

# Schemes for Extending the Network Lifetime of Wireless Rechargeable Sensor Networks

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## Abstract

*Most Wireless Rechargeable Sensor Networks (WRSN) allow simultaneous energy replenishment with data gathering. These schemes suffer from high energy consumption of mobile chargers and could require new sensor design for their integration. Thus, we propose Distributed Energy Replenishment and Data Gathering (DERDG) to reduce the energy consumption of the chargers and Spatio-Temporal Non-Concurrent Data gathering and Energy replenishment (ST-NCDR) that are easily be integratable on the sensor nodes. In these schemes, sensor nodes are divided into clusters and requests from energy-hungry nodes are arranged based on their temporal properties in DERDG, but using their spatial and temporal properties in ST-NCDR. In ST-NCDR scheme, two mobile chargers replenish the energy of energy-hungry nodes when they are not performing sensing and transmission of data, but irrespective of their operational states in DERDG scheme. Simulation results indicate the superiority of the schemes over state-of-the-art schemes in terms of energy consumption of mobile chargers and average residual energy of the nodes. Both DERDG and ST-NCDR reduced the energy consumption of the chargers, without reduction in the network lifetime, by an average of 29.45% and 73.70%, respectively, when compared to the work of Han et al. (2018), and by 71.40% and 93.80% in comparison to the work of Mikail et al. (2020). DERDG reduces data delivery delay by 95.50% in comparison to the work of Han et. al, (2018). The findings imply that ST-NCDR can be easily integrated into sensor nodes and yields a reduction in the energy of mobiles chargers use in charging the sensor nodes that translate to lower cost of network operation, in addition to improving the residual energy of nodes in WRSN. This part should state the context of the research being reported. Aim: the objective of the research should be clearly stated here Method: the research approach used in the study, justifying its suitability for the study should be stated here. Results: the findings and their implication(s) should be clearly enumerated and briefly discussed here.*

**Keywords:** Wireless charger, mobile charging, rechargeable sensor nodes, distributed algorithms, clustering, wireless energy transfer, data gathering

## 1. Introduction

Wireless rechargeable sensor networks (WRSNs) are a new paradigm of wireless sensor networks (WSN) that enable energy replenishment of sensor nodes via wireless energy transfer. Nodes in the WRSNs are embedded with batteries that are recharged via wireless energy transfer. Most of the existing schemes assumed concurrent data gathering with energy replenishment. The assumption leads to an increase in the processing power requirements of nodes because a node could require separate circuits for data gathering and for energy reception. The increase in the processing power requirement offset the low-cost requirements of sensor nodes (Li & Huo, 2016). Thus, making the schemes difficult to integrate on the sensor nodes. More so, there is the need to reduce the high energy consumption of mobile chargers to reduce the network operational cost (Hong et al. 2022; Tomar & Jana, 2021).

Two WRSNs algorithms are here by proposed: DERDG- to reduce the high energy consumption of mobile chargers and ST-NCDR that can easily be integrated into sensor nodes.

The contributions of the paper are:

- Proposed two charging schemes that reduced the energy usage of mobile chargers (MCs) and allow ease of integration into the sensor nodes.
- Relaxed the condition for recharging nodes and proposed a distributed scheme that used only temporal properties of requests to lower the energy usage of MCs when nodes are allowed to replenish their energies simultaneously with data sensing and transmission.
- Evaluated the proposed schemes via simulations and compared their performances with those of the state-of-the-art solutions.

The paper is organization is such that section 1 contains the introduction, while section 2 comprises material, methodologies and model equations used for the study. Result and discussion are presented in section 3 and 4, respectively, with section 5 containing the conclusion.

## 2. Related Works

Most of the existing schemes for enhancing the network lifetime of WRSN were possible due to the technological advancement in wireless energy transfer. Some of the schemes operate based on simultaneous energy replenishment with data collection, with a few based on non-concurrent energy replenishment with data gathering. Below is a review of the schemes for the two main categories.

Schemes based on simultaneous energy recharging and data gathering allow energy-hungry nodes to replenish their energies while performing data sensing and transmission. A sink dispatches one or more MCs to travel around the network to collect data in the network and also to recharge the energy-hungry nodes. Data collection is usually from fixed points within the network. The authors of Liu et al. (2019) proposed a joint power optimization, relay selection, and scheduling of time slots to nodes using a mobile Base Station (BS) that travels in a straight line within the sensing field. The authors achieved simultaneous data gathering with energy replenishment using separate time slots and frequencies for the two tasks. Besides, Guo et al. (2014) utilized multiple MCs that periodically leave a service station to travel and collect data and also replenish the nodes using anchor points as sojourning points. The charging scheme is for the simultaneous optimization of data generation, uploading rate, and sojourning time at recharging points. Also, Rao et al. (2019) proposed a similar recharging scheme to minimize the number of dead nodes and data loss using a vertex approach. The authors of Han et al. (2018) used two MCs that are periodically dispatched in opposite directions to follow a Shortest Hamilton Path (SHP) around the network during the process of recharging the nodes. Following the SHP reduce the data collection delay (for data to be available at the BS) associated with mobile data gathering. The MCs stay at anchor points in each cluster to recharge nodes within their charging ranges and collect data from the Cluster Heads (CHs). A statistical model was also developed to predict the remaining energies of nodes for the estimation of new anchor points for the next cycle of the MCs. Other schemes that used similar approach include Boukerche et al. 2021; Chen & Shen, 2019, Jiao et al. 2022; Srinivas et al. 2022; and Zhang & Cai, 2022.

Assumption of concurrent execution of both energy recharging and data gathering implies that a node should have two circuits, one for each of the tasks, which implies use of costly sensor nodes. The schemes also suffer from high data delivery delay.

The DERDG scheme addresses some of the highlighted drawbacks of the existing schemes. It reduces the energy consumption of MCs and data delivery delay without decreasing the average lifetime of nodes. Moreover, ST-NCDR replenishes the energy of nodes when they are not performing data sensing and transmission to avoid the need for costly nodes. It also allows the MC to travel closer to nodes to recharge them.

Non-concurrent energy replenishment and data gathering has not received much attention because researchers did not consider the implication of simultaneous execution of the tasks on the cost of the nodes. The authors of Li et al. (2021) maximized average network throughput on the assumption that nodes do not have enough processing power for concurrent data gathering and energy replenishment. The scheme allocates separate stationary wireless rechargers to each sensor node. It has high network deployment and operation costs because it requires an equal number of stationary rechargers as the number of sensor nodes. Since wireless chargers take a higher percentage of the network deployment

cost than other components, the scheme has a high operational cost. The authors of Mikail et al. (2020) proposed a state scheduling and recharging algorithm to reduce the high network deployment and operational costs. It uses a single MC to recharge nodes only when the nodes are not performing data sensing and transmission, that is, when the TDMA time slot is being utilized by other nodes. However, the scheme has huge charging latency because requests were serviced based on first-come first-serve approach. It is unsuitable for emergency data gathering due to the long waiting time before nodes access their allocated time slots. It also has a lower network lifetime especially when there are few nodes in the network.

### 3. Network Modelling

For both DERDG and ST-NCDR, we consider  $N$  static homogeneous sensor nodes deployed in an  $M$  by  $M$  region. The nodes are assumed to be capable of direct communication with the BS and are also location-aware using any of the available localization schemes such as Approximate Point In Triangulation (APIT) and Gradient algorithm (Chan et al. 2006). Multiple MCs serve the sensing region, but two at a time. A single BS positioned around the centre of the region serves as the service station. The sensor nodes are grouped into operation-independent clusters using the K-Means algorithm. Each cluster uses Time Division Multiple Access (TDMA) schemes during data sensing and transmission. A node sense and transmit data only within its allocated time slot. Nodes belonging to the same cluster select a Cluster Head (CH) among them and send sensed data to their CHs via multi-hop. In the ST-NCDR, the CHs directly transmit the data to the sink during the last time slot of the TDMA frame. A node broadcast a charging request when its energy reaches a set threshold. The BS maintains queues of recharging requests (one queue per cluster) and coordinates the activities of the MCs. Whereas in DERDG, the CHs store received data and offload it to an MC when the MC later arrives at the cluster. A node sends a recharging request to its CH, via its data flow path when the node's energy reaches a set threshold. The CHs buffer and arrange the recharging requests from their cluster members. In DERDG, the BS Periodically calculates the SHP around the network and dispatches two MCs in opposite directions to travel and replenish energy-hungry nodes without regard to whether a node is within its allocated time slot or not. The MC also collects data from the CH in each of the clusters for later uploading to the sink. However, in ST-NCDR, even after a certain time, the BS only calculates the SHP and dispatches the two MCs only when there is at least a request in any of the queues that are being maintained by the BS. An MC travel and recharge the energy of a node only when the node is not within its time slot, that is, there is enough time to travel and finish recharging the node before it is due for sensing and transmission.

#### 3.1 Energy consumption and recharging models

In both schemes, the energy consumed by a node in sensing  $l$  bit of data is given by  $E_s = r_c Yt$ , where  $r_c$  is the energy consumption rate per bit,  $Y$  is the data generation rate, and  $t$  is the sensing period (Han et al. 2019a). A node consumes of  $E_r = lE_{elect}$  when it receives  $l$  bits of data, and consumes  $E_t = l(E_{elect} + E_{amp} * d^2)$  by transmitting  $l$  bits of data to another node, a distance of  $d$  apart. The energy consumed when it receives  $l$  bits of data is given by. Where  $E_{elect}$  and  $E_{amp}$  are constants.

We adopted the charging model of He et al. (2013) which assumes an MC to be a transmitter with transmitting power of  $P_t$  and a sensor node to be a receiver. The power received by a node,  $P_r$ , is given by:

$$P_r = \frac{\alpha}{(d+\beta)^2} \tag{1}$$

The experimental values of  $\alpha$  and  $\beta$  are  $4.32 * 10^{-4}$  and 0.2316 (Han et al. 2018).

#### 3.2 Cluster formation in ST-NCDR and DERDG

After the deployment of nodes, they are divided into clusters using the K-Means algorithm. The k-Means clustering algorithm uses Euclidean distance as an evaluation index such that nodes closer to each other are grouped into a single cluster. The K-Means clustering algorithm employed by Han et al. (2018) is adopted in both ST-NCDR and DERDG.

### 3.3 Cluster head selection in ST-NCDR

Cluster members select a CH within themselves. The CHs selection process in ST-NCDR is as discussed hereunder.

Nodes belonging to the same cluster compete for the CH role by evaluating their individual  $C_m$  value. The  $C_m$  value of a node depends on the node's remaining energy and the summation of the energy consumed by nodes to send data toward it. The weighting factor for a node  $i$  is as follows:

$$C_{m_i} = \psi \frac{E_{avg}}{E_i} + (1 - \psi) \frac{\sum_{j=1}^{n-1} d_{i \text{ to } j}^2}{n * d_{avg}^2} \quad (2)$$

where  $E_i$  is the residual energy of node  $i$ .  $E_{avg}$  is the average residual energy of nodes in the same cluster.  $\sum_{j=1}^{n-1} d_{i \text{ to } j}^2$  is the summation of the square of the distance from node  $i$  to other nodes in the cluster. The average distance between one node to another in the cluster is represented by  $d_{avg}$ , with  $n$  denoting the number of nodes in the cluster, and  $\psi$  representing a weighing constant that indicate energy importance. The value of  $\psi = 0.5$  used by Han et al. (2018) is also used for both ST-NCDR and DERDG. A node with the least value of  $C_m$  serves as the CH.

The first part of Eq. (2) indicates the instantaneous energy capability of a node which is an indication of how long it can support the cluster if selected as the CH. The second part of Eq. (2) minimizes the energy consumption of other nodes in the same cluster as node  $i$  when sending data toward it. When the energy consumption of other nodes is minimal, the cluster lifetime is improved.

When the energy of a CH reaches a threshold, it notifies other cluster members to select a new head. The CH is required to relinquish its role for ease of its energy replenishment and lowers the complexity of the replenishment process.

### 3.4 Cluster head selection in DERDG

Each cluster in DERDG is assigned an identifier, and cluster nodes compete for selection as the head using their residual energies and average distances to the centre of their clusters. For instance, the centre of a cluster  $j$  is estimated using Eq. (3).

$$(x_{c_j}, y_{c_j}) = \min \sum_{i=1}^n [(x_{c_j} - x_i)^2 + (y_{c_j} - y_i)^2] \quad (3)$$

Cluster members in cluster  $j$  compete for selection as the head and each node estimates its  $C_{md}$  value. The  $C_{md}$  for node  $i$  in cluster  $j$  is evaluated using Eq. (4).

$$C_{md_i} = \psi \frac{E_i}{E_{avg}} + (1 - \psi) \frac{d_{avg}}{d_i} \quad (4)$$

where  $d_{avg}$  is the average distance of all cluster members to the centre,  $(x_{c_j}, y_{c_j})$ ;  $d_i$  is the node's distance from the centre.

The node with the highest value of  $C_{md}$  is becomes the CH.

### 3.5 The Routing protocol in ST-NCDR and DERDG

Each of the clusters in both ST-NCDR and DERDG operate independently based on the TDMA scheme, such that each node is allocated a time slot within the TDMA frame within which it must sense and transmit data. Nodes forward sensed data to their nearest neighbours but toward the direction of their CH. Figure 1 depicts the data transmission process for ST-NCDR and DERDG. Both schemes use the same data routing approach but a different energy-recharging approach. During sensing and transmission, if the energy of a node in a cluster reaches a threshold, it broadcasts a recharging request. In ST-NCDR, the BS receives and places the request in the queue allocated to its cluster members, while the CH buffers the recharging requests and waits for the arrival of a mobile charger in DERDG.

### 3.6 Remaining lifetime of a node

The maximum remaining energy of any node when it sends a recharging request is equal to the energy threshold. That is,  $E_i \approx E_{thresh}$ . So, the remaining lifetime,  $t_{di}$ , of the node is expressed in Eq. (5).

$$t_{di} = \frac{t_{-slot} * E_{thresh}}{E_r \Gamma_i + E_t} \tag{5}$$

where  $E_{thresh}$ ,  $t_{-slot}$ , and  $\Gamma_i$  represent the energy threshold, the TDMA time slot duration allocated to each node to sense and transmits data, the number of neighbouring nodes that send their data directly to node  $i$ , respectively.

### 3.7 Problem formulation

Let  $S$  represent a sensor node with an energy of  $E_i$ . A node  $i$  is alive if  $S_i = 1$  and exhausted when  $S_i = 0$ . That is

$$S_i = \begin{cases} 1, & \text{if } E_i > E_{min} \\ 0, & \text{if } E_i \leq E_{min} \end{cases} \tag{6}$$

The minimum energy required by a sensor node to be operational is  $E_{min}$ . Let  $E_{MC_r}$  and  $B$  represent the residual energy of an MC at a given time and the energy limits of each charger, respectively.

For ST-NCDR, the network is modelled to maximise the number of live nodes in the entire network. This translates into improvement in average residual energy of the nodes.

The objective function is to:

$$\max \sum_{j=1}^k \sum_{i=1}^{n_j} S_i \tag{7}$$

Subject to:

$$t_{di} > 0 \quad \forall i \tag{8}$$

$$k > 1 \tag{9}$$

$$E_{MC_r} \leq B \quad \forall MC \tag{10}$$

The remaining lifetime of node  $i$  is represented by  $t_{di}$ . Constraint in Eq. (8) ensures that each node is not exhausted. Constraint in Eq. (9) is such that there are at least two clusters in the network, and constraint in Eq. (10) is to ensure that each MC operates within its energy limits of  $B$ .

For DERDG scheme, the network is modelled to minimise the energy consumption of the mobile chargers. Its objective function and constraints are as follows:

$$\min \sum_{j=1}^k \sum_{i=1}^{n_j} [(C_d * d_{i \text{ to } i+1}) + (P_t t_{rech})] + C_d (d_{j=1, i=1 \text{ to } BS} + d_{j=k, i=n_j \text{ to } BS}) \tag{11}$$

Subject to:

$$k > 1 \tag{12}$$

$$E_i \geq E_{min} \quad \forall i \tag{13}$$

$$E_{MC\_rem} \leq B \quad \forall MC \tag{14}$$

where  $C_d$  is the cost of energy consumption of the mobile charger per unit distance,  $P_t t_{rech}$  is the energy consumption for recharging a node and  $n_j$  is the number of nodes that have sent energy recharging requests within cluster  $j$ . The distance from the BS to the CH of the first cluster, to be visited, is represented by  $d_{j=1,i=1 \text{ to BS}}$  and  $d_{j=k,i=n_j \text{ to BS}}$  represent the distance from last recharged node in the last visited cluster back to the BS.  $d_{i \text{ to } i+1}$  represent inter-distance between nodes in the same cluster.

### 3.8 Requests Priorities In ST-NCDR and DERDG

Recharging recharges are arranged in ascending order of their priorities. The position of a request in a queue of a cluster is determined by the summation of its spatial and temporal priorities in ST-NCDR and by only its temporal priority in DERDG.

The priority of request  $i$ ,  $R_{qi}$ , in ST-NCDR is calculated using Eq. (15).

$$R_{qi} = \frac{n_q * d_{node_i}}{n * d_{max}} + \frac{t_{r_i}}{\Gamma_i * t_{r-1}} \tag{15}$$

And the priority in DERDG is calculated using Eq. (16).

$$R_{qi} = \frac{t_{r_i}}{t_{r_{i-1}}} * \Gamma_i \tag{16}$$

where  $n_q$  is the number of requests already in the queue.  $n_q = 1$  if the request is the first to arrive. The number of nodes in the cluster is represented by  $n$ , and  $d_{node_i}$  is the distance of the node from its CH. The largest value of  $d_{node}$  from nodes in the queue is represented by  $d_{max}$ ,  $t_{r_i}$  is the arrival time of the request from node  $i$ ,  $t_{r_{i-1}}$  is the arrival time of the adjacent request before that of node  $i$ .  $\Gamma_i$  is the number of traffic carried by the node which stands for the number of nodes sending their data directly to node  $i$ .

### 3.9 Charging path planning in ST-NCDR and DERG

The path planning similar to that in Han et al. (2018) is employed. The path is planned using the coordinates of the CHs to estimates the Shortest Hamilton Path (SHP) in the network. In addition, the MC starts recharging a node after moving closer to it, that is,  $d \approx 0$  such that power transfer efficiency is maximum (Priyadarshani et al. 2021). Each MC uses an equal time duration in replenishing the energy of each node. The recharging time is expressed in Eq. (17).

$$t_{rech} = \frac{E_o - E_{thresh}}{P_r} \tag{17}$$

where  $E_o$  is the energy capacity of each node. An MC recharges the energy of any node toward its full capacity. However, as the remaining energy of a node will be lower than  $E_{thresh}$  before any of the MCs arrives at its location, the node is replenished partially at the end of time  $t_{rech}$ .

### 3.10 Energy replenishment in ST-NCDR and DERDG

In DERDG, two MCs are periodically dispatched in opposite directions to travel and recharge energy-hungry nodes. The MCs first travel to the location of the CH in a cluster to collect cluster and queue information before attending to energy-hungry nodes in the cluster. They recharge all energy-hungry nodes irrespective of their operation state at the time of recharging before leaving the cluster. When there is no request in a cluster, the MC visits its CH and travels to the next cluster along the SHP. When the energy of an MC is exhausted while on duty, it calls a new MC to take over the energy replenishment, and the former travels back to the service station, the location of the sink, to replenish its energy.

In ST-NCDR, the sink sends two MCs after a set time interval and only when there exists at least a request in any of the queues. An MC first travel to a CH to collect cluster information, from which the currently transmitting node

is known. It then travels to recharge nodes that had sent recharging requests only when the nodes are using the TDMA time slot and updates the queue thereafter. An MC only leaves the cluster after all energy-hungry nodes in the cluster are replenished. When a cluster has no request, the MC visits its CH and travels to the next cluster along the SHP.

In ST-NCDR, the MC considers a maximum of three requests positions at a time. A maximum of three requests is considered to be conservative in reducing the energy consumption of the MCs. That is, to stop the MCs from travelling to farther nodes when a node on a queue head cannot be recharged due to time constraints. Let the first three requests on a queue head of a cluster and the node currently using the TDMA time slot be represented by  $n_{q1}$ ,  $n_{q2}$  and  $n_{q3}$ , and  $n_t$  respectively.

The following considerations are needed before recharging the node  $n_{q1} = n_t$ . The time for the MC to travel to the location of node  $n_{q1}$  is given by  $\frac{d_{MC\ to\ n_{q1}}}{v}$ . Where  $d_{MC\ to\ n_{q1}}$  represent the distance from current position of an MC to the node with the request,  $n_{q1}$  and  $v$  stands for the velocity of the MC. Let  $t_{remain}$  represent the time remaining for a node to finish using its slot. The condition in equation (18) must be satisfied before recharging  $n_t$ .

$$\frac{d_{MC\ to\ n_{q1}}}{v} > t_{remain} \tag{18}$$

When  $n_{q1} \neq n_t$ , the total duration of a frame is given by  $n * t_{slot}$ . The time duration from the release of the TDMA frame to when the  $n_t$  is just about to use its allocated time slot is denoted by  $n_t * t_{slot}$ . The time interval from the start of the slot for node  $n_t$  to when  $n_{q1}$  is just about to use its time slot is given by  $|n * t_{slot} - n_t * t_{slot}| + t_{remain}$ . As such, the condition in Eq. (19) must be satisfied before recharging  $n_{q1}$  when other nodes are using the TDMA time frame at the point of recharging it. It is also the same as the condition for recharging  $n_{q2}$  when it is also not in the state of sensing and transmission, by replacing  $n_{q1}$  with  $n_{q2}$  in Eq. (19).

$$\frac{d_{MC\ to\ n_{q1}}}{v} + t_{rech} \leq |nt_{slot} - n_t t_{slot}| + t_{remain} \tag{19}$$

For recharging  $n_{q3}$  the condition in Eq. (20) must be satisfied before testing the condition in Eq. (21).

$$d_{MC\ to\ n_{qi=3}} < d_{MC\ to\ n_{qi=2}} \tag{20}$$

$$\frac{d_{MC\ to\ n_{q3}}}{v} + t_{rech} \leq |nt_{slot} - n_t t_{slot}| + t_{remain} \tag{21}$$

The distances  $d_{MC\ to\ n_{q1}}$ ,  $d_{MC\ to\ n_{qi=2}}$  and  $d_{MC\ to\ n_{q3}}$  respectively represent the distances from the position of the MC to the nodes  $n_{q1}$ ,  $n_{q2}$ , and  $n_{q3}$ .  $v$  stands for the velocity of the MC, the recharging duration of each node is represented by  $t_{rech}$ , and  $n$  denotes the number of nodes in a cluster.

### 3.11 Description of replenishment algorithms in ST-NCDR

A detailed explanation of the operations of the algorithm is as follows:

The two MCs are dispatched in opposite directions by the sink to travel along the estimated SHP. Whenever an MC arrives at a cluster, it goes to the location of the CH to collect information about the cluster's current TDMA frame, from which the node currently transmitting,  $n_t$ , is known. The MC then examines the queue associated with the cluster. If the queue is empty, it simply travels to the next cluster along the SHP. However, if the queue contains some requests, the MC considers the node,  $n_{q1}$ , with a request on the queue head. There are two possible cases for  $n_{q1}$ . It is either the node currently transmitting  $n_{q1} = n_t$ , or not  $n_{q1} \neq n_t$ . If  $n_{q1} = n_t$  the MC travel to replenish it if the replenishment process satisfies Eq. (18). If  $n_{q1} \neq n_t$ , the MC then estimates the total time required to travel and recharge the node. If the time is less than or equal to the remaining time for the node to start sensing and transmission, the MC travel and replenishes it and then updates the priorities of the requests based on the current location of the MC. The condition that

must be fulfilled to recharge the node is mathematically represented by Eq. (19). Moreover, when the estimated time is more than the time that  $n_{q1}$  will be due to use its time slot,  $n_{q1}$  will not be recharged, and the MC considers whether there is another request at the 2nd position on the queue. If no another request, the MC redo the above estimate towards recharging  $n_{q1}$  after waiting for a duration of one time slot. Waiting and estimation continue until the node,  $n_{q1}$ , is replenished. However, if there is another request, the node associated with the request is denoted by  $n_{q2}$  and the MC replenish it following a similar approach as earlier described. If travelling and recharging of  $n_{q2}$  cannot be complete before it is due for sensing and transmission, and there is a 3rd request, the node with the 3rd request is denoted by  $n_{q3}$  and the MC tries to replenishes it. In addition to the procedure for replenishing  $n_{q1}$  and  $n_{q2}$ , the MC first compare the distances from its current location to the locations of  $n_{q2}$  and  $n_{q3}$ . If the distance to  $n_{q3}$  is shorter, the MC travel and replenishes  $n_{q3}$  if the replenishment process satisfies Eq. (21). Otherwise, the MC makes another attempt to replenish  $n_{q2}$  after waiting for a duration of one time slot. The distance comparison is to reduce the energy consumption of the MC. If the MC blindly travels to the location of  $n_{q3}$  that may be farther from the location of the MC than  $n_{q2}$ , the sequences of replenishing the next batch of nodes (if the total number of requests is more than three) could lead to higher energy consumption by the MC.

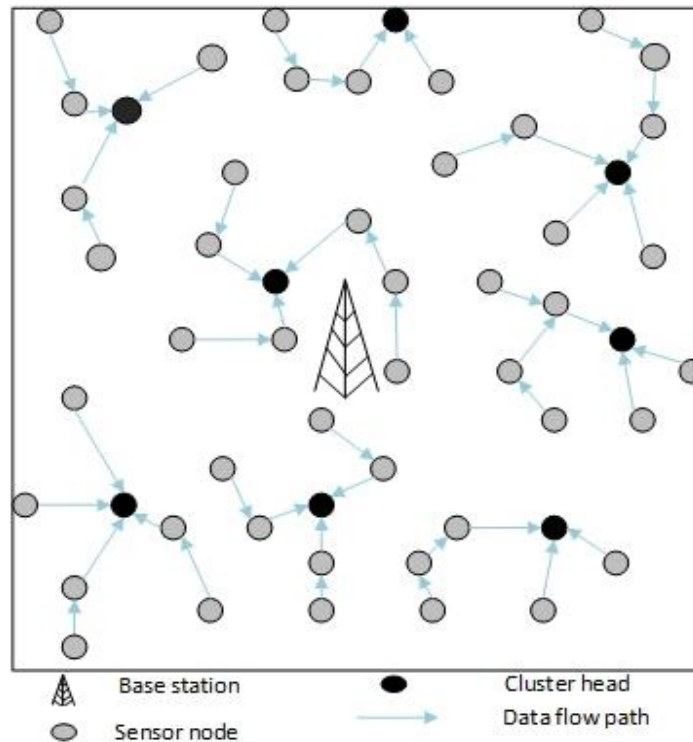


Figure 1: Data Routing Path in ST-NCDR and DERDG

#### 4. Result

The performance of ST-NCDR and DERDG were simulated using MATLAB R2018b and compared with the performance of a joint data gathering and energy replenishment (JDR) that is, the work of Han et al. (2018) and a Distributed Clustering and Operational State scheduling (DCOS), the work of Mikail et al. (2020). The parameters used for the simulation are contained in Table 1. An initial energy of nodes of 0.5 J was used to quickly see the effect of the action of the mobile chargers. Each simulation was performed twenty times to improve the accuracy of the results.



#### 4.1. Energy consumption of mobile chargers

The average energy consumption of the MCs per recharging tour for ST-NCDR, DERDG, and JDR for different numbers of nodes were compared. The result showed that MCs in ST-NCDR consumed less energy than those in JDR, as depicted in Figure 2. In JDR, an MC stayed at an anchor point of a cluster and recharged all the cluster members. If the anchor point was farther away from energy-hungry nodes, the distant nodes received low power per unit time from the MC since power reception by the nodes is inversely proportional to the square of their distances away from the anchor point. Thus, the MC stayed for a very long time in the cluster since the scheme allows the MC to leave the cluster only when all energies of the cluster members are above the energy threshold. The longer the MC stays in the cluster, the higher the energy it consumes. Differently, the MCs in ST-NCDR only replenished energy-hungry nodes, one at a time, by moving closer to them. The MC stayed at a distance closer enough to a node when charging it to reduce duration of charging time. Since the cost of travelling a unit distance is lower than that of recharging a node (Wu et al. 2019), MCs in ST-NCDR consumed lower total energy than they consumed in JDR. MCs in DERDG consumed more energy than those in ST-NCDR because they collect data from clusters in addition to replenishing the energy of nodes. Moreover, the MCs in JDR travel around the network after every time interval, unlike in ST-NCDR when they moved around only after the time interval and when there are one or more recharging requests. DERDG and ST-NCDR have reduced the energy consumption of the MCs by an average of 29.45% and 73.70%, respectively in comparison to JDR.

#### 4.2. Average residual energy of nodes

We compared the average remaining energy of all nodes in the network as a function of the number of nodes for ST-NCDR, DERDG, JDR, and DCOS. We also compared the average remaining energy of nodes per cluster for the first three schemes. ST-NCDR has a better average remaining energy of nodes in the whole network than all the remaining three schemes, except for  $N=100$ . The low average residual energy for ST-NCDR at  $N=100$  could be due to the relatively large distance between nodes when they are few. With larger inter-node distance, the spatial priority dominates and the contribution of temporal priority to the overall priority of the request is minimal. Thus, spatial priority dictates the position of requests in their queues. And since the node is farther apart, there is an increase in the time required to travel to the nodes which leads to an increase in the charging delay and ultimately reduces the average residual energy of nodes. DERDG achieved higher remaining energy than JDR and DCOS except for a case when  $N=400$  as seen in Figure 3. DERDG and ST-NCDR improved the average residual energy of nodes by an average of 24.00% and 24.46%, respectively in comparison to JDR. Also, ST-NCDR yielded higher average remaining energy per cluster than both DERDG and JDR except for nodes in clusters with identifiers of 5, 8, 10, and 12 where DERDG has higher remaining energy as seen in Figure 4. ST-NCDR recorded lower average remaining energy in clusters with identifiers of 5, 8, 10, and 12 because lots of waiting for the duration of a time slot could have happened within them due to the need to recharge their node when not in the state of sensing and transmission. The waiting resulted in a much reduction in the energy of the nodes before they were replenished. For JDR, all nodes are recharged toward a set energy threshold by the MC. Hence as simulation time increases, the average remaining energy of the nodes decreases until it stabilizes at the energy threshold. But in ST-NCDR, MCs are dispatched to partially recharge only nodes that have sent recharging requests to reduce the complexity of the energy replenishment algorithm. Whereas DERDG achieves better average remaining energy than JDR in nodes within clusters with identifiers of 2, 5, 8, 10, 11, 12, 13, 16, 17, 20, and 21.

#### 4.3. Energy consumption of one mobile charger

We also compared the performance of the ST-NCDR with DERDG using one (1) mobile charger for recharging the energy of nodes in the whole network. As depicted in Figure 5, the MC in ST-NCDR consumed the least energy per recharging tour, followed by that in DERDG. Using a single MC, DERDG, and ST-NCDR yielded a reduction in the energy consumption of MCs in comparison with JDR. Therefore, in the ST-NCDR scheme, there is no node causality provided the energy of the charger is greater than 164J, 533J, 782J, and 954J for  $N=100$ , 200, 300, and 400, respectively. To avoid node casualty in DERDG, the initial energy of the charger should be above 2862J, 2807J, 2785J, and 2893J when  $N=100$ , 200, 300, and 400, respectively.

#### 4.4. Average charging delay

In Figure 6, we compared the average charging delay per cluster in ST-NCDR and DERDG using a single MC. We defined charging delay as the time that elapsed before a node is recharge after it has sent a charging request. As expected, the average charging delay in ST-NCDR is higher than that of JDR in all clusters. In ST-NCDR, when the MC arrived in a cluster and the node on the queue head cannot be recharged before it is just about to use its time slot, the recharging process is deferred by a minimum duration of one timeslot. Deferring the energy recharging process for multiple times in a cluster could increase the average charging delay of the nodes. In DERDG, simultaneous energy recharging with data sensing and transmission is allowed. As such, the MC immediately starts recharging the energy of a node when it arrives at the node's location.

#### 4.5. Average data delivering delay with one mobile charger

Moreover, in Figure 7, we compared the data delivery delay of DERDG and JDR when a single MC is employed for performing energy replenishment of nodes in the network. We defined data delivery delay as the time interval from when the MC left the location of the BS to when it returned to offload collected data to the BS, after moving around the network via the SHP to collect data and also recharge the nodes. The MC in DERDG stays for a shorter time in a cluster than it stayed in JDR, which could be the reason for the lower data delivery delay in DERDG.

**Table 1: Simulation Parameters** (source: Han et al. 2018, 2019b; Mikail et al. 2020)

Parameter	Value
Network size	100m by 100m
Number of Nodes in the Network (N)	300
Node Initial Energy ( $E_o$ )	0.5J
Data Packet Size	4000 bits
Broadcast Packet Size	25 bits
Energy Threshold ( $E_{thresh}$ )	0.15J
$E_{elec}$	50nJ/bit
$E_{amp}$	10pJ/bit/m <sup>2</sup>
$\alpha$	0.5
Energy consumption rate for data sensing ( $r_c$ )	350pJ/bit
MC Initial Energy (B)	10800
Speed of MC	0.5m/s
Energy consumption of an MC	1J/m

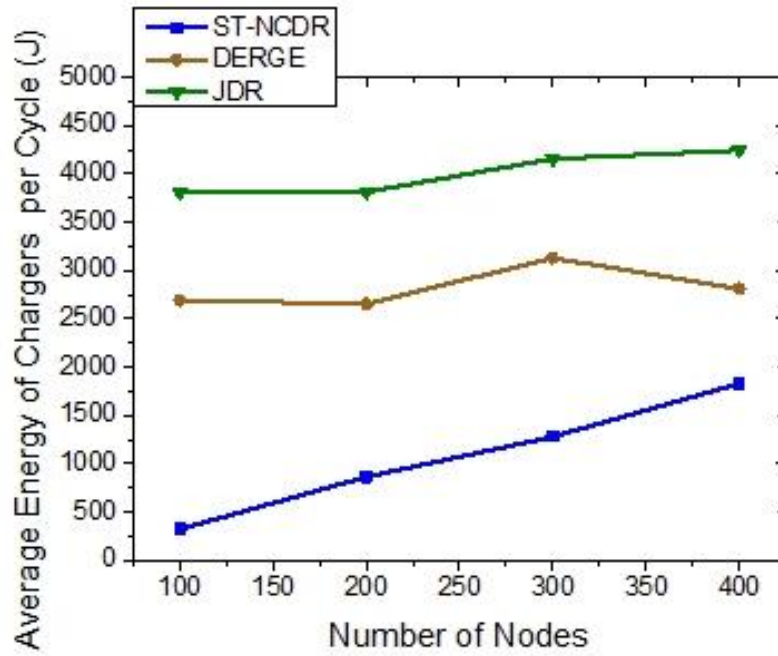


Figure 2: Average total energy consumed by mobile chargers

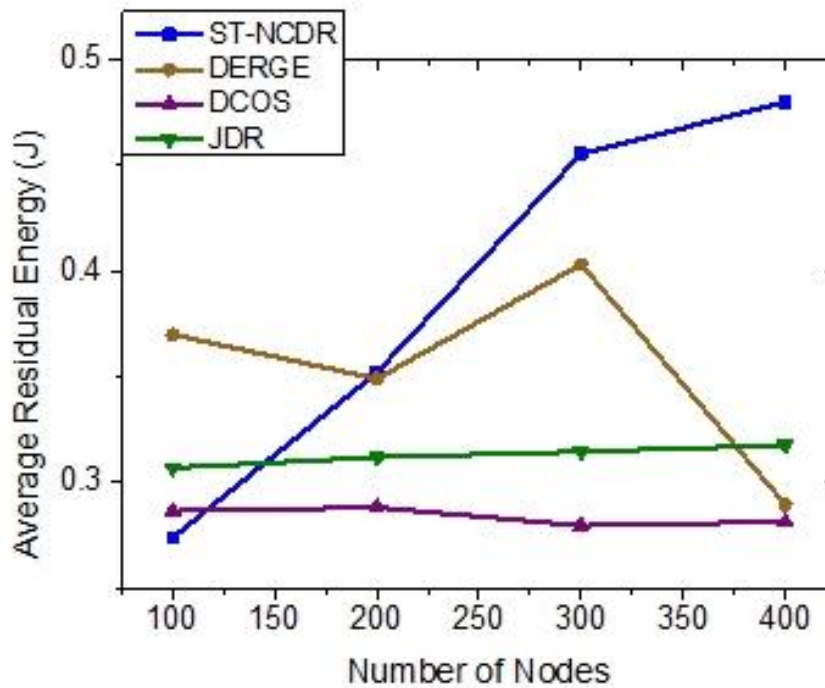


Figure 3: Average residual energy in the network

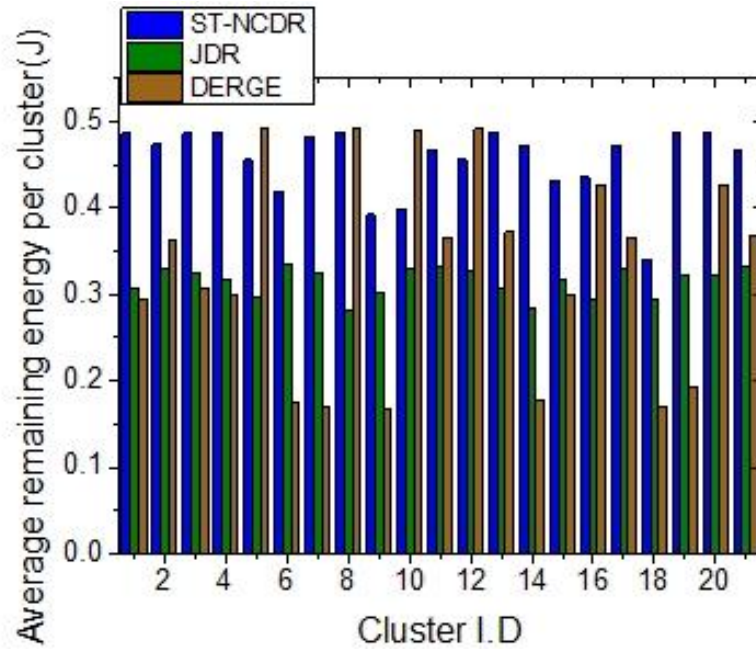


Figure 4: Average residual energy per cluster

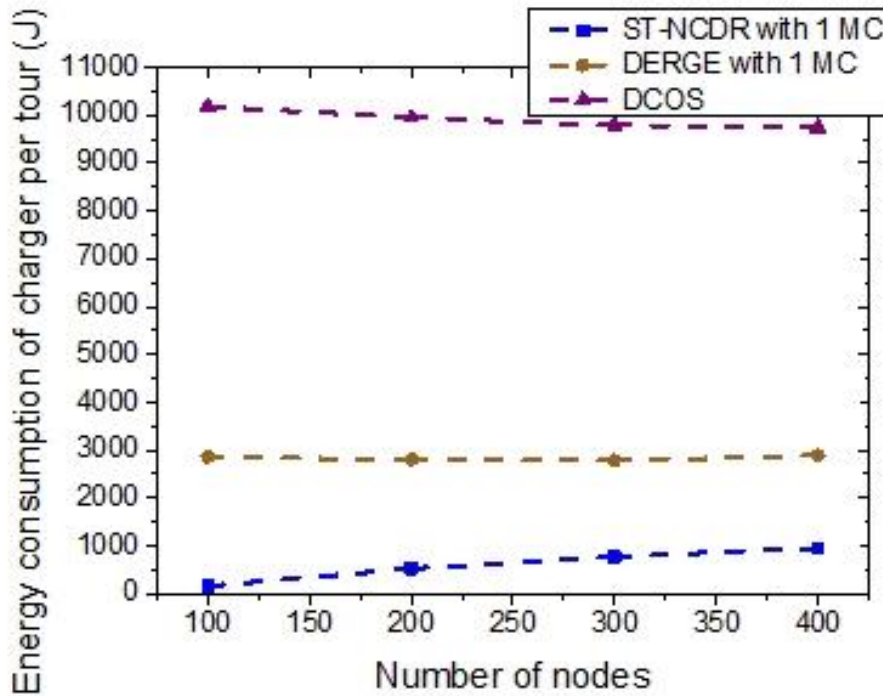


Figure 5: Average energy consumed by charger in ST-NCDR

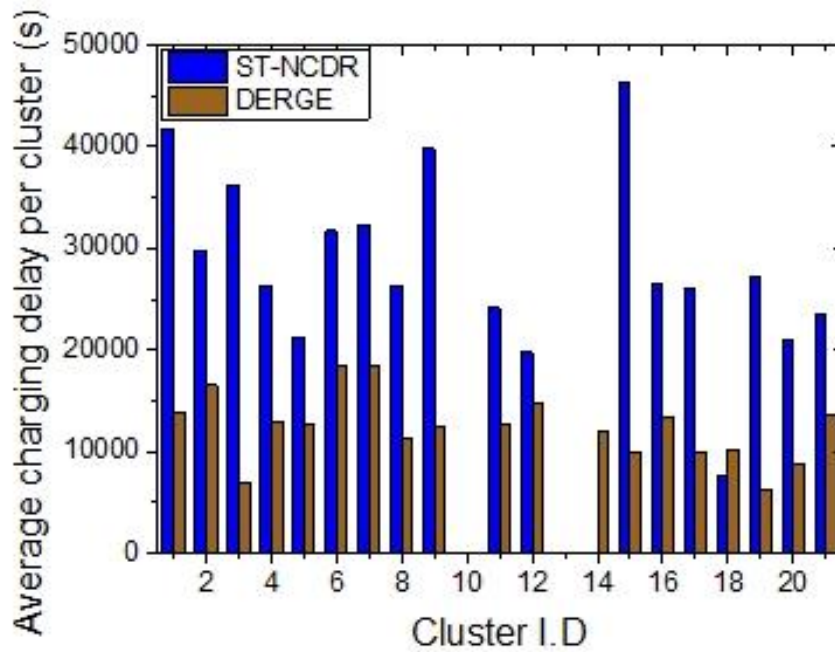


Figure 6: Average residual energy per cluster in ST-NCDR

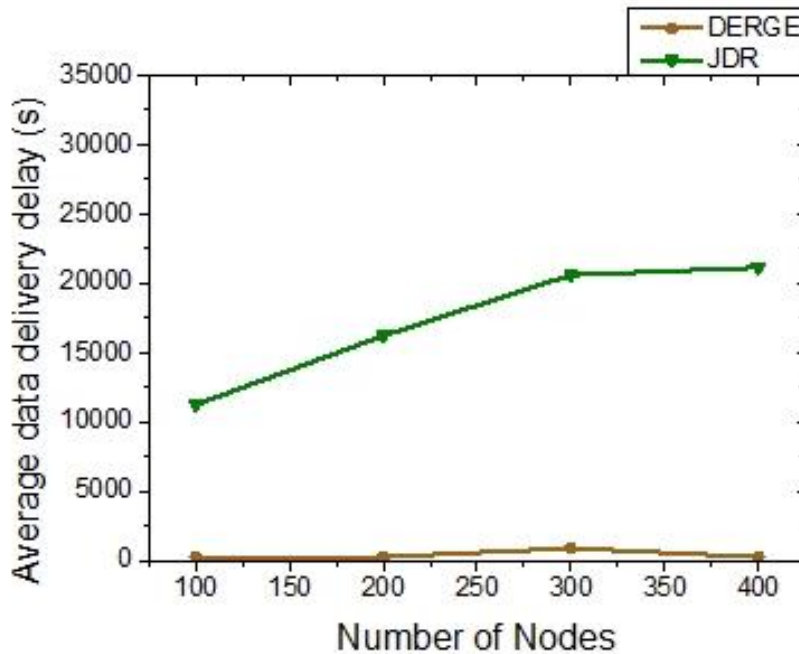


Figure 7: Average data delivery delay in DERDG and JDR

### 5. Discussion

The total energy consumption by the MCs per recharging tour could indicate the number of MCs required by the network for perpetual operation. When the average energy requirement for replenishing energy of nodes per cycle is higher than the MC’s maximum energy capacity, more than one MC is required per recharging tour. The higher the number of MCs per tour, the higher the network deployment cost. Thus, with a reduced energy consumption of MC in

the two schemes: DERDG and ST-NCDR, MC with lower energy capacity can serve the whole network which translates to a reduction in the cost of network deployment since MCs with high energy capacity cost more than those with low energy storage capacity.

The implication of the improvement in the average residual energy of the nodes by DERDG and ST-NCDR means the MC can be dispatched less frequently without node casualty. This reduces the maintenance cost of the MC and ultimately translates to a reduction in the network operation cost.

The results also show that a single MC, though with a higher energy capacity, can effectively provide energy supplement to the network. Using a single MC increases the charging latency of the nodes which could reduce the network's average residual energy. As such, a single MC suffice the network but at the risk of reduced network residual energy.

Moreover, DERDG reduced the data delivery delay as data made available to the sink for further processing quicker than in the JDR scheme. As such, the DERDG scheme is more suitable for deployment for real-time applications than the JDR scheme.

ST-NCDR not only reduces the network operation cost but can be easily integrated into sensor nodes with one circuit that shared its task between data sensing energy replenishment. ST-NCDR obviates the need for a sensor with two circuits. As such ST-NCDR is a stepping stone toward the realistic deployment of WRSN.

The two schemes both reduced the energy consumption of the mobile chargers by an average of 29.45% and 73.70% respectively, when compared to the scheme in Han et al. (2018) (JDR) and by 71.40% and 93.80% in comparison to Mikail et al. (2020) (DCOS) without reduction in the average network lifetime. DERDG reduces data delivery delay by 95.50% more than the scheme in (JDR). In the future, we will consider an optimal number of requests to be used by ST-NCDR, which may further reduce the energy consumption of mobile chargers.

A major limitation of the ST-NCDR is that it is more effective in networks with a high number of nodes per cluster.

## 6. Conclusions

Wireless Rechargeable Sensor Networks (WRSNs) schemes that operate based on simultaneous data gathering with energy recharging suffer from high energy consumption by mobile chargers and difficulty in integrating the schemes into the available sensor nodes. Thus, we proposed two schemes: Distributed Energy Replenishment and Data Gathering (DERDG) to reduce the energy consumption of mobile chargers and Spatio-Temporal Non-Concurrent Data gathering and Energy replenishment (ST-NCDR) to enable a realistic deployment of WRSN due to its ease of integration into the sensor nodes. In DERDG, sensor nodes are recharged irrespective of their operation states at the instances of energy replenishment. While in ST-NCDR, the energy-hungry nodes are recharged only when they are not in the state of data sensing and transmission. There is no node casualty in both DERDG or ST-NCDR.

The nature and frame format of the recharging requests can be considered in a future study. Moreover, the possibility of MC visiting clusters with requests without much increase in the complexity of the recharging.

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