Received September 12, 2020, accepted September 25, 2020, date of publication September 29, 2020,
date of current version October 8, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3027615

Fair Energy Division Scheme to Permanentize the Network Operation for Wireless Rechargeable Sensor Networks

ALAA OMRAN ALMAGRABI
Department of Information Systems, Faculty of Computing and Information Technology (FCIT), King Abdulaziz University, Jeddah 21589, Saudi Arabia
e-mail: aalmagrabi3@kau.edu.sa

This work was supported by the Deanship of Scientific Research (DSR), King Abdulaziz University, Jeddah, under Grant D-042-611-1439.

ABSTRACT In the past years, the energy constraint problem is known as a design issue of Wireless Sensor Networks (WSNs) due to equipping the sensor nodes with limited power supplies. During the last few years, Wireless Rechargeable Sensor Networks (WRSNs) have gained researchers attention. In a WRSN, the sensor nodes are equipped with RF circuits, which enables them to receive energy from Wireless Mobile Chargers (WMC). However, most of the existing wireless charging algorithms consider the unlimited power budget for WMCs, which is the opposite of feasibility of a real network environment. Likewise, most of the previous works fail to take full advantage of WMC as it starts recharging the nodes when their energy level reaches a threshold, which leads to increasing the inactive time of WMC. Moreover, although previous works employed WMCs, the network lifetime is limited. However, optimal division of the energy of WMC among nodes can guarantee the perpetual network operation. Therefore, proposing an efficient method that jointly solves these challenges is required. In this paper, a new Fair Energy Division Scheme (FEDS) is presented, which undertakes the permanent network operation by optimizing the energy division at the beginning of each cycle. Simulation results exhibit that FEDS achieves perpetual network lifetime. In addition, the proposed scheme improves energy efficiency, (25%) compared to Uneven Cluster-based Mobile Charging (UCMC) and (75%) compared to Nearest-Job-Next Preemption NJNP; travelling time of WMC, (50%) compared to UCMC and (75%) compared to NJNP. In conclusion, the proposed protocol significantly improves network.

INDEX TERMS Perpetual network operation, wireless rechargeable sensor networks, mobile charger scheduling.

I. INTRODUCTION

A. BACKGROUND

Unlike Traditional Wireless Sensor Networks (TWSNs), in WRSNs, employing the WMCs and rechargeable sensor nodes results in overcoming the energy constraint problem. Generally, wireless power transferring is known as a proper solution to charge the tiny electrical devices. Therefore, in WRSNs, WMCs charge the batteries of the sensor nodes after gathering energy from the environment [1]–[4].

A WRSN consists of three main components: a static Base Station (BS), static sensor nodes equipped with RF circuits [30], and WMC(s). Sensor nodes periodically send their residual energy to the BS [5] and the BS decides about the movement path and charging time based on the energy level of the nodes. Then, BS sends the control commands to the WMC. During the movement of WMC, it stops at the different anchor points and charges the nodes for a charging time. Over the last few years, several schemes have been designed which aim to optimize the movement path, anchor points, and charging time of WMCs in order to enhance the network performance and lifetime [3], [9], [23], [27], [28]. In the majority of prior works, unlimited energy budget is considered for a WMC, which is not feasible in the real network environment. Therefore, the problem becomes more realistic, when limited WMC energy supply is taken into account.

In the related schemes, where limited power supplies for WMCs has been considered, at each cycle, the WMC starts from a point, moves along the nodes to charge them and

The associate editor coordinating the review of this manuscript and approving it for publication was Chien-Fu Cheng.

returns to the start point to recharge or replace its power supply. Based on the environmental conditions, WMC needs time for recharging or energy harvesting. In the most of previous works, multiple WMCs are utilized in order to charge the nodes during the energy replenishment time of a WMC [5]. However, dispatching the multiple WMCs is costly and increases the computational complexity and network overheads. Whereas, optimal division of the energy of WMC among sensor nodes can prevent the energy depletion of nodes during the replenishment time and the charging cycle of WMC.

Furthermore, in the prior works [4], [12], it is considered that WMC starts to charge the nodes when their energy level reaches a threshold, which leads to increase the idle time of WMC and reduce the network performance. Whereas, timely recharging the nodes enhances not only the efficiency of WMC but also the operation time of the nodes.

In addition, to recharge a large scale network, utilizing the clustering is the least expensive technique, which leads to decrease the charging latency through charging the multiple nodes simultaneously. In clustered WRSNs [13], [14], WMC moves along clusters and charges the nodes located at the same cluster at the same time. In this type of the networks, it is necessary to dispatch two WMCs for charging the Cluster Heads (CH) and Member Nodes (MN) separately, which leads to achieving easier network management, latency reduction, and enhance the quality of service. However, this issue has not been considered in prior clustered WRSN-based schemes.

Thus, in this paper, a new Fair Energy Division Scheme (FEDS) is presented for a cluster-based WRSN. In the proposed scheme, two WMCs are employed to charge the CHs and MNs separately. Our proposal aims to optimize the transferred energy level from WMCs to the sensor nodes belonging to the different clusters by determining the optimal charging time of WMCs at different anchor clusters. The problem of scheduling of WMCs is formulated as an ILP problem, which the objective is to achieve perpetual operation of MNs and CHs during the cycle, while considering the energy level and energy-replenishment time of WMCs.

B. CONTRIBUTIONS

Overall, the contributions of this research are as follows:

1. In this paper, upon starting the network operation, the sensor nodes are recharged by WMCs. This task leads to reduce the idle time of WMCs and fully take advantage of WMCs.

2. In this paper, fair energy division technique is employed to recharge the nodes in such a way that each node has a share in the energy of a WMC in such a that the more energy is consumed, the more energy is assigned to the nodes.

3. The proposed FEDS guarantees the perpetual CHs and MNs operations during a cycle. This goal can be achieved by considering the energy level and energy-replenishment time of WMC in charging time optimization at the beginning of each cycle.

4. Unlike previous cluster-based WRSNs, the proposed scheme dispatches two separate WMCs to recharge the CHs and MNs individually, which results in easier network management, enhance the quality of service, and latency reduction.

C. PAPER STRUCTURE

Section II gives related works proposed for WRSNs. The network model is presented in section III. The FEDS scheme is introduced in section IV. The performance evaluation of the proposed scheme is given in section V and finally the conclusion section will be presented VI.

II. RELATED WORK

Fast development of charging technologies results in increasing the number of charging algorithms based studies. Han *et al.* [19] presented a coverage-aware hierarchical charging algorithm, which aims to balance the energy consumption among sensor nodes by optimizing the anchor points of WMCs. Moreover, in the case of densely deployed nodes, the energy consumption and coverage degree of nodes are taken into consideration in anchor point optimization, which leads to enhanced network coverage. However, in such scheme, WMC moves along sensors and recharges the nodes separately, which leads to increase the travelling time of WMC and waiting time of sensor nodes.

An uneven cluster-based mobile charging (UCMC) algorithm is introduced in [13] which aims to decrease the variance of energy level of sensor nodes and enhance the operation time of the network. The main objective of their scheme is to reduce the number of non-active nodes. Therefore, to achieve this goal, uneven clustering scheme and a charging path planning scheme cooperate in the proposed algorithm. However, in such scheme, the energy replenishment time of WMC is not taken into consideration, which leads to raise the possibility of depleting energy of nodes during the energy harvesting time of WMC.

Hu *et al.* [20] proposed an efficient slot-based periodic charging time scheduling scheme aims to reduce dispensable visits of energy-sufficient nodes. Then, they introduced a balanced charging task assignment algorithm which results in avoiding charging starvation. Moreover, a charging trajectory based algorithm is presented to achieve simultaneous charging the nodes with multiple WMCs. The experimental results show the effectiveness and competitiveness of their schemes in comparison with other related works. However, the main objective of their work is to avid the energy wasting and lifetime enhancement is not discussed, which leads to reduce the network performance.

Peng *et al.* [21] presented a new scheme to charge the sensors with multiple portable chargers which are carried by a robot. In such scheme, a robot is able to recharge the multiple nodes in a parallel way by placing the chargers inside the sensors. The aim behind this simultaneous recharging scheme is to decrease the waiting time and enhance the charging efficiency. However, such schemes are not affordable due to employing multiple WMCs and robots.

Sustainable wireless Rechargeable Sensor network scheme is proposed in [22], aims to achieve timely and efficient charging of the nodes via minimizing the number of sojourn points according to the locations and required energy level of the nodes. To achieve this goal, sojourn points selection problem has been formulated with an ILP model, which the objective is to minimize the number of sojourn points in such a way that maximum number of nodes can be served in a location. However, in such scheme, despite of employing WMC, the perpetual network operation has not been achieved. Whereas, optimal scheduling of WMC can result in permanent network operation.

A joint energy replenishment and data collection scheme is presented for a cluster-based WRSNs [24], which aims to improve the charging efficiency and prolong the network operation time. In their work, first, the optimal anchor points are calculated by BS, while considering the energy distribution in each cluster. Then, two WMCs are dispatched to visit the anchor point in each cluster by moving along the shortest Hamiltonian cycle in opposite directions. Moreover, a spare WMC is dispatched in case either of the two WMCs exhausts its power supply. In such schemes, despite of employing multiple chargers, separate charging the MNs and CHs has not been considered. It leads to occur computation complexity because of difference in energy consumption level of MNs and CHs.

A hybrid framework is presented in [4] to improve the network performance and lifetime. In such scheme, solar panels are installed in CHs in order to scavenge solar energy and MNs are wirelessly charged. In this model, the network consists of three hierarchical levels. On the first level, the positions of solar-powered CHs are optimized so that the overall cost is reduced to the fullest extent. On the second level, first, an energy balance is achieved in the network and then maintaining such balance in explored for nodes when sunlight is unavailable. Finally, tour planning problem is considered, which combines wireless charging with mobile data gathering in a joint tour, on the third level. However, equipping the CHs with solar panels is very expensive and the size of this devices is usually large, which makes this technique impractical in the large size network and its success for sensor networks remains limited in practice.

In [5], first, a novel multiple WMCs coordination framework is presented to determine the optimal moving and charging time of WMCs. likewise, in order to solve the problem of coordinating the multiple WMCs to recharge the nodes, an Optimal multiple WMCs Coordination (OMC) algorithm is proposed. The problem is formulated as a Mixed Integer Linear Programming (MILP), which the objective is to enhance the energy efficiency of MCs, while improving the network lifetime. Finally, the quality of the solution is analyzed in terms of different evaluation metrics. However, energy-replenishment time of WMC has been ignored in charging time optimization.

A joint data gathering and energy harvesting (JoDGE) problem with a Mobile BS is studied in [10], which aims to enhance the network lifetime by taken into consideration the power allocation, time scheduling problems. To achieve this goal, first the optimal joint data collection and energy harvesting scheduling algorithm is presented. Moreover, a near-optimal buffer-battery-aware adaptive scheduling scheme is designed. In their proposed work, a multi-hop data transmission model is used to transmit the data packets toward the BS which leads to occur unbalanced energy consumption of nodes and energy hole problem. However, this problem is not addressed in their work.

In [15], nearest-job-next preemption (NJNP) charging algorithm is presented, where, a WMC move to charge the nodes at a low energy level. In such scheme, whenever a WMC received charging demand from the sensors, it selects the closest node as the next anchor point. However, charging the nodes separately leads to increase the travelling time of WMC and waiting time of other nodes that require to be recharged.

By reviewing of the literature, it is concluded that in most of the related works, although WMCs are employed, the network lifetime is limited since the WMC has not been taken advantage to the fullest possible extent [10], [11]. Moreover, in the previous clustered WRSNs, separate charging of MNs and CHs is not addressed, which results in computation complexity. Thus, a new Fair Energy Division Scheme should be discovered to achieve perpetual network operation.

III. SYSTEM MODEL

Fig.1. shows the network model of the proposed WRSN. As shown in the figure, a WRSN with N sensor nodes is considered. In addition, in order to receive power from WMCs, all sensor nodes are equipped with RF circuits. The nodes are deployed randomly uniformly [31] throughout the network. Likewise, in the proposed scheme, dividing the network area into K equal size clusters leads to minimize the charging latency through charging the several nodes simultaneously. In each cluster, the node with maximum energy level and minimum distance to the center of the respective cluster is elected as the CH.

In addition, a static sink is placed at the center of the network. MNs collect l bit data per a time unit and send to their CH, then CHs transmit the aggregated data packets to the BS in a single-hop data transmission model. The energy consumption model proposed in [16] is adopted in this work. A node consumes $E_{tx} = l(E_{elec} + \propto d^n)$ and $E_{rx} = l(E_{elec})$ energy for transmitting and receiving l bits data at a distance d. Therefore, the energy consumption of a MN and CH per each time unit can be calculated as follows:

$$EMN^{CON} = l\left(E_{elec} + \propto d^n\right) \quad (1)$$

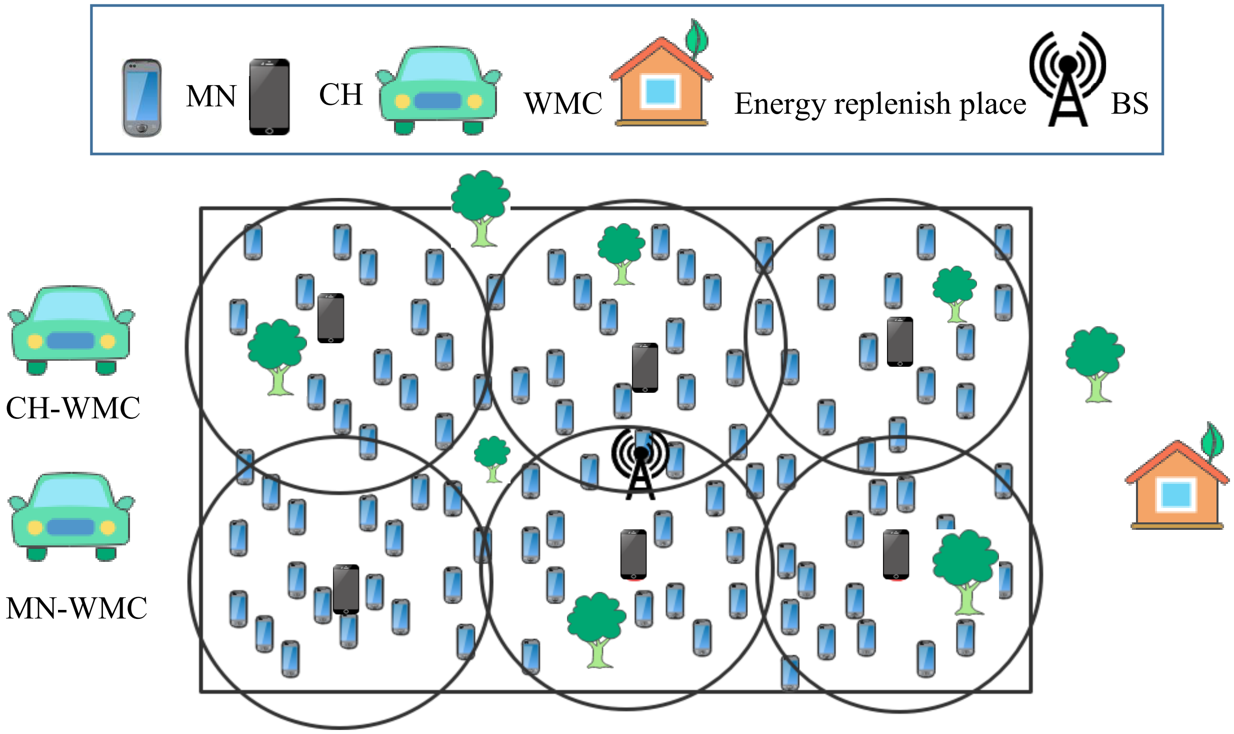

FIGURE 1. Network model of the proposed scheme.

And,

$$ECH^{CON} = l\left(\left(\frac{N}{K}-1\right)(E_{rx}) + \left(\frac{N}{K}-1\right)(E_{agg}) + \left(\frac{N}{K}.\beta\right)(E_{tx})\right) \qquad (2)$$

where β denotes the compression ratio. In the proposed scheme, it considered that the received packets from MNs is compressed into one packet. Likewise, E_{agg} denotes the energy consumption for aggregating the data packets from MNs.

Furthermore, two WMCs are employed to charge the MNs and CHs individually, which are called *WMC-MN* and *WMC-CH*, respectively. In this work, each WMC is equipped with a BS. Then, when they arrive to a cluster, the nodes belonging to the respective cluster send their data packets to the WMC directly. Likewise, wireless chargers are equipped with the energy harvesting technologies that convert the harvested energy to electricity. In each cycle, WMCs with energy level ω, start to move from a point, keep move along the clusters and stop in each cluster for a charging time to charge CHs/MNs and then move to a proper location to harvest energy or recharge their power supplies. After completing the energy replenishment time (φ) and starting a new cycle, WMCs move along clusters again in order to charge the sensor nodes.

In the proposed scheme, *WMC-MN* sojourns at the center of clusters to charge the MNs. It is assumed that the charging range of *WMC-MN* is r (radius of a cluster) in order to cover the area of a cluster. However, since *WMC-CH* supposed to charge only the CH located at the anchor cluster and it sojourns at the nearest position from CH, a short charging range is considered for *WMC-CH*.

The transferred data packets to CH/BS consists of three sections. The sensed data is stashed in the first section. The residual energy level of the nodes is stored in the second section stores. In addition, the cluster number of the respective node is stored in the third section. One duty of BS is to determine the moving tour of WMCs (trajectory and charging time). In the proposed scheme, the moving tour of WMC is optimized according to the residual energy of nodes, energy level of WMCs and their energy replenishment time (φ) via proposed fair energy division scheme. In fact, the proposed scheme guarantees that MNs and CHs will not exhaust their power supplies during the energy replenishment of WMC-MN and WMC-CH, respectively.

In this paper, the charging model introduced in [17] is considered that the WMCs and sensor nodes are the transmitter and the receiver in a two-way relation. Then the Eq. (3) is formulated.

$$P_r = \frac{G_s G_r \eta P_t}{L_P}\left(\frac{\lambda}{4\pi\,(d+\beta)}\right)^2 \qquad (3)$$

In Eq. (3), P_r and P_t denote the power of receiver and transmitter, respectively.

Where G_s is the transmitter antenna gain and G_r shows the receiver antenna gain. In addition, λ, η and L_P denote the wavelength, the rectifier efficiency and the polarization loss respectively. In addition, the distance from transmitter to receiver is signified by d. Likewise, β is a constant value used for short-distance transmissions [18]. In fact, this parameter adjusts the Friis' free space equation Then, the Eq. (3) can be rewritten as Eq. (4):

$$P_r = \frac{\mu}{(d+\beta)^2} \tag{4}$$

$$\mu = \frac{G_s G_r \eta P_t}{L_P}\left(\frac{\lambda}{4\pi}\right)^2 \tag{5}$$

In Eq. (5), the values of μ and β are 4.32×10^{-4} and 0.2316, respectively.

IV. FAIR ENERGY DIVISION SCHEME

The Fair Energy Division Scheme (FEDS) is introduced, in this section. The proposed scheme consists of two *WMC-CH*'s scheduling and *WMC-MN*'s scheduling algorithms.

A. WMC-CH'S SCHEDULING ALGORITHM

1) PATH PLANNING OF WMC-CH

the movement path for the *WMC-CH* to visit the CHs is optimized in this section. Utilizing direct data transmission manner between CHs and BS leads to the unbalanced energy consumption of CHs. In order to enhance the service to the CHs with shorter lifetime, the BS gives priority to the CHs with higher energy consumption to be served by the *WMC-CH*. Accordingly, at the beginning of *R*th cycle, BS calculates the lifetime of CHs as follows:

$$L_i^R = \frac{E_i^{Res}}{E_i^{CON}} \tag{6}$$

where E_i^{Res} denotes the remaining energy of a CH and E_i^{CON} shows the energy consumption of the *i*th CH per each time unit. Then, to evaluate the charging priorities of the CHs, BS sorts all the CHs according to their lifetimes in an increasing order as $\{l_1, l_2, \ldots, l_K\}$.

Afterward, the BS starts to determine the charging time of *WMC-CH* at each cluster, then dispatches the *WMC-CH* toward the clusters in order to their priorities.

2) CHARGING TIME OPTIMIZATION OF WMC-CH

In this phase of the proposed scheme, the BS calculates the charging time or sojourn time of *WMC-CH* in the clusters. It is determined based on the energy consumption of CH, the energy of WMC-CH (ω), and the energy replenishment-time of WMC-CH (φ) parameters.

In each cycle, a CH consumes energy during the waiting time, the charging time of *WMC-CH* at the next clusters, the moving time of the *WMC-CH* along CHs, and the energy-replenishment time of *WMC-CH*.

As shown in Fig. 2, the waiting time is defined as the total time that CHs need to wait for arriving the *WMC-CH* to their clusters from the beginning of each cycle. Moreover, after existing the WMC-CH from the cluster, the respective CH consumes energy until finishing a cycle.

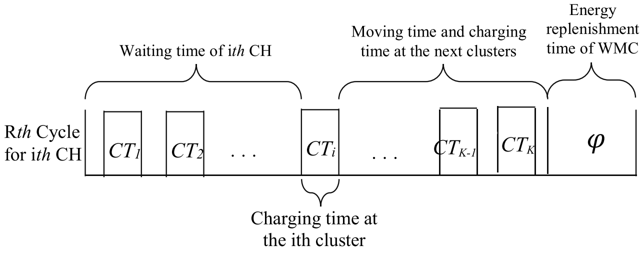

FIGURE 2. **A charging cycle of WMC-CH.**

Then, the total energy consumption level of the *i*th CH in each cycle can be formulated as follows:

$$E_i^{Tot} = \left(WT_i + \sum_{j=i}^{K}(CT_j) + \sum_{j=i}^{K-1}\left(\frac{d(PCH_j, PCH_{j+1})}{Speed}\right) + \frac{d(PCH_K, Endpoint)}{Speed} + \varphi \right) \times E_i^{CON} \tag{7}$$

In Eq. (7), WT_i is the waiting time of *i*th CH and CT_i shows the charging time of *WMC-CH* at the next clusters after leaving the *i*th CH. Moreover, the distance between the positions of the two CHs is denoted by the d notation. In addition, φ signifies the energy-replenishment time of *WMC-CH* and speed is the velocity of *WMC-CH.*

In this work, the waiting time is the summation of the charging time of *WMC-CH* in the passed clusters and the time spent during moving along the clusters with a constant speed. Therefore, the waiting time of the *i*th CH can be formulated by the following equation:

$$WT_i = \left(\frac{d(StartPoint, PCH_1)}{Speed} + \sum_{j=1}^{i-1}(CT_j) + \sum_{j=1}^{i-1}\left(\frac{d(PCH_j, PCH_{j+1})}{Speed}\right) \right) \tag{8}$$

If the energy level of *WMC-CH* after completing the energy replenishment-time is ω, the needed time to transfer ω energy from WMC-*CH* to the CHs is calculated as follows [23]:

$$\tau = \frac{\omega}{P_r} \tag{9}$$

In addition, if the $\{CT_1, CT_2, \ldots, CT_K\}$ is the set of charging time of WMC-CH in different clusters, then total charging time of WMC-*CH* in the clusters should be equal τ.

$$\tau = \sum_{i=1}^{K}(CT_i) \tag{10}$$

Moreover, the proposed algorithm supposed to achieve fair division of energy of *WMC-CH* between CHs in a cycle, while guaranteeing the perpetual operation of the CHs during a charging cycle of *WMC-CH*. Therefore, the charging time optimization problem is formulated as an Integer Linear

Problem (ILP) that takes perpetual operation of CHs during a cycle into account as follows:

$$\begin{aligned}&\boldsymbol{min}\left(\tau-\sum_{i=1}^{K}(CT_i)\right)^2\\&\mathbf{S.T}:\ \mathbf{1)}\ 1\leq i\leq K\\&\qquad\ \mathbf{2)}\ E_i^{Res}-E_i^{Tot}+(CT_i\times P_r)>0\\&\qquad\ \mathbf{3)}\ CT_i>0\end{aligned}\tag{11}$$

Accordingly, by utilizing the above ILP, τ time is fairly divided between CHs in such a way that none of the CHs will run out of their energy during a cycle.

After determining the charging times at different clusters, the BS informs the *WMC-CH* about its moving path and optimal charging time in different clusters.

B. WMC-MN'S SCHEDULING ALGORITHM

1) PATH PLANNING OF WMC-MN

The moving path of *WMC-MN* is optimized to visit all MNs located at the network in this section. In the proposed scheme, due to random uniform node distribution, $\frac{N}{K}$ number of nodes and by subtracting the CH, $\frac{N}{K}-1$ number of MNs are located in each cluster. Accordingly, the total energy consumption of MNs located at *i*th cluster is formulated as follows:

$$E_i^{Tot-MNs}=\left(\frac{N}{K}-1\right)\times E_{MN}^{CON}\tag{12a}$$

Then, by using Eq. 1, Eq. 12 can be rewritten as follows:

$$E_i^{Tot-MNs}=\sum_{j=1}^{\left(\frac{N}{K}-1\right)}l\left(E_{elec}+\propto d\left(PMN_j,PCH_i\right)^n\right)\tag{12b}$$

where PMN_j shows the position of the *j*th MN located at the *i*th cluster. PCH_i denotes the position of CH belonging to the respective cluster and $d\left(PMN_j,PCH_i\right)$ is the Euclidean distance between MN and CH. Based on the Eq. 12b, since all parameters are constant, the energy consumption of MNs depends on their distance to their destination CHs. Because of uniform node distribution and the same density of the nodes in different clusters, the following relation can be concluded:

$$E_1^{Tot-MNs}\approx E_2^{Tot-MNs}\approx\ldots\approx E_K^{Tot-MNs}\tag{13}$$

Then, because of equal energy consumption of MNs belonging to different clusters, instead of giving priority to clusters based on their energy consumption levels, the clusters take priority based on their distances to the *WMC-MN*, which results in reducing the vacation time of WMC.

If the *WMC-MN* starts to move from a *Sartpoint* and the set of anchor clusters of the *WMC-MN* is *{AC*$_1$*, AC*$_2$*,…, AC*$_K$*}*, then AC_1 and AC_j can be determined as follows:

$$\begin{aligned}&AC_1=\boldsymbol{min}\left(d\left(Sartpoint,PCC_i\right)\right)\\&\qquad\quad\mathbf{1)}\quad 1\leq i\leq K\end{aligned}\tag{14}$$

And,

$$\begin{aligned}&AC_j=\boldsymbol{min}\left(d\left(AC_{j-1},PCC_i\right)\right)\\&\mathbf{S.T}:\ \mathbf{1)}\ 2\leq j\leq K\\&\qquad\ \mathbf{2)}\ 1\leq i\leq K\\&\qquad\ \mathbf{3)}\ i\notin\{AC_1,AC_2,\ldots,AC_{j-1}\}\end{aligned}\tag{15}$$

where PCC_i denotes the position of the center of the *i*th cluster. After determining the charging cluster sequence, BS starts to calculate the charging time of *WMC-MN* in each anchor cluster.

2) CHARGE TIME OPTIMIZATION OF WMC-MN

In this section, the sojourn time of *WMC-MN* in the clusters is determined so that perpetual operation of MNs during a cycle is guaranteed.

The total energy consumption of a MN during a cycle consists of the waiting time of the MN, the charging time of *WMC-MN* at the next clusters, and the vacation time along anchor clusters. Therefore, the total energy consumption of *j*th MN located at the *i*th cluster is calculated using Eq. 16.

$$\begin{aligned}EMN_{i,j}^{Tot}=&\Bigg(MNWT_i+\sum_{s=i+1}^{K}(MNCT_s)\\&+\sum_{s=i}^{K-1}\left(\frac{d(PCC_s,PCC_{s+1})}{Speed}\right)\\&+\frac{d(PCC_K,Endpoint)}{Speed}+\varphi\Bigg)\times EMN_{i,j}^{CON}\end{aligned}\tag{16}$$

where, $MNWT_i$ shows the waiting time of the MNs belonging to *i*th cluster and $MNCT_i$ is the charging time of *WMC-MN* at the next clusters after leaving the *i*th cluster. Likewise, d is the distance between the positions of the center point of two continuous anchor clusters. In addition, φ signifies the energy-replenishment time of *WMC-MN* and speed is the velocity of *WMC-MN*.

The waiting time of the MNs located at each cluster consists of the charging time of *WMC-MN* in previous anchor clusters and the vacation time along the clusters with a constant speed.

$$\begin{aligned}MNWT_i=&\Bigg(\frac{d(StartPoint,PCC_1)}{Speed}+\sum_{s=1}^{i-1}(MNCT_j)\\&+\sum_{s=1}^{i}\left(\frac{d(PCC_s,PCC_{s+1})}{Speed}\right)\Bigg)\end{aligned}\tag{17}$$

Furthermore, if TEL_i is the total transferred energy level from *WMC-MN* to the MNs located at the *i*th cluster and the energy level of *WMC-MN* after completing the energy replenishment-time is considered as ω, the following relation can be concluded:

$$TEL_1+TEL_2+\ldots+TEL_K=\omega\tag{18}$$

In addition, since the charging range of *WMC-MN* is equal with the radius of a cluster, it is able to charge multiple MNs within its charging range simultaneously. Therefore, by using Eq. 9, the sojourn time of WMC in *i*th cluster is formulated as Eq. 19.

$$MNCT_i = \frac{\frac{TEL_i}{\frac{N}{K}-1}}{P_r} \tag{19.a}$$

Then,

$$MNCT_i = \frac{TEL_i}{P_r \times \frac{N}{K} - 1} \tag{19.b}$$

Moreover, the main objective of this section is to achieve fair division of energy of *WMC-MN* between clusters in a cycle, while guaranteeing that none of the MNs will run out of its energy during a cycle. Therefore, the optimal transferred energy level from WMC-MN to each cluster is modeled as an ILP.

$$\begin{aligned}
&\boldsymbol{min} \left(\omega - \sum_{i=1}^{K} (TEL_i)\right)^2\\
&\textbf{S.T}: \ \textbf{1)}\ EMN_{i,j}^{RES} - EMN_{i,j}^{Tot} + MNCT_i > 0\\
&\qquad \textbf{2)}\ 1 \le j \le \frac{N}{K} - 1\\
&\qquad \textbf{3)}\ 1 \le i \le K\\
&\qquad \textbf{4)}\ TEL_i > 0
\end{aligned} \tag{20}$$

Accordingly, ω energy level of WMC-MN is fairly divided between clusters in such a way that perpetual operation of MNs is guaranteed during a cycle.

Finally, after determining the charging times of *WMC-MN* at different clusters, the BS dispatches the *WMC-MN* toward clusters according to their priorities.

V. PERFORMANCE EVALUATION

A. SIMULATION ENVIRONMENT

In this paper, a WRSN is considered as a case study. The WMCs and the sensor nodes are equipped with the power cast chargers and receivers. In this paper, 100 sensor nodes have been distributed uniformly through a 100 m × 100 m area. A static sink is placed at center of the area. WMCs moves at a speed of 0.5 m/s. like the scheme proposed in [25], WMCs don't consume energy during the moving along sensor nodes. likewise, the initial energy of the nodes is 4 J. Other related system parameters are listed in Table 1 [26].

B. PERFORMANCE ANALYSIS

This section evaluates the proposed FEDS scheme in terms of different evaluation metrics. The relevant WMCs based schemes, [13] and [15] are used to benchmark against the proposed FEDS scheme as the main aim of such schemes is to improve the network lifetime by determining the optimal moving trajectory of the WMCs.

Figure 3 shows the remaining energy and energy consumption of CHs during a cycle. In CH based networks, the network lifetime is defined as the time that first CH exhausts its energy supply [26], [29]. Therefore, due to the introduction of the relation (11), the CHs will never run out their remaining energy before being recharged again, which leads to achieve permanent network lifetime. This is because the energy of WMC-CH is divided into CHs so that their energy is sufficient until sojourning of the WMC at their clusters in the next cycle. Moreover, based on the figure 4, the energy status of nodes has no changes during cycles. This is because, the moving of WMC-CH along CHs is repeated every cycles.

TABLE 1. Simulation parameters.

Parameters	Value
Number of Sensor Nodes	100
Network Area	100m ×100m
Packet size	128 bit
Initial battery level of nodes	4 J
Eelec	50e-9
energy dissipated the op-amp	0.0013e-12
Speed of WMCs	0.5 m/s
Initial Energy of WMCs (ω)	10 J
Energy Replenishment Time of WMC (φ)	10000s

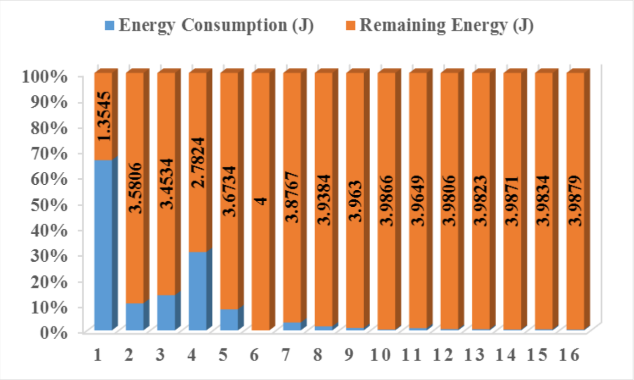

FIGURE 3. Remaining energy and energy consumption of CHs during a cycle.

In addition, figure 5 compares the total energy consumption of network as number of clusters increases. As can be observed, increasing the number of clusters leads to rising the number of CHs and results in increased communication cost in three approaches. As shown in the figure, in our proposed scheme, the CHs consume less energy in comparison with two other schemes. This is because, in the proposed FEDS, when WMC arrives a cluster, the MNs belonging to the respective cluster send their data to the WMC instead of CH, which leads to reduce the CH burden. Likewise, this figure depicts the STD average of the total energy consumption of the network under different scenarios. As can be seen, in our proposed FEDS, this value is less than other schemes.

In addition, we evaluate the impact of the number of nodes on the total energy consumption of the CHs in three different schemes. As shown in figure 6, our proposed scheme outperforms two other works. This is because, unlike two other schemes, the WMCs perform the BS task during sojourning at each cluster.

Furthermore, the number of non-functional nodes has been shown in Figure 7 during the running cycles. As shown, the number of dead nodes rises as time increases in UCMC

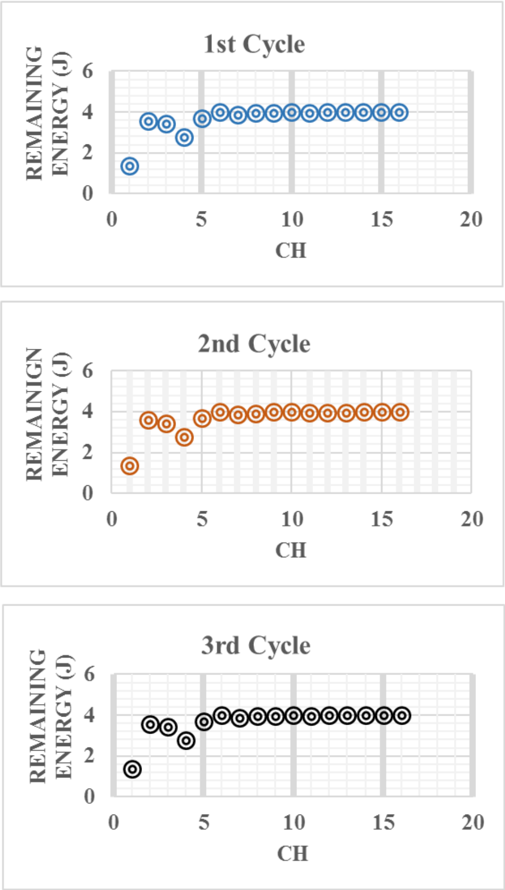

FIGURE 4. Remaining energy of nodes in three running cycles.

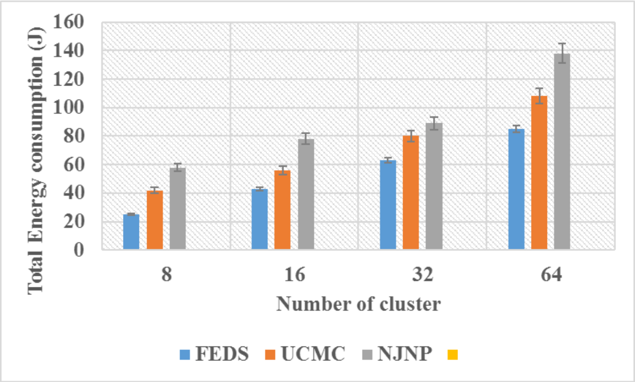

FIGURE 5. Total energy consumption of network VS Number of clusters.

and NJNP schemes, whereas in the proposed FEDS scheme, the nodes will never deplete their energy supplies before being recharged again by WMC-CH. This perpetual operation of nodes has been achieved due to the introduction of the ILP problem (11). In fact, our proposed FEDS scheme divides the energy of WMCs among sensor nodes in such a way that their energy doesn't deplete during a cycle. This energy division is repeated in each cycle which results in zero non-functional node and permanent network lifetime.

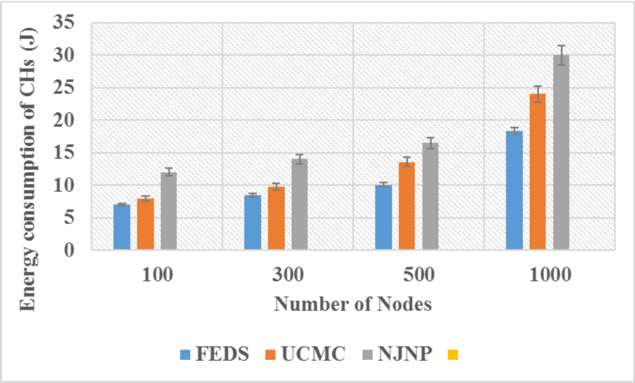

FIGURE 6. Total energy consumption of CHs VS number of nodes.

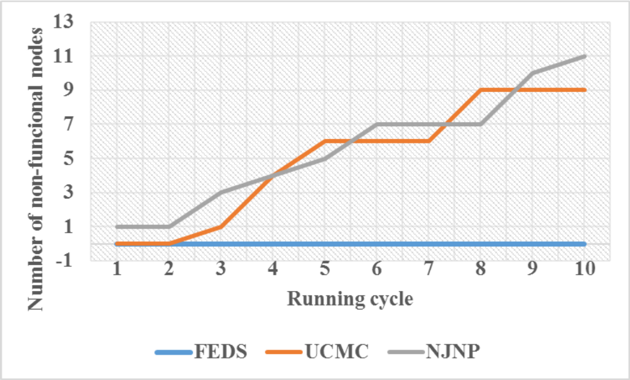

FIGURE 7. Number of non-functional nodes of three algorithms.

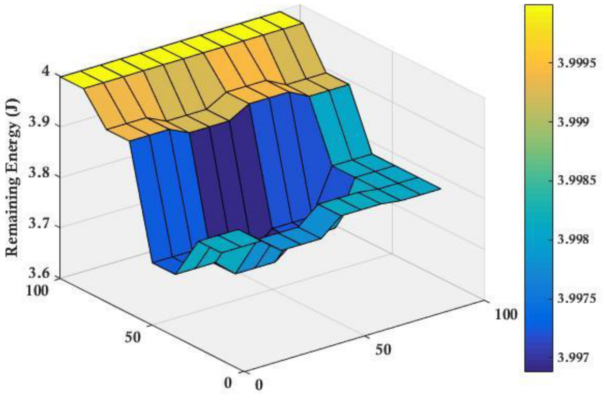

FIGURE 8. Remaining energy of MNs during a cycle.

In addition, the remaining energy of the MNs during a cycle has been represented in Figure 8. As shown, the nodes around center point have lower remaining energy in comparison with outer ones. This is because, the inner clusters are first visited by WMC-MN, which leads to reducing of their energy at the end of each cycle. In other words, the WMC-MN selects the cluster with minimum distance to its location and since the WMC-MN starts from the center of the network, the clusters around center point are first visited and recharged.

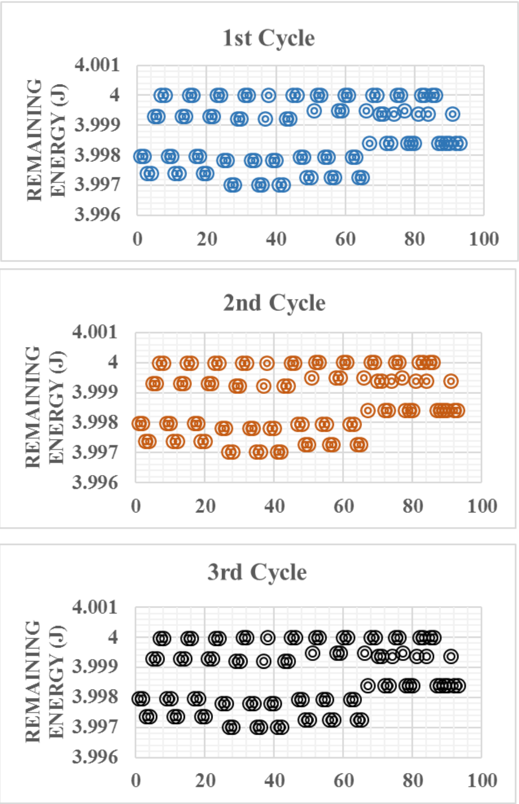

FIGURE 9. Remaining energy of MNs during three cycles.

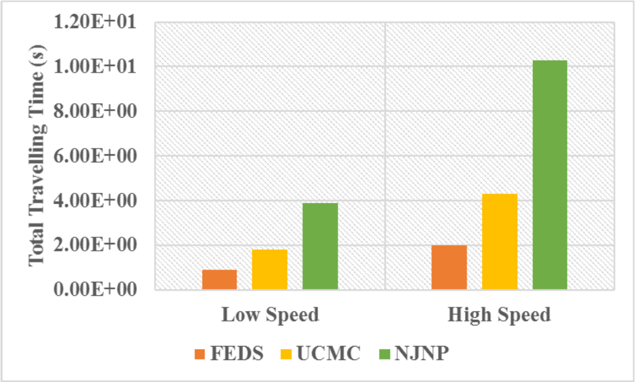

FIGURE 10. Travelling time of WMC-CH in a cycle.

Moreover, the remaining energy of MNs during three cycles has been illustrated in Figure 9. As observed, none of MNs deplete their energy during the cycles, which is achieved owing to present the relation (19). In the other word, this stems from employing the WMC-MN which charges the MNs as much as the perpetual operation of MNs during a cycle is guaranteed.

Figure 10 depicts the traveling time of *WMC-MN* in FEDS, UCMC and NJNP schemes under two different scenarios. In this paper, the traveling time is the total time that WMC spends for moving along anchor points. As seen, in our proposed scheme, the traveling time of *WMC-MN* is shorter than other related works. This is because, FEDS optimizes the moving trajectory of WMC in such a way that the clusters take priority based on their distances to the *WMC-MN*, which leads to reduce the vacation time of WMC. Moreover, it is obvious that increasing the velocity of WMC leads to reducing the traveling time along clusters.

VI. CONCLUSION

In this work, a new Fair Energy Division Scheme (FEDS) is presented for a cluster-based WRSN, which aims to permanentize the operation of CHs and MNs. Two separate WMCs have been employed to recharge the MNs and CHs, individually. In the proposed scheme, the problem of scheduling the WMCs has been studied, which formulated as ILP problem. Moreover, the energy of WMCs is fairly divided among nodes in such a way that their energy will not run out their energy during a cycle. To achieve this goal, the energy share of nodes is determined based on their energy consumption levels so that the more energy is consumed, the more energy is assigned to the nodes. Moreover, Finally, the simulation results demonstrate that the desired system requirements are satisfied using the proposed scheme.

ACKNOWLEDGMENT

The author would like to thank DSR technical and financial support.

REFERENCES

[1] M. Erol-Kantarci and H. T. Mouftah, "Wireless multimedia sensor and actor networks for the next generation power grid," *Ad Hoc Netw.*, vol. 9, no. 4, pp. 542–551, Jun. 2011.
[2] P. Kamalinejad, C. Mahapatra, Z. Sheng, S. Mirabbasi, V. C. M. Leung, and Y. L. Guan, "Wireless energy harvesting for the Internet of Things," *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 102–108, Jun. 2015.
[3] 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.
[4] C. Wang, J. Li, Y. Yang, and F. Ye, "Combining solar energy harvesting with wireless charging for hybrid wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 17, no. 3, pp. 560–576, Mar. 2018.
[5] L. Mo, A. Kritikakou, and S. He, "Energy-aware multiple mobile chargers coordination for wireless rechargeable sensor networks," *IEEE Internet Things J.*, vol. 6, no. 5, pp. 8202–8214, Oct. 2019.
[6] J. Jia, J. Chen, Y. Deng, X. Wang, and A.-H. Aghvami, "Joint power charging and routing in wireless rechargeable sensor networks," *Sensors*, vol. 17, no. 10, p. 2290, Oct. 2017.
[7] L. Xie, Y. Shi, Y. T. Hou, W. Lou, and H. D. Sherali, "On traveling path and related problems for a mobile station in a rechargeable sensor network," in *Proc. 14th ACM Int. Symp. Mobile Ad Hoc Netw. Comput. (MobiHoc)*, Jul. 2013, pp. 109–118.
[8] T. Rault, A. Bouabdallah, and Y. Challal, "Multi-hop wireless charging optimization in low-power networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2013, pp. 462–467.
[9] A. Kaswan, A. Tomar, and P. K. Jana, "An efficient scheduling scheme for mobile charger in on-demand wireless rechargeable sensor networks," *J. Netw. Comput. Appl.*, vol. 114, pp. 123–134, Jul. 2018.
[10] Y. Liu, K.-Y. Lam, S. Han, and Q. Chen, "Mobile data gathering and energy harvesting in rechargeable wireless sensor networks," *Inf. Sci.*, vol. 482, pp. 189–209, May 2019.
[11] N. T. Tam, H. T. T. Binh, D. A. Dung, P. N. Lan, L. T. Vinh, B. Yuan, and X. Yao, "A hybrid clustering and evolutionary approach for wireless underground sensor network lifetime maximization," *Inf. Sci.*, vol. 504, pp. 372–393, Dec. 2019.

[12] H. Dai, Y. Liu, G. Chen, X. Wu, and T. He, "SCAPE: Safe charging with adjustable power," in *Proc. IEEE 34th Int. Conf. Distrib. Comput. Syst.*, Jun./Jul. 2014, pp. 439–448.

[13] G. Han, H. Guan, J. Wu, S. Chan, L. Shu, and W. Zhang, "An uneven cluster-based mobile charging algorithm for wireless rechargeable sensor networks," *IEEE Syst. J.*, vol. 13, no. 4, pp. 3747–3758, Dec. 2019.

[14] C. Lin, G. Wu, M. S. Obaidat, and C. W. Yu, "Clustering and splitting charging algorithms for large scaled wireless rechargeable sensor networks," *J. Syst. Softw.*, vol. 113, pp. 381–394, Mar. 2016.

[15] L. He, L. Kong, Y. Gu, J. Pan, and T. Zhu, "Evaluating the on-demand mobile charging in wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 14, no. 9, pp. 1861–1875, Sep. 2015.

[16] O. Younis and S. Fahmy, "HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks," *IEEE Trans. Mobile Comput.*, vol. 3, no. 4, pp. 366–379, Oct. 2004.

[17] W. Na, J. Park, C. Lee, K. Park, J. Kim, and S. Cho, "Energy-efficient mobile charging for wireless power transfer in Internet of Things networks," *IEEE Internet Things J.*, vol. 5, no. 1, pp. 79–92, Feb. 2018.

[18] S. He, J. Chen, F. Jiang, D. K. Y. Yau, G. Xing, and Y. Sun, "Energy provisioning in wireless rechargeable sensor networks," *IEEE Trans. Mobile Comput.*, vol. 12, no. 10, pp. 1931–1942, Oct. 2013.

[19] G. Han, X. Yang, L. Liu, S. Chan, and W. Zhang, "A coverage-aware hierarchical charging algorithm in wireless rechargeable sensor networks," *IEEE Netw.*, vol. 33, no. 4, pp. 201–207, Jul. 2019.

[20] M. Hu, Z. Chen, K. Peng, X. Ma, P. Zhou, and J. Liu, "Periodic charging for wireless sensor networks with multiple portable chargers," *IEEE Access*, vol. 7, pp. 2612–2623, 2019.

[21] K. Peng, M. Hu, C. Cai, X. Ma, Y. Yang, and J. Liu, "On simultaneous power replenishment for wireless sensor networks with multiple portable chargers," *IEEE Access*, vol. 6, pp. 63120–63130, 2018.

[22] M. Erol-Kantarci and H. T. Mouftah, "Suresense: Sustainable wireless rechargeable sensor networks for the smart grid," *IEEE Wireless Commun.*, vol. 19, no. 3, pp. 30–36, Jun. 2012.

[23] M. Zhao, J. Li, and Y. Yang, "A framework of joint mobile energy replenishment and data gathering in wireless rechargeable sensor networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 12, pp. 2689–2705, Dec. 2014.

[24] G. Han, X. Yang, L. Liu, and W. Zhang, "A joint energy replenishment and data collection algorithm in wireless rechargeable sensor networks," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2596–2604, Aug. 2018.

[25] N. Gharaei, Y. D. Al-Otaibi, S. A. Butt, S. J. Malebary, S. Rahim, and G. Sahar, "Energy-efficient tour optimization of wireless mobile chargers for rechargeable sensor networks," *IEEE Syst. J.*, early access, Feb. 11, 2020, doi: 10.1109/JSYST.2020.2968968.

[26] S. Malebary, "Wireless mobile charger excursion optimization algorithm in wireless rechargeable sensor networks," *IEEE Sensors J.*, early access, Jun. 24, 2020, doi: 10.1109/JSEN.2020.3004758.

[27] X. Liu, H. Song, and A. Liu, "Intelligent UAVs trajectory optimization from space-time for data collection in social networks," *IEEE Trans. Netw. Sci. Eng.*, early access, Aug. 19, 2020, doi: 10.1109/TNSE.2020.3017556.

[28] B. Jiang, G. Huang, T. Wang, J. Gui, and X. Zhu, "Trust based energy efficient data collection with unmanned aerial vehicle in edge network," *Trans. Emerg. Telecommun. Technol.*, Mar. 2020.

[29] H. Yetgin, K. T. K. Cheung, M. El-Hajjar, and L. Hanzo, "A survey of network lifetime maximization techniques in wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 828–854, 2nd Quart., 2017.

[30] D. Mishra and S. De, "Effects of practical rechargeability constraints on perpetual RF harvesting sensor network operation," *IEEE Access*, vol. 4, pp. 750–765, 2016.

[31] S. Basagni, A. Carosi, E. Melachrinoudis, C. Petrioli, and Z. M. Wang, "Controlled sink mobility for prolonging wireless sensor networks lifetime," *Wireless Netw.*, vol. 14, no. 6, pp. 831–858, Dec. 2008.

• • •