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Sector-based Charging Schedule in Rechargeable Wireless Sensor Networks

Sadam Alkhalidi[1], Dong Wang[1*] and Zaid A. Ali Al-Marhabi[2]
[1] College of Computer Science and Electronic Engineering
Hunan University, Changsha, China
[E-mail: khalidi, wangd@hnu.edu.cn]
[2] Faculty of Applied Science, Computer Science dept.
Hajjah University, Hajjah, Yemen
[E-mail: marhabi2000@gmail.com]
*Corresponding author: Dong Wang

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Abstract

Adopting mobile chargers (MC) in rechargeable wireless sensors network (R-WSN) to recharge sensors can increase network efficiency (e.g., reduce MC travel distance per tour, reduce MC effort, and prolong WSN lifetime). In this study, we propose a mechanism to split the sensing field into partitions that may be equally spaced but differ in distance to the base station. Moreover, we focus on minimizing the MC effort by providing a new charging mechanism called the sector-based charging schedule (SBCS), which works to dispatch the MC in charging trips to the sector that sends many charging requests and suggesting an efficient sensor-charging algorithm. Specifically, we first utilize the high ability of the BS to divide the R-WSN field into sectors then it select the cluster head for each sector to reduce the intra-node communication. Second, we formulate the charging productivity as NP-hard problem and then conduct experimental simulations to evaluate the performance of the proposed mechanism. An extensive comparison is performed with other mechanisms. Experimental results demonstrate that the SBCS mechanism can prolong the lifetime of R-WSNs by increasing the charging productivity about 20% and reducing the MC effort by about 30%.

Keywords: charging productivity, sector-based charging schedule, rechargeable wireless sensors network, mobile charger

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1. Introduction

Wireless sensor networks (WSNs) consist of many small, spatially distributed autonomous devices. They have the ability to work with minimal human intervention. Energy is the most concentrated term in WSNs because of the dynamism of the network. Prolonging lifetime for WSNs by minimizing node energy consumption or maximizing the network lifetime for sensor nodes powered by non-renewable batteries is very important target for researchers [1]-[3]. With the breakthrough in wireless charging technology studies have been conducted on the dynamic features and irregularity of environment energy that prevents the development of harvesting sensor networks [3] [4].

Rechargeable WSNs (R-WSNs) are a promising technology in addressing energy problems in WSNs, and they are attracting an increasing number of researchers and manufacturers [5] [6]. The most attractive features of this technology are having high-energy transfer efficiency even under omni-directional transmission, not requiring line of sight, and being insensitive to the neighboring environment [7] [8]. Recharging and topological activity are such hot spots in R-WSN, where recharge energy is used to ensure the sustainability of the network. Therefore, charging energy is reliable and stable.

Several studies utilizing mobile charger (MC) with high capacity batteries to recharge R-WSNs have been studied in [9]-[13]. For instance [5], [14] considered replenishing sensor energy for R-WSNs where each sensor periodically recharge. They assumed that the sensing rates of each sensor are fixed, the shortest traveling path of the MC is a known or found in advance and these data sent to the base station (BS) through multi-hop transfers. They figured a joint optimization issue of energy recharging and data flow transmitting, they demonstrated that if the sensing field has MC can recharge sensors periodically, the network will be sustainable and no sensor will run out of its energy. The authors in [6] developed a solution to recharge multiple sensors simultaneously. In [31] they employed the mobile charger to recharge sensors and collect sensing data at the same time along its trip and formulated the recharging energy problem as efficiency maximization problem under the restraints of flow conservation, energy balance. In [15] they studied energy recharging in event detection scenarios and proposed a solution with random recharging. However, in terms of different scenarios (e.g. detection cases), both the energy depletion and sensing rate of each sensor is different over time. Therefore, these existing solutions are not appropriate for such dynamic energy depletion and sensing application scenarios.

The disadvantage of these mentioned techniques to combining wireless recharging and data collection utilize MC are that the mobile BS should move to the area where there is heavy load of data collecting, while the MC has to recharge the sensors which are run out of their energy. However, the shortest traveling path of the MC is a known in advance. From our best knowledge, none of the mentioned researches considered reducing the MC effort and increase charging productivity to help the R-WSN to be more sustainable.

On the other hand, researches [18]-[21] have focused on exploring resource-abundant and unconstrained energy sources in WSNs. The BS has many characteristic such as resource abundance, unlimited processing capability, large computational ability, bulky memory and physical location accessibility among others, all these advantages makes BS a powerful asset for WSNs. This approach taps into the capabilities at the edge BS like its ability to divide the WSNs field into small parts and selecting CH this leads to reducing the intra-node communication for electing CH between sensors inside these parts. Therefore, it has not fully exploited in energy recharging schemes.

In this paper, we consider R-WSN in which sensors have significant differences in energy consumptions and sensing rate. An ordinary case is that a deployed sensors for the natural study consist of sensors of different modalities including moisture monitoring, temperature monitoring,…etc. The sensing rate of the sensors is different depending on their physical phenomena. Therefore, we study an on demand wireless sensors charging model [12]. Which is each sensor in R-WSN sends their recharging requests to the BS according to their residual energy status, and then BS sends the MC to start a round trip to recharge these requested sensors. The essential difference between their work and ours is that they did not put any constraint on the MC in consideration. While we consider some important aspects like the trip time constraint on the MC, finding an optimal path for the MC in R-WSNs by dividing the sensing field to sectors, minimize the MC effort per round trip, and the charging productivity to improve the R-WSN network efficiency.

1.1 Related Studies

An unequal clustering mechanism is presented in [16], in which energy-efficient unequal clustering (EEUC) is used to balance energy consumption among clusters heads to address the hotspot problem. EEUC forms small clusters near the BS and the size increases as the distance progress. Thus, the CHs close to the BS preserve their energy for inter-cluster communication. The author also proposes an energy-aware multi-hop routing protocol for inter-cluster communication in the EEUC mechanism.

Applied wireless changing technology for WSNs where a mobile station is employed for both energy charging and collect data in [14]. They formulated an optimization problem that jointly considers the traveling path, the charger stopping locations, sensor-charging schedule and data flow routing, and developed a provably near-optimal solution. The study [17] proposed that one or more clusters can be nested together according to their residual energy with time, and the MC moves along the shortest TSP path among these nested clusters, this method is appropriate for networks in which all nodes have similar energy consumption rates.

The study [20] presents a novel edge-based routing protocol called BeamStar for WSNs. The researchers divide the network into rings then to sectors. Thereafter, they use the power-controlled capability of the BS to scan the network with different power transmission levels to provide location information for the nodes. [21] present another routing protocol for edge-based WSNs called Cluster-based BeamStar (CBS). CBS is introduced to overcome some of the disadvantages of BeamStar. CBS uses the same technique a BeamStar but with a developed scan process to provide sensor nodes with location information. It is successful in using network resources optimally and in reducing the inter-node communication load. CBS is explained in three different phases: locating phase, cluster building phase, and data transmission phase. In the first phase, the entire field is scanned using different transmission power levels (R). Our proposed model uses the same mechanism to explore the potential infrastructure support by an edge BS to scan the whole area of the R-WSNs and divide it into rings and sectors using the BS capabilities.

The study [22] proposes a new mechanism called first-come-first-served (FCFS) and shortest-available-job-first (SAJF) algorithms. In both online algorithms, a queue is maintained to contain all the jobs that have arrived but have not been executed. However, in the FCFS and SAJF schedules, the incoming charging requests are based only on their temporal property and can lead to a high load and a back-and-forth movement for the MC [23]. In addition, one sensor with the shortest service time is chosen from among all existing recharging requests. We assume that the MC currently remains at the first sensor location and completes its charging.

In this paper, we distinguish our work from these works as follows. We study the mobile charging problem and propose a new charging mechanism to increase the charging productivity, it utilizes the characteristics of resource abundant and unconstrained network components, such as BS, to divided the monitoring field and analyze the recharging requests which coming from the sensors in sectors then send the MC depending on these requests. This mechanism can highly increase the R-WSN charging productivity, efficiency and reduce the MC effort.

1.2 Contributions

The contributions of this study are summarized as follows.

- The WSN lifetime is prolonged and high network efficiency is provided.
- Intra-node communication for electing CH is cancelled to become a BS job. The BS sends a control message to all nodes about the new CH, thus all nodes in the sector can communicate through it.
- The high ability of the BS to divide the R-WSN field into sectors is used, as the BS does not have energy constraints.
- Any node is allowed to send a recharge request message if the residual energy is less than the threshold, consistent with the BS.
- The MC effort is reduced and the MC is allowed to recharge many nodes per round trip (RT) within time (T) .
- Recharge the sectors which send the highest amount of recharging requests by priority.
- Through continuous synchronized information exchange with the BS, the MC is able to determine whether it can recharge extra sectors after completing the first mission (i.e., recharging sector nodes that are already planned before the MC

departure). After calculate the amount of energy consumed to reach the Sector+1 , number of nodes that must be recharged within the Sector+1 (i.e., these nodes consume the same amount of energy) and determine the MC residual energy which it need to return to the BS.

The rest of this paper is organized as follows. Section 2 introduces the network model and problem definition statement. Section 3 presents the simulation results. Finally, Section 4 concludes the paper.

2. Modeling And Formulation

In this section, we present our mechanism, which suggests a unique way of dealing with sensor field partitions, choosing CHs, and receiving and sending recharge requests between the BS and the nodes. The notations and their corresponding definitions are listed in **Table 1**.

Table 1. List of Notations

Notation	Definition
N	Set of nodes
BS	Base station
MC	Mobile charger
n_k	Node
R	Radius (Transmission power level)
SN	Number of sectors
RN	Number of rings
θ	Beam width angle
A_m	The areas of sectors on the same ring
AS_m	One sector area
Qc	Request queue
DE_k	Energy threshold
RE_k	Residual energy
ECs	Energy to recharge sequence
Eq_k	Energy request for each node
CS_i^{Time}	Charging time for one sector
Cn_i^{Time}	Charging time for one node in one sector
SN_i^j	Sector No. jth rings of ith sectors

NC	Number of nodes needed to be recharged in one sector
NC_{total}	Total number of recharged nodes
B_k	Battery capacity
S	MC speed
rt	Release time
T	Round trip time
T_0	Mobile charger starting time from the base station
RT	Round trip
CH	Cluster head
AHM	Auto hi message

1.3 Network Design Mechanism

We consider a sensor network consisting of N heterogeneous sensors and a stationary BS deployed over a circular sensing field. We find an appropriate and effective mechanism to divide the R-WSN field into convergent partitions in space but with different numbers of nodes under the geographical constraint of the R-WSN field. Therefore, we assume that the BS located at the center of the network field to have no energy constraint in the BS. The BS in the network is equipped with a power-controlled capability directional antenna, which can reach any part of the network [24]. It provides location identity to every sensor node in the network by varying its transmission power level in different directions. In addition, the directional antenna is used to send control information to the network nodes and helps in dividing the R-WSN field using an antenna beam width (θ) to define the ring no. (RN) and sector no. (SN). The same scan order of CBS in [21] is considered in this study. We examine one quarter of the network for simplification. We consider the field to be distributed into four main quarters, and each quarter is divided into a given number of sectors by varying its transmission power level (R) or radius and beam width (θ). The signal sent by the BS to define radius R_m of the mth ring is calculated using Equation (1).

$$R_m = m * R_1 \ , \ \forall_m = 1,2,3 \ldots, \tag{1}$$

where R_1 is the radius of the first ring, which is used to obtain the angle of beam width (θ_m) for the mth ring in Equation (2).

$$\theta_m = 90/((2*m)-1) \quad \forall_m = 1,2,3 \ldots \tag{2}$$

From (1) and (2), the area A_m of all sectors in the mth ring is obtained, as shown in the following equation:

$$A_m = \pi R_m^2 \,/4 \qquad \forall_m = 1,2,3 \ldots , \tag{3}$$

where A_m is the area of the mth ring with radius R_m. The areas of sectors on the same ring are equal, and the area of one sector is calculated as

$$AS_m = \frac{\pi R_m^2 \ - \pi R_{m-1}^2}{SN} \qquad \forall_m = 1,2,3 \ldots \tag{4}$$

To find the area for a specific sector AS_m, SN represents the number of sectors and R_m^2 is the radius of the last ring.

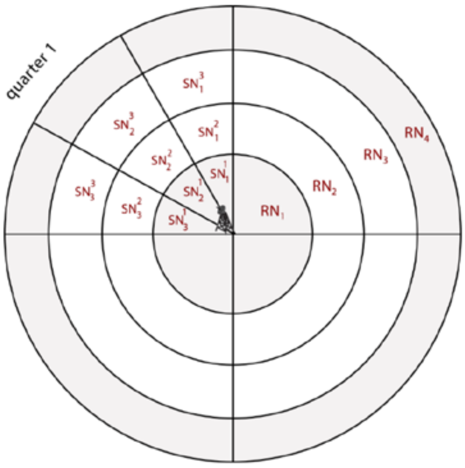

Fig. 1. Network design mechanism with SN_i^j jth rings of ith sectors. Each ring has an equal sector area. These equally spaced sectors are used to form even-sized clusters in the network.

The complete process of the network partition mechanism is illustrated in **Fig. 1**. The first quarter shows the first phase of the network division process, in which the network field is divided into a set of rings with different transmission power levels. It also represents the corresponding sectors with their rings. The other quarter shows the beam width, which is used to divide the field into rings. The beam width value enables the antenna to scan the network field and provides the location details of each sensor node. After the R-WSN field is divided into rings and sectors, the BS can begin the next phase by selecting the CH and then receiving the charging requests from the nodes. The energy of the nodes decreases and needs to be recharged.

1.4 Clustering Mechanism

In the network initialization phase, we assume that the BS broadcasts an advertisement to all sensor nodes in the network after random deployment in the R-WSN field. According to the received signal strength in which each node calculates its distance with the BS [25], each node needs to send its location information to the BS with an Auto Hi Message (AHM). This message contains node no. (n_k), residual energy (RE_k), and message release time (rt). We assume that the nodes send the first AHM massage, as shown in (5).

$$AHM_k = (n_k, RE_k, rt_k)\ . \tag{5}$$

This message is the first that every node must send, and the nodes have not chosen the CH for each part (Sector) yet. Therefore, the nodes can use the normal aggregation style to send this messages to the BS. The BS starts to collect and analyze these data to determine the nodes' location and geographical relation among themselves [26]. Thereafter, the network R-WSN field is divided into rings and sectors, as mentioned in the previous section, and the CH for each sector is selected (supposed to be in the middle of the sector, contain more energy than other nodes, and be preferred to be directly connected with all nodes in the sector). The BS automatically informs all nodes in the network that are the CHs for sectors (SN). More than one CH may exist in one sector, especially for the sectors that are far from the BS. This technique highly reduces the energy required for internal communication among nodes to select the CH as in **Algorithm 1**. In addition, this study proposes that all nodes send a periodical message (specified in advance) to inform the BS about the residual energy of the nodes, as mentioned in the previous message, and the BS analyzes these report messages.

Algorithm 1: Cluster Head selection

```
    Input: $N$ set of nodes.
    Output: select $CHs$ for each sector.
1:  Let $N = (n_1, n_2,\ldots,n_k)$ denote the set of n nodes
2:  $RE_k$ denote residual energy of nodes
3:  $SN_i^j$ denote node sector location
4:  $CH$ denote cluster head node.
5:  $DE_k$ denote the threshold value of node
6:  Create node $n_k$
7:  Divide the monitoring field into sectors $SN_i^j$
8:  Set node position $SN_i^j$ Clusters formation
9:  Select CH from $SN_i^j$ based on $RE_k$ & middle location
10: if $n_k \in SN_i^j$ & $RE_k > DE_k$ & has not been $CH$ yet then
11:     $n_k = CH$ for $SN_i^j$
12: else
13:     $n_k$ normal node
14: end if
15: inform nodes in $SN_i^j$ about their $CH$
16: $CH$ sends data to $BS$
17: Repeat the steps 12 to 16 for different rounds
```

Algorithm 1 CH selection depends on the location of the node inside the sector and residual energy [27]. During the setup phase, each node sends the AHM which contain the release time and residual energy to the BS as in in (5). BS estimates the RE_k from the collected energy information. It finds that which node energy level is higher than average energy level, and those nodes will be selected as CH. After selection BS broadcasts the message along with selected CH to all nodes.

Unlike other techniques from previous studies [17, 12], in the current study, we adopt different techniques for recharging sensors in the R-WSN field. We consider the location information, mobile charger status, and serving time of the nodes. We also assume that the batteries of all nodes can be recharged quickly (ultra-fast charging material inventions) [28]. MC uses electricity or petrol for either travelling or charging and is equipped with a powerful wireless charger [12]. In addition, it communicates directly and continuously with the BS to obtain updates about the nodes with low energy through a long range radio [13]. Some previous studies assumed that the MC recharges the nodes through the FCFS technique, which has been extensively examined by the queuing theory community [29], SAJF, or both [22]. In both algorithms, a queue is maintained to contain all the jobs that have arrived but have not been executed. However, in the FCFS and SAJF schedules, the incoming charging requests are only based on their temporal property and can lead to high load for the MC.

By observing the restriction of FCFS, we introduce a new recharging scheme called Sector-based Charging Scheduling (SBCS). This scheme significantly reduces the MC efforts. We consider the transmission behaviors of sensors and dynamic sensing to make the network more controllable and scalable by providing this recharging scheme (i.e., SBCS) and proposing a new mobile charging algorithm. Therefore, in each recharging RT, the MC selects the sector SN that sends the largest amount of recharging request, and in the next RT, it selects the SN_i first and then the next $SN_i + 1$, which has the largest number of recharge requests among the previous assumptions assuming the arrangement of recharging requests under the principle of FCFS or SAJF. This method is conducted because it makes the MC travel a longer distance to recharge one node and then return to the approximating location near the first location.

This procedure wastes the effort and energy of MC. In addition, a few number of nodes can be recharged per RT. To avoid node death, we assume that when the node residual energy RE_k falls below the threshold it goes to sleep mode, which is pre-defined $DE_k = \alpha \cdot B_k$, where α is a constant with $0 < \alpha < 1$ and B_k is the battery capacity. The node load-off is conduct to enable another neighboring node to take place where the node energy consumption is reduced and the node is kept alive. **Fig. 2** shows the MC traveling to recharge a sector and moving to another one.

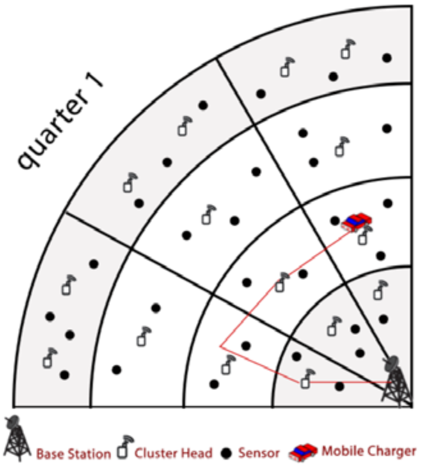

Fig. 2. MC movement to recharging sensors when it travels from one sector to another

1.5 SBCS

Given a recharge trip time (*T)* per round trip (*RT)* by the MC, the BS may receive many recharging requests from different sensors, depending on the network scale and energy status of the sensors inside the sectors. We let *Qc* be the queue of recharging requests and SN_i^j be the sector with the largest number of recharging requests, which is updated dynamically as energy request (Eq_k) for each node arriving one at a time. The *MC* takes time when it travels in the monitoring field. Thus, recharging all requested sensors per *RT* within *T* may not be possible all the time. Thus, reducing the MC distance problem involves finding one or more sectors within *T* with the largest number of recharging requests quickly and recharging all nodes with low energy in a *RT*. In this case, the *MC* effort is minimized and the charging productivity increases.

From (3), nodes still do not know the CH number. As mentioned previously, the BS receives recharging requests from node n_k, where $n_k \in N$ and it can determine the sector and ring SN_i^j to which this node belongs, jth represents the ring no., and ith represents the sector no. Therefore, after analyzing these messages, the BS uses this information to determine the nodes' location and to select the *CH*s for each sector. Thereafter, the BS informs the nodes about this update as (n_k, SN_i^j, CH), which contains the node no. n_k , node location SN_i^j, and node *CH*. Therefore, the next message is the recharging request (Eq_k) message that adds the location, as shown in (6):

$$Eq_k = \left(n_k, SN_i^j, RE_k, rt_k, \right). \tag{6}$$

$$Qc = \{Eq_k, Eq_{k+1}, \dots \dots\} \quad , k \geq 1. \tag{7}$$

The BS receives the sensor requests Eq_k to the Qc, as shown in (7), analyzes these data, and decides on the sectors that should have priority to recharge depending on their requests. Therefore, the BS organizes the requests and sends the energy charging sequence (*ECs)* to the MC to start the RT, as shown in Equation (8):

$$ECs = \{(SN_i^j, NC_i), (SN_i^j + 1, NC_{i+1}), \ldots\}, \tag{8}$$

where NC_i is the number of sensors that must be recharged in sector SN_i^j and NC_{i+1} is the number of sensors that must be recharged in sector $SN_i^j + 1$. Thereafter, BS dispatches the MC to start RT to recharge these requested nodes, and all energy recharging requests Eq_k depend on the sector that has more requests than others. In addition, the MC energy considers the time required by the MC for it to return to the *BS* to recharge or to receive maintenance. For simplicity, we assume that the MC has enough energy to recharge all sensors [13]. Thereafter, the time from the BS, which starts from $T_0 = 0$, to the destination sector is calculated. For example, if $ECs = \{(SN_4^3, 6)\ (SN_3^2, 5)(SN_2^2, 1)\}$, then MC according to ECs will start to recharge the nodes in sector SN_4^3 first because it has six nodes that need to be recharged, i.e., a large number of *Eq* than SN_3^2. If it still has energy to recharge the next sector and so on within time T, then we assume that each RT of the MC is bounded by a T, as shown in the following equations:

$$T_{SN_i^j} = T_0 + T(BS, SN_i^j) + CS_i^{Time} + T(SN_i^j, BS), \tag{9}$$

$$T_{SN_i^j+1} = T_{SN_i^j} + T(SN_i^j, SN_i^j + 1) + CS_{i+1}^{Time} + T(SN_i^j + 1, BS) - T(SN_i^j, BS), \tag{10}$$

$$CS_i^{Time} \geq \sum_{i=1}^{m} Cn_i^{Time} \qquad , m \leq NC_{total}, \tag{11}$$

where $T(BS, SN_i^j)$ is the distance time from the BS to the sector SN_i^j, CS_i^{Time} is the time for each sector to recharge all nodes that need to be recharged, and Cn_i^{Time} is the time for each node to recharge inside one sector. In the previous example, the BS can send the MC in RT to recharge two sectors only: SN_4^3 and SN_3^2. Therefore, the total number of recharging nodes is $NC_{total} = NC_i + NC_{i+1}$, and thus sector SN_4^3 has six nodes that need to be recharged and sector SN_3^2 has five nodes. Therefore, the recharging productivity for this RT is 11 nodes within T. This value is used to obtain the total of T if the MC recharges more than one sector in one *RT* by the following equation:

$$T = T_{SN_i^j} + T_{SN_i^j+1} \tag{12}$$

After all the requested sensors inside the sectors with the largest number of recharging requests are recharged and no other request is pending, the MC returns to the BS by adopting a minimum spanning tree (MST) heuristic and the TSP [30]. After performing simulation and evaluation, we notice that in the proposed algorithms in [22], the MC spends a significant amount of time T to move between nodes, and sometimes it consumes much time traveling to find a single node that must be recharged. This process is a waste of MC energy and increases MC effort. This scenario means that most of the time is wasted in transportation from the BS to n_k node than to the BS or to the last position of the MC. In this study, we assume that the MC can recharge many sectors containing many sensor nodes; therefore, the number of recharged nodes (*Charging Productivity*) in SBCS is significantly higher than that in the previous mechanism. In addition, the MC energy is consumed in recharging the nodes. Previous studies supposed that the MC energy is consumed in recharging and in moving from one node to another node, which is probably far from the first node.

Algorithm 2: SBCS Algorithm

```
Input: A set $NC$ of sensors that needs to recharge, trip time T, and a specified sector SN have the largest $Eq$.
Output: A round trip RT starts from BS.
$RT \leftarrow \langle BS \rangle$;
$SN_i^j \leftarrow SN$;
/* the current location of the mobile charger */
$SN_i^j \leftarrow BS$;
/* the current time */
$T \leftarrow 0$;
while $T > CS_i^{Time}$ do
    Apply the SBCS mechanism to obtain $SN_1^1, SN_2^1, SN_3^1, \ldots, SN_i^j, SN_i^j + 1$;
    For each sector, find the SN with the largest number of requests and then form a path from $BS$ that visits nodes within this sector, and finally return to $BS$ by adopting an MST heuristic and the TSP;
    If no recharging request is found, then apply the SBCS mechanism again and repartition.
    if $ECs \leq 0$ then
        /* the mobile charger return to $BS$ */
        Break;
    end if;
    Check the energy charging sequence;
    /* Assuming sector $SN_i^j$ has the largest amount of recharging requests Eq, the mobile charger then goes to charge sensors in this sector by following the found path */
    Update ECs and $T$ accordingly;
    /* reset Qc for next RT */
```

```
$SN \leftarrow SN_i^j$;
end while;
return $RT$
```

Algorithm 2 is recursive. First, the BS receives the energy requests Eq, analyzes the data, and checks the Sector SN with the largest number of Eq. The requests in the energy charging sequence ECs are collected, and then MC begins the RT from the BS to the sectors. If no energy requests are found, then SBCS mechanism is applied again and repartitioning is performed. This procedure continues until T is no longer met.

3. Performance Evaluation

In this section, we evaluate the performance of the SBCS mechanism through an experimental simulation and compare it with the FCFS and SAJF mechanisms. We then investigate the MC status (efficiency and effort).

1.6 Simulation Results

Table 2. Default Parameter Setting

Parameter	**Value**
Network size (small)	10–30 nodes
Network size (large)	100–1000 nodes
Time T (small)	600 s
Time T (large)	1800 s, 3600 s
Radius R (small)	100 m
Radius R (large)	600 m
MC speed	8 m/s
Charging time for each sensor	2 s

As listed in **Table 2**. two differently sized networks are examined in our experiments: a large and a small network. We investigate the performances of FCFS and SAJF and then compare them with that of the proposed SBCS mechanism. We examine the influence of these mechanisms on both networks to show the effectiveness of our proposed mechanism in large and small networks. Therefore, we investigate a small network consisting of 10–30 nodes randomly deployed in a circular area with radius $R=100\ m$ and a large network consisting of 100–1000 nodes with radius $R=600\ m$. The BS is located at the center of the field and at the corner of each quartet of the R-WSN monitoring area. As explained in section 2, the BS divides the network field into a number of rings and sectors using the BS capabilities that are equipped with a directional antenna with power control capabilities. In addition, the BS helps to select the *CH* for each sector after receiving information from sensors by automatically informing all nodes in each sector about the CH for the sector.

Our working environment is a dynamic sensing activity in which each sensor randomly sends its recharging requests to the BS. The BS analyzes the requests and checks the sector with the largest amount of energy request. It then sends the *MC* on an *RT* within a given *Trip Time* T. We set T= 600s for a small network and T= 1800 s and T = 3600 s for a large network. We examine a large monitoring field twice to show the network scalability. We assume that the *MC* travels at a constant speed of *8* m/s and that the constant charging time for each sensor is *2* s. Every esteem in the figures is the mean of the outcomes by applying each mentioned mechanism to 20 different scans of the field of the same network size.

We first examine the performances of FCFS, SAJF, and the proposed SBCS mechanism in small networks by varying the network size from 10 to 30 sensors within T=600 s. **Fig. 3** shows that the charging productivity of the SBCS mechanism exceeds the FCFS and SAJF mechanisms significantly. Clearly, when the charging productivity reaches 13%, an intersection point is created between FCFS and SBCS, and then SBCS again overcomes the FCFS mechanism because in a small network, recharging requests account for some of the workload when the network begins.

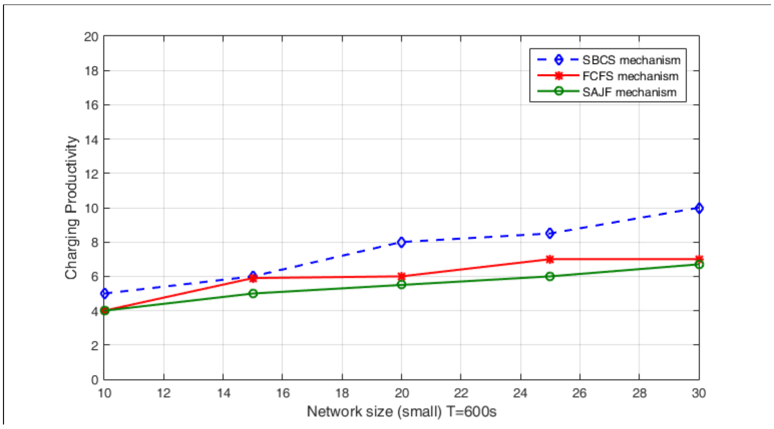

Fig. 3. Charging productivity performance in a small network with 10–30 nodes and T=600 s

Second, we study the performances of FCFS, SAJF, and SBCS mechanisms in a large network by changing the network size from 100 to 1000. When the network size is greater than 100 and T is 1800s, the charging productivity of SBCS is at least 17% more than those of the FCFS and SAJF mechanisms. In **Fig. 4**, the performance gap between them increases to 23% when the network size increases.

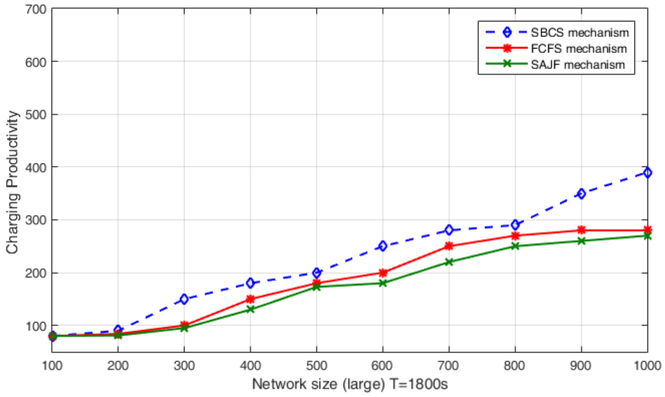

Fig. 4. Charging productivity performance in large network with 100–1000 nodes T=1800 s.

Similarly, in **Fig. 5**, when the network size is greater than 200 and T is 3600 s, the charging productivity of SBCS is at least 30% greater than those of the FCFS and SAJF mechanisms. With a larger time period T, the charging productivities of both mechanisms increase as the MC has much time available to serve the recharging requests. We conclude that our proposed mechanism can work effectively in large networks.

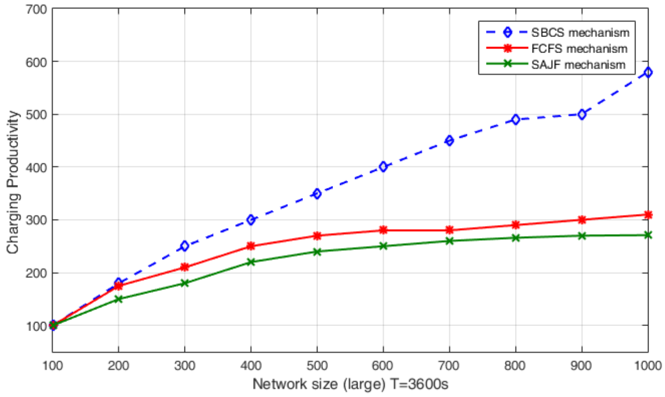

Fig. 5. Charging productivity performance in a large size network 100–1000 nodes T=3600 s

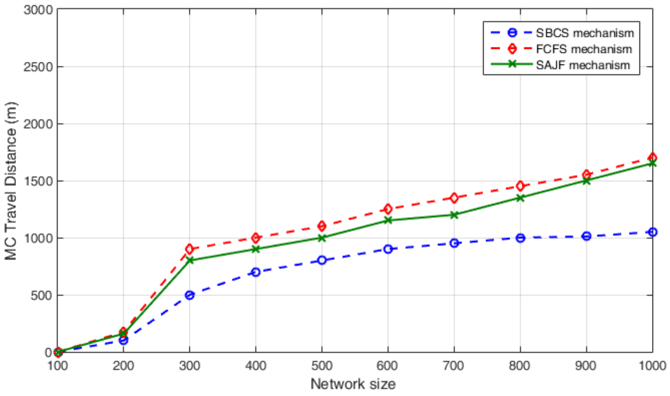

Fig. 6. MC travel distance performance in a large network

In addition, we examine the MC effort by measuring the travel distance of the MC in visiting and recharging the sectors with large amounts of energy requests. **Fig. 6** shows a large distance when the MC uses the FCFS mechanism, spatially when it serves more than 200 sensors, it needs to travel a large distance between these sensors to recharge them, and this distance increases with network size, such as that of SAJF. Unlike the SBCS mechanism, the MC goes high but becomes stable in the 800th node, thus indicating that the travel distance difference between both mechanisms is 17%. Therefore, the proposed SBCS mechanism outperforms the FCFS and SAJF mechanisms.

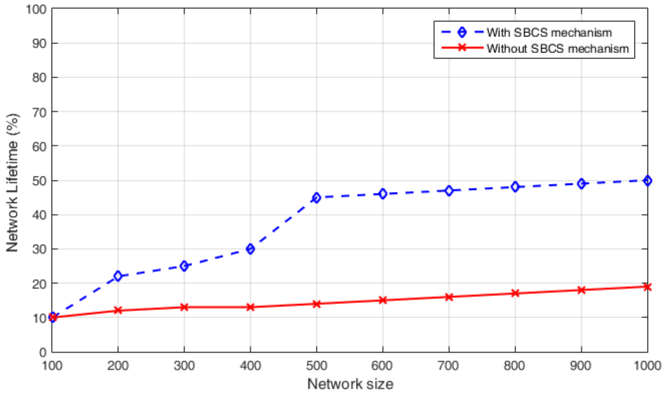

Fig. 7. Comparing network lifetimes using SBCS

Finally, we investigate the effect of the proposed SBCS mechanism on network lifetime. A node spends a large amount of energy to communicate in selecting CH because choosing the CH is becoming the task of the BS. Therefore, this situation leads to a decrease in sensor interconnection, high network efficiency, and prolonged network lifetime. **Fig. 7** shows that when applying the SBCS mechanism, the difference when using the SBCS mechanism is more than 30% which is the gap between them i.e. using SBCS mechanism and without SBCS.

4. Conclusion

In this study, we investigated the problem of finding an optimal path for an MC in R-WSNs by splitting the sensing field into partitions that could be equally spaced but could differ in distance from the BS. Then, we formulated the problem as a charging productivity problem to improve the R-WSN network efficiency and minimize the MC effort per round trip. Thereafter, we provided a new charging mechanism called SBCS and suggested efficient sensor-charging algorithms. Finally, we evaluated the performance of the proposed mechanism through an experimental simulation and provided statistical results to validate the efficiency of the proposed mechanism. However, our work generally focuses on minimizing the MC effort using BS capability, which may result in unfair charging behaviors in some extreme cases in which some sectors far from the base station have a few chances to be charged persistently. Therefore, our future work involves examining this fairness issue, we will study it with more concentrate and doing some experiments.

5. References

[1] A. A. Aziz, Y. A. Sekercioglu, P. Fitzpatrick and M. Ivanovich, “A survey on distributed topology control techniques for extending the lifetime of battery powered wireless sensor networks,” *Communication Surveys & Tutorials*, vol. 15, no. 1, pp. 121-144, 2013. Article (CrossRef Link).

[2] J. H. Chang, L. Tassiulas, “Maximum lifetime routing in wireless sensor networks,” *IEEE Transactions on Networking*, vol. 12, no. 4, pp. 609-619, 2004. Article (CrossRef Link).

[3] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, “Wireless power transfer via strongly coupled magnetic resonances,” *Science*, vol. 347, no. 5834, pp. 83-86, 2007. Article (CrossRef Link).

[4] A. Karalis, j. D. Joannopoulos, and M. Soljacic, “Efficient wireless nonradioactive mid-range energy transfer,” *Annals of Physics*, vol. 323, no. 1, pp. 34-48, 2008. Article (CrossRef Link).

[5] Y. Shi, L. Xie, Y.T. Hou, and H.D. Sherali, “On renewable sensor networks with wireless energy transfer,” in *Proc. of IEEE INFOCOM*, pp. 1350–1358, April 2011. Article (CrossRef Link).

[6] L. Xie, Y. Shi, 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. of IEEE SECON*, pp. 10–18, June 2012. Article (CrossRef Link).

[7] C. Schurgers, M. B. Srivastava, “Energy efficient routing in wireless sensor networks,” *MILCOM*, pp. 357-361, 2001. Article (CrossRef Link).

[8] D. Gao, G. Wu, Y. Liu and F. Zhang, “Bounded end-to-end delay with transmission power control techniques for rechargeable wireless sensor networks,” *International Journal of Electronics and communications*, vol. 68, no. 5, pp. 395-405, 2014. Article (CrossRef Link).

[9] C. M. Angelopoulos, S. Nikoletseas, T. P. Raptis, C. Raptopoulos, and F. Vasilakis. “Efficient energy management in wireless rechargeable sensor networks,” in *Proc. of MSWiM*, pp. 309-316, 2012. Article (CrossRef Link).

[10] H. Dai, L. Jiang, X. Wu, D. Yau, G. Chen, S. Tang, and X. Li., “Near optimal charging and scheduling scheme for stochastic event capture with rechargeable sensors,” in *Proc. of of MASS*, pp. 10-18, 2013. Article (CrossRef Link).

[11] L. Fu, P. Cheng, Y. Gu, J. Chen, and T. He., “Minimizing charging delay in wireless rechargeable sensor networks,” in *Proc. of IEEE INFOCOM*, pp. 2922–2930, 2013. Article (CrossRef Link).

[12] L. He, Y. Gu, J. Pan and T. Zhu, “On-demand charging in wireless sensor networks: theories and applications,” *MASS*, pp. 28-36, 2013. Article (CrossRef Link).

[13] Z. Li, Y. Peng, W. Zhang, and D. Qiao, “J-RoC: A joint routing and charging scheme to prolong sensor network lifetime,” in *Proc. of of Network Protocols (ICNP)*, pp.373-382, 2011. Article (CrossRef Link).

[14] 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 transactions on networking*, vol. 20, no. 6, pp. 1748-1761, 2012. Article (CrossRef Link).

[15] C. Wang, Y. Yang, and J. Li, “Stochastic mobile energy replenishment and adaptive sensor activation for perpetual wireless rechargeable sensor networks,” *WCNC*, pp. 974-979, 2013. Article (CrossRef Link).

[16] Vrinda Gupta and Rajoo Pandey, “An improved energy aware distributed unequal clustering protocol for heterogeneous wireless sensor networks,” *Engineering Science and Technology*, vol. 19, no. 2, pp. 1050–1058, 2016. Article (CrossRef Link).

[17] L. He, L. Fu, L. Zheng, Y. Gu, P. Cheng and J. Pan, “ESync: an energy synchronized charging protocol for rechargeable wireless sensor networks,” *MobiHoc*, pp. 247-256, 2014. Article (CrossRef Link).

[18] K. Chen, J. Huang, and C. Hsiao, “CHIRON: an energy-efficient chain-based hierarchical routing protocol in wireless sensor networks,” in *Proc. of the Wireless Telecommunications Symposium (WTS '09)*, Prague, Czech Republic, pp. 1–5, April 2009. Article (CrossRef Link).

[19] Muni Venkateswarlu Kumaramangalam, Kandasamy Adiyapatham, and Chandrasekaran Kandasamy**,** “Zone-Based Routing Protocol for Wireless Sensor Networks,” *International Scholarly Research Notices*, vol. 2014, 2014. Article (CrossRef Link).

[20] S. Mao and Y. Hou, “BeamStar: An edge-based approach to routing in wireless sensor networks,” *IEEE Transactions on Mobile Computing*, vol. 6, no. 11, pp. 1284–1296, 2007. Article (CrossRef Link).

[21] W. H. Li and C. Y. Yang, “A cluster-based data routing for wireless sensor networks,” in *Proc. of ICA3PP*, Springer, vol. 5574, pp. 129–136, 2009. Article (CrossRef Link).

[22] W. Mao, R. K. Kincaid, and A. Rifkin, “On-line algorithms for a single machine scheduling problem,” *The Impact of Emerging Technologies on Computer Science and Operations Research*, pp. 157-173, 1995. Article (CrossRef Link).

[23] Y. Peng, Z. Li, W. Zhang, and D. Qiao, “Prolonging sensor network lifetime through wireless charging,” in *Proc. of RTSS'10*, 2010. Article (CrossRef Link).

[24] Y. Ko and N. Vaidya, “Location-Aided Routing (LAR) in Mobile Ad-Hoc Networks,” *Wireless Networks*, vol. 6, no. 4, pp. 307-321, 2000. Article (CrossRef Link).

[25] S. Naeimi, H. Ghafghazi, C. Chow, H. Ishii, ”A Survey on the Taxonomy of Cluster-Based Routing Protocols for Homogeneous Wireless Sensor Networks,” *Sensors*, vol. 12, pp. 7350-7409, 2012. Article (CrossRef Link).

[26] Zaid A. Ali Al-Marhabi, LiRen Fa, FanZi Zeng, Ayeda G. Ali Al-Hamdi, ”The Design and Evaluation of a Hybrid Compression Technique (HCT) for Wireless Sensor Network,” *JDCTA: International Journal of Digital Content Technology and its Applications*, vol. 5, no. 5, pp. 201-207, 2011. Article (CrossRef Link).

[27] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energy-efficient communication protocol for wireless microsensor networks,” in *Proc. of HICSS*, 2000. Article (CrossRef Link).

[28] B. Kang and G. Ceder, “Battery materials for ultrafast charging and discharging,” *Nature*, vol. 458, pp. 190-193, February, 2009. Article (CrossRef Link).

[29] D. Gross, *Fundamentals of Queueing Theory*, 4th Edition., New Jersey: John Wiley & Sons, p. 232, 2008. Article (CrossRef Link).

[30] K. Bharath-Kumar and J.M. Jaffe, “Routing to multiple destinations in computer networks,” in *Proc. of IEEE Transactions on Communications*, Vol. 31(3), pp. 343,351, March 1983. Article (CrossRef Link).

[31] J. Li, M. Zhao and Y. Yang, “OWER-MDG: a novel energy replenishment and data gathering mechanism in wireless rechargeable sensor networks,” *Globecom*, pp. 5350-5355, 2012. Article (CrossRef Link).

Sadam Alkhalidi received his B.S. degrees in computer science from Zarqa University, Jordon, in 2004 and M.S. degrees in computer science from Hunan University, China, in 2012. Currently, he is a Ph.D. candidate in computer science, Hunan University, China. His research interests focus on sensors networks.

Dong Wang received M.E. and Ph.D. degree in computer science from Hunan University, China. His Ph.D. director and a director to overseas graduate students in College of Computer Science and Electronics Engineering, Hunan University. His main research interests are computer networks and vehicular multimedia networks.

Al-Marhabi Zaid Ali received his B.S. degrees in Electronic Information Engineering from Central South University, China, in 2005. His M.S. degrees in Communication Engineering from Hunan University, China, in 2009 and Ph.D. degrees in Computer Science from Hunan University, China in2013. Assistant professor in 2013, Head of Communication and Networking Department in 2014, Vice Dean in 2015 in Faculty of Applied Science, Hajjah University .research interests focus on Wireless and WSN.