applied sciences

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Adaptive Dual-Mode Routing-Based Mobile Data Gathering Algorithm in Rechargeable Wireless Sensor Networks for Internet of Things

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Received: 7 February 2020; Accepted: 4 March 2020; Published: 6 March 2020

Abstract: Great improvement recently appeared in terms of efficient service delivery in wireless sensor networks (WSNs) for Internet of things (IoT). The IoT is mainly dependent on optimal routing of energy-aware WSNs for gathering data. In addition, as the wireless charging technology develops in leaps and bounds, the performance of rechargeable wireless sensor networks (RWSNs) is greatly ameliorated. Many researches integrated wireless energy transfer into data gathering to prolong network lifetime. However, the mobile collector cannot visit all nodes under the constraints of charging efficiency and gathering delay. Thus, energy consumption differences caused by different upload distances to collectors impose a great challenge in balancing energy. In this paper, we propose an adaptive dual-mode routing-based mobile data gathering algorithm (ADRMDGA) in RWSNs for IoT. The energy replenishment capability is reasonably allocated to low-energy nodes according to our objective function. Furthermore, the innovative adaptive dual-mode routing allows nodes to choose direct or multi-hop upload modes according to their relative upload distances. The empirical study confirms that ADRMDGA has excellent energy equilibrium and effectively extends the network lifetime.

Keywords: adaptive dual-mode routing; mobile data gathering; wireless energy transfer; rechargeable wireless sensor networks; Internet of things

1. Introduction

Internet of things (IoT) can be used in many environments such as healthcare, smart grids, and security monitoring, with the aim of providing a wide range of connections for various terminals [1]. Wireless sensor networks (WSNs) own a dominant position in IoT on account of their convenient communication mode for attractive applications [2]. However, lifespans of sensors are subject to limited battery power, and battery replacement is usually quite difficult [3]. Thus, prolonging the network lifetime of WSNs is a key consideration point for researchers [4].

Many studies were committed to prolonging the network lifetime through energy replenishment. Kurs [5] demonstrated that it is viable to wirelessly transfer energy. Within a certain distance, energy can be transferred to sensors via coupling resonances. The wireless energy transfer device placed on the mobile vehicle can supply energy for sensors, such that the lifetime of network is steadily extended [6].

In addition, a mobile sink is also an effective method to prolong the network lifetime [7]. Compared with a mobile sink, large-scale networks with a static data collector usually have poor energy balance. Many nodes have to upload data through a multi-hop relay, and the nodes near the sink bear heavy traffic load [8]. Thus, the mobile data gathering mode can decentralize the load and effectively extend the network lifetime [9].

Attracted by the advanced energy replenishment scheme and high efficiency of the mobile data gathering mode, some works proposed schemes that combined data gathering with wireless charging. However, the mobile collector cannot visit each node under the constraints of charging efficiency. Energy consumption differences caused by different upload distances impose a great challenge in balancing energy.

Based on the analyses above, an adaptive dual-mode routing-based mobile data gathering algorithm (ADRMDGA) in rechargeable wireless sensor networks (RWSNs) for IoT is proposed in this paper. A mobile vehicle with both wireless charging and data gathering functions (MCGV) is proposed. The moving path of MCGV is determined based on the charging efficiency and moving distance threshold. The energy replenishment capability of the MCGV is reasonably allocated to low-energy nodes according to our objective function. In addition, an innovative adaptive dual-mode routing is used to balance energy when the MCGV gathers data. Each node can choose a direct upload or multi-hop upload mode according to its relative upload distance. The empirical study confirms that ADRMDGA has excellent performance in extending the network lifetime via an energy balance strategy.

Our major contributions in this paper are summarized below. Firstly, we consider comprehensive factors of energy replenishment including energy consumption, residual energy, and an optimal energy allocation scheme, to better charge the network. Secondly, we empower a data gathering function on the mobile charging vehicle in order to better develop the effectiveness of its mobility. Thirdly, an adaptive dual-mode routing strategy is proposed, which can effectively balance the energy consumption of nodes when the MCGV gathers data. Finally, we prove its performance, where the MCGV can prolong the network lifetime by balancing energy when gathering data and by replenishing the low-energy nodes in a timely manner.

The rest of the paper consists of five sections. In Section 2, we summarize related works of routing algorithms and charging scheme. The system model is given in Section 3. Section 4 shows our energy replenishment strategy, and Section 5 proposes the data gathering algorithm. Section 6 introduces the performance of our algorithm. Section 7 provides a conclusion and proposes future work.

2. Related Work

Wireless energy transfer is recognized as an effective technology for extending network lifetime. A large number of studies were aimed at optimizing the efficiency of charging devices. Magadevi [10] proposed a wireless charging scheme based on a single mobile anchor. Tang [11] introduced an optimal charging algorithm based on a novel concept called "shuttling" in order to minimize the charger number. Tu [12] set an energy replenishment strategy based on the residual energy level and moving distance of the vehicle. Xie [13] studied an optimization problem whose objective was to minimize the wireless charging vehicle's moving time. Zhang [14] optimized charging efficiency by optimizing power allocation and considering the location of the charger. However, the mobile vehicle cannot gather data while replenishing energy in the algorithms above, which resulted in failure to fully exploit its effect. In this paper, the effect of the mobile vehicle can be fully exploited through wireless energy transfer and mobile data gathering.

Another effective strategy to prolong network lifetime is to optimize multi-hop or clustering routing strategies, and several energy balance routing algorithms were proposed. A dynamic max flow-based energy balance routing was proposed by Cai [15] for extending network lifetime via an energy balance strategy. Haseeb [16] proposed an energy-aware and secure multi-hop routing algorithm based on a secret sharing scheme, which could improve the efficiency of energy balance with a multi-hop relay. A novel energy-efficient clustering algorithm was found to improve the energy efficiency by improving energy consumption equilibrium [17]. However, the significant energy consumption difference is inevitable due to large differences in upload distance in the sensor networks with a single static sink. For example, in the multi-hop routing algorithm, nodes close to the sink need to relay the traffic of the entire network, which consumes a lot of energy, resulting in them often dying first. Our algorithm can balance the distributions of traffic load and energy through adaptive dual-mode routing-based mobile data gathering. Furthermore, the network lifetime can be prolonged efficiently.

In addition, some works were aimed at introducing wireless charging technology into traditional multi-hop routing algorithms for networks with a single static sink. The autonomous load regulation mechanism-based routing (ALRMR) [18] was an efficient framework of joint wireless energy transfer and multi-hop routing where the routing strategy was adapted to the charging scheme. Aslam [19] attempted an approach based on the shortest path algorithm and grid clustering to save and renew power in a way that minimized energy consumption and prolonged the overall network lifetime of WSNs. Tang [20] proposed an optimization algorithm from the aspects of both charging and routing processes. Furthermore, a joint energy supply and routing path selection algorithm was proposed to extend the network lifetime based on an initiative power supply [21]. These algorithms could prolong the network lifetime to a certain extent. However, load imbalance is still unavoidable in the networks with a single static sink, and the algorithms also failed to fully exploit the effect of the mobile vehicle. In our algorithm, the mobile vehicle includes wireless energy transfer and data gathering functions. Due to the benefit of mobile data gathering, the average energy consumption of all nodes can be reduced significantly, and the load can be efficiently balanced.

According to the observation above, many researches were aimed at integrating data gathering and the energy replenishment function in mobile vehicles. Using a mobile vehicle with a wireless charging function, He [22] proposed a novel way of "upgrading" the charging efficiency of "bottleneck" nodes. Guo [23] presented a framework that integrated wireless charging and mobile data gathering, which analyzed the causes of energy balance. An anchor selection algorithm that considered neighbor distribution and residual energy was proposed to collect zonal data [24]. Xie [25] pursued a novel optimization mode by considering the moving path, traffic routing, and charging time. However, data upload modes in the algorithms above were relatively single, and all nodes directly communicated with collectors on mobile vehicles. The energy consumptions of nodes are different because of the variety of upload distances to collectors. Hence, the energy balance problem in mobile data collection should also be taken seriously. Combined with our adaptive dual-mode routing mechanism, each node can choose direct upload or multi-hop upload modes according to the relative energy consumption level. The energy consumption can be balanced when the MCGV gathers data, and the network lifetime can be effectively prolonged.

3. System Model

An MCGV is introduced for charging battery and gathering data. According to our assumption, the MCGV is expected to sojourn anywhere to wirelessly charge nodes. However, too many possible locations may greatly increase the computational complexity. Hence, a logical cellular structure is laid out to simplify this problem, as shown Figure 1. We use many adjacent hexagonal cells with a side length D to represent a two-dimensional plane. The cells that the MCGV needs to visit are determined by their discharge rates. The MCGV only works at their centers, and we call these points anchor points. We assume that the base station is on the edge of the network in this paper. The MCGV travels from the base station to each selected cell, i.e., the charging cell, at a speed of S. The MCGV recharges nodes in these charging cells and gathers data from nodes which are in or near charging cells. The distance between a node and the anchor point in its nearest charging cell is defined as the upload distance. Due to the low power reception efficiency caused by long distances, we stipulate that the sensor can only be charged when the MCGV sojourns at the cell in which it is located. After visiting all charging cells, the MCGV goes back to the base station. When the MCGV completes the above process, we assume that the network completes a round and the time T taken for each round is fixed.

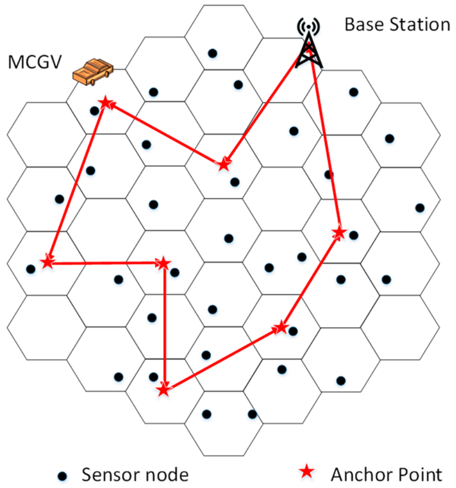

Figure 1. Example of system model with a mobile vehicle with both wireless charging and data gathering functions (MCGV).

The graph G(C,V,E) defines the network. $c_m \in C$ represents one cell. Each vertex $v_m \in V$ denotes a node. Each edge $l_{ij} \in E$ is the upload link between the node v_i and its next hop. v_j falling into the transmission range of v_i is necessary for the existence of the communication link. The two-dimensional plane is dotted with N random fixed homogeneous nodes. They have the same battery capacity of E_o and the same maximum communication distance of R. Most energy is consumed in the process of collecting, receiving, and sending data. Hence, we do not consider the remaining energy consumption, and all packets in the study are the same dimensionally [26].

3.1. Energy Transfer Model

The MCGV is able to charge multiple nodes in one cell at the same time. For instance, the energy transfer efficiency η_i of node v_i is obtained using Equation (1) [27].

$$\eta_i = \frac{\tau}{(d_{i,c_m} + \beta)^2} \times 100\%, i \in c_m, \tag{1}$$

where $\tau = \frac{G_S G_R \delta}{L_P}\left(\frac{\varphi}{4\pi}\right)^2$, G_s denotes the source antenna gain, G_R is the receive antenna gain, δ can be referred to as rectifier efficiency, φ represents the wavelength, L_P means polarization loss, and β represents the parameter used to change the Friis free space equation. d_{i,c_m} symbolizes the distance between the node v_i and its cell center. The charging efficiency decreases with the increase in distance.

3.2. Traffic Load Model

In the traffic load model, every node relay decides its load. We quantize the load using Equation (2) according to the assumption that each node produces λ_i^s data packets in each round.

$$l_i = \lambda_i^s + \sum_{j \in BF(i)} l_j, \tag{2}$$

where l_i denotes the traffic load of node v_i, whereas l_j is the traffic load of node v_j. $BF(i)$ represents the children set of node v_i, i.e., the nodes which upload data via the relay of node v_i. l_i reflects the node's traffic load, referring specifically to the number of data packets set to be uploaded every round. The nodes which fall in the traffic concentration region bear a high load.

4. Energy Replenishment Strategy

Given that not all cells are charged in one round, the energy replenishment efficiency depends on how smart the selection system is. In this section, an intelligent recognition system and an energy replenishment algorithm for nodes based on their energy states are provided.

4.1. Charging Cell Selection

The selection of charging community has a great impact on the overall energy replenishment effect. In order to reduce the average upload distance of all nodes, the MCGV should gather data from as many different cells as possible. However, visiting too many cells increases the moving time of the MCGV and decreases the benefit of charging. In light of the above analyses, a rule is introduced to select charging cells.

At the start of each round, the MCGV checks discharge rate of each cell according to the state information of all nodes. For instance, the cell c_m's discharge rate is calculated via the formula below.

$$ce_{c_m} = \max_{i \in c_m}\left(\frac{e_i}{E_i}\right), \tag{3}$$

where e_i denotes the energy consumption in the last round. E_i is node v_i's residual energy. The discharge rate is related to how quickly the charge is drawn down. The node with high energy consumption or low residual energy should be charged in a timely manner, so as to avoid energy gaps between nodes. The assumption is that there is zero energy consumption, and the residual energy is initially E_o.

Then, the cells are sequenced from high to low based on the discharge rate, and the sequence is recorded by the set PAS. $PAS(m)$ represents the m-th element of the PAS, denoting the cell with the m-th highest discharge rate. Thus, the PAS is a sorted list of cells based on discharge rate. The MCGV, starting from the first element, visits charging cells sequentially according to the PAS, and the charging cell set can be determined as follows:

$$CV = \{PAS(m)\big| m \in [1, N_{ac}], L(m)/S \leq \alpha \cdot (T - m \cdot t_o)\}, \tag{4}$$

where CV is the charging cell set, and m represents the serial number of cells in PAS. N_{ac} denotes the number of cells in which the node is dotted. $L(m)$ is the shortest moving distance to visit the top m cells in PAS. α is the moving distance constraint factor, where $\alpha \in [0, 1]$. It is used to determine the maximum time that can be allocated for moving in a round in order to control the time for charging. A larger α means more time for MCGV to visit different cells and reduce the average upload distance of all nodes while reducing the total charging time. Correspondingly, a smaller α means more time for MCGV to charge and focus on replenishing low-energy nodes while reducing the number of charging cells and increasing the average upload distance. Hence, the number of charging cells and the performance of the algorithm are related to α. t_o is the threshold time to ensure stable data gathering, and the sojourn time of the MCGV in each charging cell is at least t_o. It is assumed that t_o is far less than round time T. We find the maximum number of charging cells without exceeding the moving distance threshold in order to minimize the average upload distance.

4.2. Sojourn Time and Charging Power Allocation

In an attempt to maximize the lifetime of the network, the MCGV works by charging cells to charge for nodes. According to the order which the MCGV follows, an optimization problem for the sojourn time and the allocation of the charging power is proposed below.

$$\max \sum_{m \in CV} \sum_{i \in c_m} \log(1 + \frac{\eta_i P_i (t_o + t_{c_m})}{E_i}), \tag{5}$$

subject to

$$\sum_{i \in c_m} P_i \leq P, \tag{6}$$

$$\eta_i P_i t_{c_m} + E_i \leq E_o, i \in c_m, \tag{7}$$

$$t_{c_m}/ce_{c_m} = t_{c_k}/ce_{c_k} \forall m, k \in cv, \tag{8}$$

$$\sum_{m \in AS} t_{c_m} \leq T - t^{move} - t_o \cdot |CV|, \tag{9}$$

where P_i denotes the charging power of node v_i. t_{c_m} and t_{c_k} are the sojourn times for charging cell c_m and cell c_k, respectively. t^{move} represents the time the MCGV spends visiting every cell in CV, and $|CV|$ is the number of cells that the MCGV needs to visit. T is the time of a round.

According to the charging power constraint in Equation (6), the total power charging one cell must be less than the MCGV's maximum power. The battery capacity constraint in Equation (7) states that the sum of supplementary energy and residual energy for any node in a round cannot exceed the battery capacity of sensors. Complying with these constraints contributes to a good charging performance and ensures that the MCGV does not charge nodes that are fully charged.

In view of the energy balance constraint in Equation (8), the duration for charging each cell is positively correlated with its own discharge rate. The cell with a high discharge rate is allocated more time to be charged. The charging time constraint in Equation (9) shows that the time for charging is related to mobile time, data gathering time, and round time

In light of the objective function in Equation (5), the charging performance of all designed schemes is calculated. According to the optimal solution, the MCGV allocates sojourn time for each charging cell in CV and the charging power for each node in the same cell based on multi-point charging technology. As a result, the charging for all nodes becomes more efficient.

5. Adaptive Dual-Mode Routing-Based Mobile Data Gathering Algorithm

The number of charging cells is limited, and some nodes may have relatively longer upload distances when communicating with the MCGV directly, and they should select the next hop to relay data. However, the nodes near the MCGV should upload their data directly to avoid energy waste caused by the multi-hop mode. It is important to choose the appropriate upload mode for each node in order to balance energy. Thus, in this section, we propose adaptive dual-mode routing which comprises direct and multi-hop modes.

5.1. Direct Upload Mode Threshold

According to the analysis above, the upload mode of each node should change from direct to multi-hop mode as the upload distance increases. Based on the distribution of charging cells, the distance threshold for choosing the upload mode can be calculated as follows:

$$d^{th} = \frac{1}{N} \sum_{i \in V} d_{i,a_i}, a_i \in AS, \tag{10}$$

where AS is the anchor point set, which records the central locations of all charging cells in CV. a_i and d_{i,a_i} are the nearest anchor point of node v_i in AS and the corresponding upload distance, respectively. d^{th} is distance threshold for all nodes, and it denotes the average upload distance for all nodes. Compared with this threshold, the nodes with longer upload distances should choose the multi-hop mode to avoid high energy consumption. On the other hand, the nodes with shorter upload distances should choose the direct upload mode to avoid energy waste caused by the multi-hop mode.

5.2. Multi-Hop Mode Based on Energy Endurance

The energy endurance is designed to reasonably choose the optimal next hop based on the aspect of energy balance. In order to visually represent the spatial relationship of nodes, we establish the forward neighbor set for each node before calculating energy endurance as follows:

$$FN(i) = \left\{ j \middle| d_{j,a_j} \leq d_{i,a_i}, d_{i,j} < R, \left\{ a_i, a_j \right\} \subseteq AS, \right. \tag{11}$$

where $FN(i)$ is the forward neighbor set of node v_i. Forward neighbors of node v_i include some of its neighbors with shorter upload distances. These neighbors act as available next hops to ensure that data from the source node are closer to the MCGV in the process of relaying. This set records all available next hops of node v_i.

In order to balance energy when choosing the next hop, the energy storage level is a necessary consideration. Assuming that node v_i takes node v_j as the next hop, the energy storage level of node v_j can be calculated as follows:

$$es_{ij} = \frac{E_j + E_j^c}{l_i + l_j}, j \in FN(i), \tag{12}$$

where E_j^c is the energy replenishment for node v_j in the current round. l_i and l_j are the traffic loads of node v_i and node v_j, respectively, according to the traffic load mode in Section 3. es_{ij} denotes the available energy for the unit load of node v_j. This indicator is used to quantize the energy state corresponding to the current load.

In addition, it is also a key factor to balance the energy consumption of forward neighbors when nodes choose the next hop. We quantize this factor using Equation (13) in order to reasonably control energy consumption fluctuations.

$$\delta_{ij} = \frac{\sum\limits_{k \in FN(i)} l_k{}' \left| e_{k,a_k} - me_{ij} \right|}{\sum\limits_{k \in FN(i)} l_k{}' \, me_{ij}}, \tag{13}$$

where δ_{ij} denotes the energy consumption balance of node v_i's forward neighbors when node v_j is its next hop. $l_k{}'$ is the updated load, which is the sum of l_k and l_i only if $k = j$. e_{k,a_k} is the corresponding energy consumption when node v_k uploads the traffic corresponding to the unit load to its nearest anchor point. me_{ij} is the average relay energy consumption of the forward neighbors of node v_i when node v_j is its next hop, which can be calculated as follows:

$$me_{ij} = \frac{\sum\limits_{k \in FN(i)} l_k{}' \, e_{k,a_k}}{\sum\limits_{k \in FN(i)} l_k{}'}, j \in FN(i). \tag{14}$$

According to the average relay energy consumption, the node aims to balance load distribution in its forward area when choosing the next hop. The low-load node with a short upload distance has high precedence with respect to relaying traffic in order to balance energy.

The endurance ability of each node is closely related to its energy storage level and corresponding energy consumption equilibrium. Based on these two factors, we calculate the relative energy endurance EE_{ij} of node v_j when it is the next hop of node v_i as follows:

$$EE_{ij} = \log{(1 + \frac{es_{ij}}{e_{j,a_j}})}^{\delta_{ij}}, j \in FN(i). \tag{15}$$

This indicator integrates the energy state, energy replenishment, load distribution, and relay consumption to quantize the relative energy endurance compared with other nodes. Combined with the energy consumption balance of the forward area, the source node chooses the next hop, which features a high energy storage level with proximity to the anchor point. The energy balance can be enhanced in the process of data upload.

5.3. Routing Set-Up and Update

The state of each node changes with time, and the network needs to update routing in a timely manner according to the distribution of charging cells in each round. The MCGV broadcasts the charging scheme and the relative state parameters of all nodes in the previous round at the beginning of the round. Each node determines its next hop according to the information. This process is outlined in Algorithm 1.

Algorithm 1: Adaptive dual-mode routing-based mobile data gathering algorithm.

Inputs: Sensor list V, Anchor point set AS,
Outputs: Network Routing $V.next$;
for all $v_i \in V$
$FN(v_i) = \left\{v_j \middle| d_{i,a_i} > d_{j,a_j}, d_{i,j} \leq R, \left\{a_i, a_j\right\} \subseteq AS\right\}$
if $d_{i,a_i} \leq d^{th}$ or $FN(v_i) \in \phi$ **then** $v_i.next \leftarrow a_i$;
else $v_i.next \leftarrow \arg\max_{v_j \in FN(v_i)}\left\{EE_{v_j}\right\}$;
end if
end for
$V.next = \{v_i.next | \forall v_i \in V\}$

Each node collects sensor data and determines its next hop according to adaptive dual-mode routing, as shown in Algorithm 1, at the beginning of the round. The nodes which adopt the multi-hop mode send their data packets to their next hops until these data packets reach the nodes which adopt a direct upload mode. The MCGV broadcasts its location to the network when visiting each charging cell in CV in order to charge the nodes in these cells. Meanwhile, it gathers data packets from the direct upload nodes upon reaching the nearest charging cells. Compared with the single upload mode, adaptive dual-mode routing for mobile data gathering in this paper can optimize the energy balance effect.

The operation principle of adaptive dual-mode routing is described in Figure 2. The average upload distance of nodes is relatively short in mobile data gathering, but some nodes still have a longer upload distance, and their energy consumption is higher than that of other nodes. According to adaptive dual-mode routing, the nodes near anchors still employ the direct upload mode. However, the nodes with a long upload distance can change to the multi-hop mode, which decreases their energy consumption and balances energy. Moreover, the network lifetime can be prolonged based on this routing strategy.

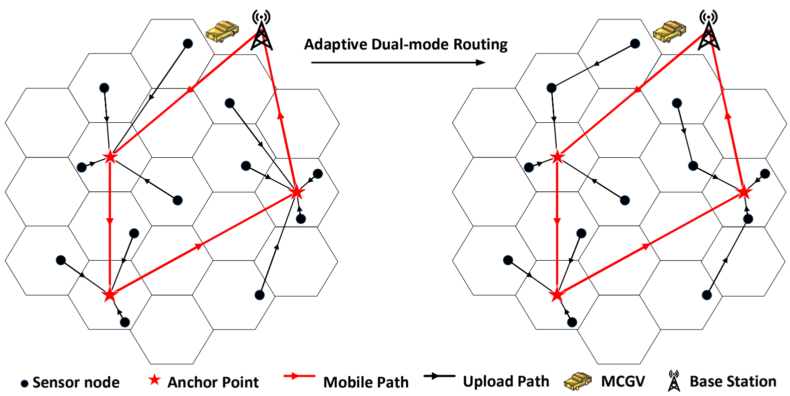

Figure 2. Operation principle of adaptive dual-mode routing.

6. Performance Evaluation

In order to evaluate the performance of the algorithm, we used MATLAB to simulate the algorithm. Each node was randomly distributed in a circular area with a radius of 100 m, and the simulation parameters were as shown in Table 1. The simulation results are given below.

Table 1. Simulation parameters.

Simulation Parameters	Value
τ	4.32×10^{-4}
β	0.2316
N	100–250
R	30 m
E_o	0.1 J
T	800 s
T_o	3 s
S	5 m/s
D	5 m
P	0–0.5 W

6.1. Algorithm Performance Analysis with Different α

In order to analyze the impact of α on performance, we ran the simulator with different values of α with a charging power of 0.3 W. Without the loss of generality, we conducted 10 simulations and selected the average of the experimental results for analysis. The corresponding results are described below.

Figures 3 and 4 respectively show the changing trends of the average moving time and average energy consumption as α increased. The average moving time is the average time that the MCGV uses to move in each round, and it was found to lengthen as α increased. This is because the time for the MCGV to move was longer. The average energy consumption is the mean of the average energy consumption of all nodes in each round, and it was found to decrease as α decreased. This is because the node upload distance also decreased. Based on these observations, the changing trend of lifetime could be ascertained.

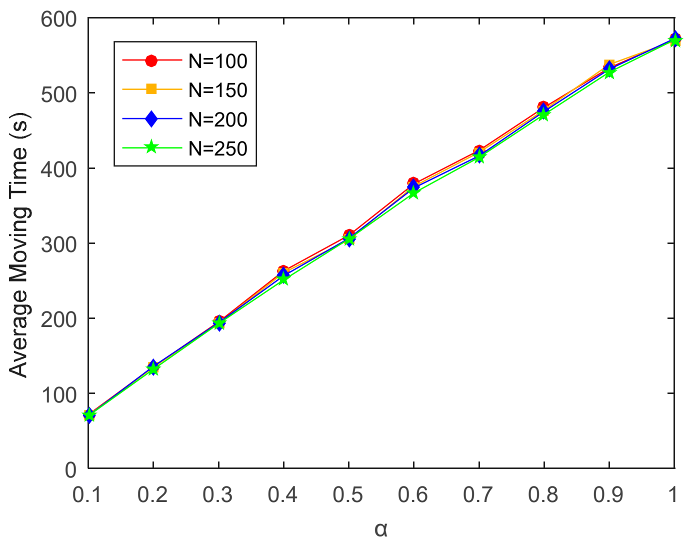

Figure 3. Impact of α on average moving time (P = 0.3 W).

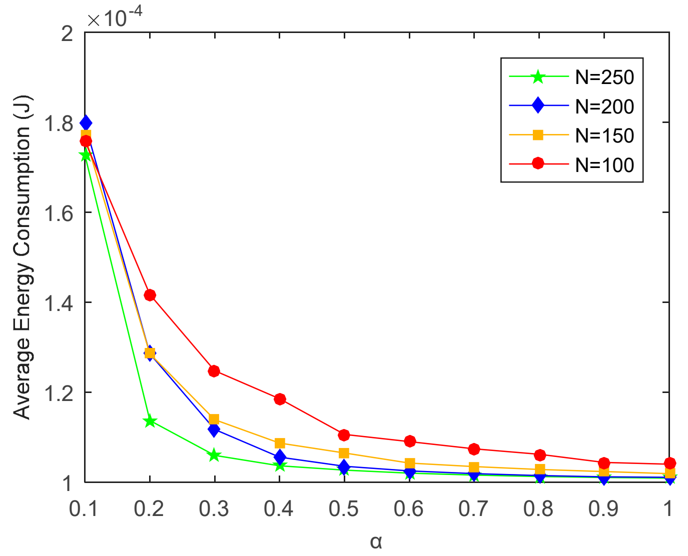

Figure 4. Impact of α on average energy consumption (P = 0.3 W).

The lifetime is the round number when the first dead node appears. We found that the network lifetime increased with the increase of α in the range [0, 0.4], reaching the maximum when $\alpha = 0.4$, while it decreased in the range [0.7, 1], as shown in Figure 5. This is because larger α can increase the number of charging cells and, thus, reduce the average energy consumption of all nodes, which can prolong the network lifetime. However, excess charging cells increase the moving time of the MCGV and reduce the charging time in each round. The network lifetime, therefore, decreases dramatically when α is high.

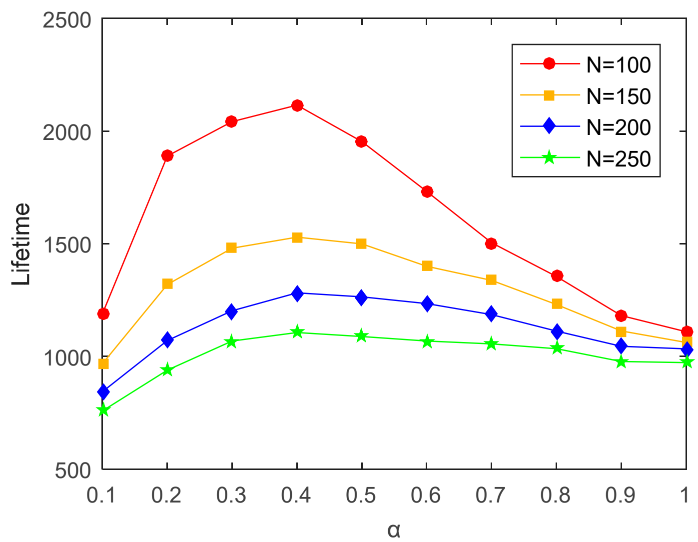

Figure 5. Impact of α on network lifetime (P = 0.3 W).

6.2. Performance Comparison Analysis of Different Algorithms

In order to verify the effect of the proposed algorithm in prolonging the network lifetime, we compared the ADRMDG with ADRMDG in direct upload (ADRMDG-DU), low-energy adaptive clustering hierarchy with energy replenishment (LEACH-ER), and autonomous load regulation mechanism-based routing (ALRMR). In ADRMDG-DU, each node uploads data directly without adaptive dual-mode routing when the MCGV sojourns at its nearest anchor point, as shown for the network on the left of Figure 2. In LEACH-ER, we add the same charging strategy of ADRMDG to LEACH [28] in order to make a relatively fair comparison with traditional clustering routing. ALRMR is an efficient framework of joint wireless energy transfer and multi-hop routing, where the routing strategy is adapted to the charging scheme. The corresponding results are described below.

We firstly analyzed the lifetimes of different algorithms as the node number changed. The MCGV needed to charge more nodes as the node number increased, but its maximum power did not change. This means that the charging efficacy of the MCGV was diluted with an increasing number of nodes. Hence, as shown in Figure 6, the network lifetime inevitably declined as the node number increased. Compared with the traditional single sink mode in ALRMR and LEACH-ER, the network lifetime could be extended through mobile data gathering in ADRMDG-DU. In addition, the network lifetime could be further enhanced with the introduction of adaptive dual-mode routing in ADRMDG, as demonstrated in Figure 7.

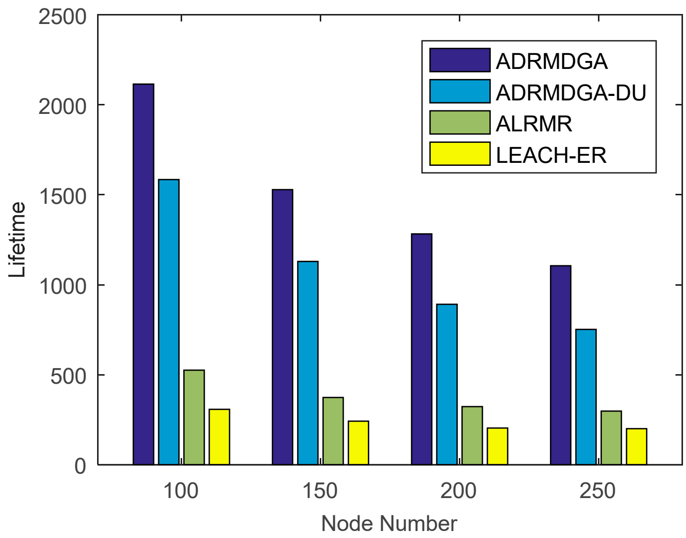

Figure 6. Impact of node number on network lifetime in different algorithms (P = 0.3 W).

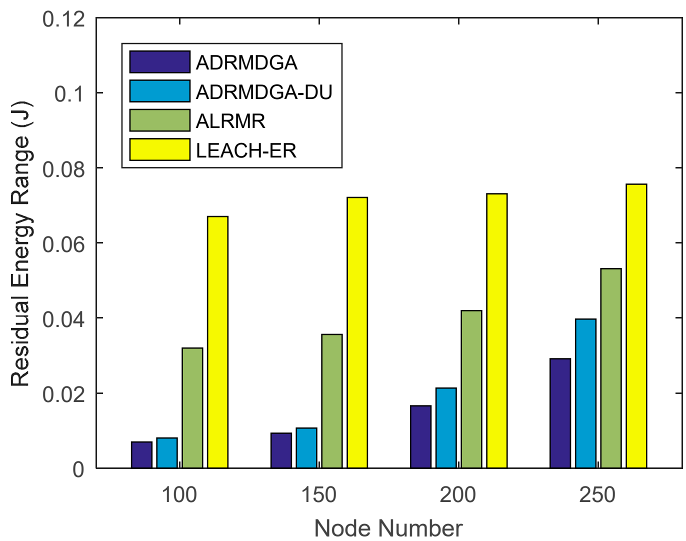

Figure 7. Impact of node number on residual energy range in different algorithms (P = 0.3 W).

Figure 7 shows the corresponding residual energy ranges of different algorithms. The residual energy range is the difference between the maximum and minimum residual energy when the first dead node appears, and it is used to reflect the energy balance of algorithms. We found that the residual energy ranges of LEACH-ER and ALRMR were very large. This is because there was only a static single sink to collect data in these two algorithms. Fringe nodes have to upload data over a long distance, which means that some nodes have higher energy consumptions due to them relaying too much traffic. Their energy equilibrium is weak, and the network lifetime is small. After introducing mobile data gathering, the load distribution becomes more uniform and the average energy consumption decreases. The residual energy range of ADRMDG-DU decreased obviously, which prolonged the network lifetime. However, the number of anchor points was constrained by the charging efficiency, and some nodes still had relatively higher energy consumption caused by the longer communication distance when directly communicating with the MCGV. Combined with adaptive dual-mode routing, the energy consumption of nodes could be balanced effectively when the MCGV gathered data, and the residual energy range of ADRMDG was the smallest. Thus, its network lifetime was the longest.

Finally, we analyzed the charging efficiencies of different algorithms, as shown in Figure 8. It can be seen that the network lifetime could be prolonged significantly as the charging power increased. This is because the effect of energy balance could be enhanced with the increase in charging power. Furthermore, the charging efficiency of ADRMDG was the highest, as demonstrated in Figure 9.

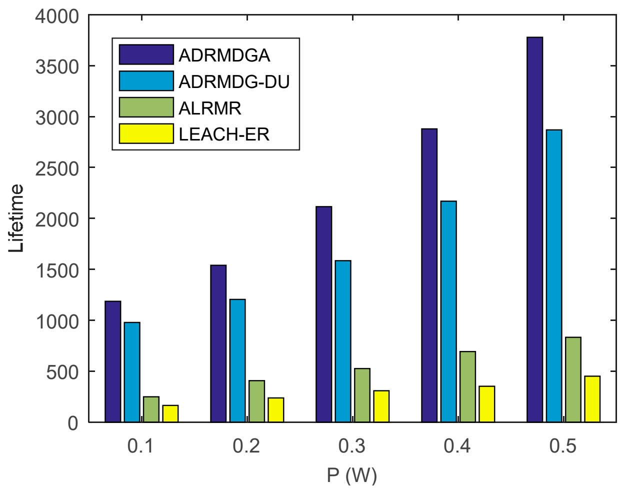

Figure 8. Impact of charging power on network lifetime in different algorithms (N = 100).

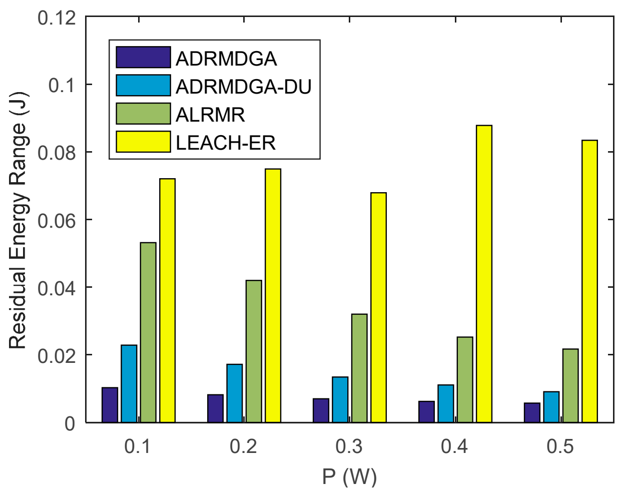

Figure 9. Impact of charging power on residual energy range in different algorithms (N = 100).

In Figure 9, it can be seen that the residual energy range of LEACH-ER was the highest and could not decrease as the charging power increased. This means that more charging power could not enhance the effect of energy balance in LEACH-ER, and its lifetime could not be prolonged significantly. The residual energy ranges of ALRMR and ADRMDG declined stably as the charging power increased, and their lifetimes could be prolonged significantly. However, their energy balances were lower than that of ADRMDG with the same charging power, and low-energy nodes had a higher probability of occurrence, which decreased the charging efficiency of the MCGV. Thus, ADRMDG maximized the charging efficiency of the MCGV and had the longest network lifetime.

7. Conclusions

We proposed an adaptive dual-mode routing-based mobile data gathering algorithm for RWSNs in this paper. The MCGV prioritizes the energy supplementation of low-energy nodes when gathering data. Due to the joint action of mobile data gathering and the adaptive dual-mode routing mechanism, the energy equilibrium improves, and the network lifetime is effectively prolonged.

In addition, we would like to point out that there are some interesting issues that may be studied in our future work. Firstly, the optimal anchor point locations can be further researched on the premise of ensuring that the calculation amount is not too large. Secondly, the energy transfer among nodes can be considered to better balance the energy if the energy waste of this process can be effectively controlled.

Author Contributions: Conceptualization, H.G; methodology, H.G. and L.T.; software, H.G.; validation, H.G.; formal analysis, R.W. and H.G.; investigation, H.G.; resources, R.W. and L.T.; data curation, H.G.; writing—original draft preparation, H.G.; writing—review and editing, R.W. and L.T.; visualization, H.G.; supervision, R.W. and L.T.; funding acquisition, B.F. All authors have read and agreed to the published version of the manuscript.

Funding: This work was partially supported by the National Natural Science Foundation of China under grant number 51677065.

Conflicts of Interest: The authors declare no conflict of interest.

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