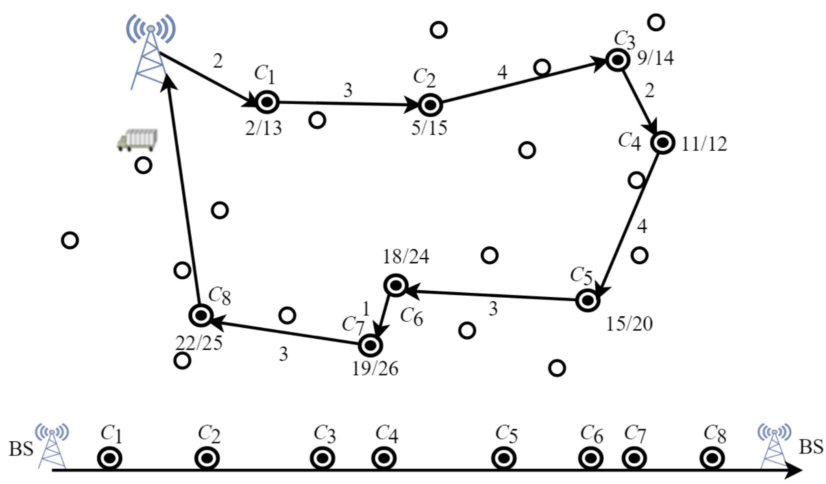
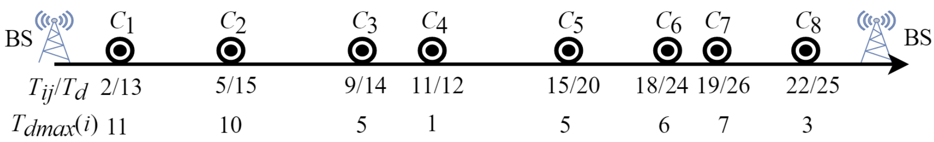


Figure 9. Charging path conversion diagram



The WCV starts from the BS and will return when the mission is completed. The sensors are lined according to the distance from sensors to BS. C_i is the identifier of the sensor to be charged. T_{ij} represents the moving time of the WCV from C_i to C_j, and T_d is the remaining time of sensor C_i. $T_{dmax}(i)$ is the maximum degree of freedom for C_i, which is the maximum time allowed for recollection.

3.3.2 Segmenting the Charging Route in the Length Direction

The following is the segmentation that restricts the scheduling computation range in the length direction. As shown in Figure 10, $T_{dmax}(i)$ in the charging route is 1, which is the maximum time that can be used for recollection from C_1 to C_4. Similarly, $T_{dmax}(i)$ between C_4 and C_8 is 3. By segmenting the WCV's moving route according to $T_{dmax}(i)$, the scheduling computation range in the length direction can be reduced.

According to the number of sensors N_r, as shown in Equation (8), N_{seg} is the criterion for determining whether to segment, and N_{sec} represents the number of segmentations. Then, according to Equation (11), it is evaluated whether the remaining charging path needs to be segmented.

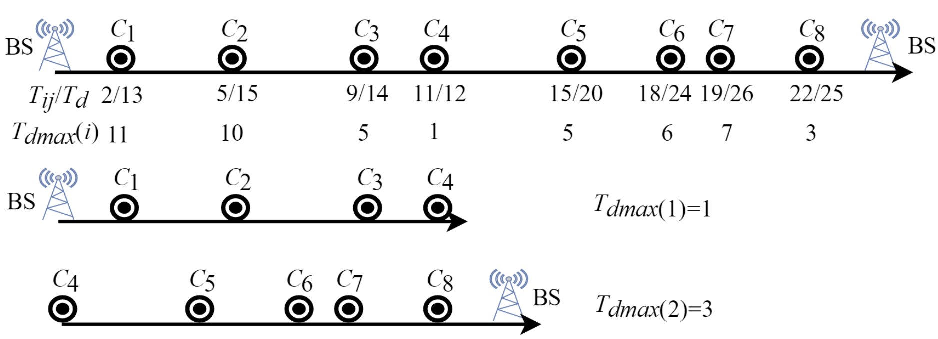
$$f\left(\boldsymbol{N}_{sec}\right)=\begin{cases}0 & \boldsymbol{N}_r<\boldsymbol{N}_{seg}\\1 & \boldsymbol{N}_r\geq\boldsymbol{N}_{seg}\end{cases} \tag{8}$$

If f=0, the Algorithm 4 will be executed. If f=1, N_{sec} will be incremented by one, as shown in Equation (9). Then, select the piecewise sensor according to $T_{dmax}(i)$, as shown in Equation (11), and $t_r(i)$ represents the maximum time that can be used for recollecting chargers. The algorithm is shown in Algorithm 1.

$$\boldsymbol{N}_{sec}\leftarrow\boldsymbol{N}_{sec}+1 \tag{9}$$

$$T_{dmax}\left(i\right)=T_d\text{-}T_{ij} \tag{10}$$

Figure 10. Segmentation



$$t_r(i) = min\left\{T_{dmax}(i)\right\} \tag{11}$$

$$f(N_{sec}) = \begin{cases} 0 & \boldsymbol{N_r} - \boldsymbol{i} < \boldsymbol{N_s} \\ 1 & \boldsymbol{N_r} - \boldsymbol{i} \geq \boldsymbol{N_s} \end{cases} \tag{12}$$

Algorithm 1: Segmentation

Step 1: Initialize num_charging_task = Min (num of chargers in per car, N_r); no = num_charging_task; min_free_time = a[min_no]; N_{sec} = 0.

Step 2: For *j* from min_no to num_charging_task. If a[*j*] < min_free_time, then proceed to step 3. If (no - *j*-1) > N_{seg}, then proceed to step 4.

Step 3: min_free_time = a[*j*]; recycle_time (min_no, *j*).

Step 4: Return to Algorithm 3; N_{sec} ++.

3.3.3 Limitation by h in the Width Direction of the Charging Route

After segmentation, the system needs to calculate the range of recollection in the width direction according to the lifetime of sensors, the speed of the WCV and other parameters. Here, *h* is derived from Equation (13), where *v* is the speed of the WCV. S_{max} is the maximum distance between the sensors that need to be charged on the scheduled path. This parameter is calculated by Equation (14). The value of $T_{dmax}(i)$ is the difference between the remaining time of the segmentation node and the WCV moving time.

$$h = \frac{t_r(i)^2 v^2 + 2t_r(i)S_{max}}{4\left(t_r(i)v + S_{max}\right)} \tag{13}$$

subject to:

$$S_{max} = \max\left\{S_{ij}\right\} \qquad 0<i<j<N_r \tag{14}$$

Subsequently, calculate d_i from the sensor to the charging path, as shown in Equation (15), where (x, y) is the coordinate of the charger needing to be recycled and (x_i, y_i) and (x_j, y_j) are the coordinates of two adjacent sensors waiting to be charged, respectively. The condition of chargers to be recollected is $d_i < h$. The specific operation process is shown in Algorithm 2.

$$d_i = \frac{kx - y - C}{\sqrt{k^2 + 1}} \tag{15}$$

subject to:

$$k = \left(y_j - y_i\right)/\left(x_j - x_i\right) \tag{16}$$

$$C = y_i - kx_i \tag{17}$$

Finally, the recollection list in order of d_i is obtained. Specific details can be found in Algorithm 3.

Algorithm 2: Limitation
Input: N_c: Number of chargers to be recollected. h: Recollection vertical distance. S_{max}: Maximum charging path. $T_{dmax}(i)$: Maximum time of the i^{th} charging node that can be used for recollection.
Output: Recollecting the node list: temp list {node_id}.
Step 1: Reduce the scope of the recycling node by h.
Step 2: Sort each node by the recollection loss.
Step 3: Determine the specific number of segments and node_id.
Step 4: Transfer Algorithm 3: Sequence.
Step 5: Return temp_list.
Algorithm 3: Sequence
Input: temp {node_id.x, node_id.y}; request_temp_list {x,y}.
Output: revised recycling node list: temp_list {node_id}.
Step 1: Initialize temp = {node_id}.
Step 2: For i from 0 to n. temp_list.sort (delegate (temp req1,temp req2)).
Step 3: Then, compare req1.distance. to req2.distance.
Step 4: Return temp_list = {node_id}.

3.3.4 Optimize the Order of Chargers to be Recollected

Although the charger's recollection range is reduced by the above two steps, the charger must meet the conditions of $T_{total} < t_r(i)$ before it can be recollected. Here, $t_{node}(k)$ represents the time spent on the charger recollection. T_{total} is calculated as shown in Equation (18), where N_{ni} represents the number of chargers to be recollected in each segment of the WCV's charging path, which will be obtained by Algorithm 4. The recollection order of these chargers will also be determined by Algorithm 4. Then, the computation results of all segments are merged into a new scheduling of the whole route by Algorithm 5.

$$t_{node}(k) = \frac{\sqrt{\left(x_k - x_i\right)^2 + \left(y_k - y_i\right)^2} + \sqrt{\left(x_k - x_j\right)^2 + \left(y_k - y_j\right)^2} - S_{ij}}{v} \tag{18}$$

$$T_{total} = \sum_{k=1}^{N_{n_i}} t_{node}(k) \tag{19}$$

Algorithm 4: Selection
Input: temp_list = {node_id}; request_charging_list {node_id}.
Output: Precise selection recycling node list: temp_list_last {node_id}.
Step 1: For k from 1 to N_{ni}, $T_{total} = T_{total} + t_{node}(k)$
Step 2: Find the minimum value of $T_{dmax}(i)$, and assign it to $t_r(i)$.
Step 3: If $T_{total} > tr(i)$, return N_{ni}.
Step 4: node_id from 0 to N_{ni}, return temp_list_last = {node_id}.
Algorithm 5: Combination
Input: temp_list_last; request_charging_list.
Output: temp_list_combine {node_id}.
Step 1: Find the segmentation of the charging route.
Step 2: Insert temp_list_last into the request_charging_list.
Step 3: Determine the recollection order base to the distance of the charger to the WCV.

3.4 Case Illustration of the OCRA

The following is a case illustration of the OCRA. Figure 8 is a charging simulation scenario, and Figure 11 is an analysis of the simulated scene after being mapped into a line.

- The steps of segmenting the charging route are as follows:
  - Evaluating whether the number of requesting sensors N_c is greater than N_{seg}, where N_{seg}=1 is a reference for judging whether to perform the piecewise operation. In the simulation scenario, N_c =8, so the piecewise operation is performed because of the $N_c > N_{seg}$.
  - Selecting the smallest d_i in the charging route. (If WCV recollects the charger with time more than the minimum $t_r(i)$, the sensor may fail. Therefore, the system must ensure the recollection time $t < t_r(i)$.) Select the first segmenting point C_4, and divide the charging route into two parts, S_{14} and S_{48}.
  - Performing the same judgment of piecewise operation on S_{48}; repeat steps 1 and 2 until the condition $N_c > N_{seg}$ is not satisfied.
- The steps for evaluating and selecting the specific recollection chargers in the S_{14} segment are as follows:
  - The path to be processed according to the segmentation consequence is shown in Figure 12. First, when the vertical distance d_i from the charger to the charging path is less than h, it will be included in the recollection evaluation list. Therefore, it is necessary to calculate d_i to ensure that $d_i<h$. The sensors satisfying such conditions in segment S_{14} are 1, 3, 4, and 5.
  - o Second, the recollection time consumption $t_{node}(k)$ of the WCV is taken as a selection reference value. Equation (18) demonstrates a calculation method of $t_{node}(k)$. The order is $t_{node}(3)< t_{node}(1)< t_{node}(5)< t_{node}(4)$, as shown in Figure 13. Since v does not change, the size of the distance reflects the length of time.

Figure 11. An analysis of the simulated scene

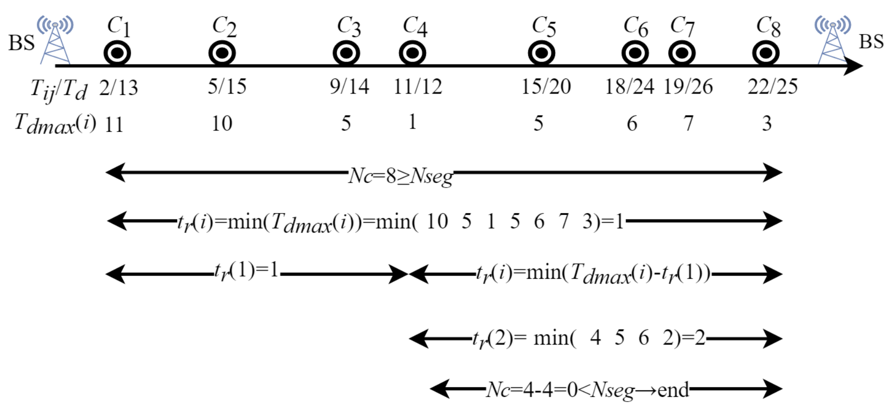
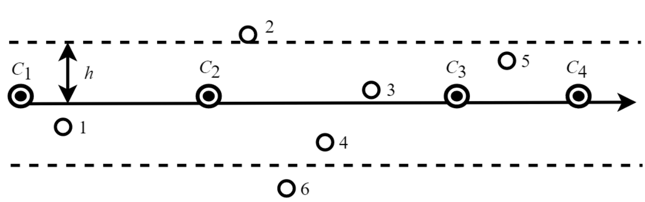


Figure 12. S_{14} road segment conversion diagram



- Because $t_{node}(3)$ is the smallest of the parameters, the size of $t_{node}(3)$ and $T_{dmax}(i)$ will be compared at the first. As a result, $t_{node}(3)<T_{dmax}(i)$ can be obtained. Thus, $t_{node}(3)$ can be added to the recollection list. Then, the work of comparing $T_{dmax}(i)$ with $t_{node}(3+1)$, $t_{node}(3+5)$ and $t_{node}(3+4)$ is executed, and the result is $t_{node}(3+1)>T_{dmax}(i)$ && $t_{node}(3+5)>T_{dmax}(i)$ && $t_{node}(3+4)<T_{dmax}(i)$. Therefore, the chargers that can be recollected under time constraints are chargers 3 and 4. Since $t_{node}(k)$ is calculated separately, T_{total} is the maximum recollection time consumption. The final recollection time must be less than T_{total}.
- Finally, the specific recollection order is determined by the distance between the recollection charger and the charging sensor, as shown in Figure 14. Because the distance from C_2 to 4 is less than the distance from C_2 to 3, the final order of recycling is 4, 3. The process is shown in Figure 14(b).

The recollection method in the S_{48} section is the same as that of S_{14}. Finally, the node list is reordered to obtain the final moving schedule of the WCV.

4. EXPERIMENT

The concept of the separable charging mode has not been proposed for a long time; only Xu et al. (2018) have considered the recollection problem of the charger and proposed a charger recollection algorithm (BRA). Therefore, to evaluate the effectiveness of the OCRA, we will perform some experiments by simulating the two scheduling schemes of the BRA and OCRA with the same parameters.

Figure 13. Selection of charger recollection in the S_{14} section

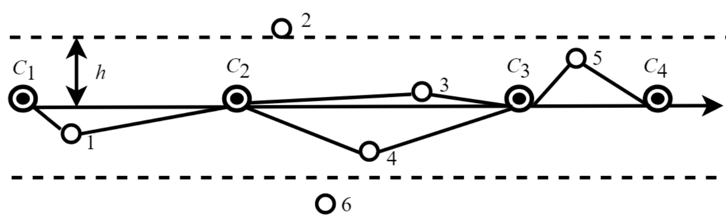
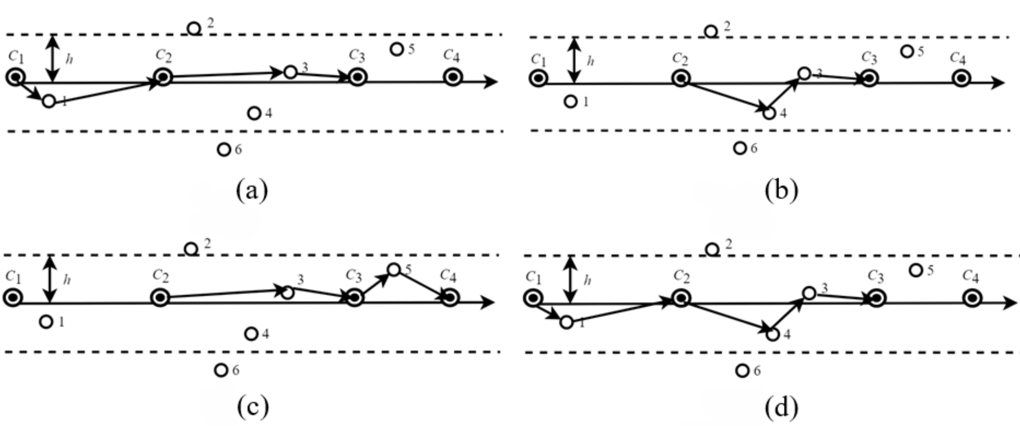


Figure 14. Possible recollection route of the WCV in the S_{14} section



4.1 Simulation Parameters

As shown in Table 2, in the simulation experiment, the total number *N* of sensors is set to 100, which are randomly and evenly distributed in a rectangular area of 600 m×600 m. The coordinates of the BS are the center of the rectangular area *Rr* (300 m, 300 m). The speed *v* of the WCV is 10 m/s. The sensor's power level threshold *Et* refers to the battery's remaining time in seconds that triggers the charging request to be 1500±100, and the size *W* of the experimental window is set to 7. Finally, *h* is a fixed value for ease of comparison.

In the experiments, we will compare the lifetime of the above two algorithms 100 times to alleviate the influence of randomness. The lifetime of the WRSN ends until the failure of the first sensor.

4.2 Performance Comparison

4.2.1 Overview

With the same simulation parameters, we will compare the performance of the two recollection approaches, BRA and OCRA, in many aspects. The BRA and OCRA were applied to four different charging schemes: EDF, REDF_A, REDF_L and REDF_AL. First, we compare the charger recollection rate of the OCRA to that of the BRA. Second, with different recollection distance ranges *h*, the experimental results of the two algorithms are compared in terms of the efficiency, quantity and life cycle of the recovered charger. Finally, by changing the distribution range R_r of the sensor nodes, the recollection rate and sensor mortality of the OCRA algorithm are compared. Each recollection scheme was simulated 200 times.

4.2.2 Comparison of the Recollection Rate of the Charger

As shown in Figure 15, the two recollection algorithms of the BRA and OCRA are applied to four charging schemes. When different values are taken, the recollection rate of the OCRA is significantly higher than that of the BRA, which is approximately 2 times. Moreover, the overall recollection rate of the OCRA is 40%, while that of the overall BRA algorithm is less than 30%. Therefore, the OCRA has better performance than the BRA in terms of the charger recollection rate.

Under the same conditions, the OCRA and BRA methods are applied in four different charging schemes. In Figure 16, the recollection rate of the OCRA algorithm is more stable than that of the BRA algorithm. When using the OCRA, the recollection rate will not drop dramatically, which is beneficial for the application of the system.

The OCRA and BRA are compared in different charging schemes, and each scheme is simulated 10 times. The system lifetime is shown in Figure 17 as the simulation results. By using the OCRA method, the system lifetimes in the charging scheme of EDF, REDF-A, REDF-L are all greatly improved, as shown in Figure 18(a). Only in REDF-AL is the system lifetime of the OCRA lower than that of the BRA method. As shown in Figure 18(b), with the REDF-L charging scheme, the OCRA obtained the best performance. Therefore, the REDF-L charging scheme will be further analyzed in the following experiments.

As shown in Figure 19(a), the two recollection algorithms are applied to the REDF-L charging schemes. When *h*=20 m, the recollection rate of the OCRA is 1.98 times that of the BRA. When *h*=10 m, the recollection rate will increase to 3 times. When the *h* value is small, the recollection rate of the BRA is very low. As shown in Table 3, when *h* is reduced, using the OCRA does not result in a rise in sensor failure. Figure 19(b) shows that the minimum value of the number of recollected chargers using the BRA is less than that of the OCRA.

Table 2. Simulation parameters

Parameter	*N*	*Rr*	BS	*v*	*Et*	*W*
Values	100	600 m×600 m	(300 m, 300 m)	10 m/s	1500±100	7

Figure 15. BRA and OCRA were applied to four different charging schemes: EDF, REDF_A, REDF_L and REDF_AL. Compare the charger recollection rates of the BRA with OCRA when h takes different value

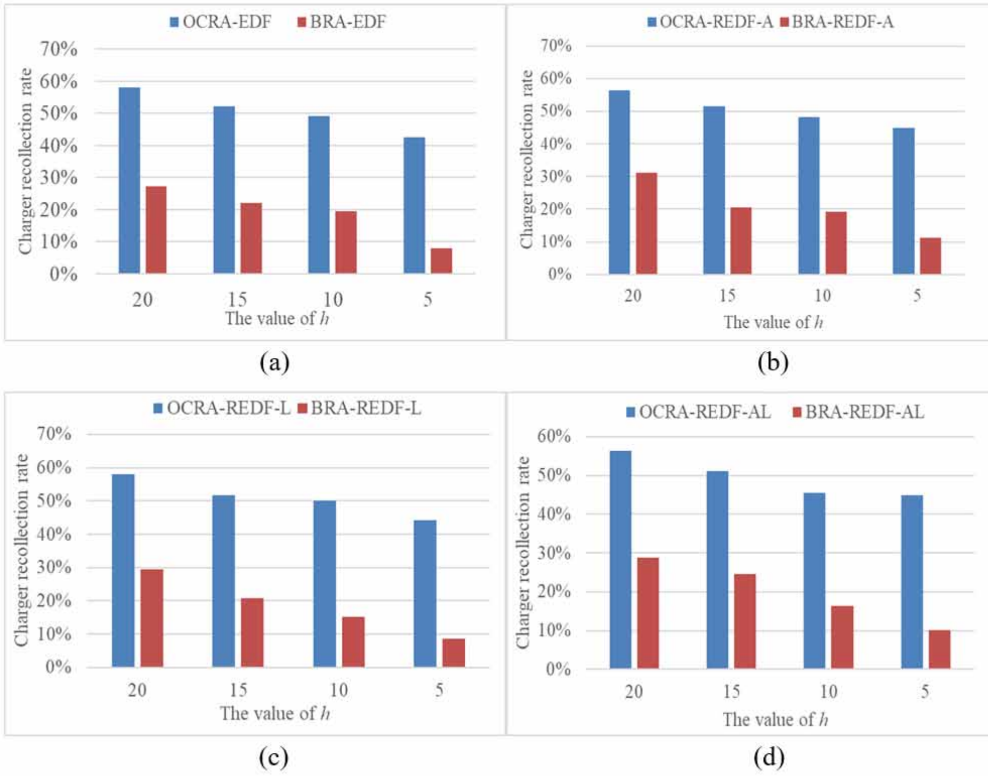
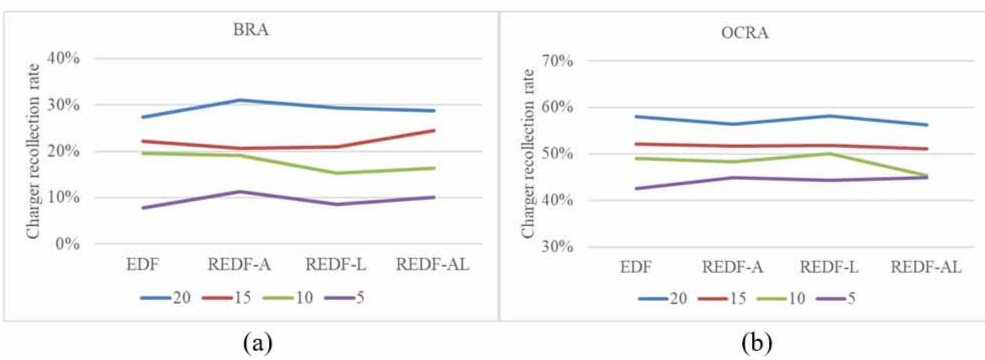


Figure 16. Performance in four charging schemes with different recollection distances h, (a) recollection rate of the BRA and (b) recollection rate of the OCRA



4.2.3 Comparison of Regional Extents of Sensors Failures with Different Recollection Distances

Through simulation experiments, it is clear that the OCRA method performs better in the rectangular region of 600 m×600 m when compared with the BRA method. As shown in Table 3, charger failure occurred when h=20 m. However, as h decreases, charger mortality also decreases. Therefore, different

Figure 17. With h taken as 20, Figures (a) and (b) show the survival time of the system when the charger is recovered using the OCRA and the BRA, respectively

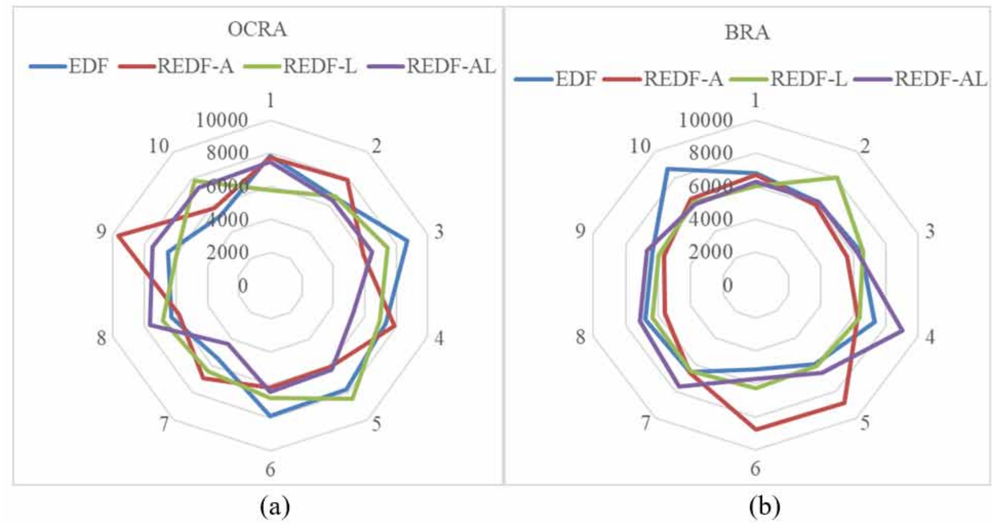
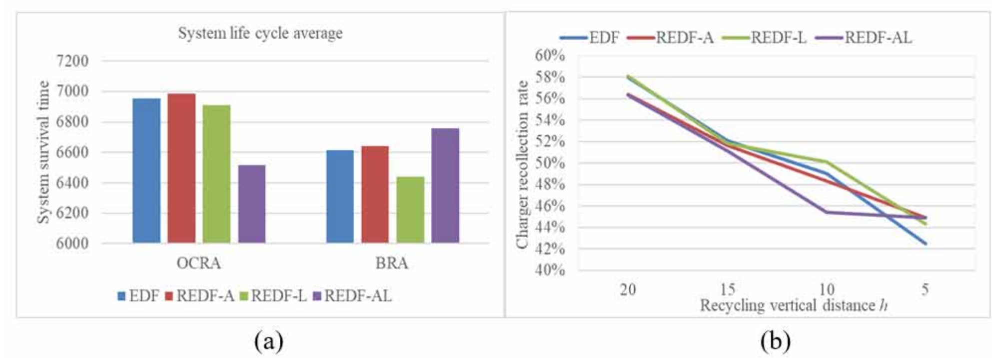


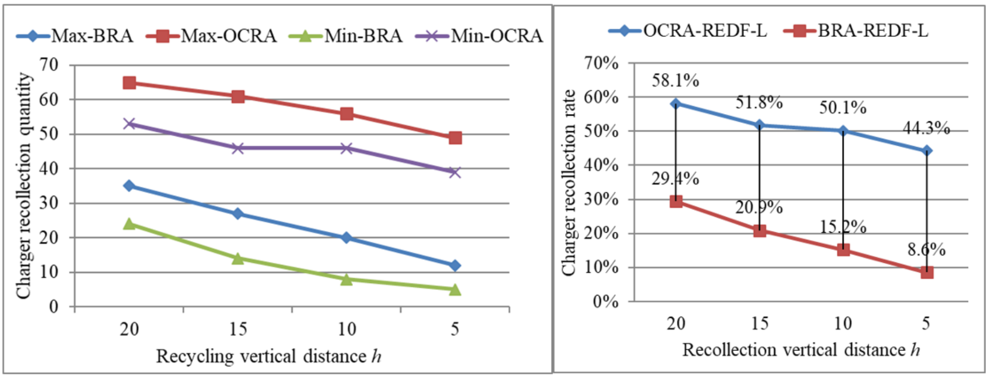
Figure 18. Under the same conditions, (a) shows a comparison of the average survival time when the OCRA and the BRA are applied in different charging schemes. With h changing, (b) is a comparison chart of the recollection rate of the charger when the OCRA is applied in different charging schemes



system ranges are compared to determine the proper border of the system range, out of which the failure of the charger may appear. The relationship between the recollection rate of the charger and the mortality of the sensor in different ranges is analyzed below.

As shown in Figure 20(a), when h=10 m, the sensor fails when the area is 900 m × 900 m. If the area expands, the probability of sensor failure will increase. The recollection rate of the OCRA will not change significantly and will remain higher than 40%. As shown in Figure 20(b), when h=5 m, the sensor will fail when the area is 910 m × 910 m, and the probability of sensor failure is increasing. The recollection rate of the OCRA will drop significantly to between 30% and 40%, and it will also be unstable. Therefore, when h=10 m, the OCRA algorithm performs better when the area is limited to 900 m×900 m.

Figure 19. With h taking different values, (a) the difference of charger recollection rates between the OCRA and BRA. (b) The charger recollection quantity of the OCRA and BRA

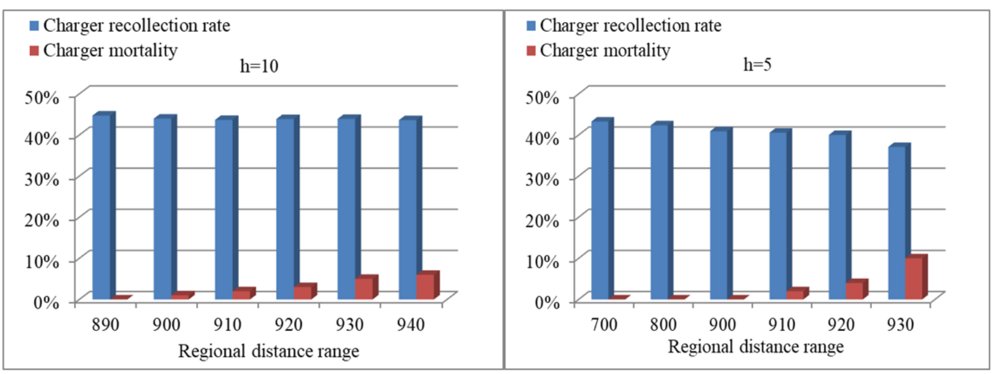


(a) (b)

Table 3. Sensor node mortality approximation

h	**20**	**15**	**10**	**5**
OCRA	2%	1%	0%	0%
BRA	2%	1%	0%	0%

Figure 20. Using the OCRA algorithm: (a) the recollection rates of the charger and the sensor mortality of different system ranges when h=10 m, and (b) the recollection rates of the charger and the sensor mortality of different system ranges are dead when h=5 m



(a) (b)

CONCLUSION

In this article, we propose an opportunistic charger recollection algorithm for wireless rechargeable sensor networks with separable charger arrays. The goal of the OCRA algorithm is to recollect chargers as many as possible on the charging method of the WCV, while the WCV can still perform its charging mission in time. The overall performance of the system is improved by extending the life of the WRSNs. The simulation results show that when compared with other solutions, e.g., the backward recollection algorithm, our approach has made a significant improvement in recollection effectiveness. Moreover, the failure rate of the sensors does not increase. Although the algorithm has greatly improved the efficiency of charger recollection, we need to further study a more accurate and ideal system model under various constraints. In the future, we will continue to study the recollection problem for a more effective solution.

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