Received June 14, 2017, accepted July 6, 2017, date of publication July 18, 2017, date of current version August 22, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2727041

MCRA: A Multi-Charger Cooperation Recharging Algorithm Based on Area Division for WSNs

GUANGJIE HAN[1,2], (Member, IEEE), ZHIFAN LI[3], JINFANG JIANG[3], LEI SHU[4,5], (Senior Member, IEEE), AND WENBO ZHANG[6]

[1]Department of Information and Communication Systems, Hohai University, Changzhou 213022, China
[2]State Key Laboratory of Acoustics, Institute of Acoustics, Chinese Academy of Sciences, Beijing 100190, China
[3]School of Information and Communication Systems, Hohai University, Changzhou 213022, China
[4]Guangdong Provincial Key Laboratory of Petrochemical Equipment Fault Diagnosis, Guangdong University of Petrochemical Technology, Maoming 525000, China
[5]School of Engineering, University of Lincoln, Lincoln LN6 7TS, U.K.
[6]School of Information Science and Engineering, Shenyang Ligong University, Shenyang 110159, China

Corresponding author: Guangjie Han (hanguangjie@gmail.com)

This work was supported in part by the National Natural Science Foundation of China under Grant 61572172 Grant 61602152, and Grant 61401107, in part by the Fundamental Research Funds for the Central Universities under Grant 2016B10714 and Grant 2016B03114, in part by the Changzhou Sciences and Technology Program under Grant CE20165023 and Grant CE20160014, in part by the Six Talent Peaks Project in Jiangsu Province under Grant XYDXXJS-007, in part by the Open Fund of State Key Laboratory of Acoustics under Grant SKLA201706, and in part by the Maoming Engineering Research Center on Industrial Internet of Things under Grant 517018.

ABSTRACT Recent breakthroughs in wireless charging technologies have greatly promoted the development of rechargeable wireless sensor networks (WSNs). To improve the lifetime of WSNs in many applications, the charging efficiency of mobile chargers (MCs) and the energy supplement of MCs should be improved. Although optimized charging path schemes in WSNs have been studied extensively, little attention has been paid to determine the energy consumption of MCs while charging and their movement during the charging tasks. In this paper, we analyze the relationship of the movement energy consumption of MCs and their energy transfer to the nodes and put forward our algorithm for improving the charging efficiency of the MCs. We divide the entire network into different charging regions and propose three charging schemes based on different situations in each region. The idea of cooperation among the MCs to charge MCs further enhances the charging efficiency of the MCs. A simulation demonstrates the advantages of our algorithm for improving the lifetime and charging efficiency of the MCs. This paper aims to improve the lifetime of WSNs and to decrease the cost for charging nodes and results in a longer lifetime for WSNs in applications with limited energy.

INDEX TERMS Wireless sensor networks, mobile chargers, charging efficiency, movement energy consumption.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have many applications, such as monitoring of the structural health in coal mines, toxic gas monitoring in industrial areas, and prevention of forest fires. Many efforts have been made to improve the working efficiency of WSNs. The WSNs require sufficient power for long operating times, however, sensor nodes in WSNs are equipped with small batteries that have relatively little power; thus, the entire network has a limited lifetime. Existing methods to prolong the lifetime of sensor nodes have been put forward and include energy savings [1], energy harvesting [2], and node reclamation [3]. However, using these methods, it is difficult to maintain a steady energy supply to guarantee a long lifetime of the nodes, which has a great influence on the service quality of WSNs.

Recently, advances in wireless energy transfer have made a breakthrough. Therefore, the problem of the energy supply for the nodes can be solved reliably. The feasibility of wireless energy transmission has been demonstrated by Kurs in [4]. In [4], a high-efficient energy supply is obtained over a distance by coupling resonance. Furthermore, Kurs developed a series of prototype devices for wireless energy transmission. This technology has brought forth new ideas for supplying energy for WSNs. Prior studies have proposed that wireless chargers equipped with coupling coils are able to recharge near sensor nodes using this new technology. These chargers are located on vehicles or mobile robots and all nodes in the WSN can be recharged as the vehicles move around the WSN. The lifetime of the WSNs is extended by using these mobile chargers (MC), which provide a stable supply of energy.

However, the limited capacity of battery influences a MC's working hours. Due to the limited power a MC carries, the energy consumption has a great impact on the MC's work. The energy consumption of a MC in charging tasks can be divide into two parts: 1.energy consumed by charging nodes; 2. movement energy consumption. (Compared with these two parts, other energy consumption is too little to be ignored.) So reducing movement energy consumption will enhance working hours of MCs. In this paper, we propose a multi-charger cooperation recharging algorithm (MCRA) based on an area division for WSNs to reduce the movement energy consumption of MCs. First, we divide the entire network area into small rechargeable regions and the nodes in each region are recharged by a MC that is deployed only in this region. Further, we design the different working modes and energy supplies of the MCs based on their locations and working loads. Moreover, the idea of cooperation between neighboring MCs is proposed to reduce the movement energy consumption of the MCs.

The main contribution of this paper is that we propose MCRA and prove its practicability by theoretical derivation and simulation. Compared with other algorithms, MCs in different regions select more appropriate working modes and energy supply methods in MCRA. Moreover, the method that MCs cooperate with its neighboring MCs is proposed to further reduce movement energy consumption.

The remainder of this paper is organized as follows: Section II summarizes recent developments for charging algorithms in WSNs. Section III describes our charging algorithm in detail. Section IV presents our simulation results and Section V presents a summary and projects future work.

II. RELATED WORKS

Many researchers have devoted much effort over many years to optimize the charging algorithms that can prolong the lifetime of WSNs. For instance, Xie *et al.* in [5]–[7] proposed many improvements for algorithms related to wireless recharging of networks.

A number of studies have focused on the adjustments of the traverse route and the working mode of a single MC. In [8], Fu *et al.* proposed a charging algorithm aimed at reducing the amount of time that a MC spends in one location. In [9], Shu *et al.* proposed an algorithm that allows a MC to charge nodes while moving instead of stopping to recharge. The basis of his article is that an MC can charge a sensor node effectively within a certain distance. In [10], Han *et al.* proposed a grid-based joint routing and charging algorithm that projects the charging path of the MC in industrial wireless rechargeable sensor networks.

In contrast, some researchers have focused on the operation of multi-chargers and their cooperation. In [11], Yao *et al.* proposed three multi-charger schemes, termed the Region Patrol Charge Scheme (RPC), the Region Inquire Charge Scheme (RIC), and the Distance and Energy Aware Charge Scheme (DEC). In [12], Zhao *et al.* proposed a multi-charger scheme that classifies the nodes based on a threshold value and charges different kinds of nodes in different manners. In [13], Zhang *et al.* proposed an algorithm involving collaborative mobile charging and termed PushWait. In [14], Lin *et al.* proposed a game theoretical collaborative charging scheme for wireless rechargeable sensor networks. In [15], Madhja *et al.* proposed an algorithm using different types of MCs. The authors stated that the MCs can be categorized into two types; one is a common MC that charges the nodes and the other type is called a super MC that charges common MCs.

In the above-mentioned studies, the charging strategy of the MCs has been improved in various ways. However, few articles have focused on the MCs movement energy consumption and energy supply although these two factors have a strong impact on the working efficiency of the MCs. Therefore, in this study, we take the movement energy consumption into consideration and propose a solution for large-scale WSNs. Reducing the scale of the working area facilitates saving battery power so that the MCs can operate for a longer time period. By solving the problem of the MCs energy supply, the time required for MCs to return to the base station for recharging is minimized. The highlight of our study can be summarized with regard to two aspects: 1) the network is divided into several parts based on the regional characteristics (the energy state of sensor nodes and the distance between the base station and the node), and 2) the design of the cooperation of multiple MCs solves the problem of the energy supply for remote MCs.

III. A MULTI-CHARGERS COOPERATION RECHARGING ALGORITHM

In this section, we show the detail of our proposed algorithm, including dividing charging regions, designing working mode of MCs, projecting energy supply approaches of MCs.

A. NETWORK MODEL

Our model can be described as follows. There are N stationary sensor nodes distributed uniformly over the network. S MCs are deployed in the WSN to charge the sensor nodes that have a low battery. The entire network is represented as a large-scale square region with a side length L; a base station at the center of the region collects the data and charges the MCs. We assume that all sensor nodes know their location and their neighbors' locations and the base station is aware of the locations of all MCs. The sensor nodes consume power by receiving and transmitting data packets wirelessly with a communication range of r. The sensor nodes pass the packets to the neighboring node, which is closest to the base station. In this manner, packets are delivered to the base station with the least number of transmissions, in other words, with the least amount of energy consumption in the network. However, this means that nodes near the base station spend more energy transmitting packets while others away from the base station consume less energy.

Figure 1 illustrates the distribution of the energy consumption of the nodes. The nodes that are mostly black consume

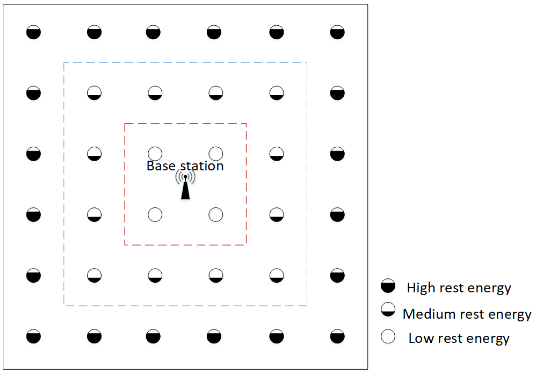


FIGURE 1. An example of the energy consumption of the nodes.

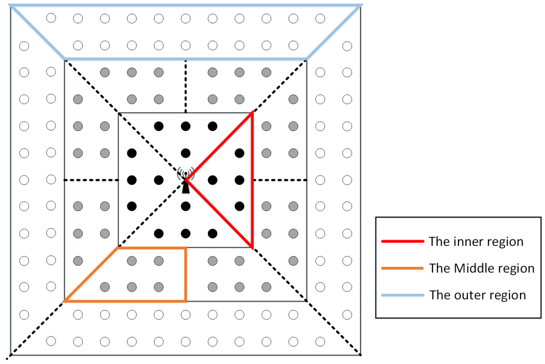


FIGURE 2. Division of the charging regions.

energy slowly and the nodes that are half black consume energy more quickly while nodes that are mostly white consume energy at the highest rate. We can see that sensor nodes closer to the base station have a shorter life time.

In this study, every MC has the same structure as an RFID reader and represents an intelligent mobile vehicle. The MCs have limited battery power E_{MC}. Further, the MCs move at a constant speed V to traverse the sensor nodes that require energy. For efficient energy transmission, we stipulate that the antenna of the MC is directional and that an MC can charge only one sensor node at the same time. We define that the distance for every transmission should have the lowest value, for example, 0, for maximizing the efficiency of the transmission.

We propose an important parameter called the charging efficiency that has great influence on the MCs working efficiency. The charging efficiency is defined by the following formula:

$$e_C = \frac{E_C}{E_T} \tag{1}$$

where e_C is charging efficiency, E_C is the energy that the MC provides to the nodes and E_T is the total energy consumption of the MC. A high charging efficiency means that the MC provides more energy to the nodes and consumes less energy during movement. Therefore, our goal is to develop a highly efficient charging algorithm.

B. DIVISION OF THE CHARGING REGION

As illustrated in Fig. 1, nodes in different regions have different energy consumption rates. Nodes near the base station have the shortest lifetime without charging while nodes further away from the base station have a much longer lifetime. Therefore, we divide the network into three different regions based on the different lifetime lengths. The area is divided into three concentric squares with the base station located in the center. Three different charging regions exist, the inner region, the middle region, and the outer region. Sensor nodes in the inner region consume energy fastest because they not only collect information but also transfer packets from other regions while the nodes in the outer region consume relatively small amounts of energy during the same time. The MCs are deployed in these regions to charge the nodes. Because one MC cannot charge the sensor nodes in a large region in time, we divide the three regions into smaller regions by inserting diagonals into the square. As illustrated in Fig. 2, the inner region is divided into four triangle regions while the middle and outer regions are divided into four trapezoids. Next, the isosceles trapezoid in the middle region is split into two trapezoids. The triangle outlined in red represents the final inner region, the trapezoid outlined in orange is the final middle region, and the isosceles trapezoid outlined in blue is the final outer region. The MCs are responsible for charging the nodes in only their regions and we name them the inner MCs, the middle MCs, and the outer MCs according to their locations. We assume that node density is ρ and the height of the inner region, the middle region and the outer region are respectively H_1, H_2 and H_3. The number of nodes in these three region are N_1, N_2 and N_3. Therefore we can calculate the movement energy consumption of MCs in different regions as E_{M_1}, E_{M_2} and E_{M_3}:

$$E_{M_1} = E_M \cdot (N_1 \cdot \rho^{-\frac{1}{2}} + H_1) \tag{2}$$

$$E_{M_2} = E_M \cdot (N_2 \cdot \rho^{-\frac{1}{2}} + H_2) \tag{3}$$

$$E_{M_3} = E_M \cdot (N_3 \cdot \rho^{-\frac{1}{2}} + H_3) \tag{4}$$

where E_M is the movement consumption rate of an MC. Because the nodes are uniformly distributed, the distance between any two neighboring nodes can be calculated as $\rho^{-\frac{1}{2}}$. In consideration of MC back to start position of charging task, the length of the height, for example, H_1 is added to the movement path length in the above formula. Next, it's important to calculate the energy consumption of an MC that is transferred to the nodes in one charging cycle, E_{C_1}, E_{C_2}, E_{C_3} as follows:

$$E_{C_1} = \sum_{n=1}^{N_1} \frac{E_n}{\eta} \tag{5}$$

$$E_{C_2} = \sum_{n=1}^{N_2} \frac{E_n}{\eta} \tag{6}$$

$$E_{C_3} = \sum_{n=1}^{N_3} \frac{E_n}{\eta} \tag{7}$$

where E_n is the energy node n receives from an MC, and η is the energy transfers efficiency rate. Therefore, the total energy consumption of the MCs in the three regions in one charging cycle is proposed as follows:

$$E_{T_1} = E_{M_1} + E_{C_1} \tag{8}$$
$$E_{T_2} = E_{M_2} + E_{C_2} \tag{9}$$
$$E_{T_3} = E_{M_3} + E_{C_3} \tag{10}$$

In above formulas, ρ, η, E_M are constants. Therefore E_{C_1}, E_{C_2} and E_{C_3} are only related to the value of the region's height H_1, H_2, H_3 and E_n. E_n is also related to the sensors' location. Therefore, the heights of the regions have great impact on the MCs' energy consumption.

In this study, we assume that the inner MC survives for at least one charging cycle and retains enough energy to charge the middle MC. The middle MC should also survive for at least one charging cycle without any recharging from the inner MC. The longer the middle MC survives, the greater the error-tolerance rate of the scheme becomes. The middle region should not be too large. We assume that the energy consumption of the MCs in the inner and middle regions should satisfy the following formula:

$$E_{T_1} \geq \frac{1}{3} E_{MC} \tag{11}$$
$$E_{MC} - E_{T_1} \leq \frac{1}{2} E_{T_2} \tag{12}$$

where E_{MC} is the battery capacity of the MCs. The formula shows that the inner region should not be too small so that the inner MC charges a sufficient number of nodes to lighten the burden for the MCs in the other regions. The middle MC should not exhaust its energy during the time when the inner MC completes at least two charging cycles because the inner MC only charges the middle MC every two charging cycle. In this study, the outer MC is unable to charge all the nodes in the outer region without an additional energy supply. Therefore, this MC can choose the outer region and limit the number of times that the outer MC returns to the base station. This number was set as a threshold value R_n of 5, meaning that the outer MC returns to the base station no more than five times before it charges all the nodes in the outer region. Based on these restrictions, we confirm the values of H_1, H_2, and H_3. However, there are several combinations of H_1, H_2, and H_3 that satisfy our demand. And we choose the approach where H_1 is the minimum because this decreases the time required for one charging cycle of the inner MC, which results in more frequent charging of the middle MC by the inner MC. Based on the requirement that the outer MC returns to the base station as few times as possible, H_3 should be as large as possible to decrease the workload of the inner and middle MCs. Our simulations proved our conclusion.

C. DETAILS OF MCRA

1) THE WORK MODE OF THE INNER MC

Sensor nodes in the inner region have the greatest load to transfer data packets from other regions to the base station. The energy consumption rate of the sensor nodes in the inner region is higher than for the nodes in the other regions. The workload of the MCs in the inner region is heavier. Every node in the inner region has to be charged in time or it will run out of power. Due to these conditions, we propose the following charging scheme to solve these problems:

Firstly, the MC near the base station is fully recharged and waiting for orders. When node i in the inner region detects that the battery is below the energy threshold value, it sends a charging request to the base station. The base station requests that the MC responsible for this region begin its charging cycle. The MC receives the charging task and moves to node i to charge it. After fully charging node i, the MC continues its charging task by charging node j, the node that is near node i and has low energy. When node j is fully charged, the MC chooses node k, the brother adjacent to node j, as the next charging node. Here, brother node indicates a node that is in the same horizontal position as the reference node. The father node is the node that lies in the horizontal position closer to the base station while the son node is the node that lies in the horizontal position farther away from the base station. Therefore, the charging route path of the inner MC is described as follows:

Routing Path A (RPA): When the MC completes its current charging task, it first chooses its nearest brother node as the next charging target. If there is no brother node, the MC charges the son node, which is close to the MCs current position and farther away from the base station. After finishing the charging cycle, the MC returns to the base station and waits for the next charging cycle.

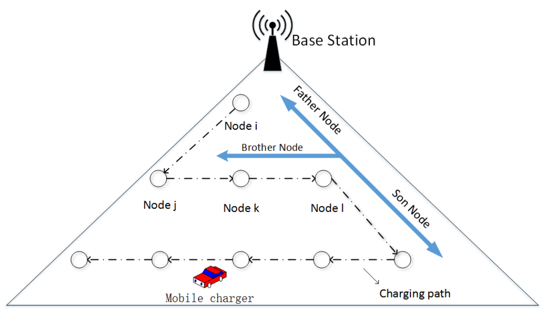


FIGURE 3. An example of the charging path in the inner region.

As illustrated in Fig. 3, the MC chooses its charging path as it moves along the line connecting node i, node j, node k, and node l. In RPA, node i is chosen first because it is the node closest to the base station and has the lowest lifetime in the inner region. When node i requests a charging, the MC begins its charging cycle. After charging node i, the MC chooses node j, the son node of node i with the least amount of energy and farthest away from the base station. Then, node k is chosen as the next charging node because it is the only brother node of node j. In RPA, a charged node has only one uncharged brother node. All nodes in the inner region can be traversed and charged in this manner.

In some studies, a charging scheme has been proposed in which the MC charges a sensor node after and only after

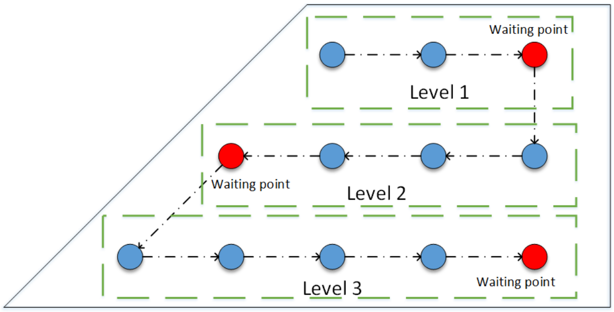


FIGURE 4. An example of the charging path in the middle region.

the node has sent the charging request to the MC or to the base station. In this study, this type of charging scheme is not suitable because the nodes in the inner region are consuming energy rapidly all the time. Moreover, based on routing the data packets using the shortest path, the neighboring sensor nodes have similar energy consumption because the flow of packets through them is roughly the same. Therefore, if a sensor node determines that its rest energy is below the threshold value, its neighbor nodes, such as the brother or son's nodes, will soon have low energy as well and will request charging.

2) THE WORK MODE OF THE MIDDLE MC

Nodes in the middle region have a relatively low workload and their energy consumption is much lower than that of the nodes in the inner region. Therefore, the charging task is lighter for the MCs in the middle region than for the MCs in the inner region. The charging scheme, RPA, can also be applied in the middle region; however, it would require some modifications. Due to a lower energy consumption rate of the nodes in the middle region, the MC has sufficient time to charge the low-power nodes before they die. In this study, we propose Routing Path B for the middle MC.

Routing Path B (RPB): When the MC finishes its current charging task, the base station checks whether any uncharged brother nodes exist. If this is the case, the MC will choose the closest brother node as the next charging node. Otherwise, the MC remains until one of son node sends its charging request to the base station. After receiving the charging request, the base station commands the MC to charge the son node located at the edge of the region and close to the current location of the MC. However, the base station detects when it is time to begin the next charging cycle. If this is the case, the MC can remain at the following waiting point. If this is not the case, the MC has to begin charging the remaining nodes without any hesitation. After finishing the charging cycle, the MC returns to the origin and waits for next charging cycle.

As shown in Fig. 4, the MC first stays within the boundary of the inner region and the middle region. A node in level 1 is low in energy and sends a charging request to the base station, indicating that the remaining energy of the nodes in level 1 is approximately at the energy threshold. The MC begins its charging cycle by charging nodes in level 1. The MC follows RPB to choose the first node for charging in level 1. After charging the last node in level 1, the MC remains and waits for a charging request in level 2. However, after the MC finishes charging in level 3, the base station detects that nodes in level 1 need to be charged shortly. As a result, the MC does not wait in level 3 and immediately charges the remaining nodes. In this manner, the MC charges all the nodes in the middle region. If charging requests from the next level are sent to the base station before the MC finishes charging nodes in the current level, the MC will first charge nodes in the current level and then begin charging nodes in the next level without waiting any longer.

In RPB, all nodes in the region are classified as being in different levels based on their horizontal location. Each level has a similar energy consumption rate because of the network model. The energy consumption rate of the nodes decreases progressively from level 1 to level 3. So as shown in Fig. 4, the MC always moves from level 1 to level 3 during the charging cycle because the nodes in level 1 send their charging requests first. Compared with RPA, the charging scheme in RPB ensures that the MC remains at the respective level at the end of the charging cycle because this maximizes the amount of energy the MC transfers to the nodes during each charging cycle. If the MC charges in the next level without waiting for a charging request, the energy amount that the MC transfers to the nodes is lower because the nodes have energy remaining in their batteries. The charging efficiency is low if many nodes have excess rest energy. Therefore, it is wise for the MC to wait so that the nodes in the next level can consume more energy. Furthermore, the waiting time of the middle MC facilitates the idea of the cooperation of multiple MCs (we will introduce the idea of cooperation later).

3) THE WORK MODE OF THE OUTER MC

Sensor nodes in the outer region consume less energy for a longer time. Compared with the MCs in the inner and middle regions, the outer MC has a lower workload. However, in the outer region, an MC is responsible for more nodes than in the other regions. In other words, the area of the outer region that the MC serves is larger than the other regions. Therefore, if the MC wants to complete a charging cycle in the outer region, it will consume more energy during the movement. In RPA and RPB, the MC carries out its charging task by the unit as a charging cycle. But in the outer region, the MC does not charge any nodes in advance. The MC charges a node after the node has sent its charging request to the base station. This scheme ensures that the nodes consume more energy stored in their batteries until they sound an energy alarm. It does not matter that many sensor nodes send their charging requests at the same time because the remainder of the nodes that are not chosen immediately by the MC can survive for a relatively long time due to their low energy consumption rate. The MC has enough time to charge these nodes one by one. According to the above-mentioned issues, the Routing Path C is suitable for the outer MC.

Routing Path C (RPC): When the MC finishes its current charging task, it remains at the current location and waits for the next charging task assigned by the base station. The base station receives the charging request from the node that has a low life time and sends the charging task to the MC. If there are two or more charging requests sent to the base station at the same time, the base station will choose the node that has the lower rest energy and is closer to the current location of the MC.

In RPC, the outer MC focuses on its current charging task and waits for the next task. The life time of the nodes that have low power is long enough to survive until the MC charges them. However, in RPC, the MC may traverse a previously travelled path to charge an uncharged node, which requires additional energy consumption for movement energy consumption. It is inevitable that the MC consumes additional energy due to a high usage rate of the nodes battery power, which causes the MC to transfer more power in one charging task.

D. ENERGY SUPPLY FOR THE MCs

In this study, MCs in different regions have different workloads and consume different amounts of energy. The inner MC requires a higher frequency of energy supply to maintain its routine work, while the outer MC can operate for a long time without an energy supply. Therefore, we propose different energy supply schemes for the MCs in different regions.

Based on the high energy consumption rate of the inner MC, the MC should obtain an energy supply after completing each charging cycle. The MC obtains the energy supply from the base station after it returns from a charging cycle. The energy consumption of the MC returning to the base station is not high because the inner region is not large and the MC can reserve sufficient amounts of energy for returning to the base station.

However, this approach is not suitable for the middle MC because the path is too long for the MC to return to the base station. If the middle MC spends time returning to the base station, the sensor nodes that the MC is responsible for are in danger of running low on energy during this period. On the other hand, the MC has to reserve enough energy to return to the base station, which limits the amount of energy that can be transferred to the nodes. We propose that the inner MC cooperates with the middle MC to obtain an energy supply by using the remainder of the energy of the inner MC. The scheme is illustrated as follows:

When the inner MC finishes its charging cycle, it does not return to the base station directly but begins charging the middle MC. The inner MC travels to one of the middle regions and informs the middle MC that it requires charging. When the middle MC receives this information, it sends its location to the inner MC, so that it can finish its charging task at the current level and waits for the charging request for the next level. This means that the inner MC confirms the location where it will transfer energy. The two MCs meet at the location and begin the energy transmission. During this process, the inner MC reserves only the energy that is required to return to the base station and transfers the remainder of the energy to the middle MC. Subsequently, the inner MC returns to the base station and the middle MC continues its charging cycle. After the next charging cycle of the inner MC, it will charge the MC of the other middle region in the same way. Using the principle of cooperation, the inner MC charges the two middle MCs.

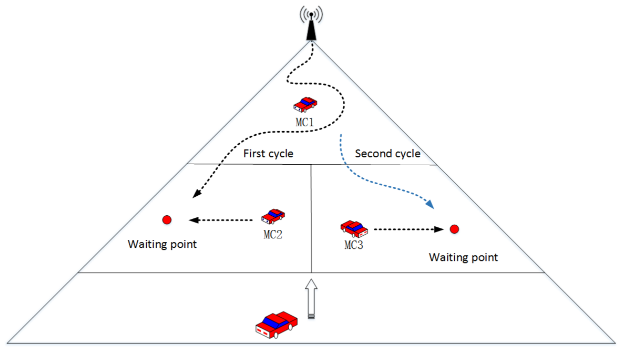


FIGURE 5. An example of the MCs energy supply.

As shown in Fig. 5, MC1 charges MC2 after the first charging cycle and charges MC3 after the second charging cycle because the rest energy is lower for MC2 than for MC3. Both MC2 and MC3 obtain the energy supply in a non-conflicting manner.

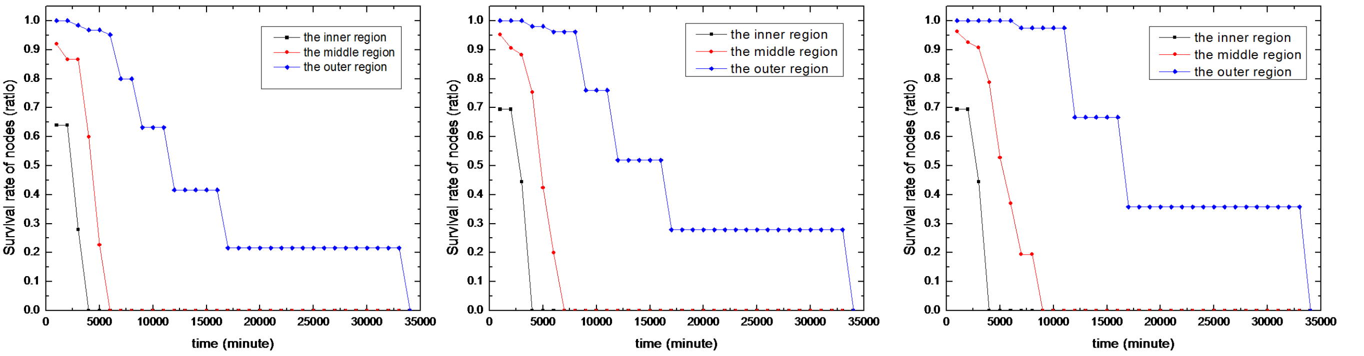
In our algorithm, the middle MC obtains an energy supply without returning to the base station. This minimizes the issue of energy supply and allows the middle MC to focus on its charging task. The inner MC requires additional energy consumption for movement in this cooperation scheme. However, compared with the case of the middle MC returning to the base station and back, this small amount of energy movement energy consumption is acceptable.

The outer MC consumes its energy at a relatively slow rate and its battery can operate at a low energy value in a long time. Every time the outer MC requests a supply of energy, its battery is almost empty and has to be fully recharged. This large dose of energy supply is only well executed by the base station. Therefore, the outer MC returns to the base station for its energy supply. Due to the long lifetime of the nodes in the outer region, the outer MC has sufficient time to return to the base station and back and it is unnecessary to use the same cooperation scheme as in the middle region.

IV. SIMULATION

A. EVALUATION SETUP

The simulation performance of the charging algorithm was evaluated using MATLAB. The details of the significant parameters and their values are as follows. There are 900 nodes uniformly deployed in a 1800 m * 1800 m square sensing area. The minimum distance to a neighbor node is 60 m. Every 20 seconds, the nodes sense the data and transfer the data packets to the base station. The energy consumed in every transmitting procedure is 0.01 J. The battery capacities of the MC and the node are respectively 30000 J



(a) (b) (c)

FIGURE 6. **(a) the survival rate of nodes in 5-5-5 the division (b) the survival rate of nodes in 6-6-3 the division (c) the survival rate of nodes in the 6-5-4 division.**

and 900 J. The MC maintains a speed of about 1 m/s during its charging task. The consumption of movement is 5 W.

We mainly focus on two parameters, the survival rate of the nodes and the charging efficiency, to determine the performance of the MCRA. The survival rate of the nodes is a crucial parameter for measuring network performance. All the schemes for charging the nodes are designed to enhance the survival rate of the nodes. The charging efficiency is also important in the charging schemes and determines the working efficiency of the MCs. A higher charging efficiency results in a better charging performance of the charging algorithm. We propose three different approaches to divide the network into three regions. We call these three division 5-5-5 division, 6-6-3 division, and 6-5-4 division. For example, in the 5-5-5 division, the height of the regions is 300 m. In other words, the MCs in the three regions are responsible for five rows of nodes. In the 6-6-3 division, the inner MC and the middle MC are responsible for six rows while the outer MC is responsible for only three rows of nodes. By comparing these three approaches, we can determine a suitable division approach.

We compare our algorithm with the No Knowledge No Coordination (NKND) scheme proposed by Madhja *et al.* [15], which classifies MCs as super MCs and common MCs. In addition, we add a non-collaborative scheme of division charging for an additional comparison and in this scheme, the MCs scan only their charging area without any collaboration. These two schemes and the MCRA consume little communication overhead of the MCs; therefore, we ignore this overhead in our simulation. Our simulation begins when the network starts to operate and ends when all the nodes in the network have been charged at least once.

B. EVALUATION RESULTS

As shown in Fig. 6, we compare the survival rate of the nodes without any charging in the three divisions to determine whether the nodes in the same region have approximately the same lifetime. We can see that the nodes in the middle region (Fig. 6(a)) have a similar lifetime and a shorter life time because the rows in the middle region in the 5-5-5 division are closer to the base station. Therefore, these nodes have a shorter lifetime and a concentrated energy consumption rate. The 5-5-5 division and the 6-5-4 division perform better than the 6-6-3 division in the outer region because the lifetimes in these two regions are more discrete, indicating that the outer MC has less charging tasks during the same time.

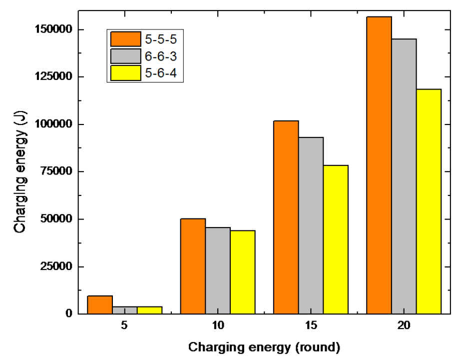


FIGURE 7. **Charging energy from inner MC to middle MC.**

In Fig. 7, we compare the charging energy transferred from the inner MC to the middle region in every five charging cycles to determine how much energy the inner MC transfers to the middle MC in the three divisions. In the first five rounds, the energy consumption of the nodes in the middle region is not high because the inner MC is responsible only for its nodes in the first three rounds. In round four, the inner MC in the 5-5-5 division first charges the middle MC, because the sixth row of nodes has low energy and the middle MC begins its charging cycle. In rounds 6-20, the inner MC in the 5-5-5 division transfers more energy to the middle MC because the middle MC is responsible for more high-consuming nodes, although the total number of nodes is higher in the 6-6-3 than in the 5-5-5 division. The total energy that the inner MC transfers to the middle MC increases as the charging cycle increases because an increasing number of nodes in the middle region is in danger.

In Fig. 8, we compare the received energy of the two middle regions in the 5-5-5 division. Both middle MCs remain in

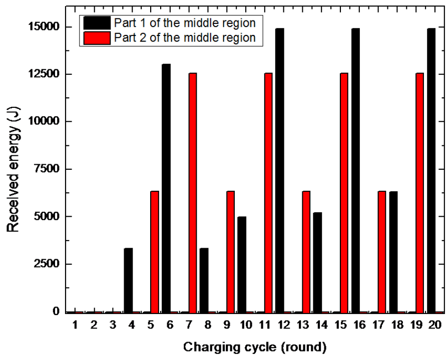


FIGURE 8. **Received energy of the two middle regions in 5-5-5 division.**

their positions in the first three charging cycles of the inner MC. In the 4th round, the inner MC first charges part 1 of the middle MCs because, in this simulation, we placed the nodes in part 1 at the boundary of the two parts. Therefore, the total energy consumption is higher for part 1 than for part 2 and the inner MC first charges part 1. In the next round, the inner MC changes its target to charge part 2. Hence, the MC in part 1 receives energy in the even round while the MC in part 2 receives energy in the odd round. Figure 8 shows that the received energy differs greatly for the different rounds because the energy consumption differs for each round. For example, in round 10, the MC in part 1 receives less than 5000 J of energy but receives nearly 15000 J in round 12. The energy consumption of the middle MC during rounds 8-10 is high because the MC charges more nodes away from the base station and consumes a large amount of energy for moving. During this time, the MC charges only a few nodes near the base station or remains at the origin and waits for a charging request.

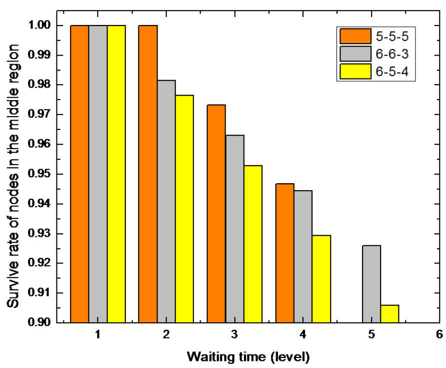


FIGURE 9. **Waiting time of the middle MC.**

In Fig 9, we focus on the relationship between the survival rate of the nodes in the middle region and the wait times for the middle MC. As we can see, in level 1, the middle MC waits at the first waiting point but does not wait at the following points and all the nodes can survive before the next charging cycle in all three divisions. In level 2, the middle MC waits at two points and finishes its charging cycle, while the MCs in the other two divisions cannot wait any longer to guarantee the survival of the nodes because in the divisions 6-6-3 and 6-5-4, the second waiting point lies at the edge node of row 8 and the MC waits for the nodes that have low energy in row 9. The lifetime of the nodes in row 9 is too long for the MC to begin a new cycle to guarantee the survival rate of the nodes close to the base station. Therefore, the middle MC in division 5-5-5 can wait at points in two levels while the middle MC in 6-6-3 and 6-5-4 waits at only one level to guarantee the survival rate of the nodes. Therefore, the middle MC in division 5-5-5 exhibits a high charging efficiency.

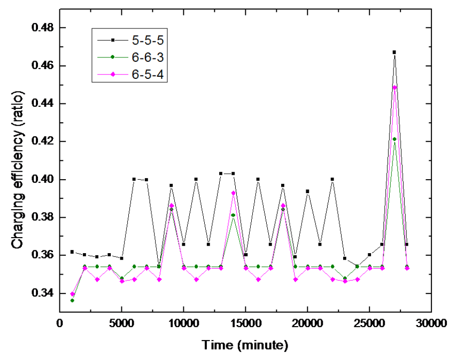


FIGURE 10. **The total charging efficiency.**

In Fig. 10, we compare the total charging efficiency for the three divisions. It is evident that the 5-5-5 division has the best efficiency and that the efficiency in the three divisions fluctuates greatly because during certain times, for example at 26000 minutes to 27000 minutes, nodes in the outer region are all in danger. Therefore, the outer MC charges more nodes with same movement energy consumption and the number of nodes is higher in the outer region than in the other regions, which has a great influence on the total charging efficiency. The efficiency increases when the nodes in the outer region are in danger and decreases when the nodes are safe.

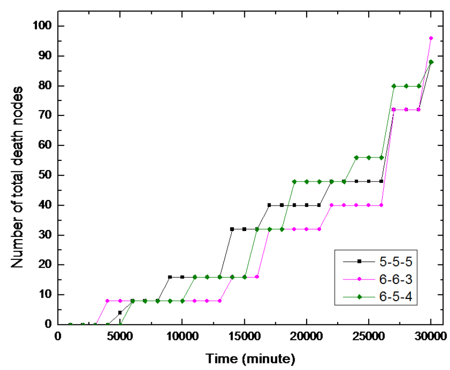


FIGURE 11. **Number of total death nodes in the three divisions.**

In Fig. 11, we compare the number of death nodes in the three divisions. (A node is able to die twice as long as it is fully charged after its first death.) It is evident that the 5-5-5 division has the highest death rate during 8000-16000 min because during this time, some nodes in the outer region are in danger and the same nodes belong to the middle region in 6-6-3 and 6-5-4. As the time increases, the nodes in the middle region in 6-6-3 and 6-5-4 begin to die and their death rate increases. During 26000-27000 min, all the nodes in the network are in danger, and the death rate during this period increases sharply in Fig. 11. The death rates in the 6-6-3 and 6-5-4 divisions exceed the death rate in the 5-5-5 division as time passes.

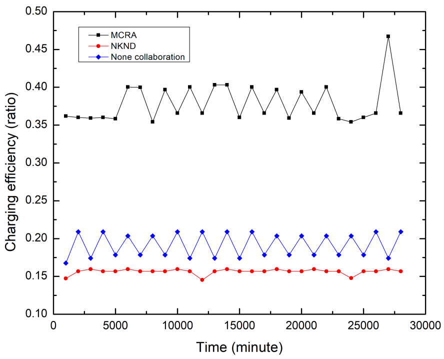


FIGURE 12. The total charging efficiency in the three schemes.

In the following section, we compare the MCRA with the NKND and a non-collaborative charging scheme based on region division. The charging efficiency of the three schemes is shown in Fig. 12. We can see that the MCRA performs better than the other two charging schemes because every MC in the non-collaborative scheme traverses its triangle charging region in one charging cycle. Therefore, the movement energy consumption of the MC is high and it is not necessary to charge certain nodes that are a distance away from the base station. In the NKND scheme, the MC also traverses the triangle and consumes a lot of energy due to movement. Moreover, the super MC in the NKND traverses a larger region than any of the other common MCs and consumes more energy; therefore, these two schemes obtain lower charging efficiencies.

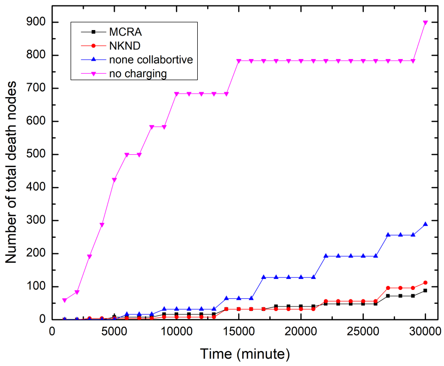


FIGURE 13. Number of death nodes for the three schemes.

Figure 13 shows the survival rate of the nodes in the three schemes. (A node dies just one time even though it is charged after its first death and dies again.) The survival rates are similar for the three schemes prior to 10000 minutes. During this period, some nodes in the outer region of the MCRA die. As time passes, more and more nodes die in the other two schemes while in the proposed algorithm, no other nodes run out of energy. However, in our algorithm, some nodes die twice and three times because the outer MC is too busy to charge these nodes. However, the number of these nodes is relatively small. At 30000 minutes, we observe that in our algorithm, the least number of nodes have died compared to the other two schemes. It is evident that our algorithm provides a better performance for nodes that are in close proximity to other nodes and obtains a higher charging efficiency. The MCs in our algorithm charge nodes in a more timely fashion compared with the other schemes.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we propose a charging algorithm for WSNs. The simulation results show that the MCRA performs better with regard to charging efficiency and node survival rate than other schemes. The reasons that our algorithm obtains a better performance are as listed follows: 1) we divide the network into three regions, which follows the rule of variation in the energy consumption rate of the nodes, and 2) we propose a new approach for supplying energy to the MCs, resulting in a greater work efficiency of the MCs. By using this approach, our algorithm enhances the charging efficiency of the MCs in WSNs and further enhances the lifetime of the nodes.

However, one drawback is that nodes located in the outer regions and with a high energy consumption rate may die before being charged. In future research, we plan to improve our algorithm and propose a more efficient charging algorithm that charges the nodes in danger in a more timely manner. In the future, a charging scheme that focuses on cooperating MCs without a regional division should be taken into consideration.

REFERENCES

[1] S. Kandukuri, J. Lebreton, N. Murad, R. Lorion, and D. Genon-Catalot, "Data window aggregation techniques for energy saving in wireless sensor networks," in *Proc. IEEE Symp. Comput. Commun. (ISCC)*, Jun. 2016, pp. 226–231.

[2] A. Sunny, "Joint scheduling and sensing allocation in energy harvesting sensor networks with fusion centers," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 12, pp. 3577–3589, Dec. 2016.

[3] B. Tong, G. Wang, W. Zhang, and C. Wang, "Node reclamation and replacement for long-lived sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 22, no. 9, pp. 1550–1563, Sep. 2011.

[4] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljačić, "Wireless power transfer via strongly coupled magnetic resonances," *Science*, vol. 317, no. 5834, pp. 83–86, 2007.

[5] Y. Shi, L. Xie, Y. T. Hou, W. Lou, H. D. Sherali, and S. F. Midkiff, "On renewable sensor networks with wireless energy transfer: The multi-node case," in *Proc. IEEE Int. Conf. Soc. Comput. Commun.*, Jun. 2012, pp. 10–18.

[6] L. Xie, Y. Shi, Y. T. Hou, and H. D. Sherali, "Making sensor networks immortal: An energy-renewal approach with wireless power transfer," *IEEE/ACM Trans. Netw.*, vol. 20, no. 6, pp. 1748–1761, Dec. 2012.

[7] L. Xie, Y. Shi, Y. T. Hou, and A. Lou, "Wireless power transfer and applications to sensor networks," *IEEE Wireless Commun.*, vol. 20, no. 4, pp. 140–145, Aug. 2013.

[8] L. Fu, P. Cheng, Y. Gu, J. Chen, and T. He, "Optimal charging in wireless rechargeable sensor networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 278–291, Jan. 2016.

[9] Y. Shu *et al.*, "Near-optimal velocity control for mobile charging in wireless rechargeable sensor networks," *IEEE Trans. Mobile Comput.*, vol. 15, no. 7, pp. 1699–1713, Jul. 2016.

[10] G. Han, A. Qian, J. Jiang, N. Sun, and L. Liu, "A grid-based joint routing and charging algorithm for industrial wireless rechargeable sensor networks," *Comput. Netw.*, vol. 101, pp. 19–28, Jun. 2016.

[11] W. Yao, M. Li, and M. Wu, "Inductive charging with multiple charger nodes in wireless sensor networks," in *Advanced Web and Network Technologies, and Applications*. Berlin, Germany: Springer-Verlag, 2006, pp. 262–270.

[12] J. Zhao, X. Dai, and X. Wang, "Scheduling with collaborative mobile chargers inter-WSNs," *Int. J. Distrib. Sensor Netw.*, vol. 11, no. 1, 2015, Art. no. 921397, doi: 10.1155/2015/921397.

[13] S. Zhang, J. Wu, and S. Lu, "Collaborative mobile charging," *IEEE Trans. Comput.*, vol. 64, no. 3, pp. 654–667, Mar. 2015.

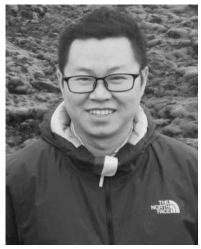
[14] C. Lin, Y. Wu, Z. Liu, M. S. Obaidat, C. H. Yu, and G. Wu, "GTCharge: A game theoretical collaborative charging scheme for wireless rechargeable sensor networks," *J. Syst. Softw.*, vol. 121, pp. 88–104, Nov. 2016.

[15] A. Madhja, S. Nikoletseas, and T. P. Raptis, "Hierarchical, collaborative wireless energy transfer in sensor networks with multiple mobile chargers," *Comput. Netw.*, vol. 97, pp. 98–112, Mar. 2016.

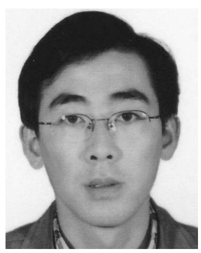
GUANGJIE HAN (S'03–M'05) received the Ph.D. degree from Northeastern University, Shenyang, China, in 2004. From 2004 to 2006, he was a Product Manager with ZTE Company. In 2008, he finished his work as a Post-Doctoral Researcher with the Department of Computer Science, Chonnam National University, Gwangju, South Korea. From 2010 to 2011, he was a Visiting Research Scholar with Osaka University, Suita, Japan. He is currently a Professor with the Department of Information and Communication System, Hohai University, Changzhou, China. He has authored over 230 papers published in related international conference proceedings and journals, and holds 100 patents. His current research interests include sensor networks, computer communications, mobile cloud computing, and multimedia communication and security. He is a member of ACM. He received the ComManTel 2014, ComComAP 2014, Chinacom 2014, and Qshine 2016 Best Paper Awards. He has served as a co-chair for over 50 international conferences/workshops and a technical program committee member of over 150 conferences. He has served on the editorial boards of up to 14 international journals, including the IEEE Access, *Telecommunication Systems*, the *International Journal of Ad Hoc and Ubiquitous Computing*, the *Journal of Internet Technology*, and the *KSII Transactions on Internet and Information Systems*. He guest edited a number of special issues in IEEE journals and magazines. He has served as a reviewer of over 50 journals.

ZHIFAN LI received the B.S. degree from Hohai University, Nanjing, China, in 2015, where he is currently pursuing the M.S. degree with the College of Internet of Things Engineering. His research interests include recharging technology in wireless sensor networks.

JINFANG JIANG received the B.S. degree in information and communication engineering and the Ph.D. degree from Hohai University, Changzhou, China, in 2009 and 2015, respectively. She is currently a Lecturer with the Department of Information and Communication System, Hohai University. Her current research interests are security and localization for Sensor Networks.



LEI SHU (M'07–SM'15) is currently a Lincoln Professor with the University of Lincoln, U.K., and a Distinguished Professor with the Guangdong University of Petrochemical Technology. He is also the Executive Director of the Guangdong Provincial Key Laboratory of Petrochemical Equipment Fault Diagnosis, China. His main research field is wireless sensor networks. He received the Globecom 2010, ICC 2013, and IEEE Systems Journal 2017 Best Paper Award. He has served as more than 50 various co-chair for international conferences/workshops, such as IWCMC, ICC, ISCC, ICNC, and Chinacom, especially a Symposium Co-Chair for IWCMC 2012 and ICC 2012, a General Co-Chair for Chinacom 2014, Qshine 2015, Collaboratecom 2017, and Mobiquitous2018, and a Steering and TPC Chair for InisCom 2015, and TPC members of more than 150 conferences, such as ICDCS, DCOSS, MASS, ICC, Globecom, ICCCN, WCNC, and ISCC. He has been serving as an Editor-in-Chief of the *EAI Endorsed Transactions on Industrial Networks and Intelligent Systems*, and an Associate Editor of the IEEE Transactions on Industrial Informatics, the IEEE Systems Journal, and the IEEE Access.



WENBO ZHANG received the Ph.D. degree in computer science with Northeastern University, China, in 2006. He is currently a Professor with the School of Information Science and Engineering, Shenyang Ligong University, China. He has published over 100 papers in related international conferences and journals. His current research interests are ad hoc networks, sensor networks, satellite networks, and embedded systems. He received the ICINIS 2011 Best Paper Awards and up to nine Science and Technology Awards, including the National Science and Technology Progress Award and Youth Science and Technology Awards from the China Ordnance Society. He has served in the Editorial Board of up to ten journals, including the *Chinese Journal of Electronics* and the *Journal of Astronautics*.