Energy Harvesting in Wireless Sensor Network with Efficient Landmark Selection using Mobile Actuator

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***Abstract*—In this paper, we present an approach to ensure efficient energy distribution among all the nodes in a wireless sensor network by employing mobile chargers from several landmark locations within each sensor cluster with timing constraint. Mobile chargers are considered to use radio frequency signals for the charging purpose and use Hamiltonian cycle to ensure minimum time required to visit landmarks within each sensor cluster. This scheme helps increase the docking time compared to the total cycle time for the mobile chargers to get recharged from the docking station. It also increases the battery lifetime for the sensors which is one of the major bottleneck for wireless sensor networks. The optimum number of landmarks for each cluster is selected with the help of critical nodes whose energy goes below the defined threshold. Later, the mobile chargers calculate the minimum distance among the landmarks and initiate the energy transfer by certain percentage from their own reservoirs. The simulation results show that the proposed approach successfully provides prolonged lifetime for the sensor battery, less waiting time for the sensor nodes to get recharged from the mobile chargers, and maximize docking time for the mobile chargers.**

***Index Terms*—Wireless Sensor Networks, Radio Frequency, Landmark Selection, Mobile Actuator, Energy Harvesting.**

I. Introduction

Wireless Sensor Network (WSN) is promising for efficient monitoring and processing of information collected from remote, hostile, and hazardous regions with difficult human reachability. WSN is formed with collection of autonomous sensors to monitor different environmental or physical states such as sound, pressure, temperature, water quality, natural disaster, machine health monitoring, forest fire detection, air pollution, health care management, etc. The autonomous sensor nodes are responsible for sending the sensed data via the network to main server. Sensor networks can be both uni-directional and bi-directional in terms of data transmission. Uni-directional sensors can only send information to the server. Bi-directional sensors can both send and receive data to and from the server, which makes them more popular. However, it is required to track the sensor energy status to avoid unintentional interruption in data transmission. Bi-directional sensors are perfect for these uses. Memory, speed, and bandwidth of sensors depend on the cost and sensor size, which can vary from tiny dust particle to the size of a bigger shoebox [1]. The network topology also varies from simple star to multi hop wireless mesh network. On the other hand, efficient energy management is one of the major bottlenecks in sensor network. As the sensors are typically spread in different regions of the environment, protocols and algorithms need to address the issues of network lifetime maximization, robustness, fault tolerance, etc. The sensor device should minimize the energy consumption to provide prolonged and uninterrupted network lifetime. Another solution can be recharging the sensors in a timely manner.

There are several possible solutions available for maximizing the network lifetime, but they have their limitations as well. Ambient energy harvesting such as solar powered sensors can be used to mitigate the power outage issue. But the energy is only available at daylight, thus there should be some mechanism to preserve the energy during the day and distribute them when needed. Renewable energy sources are possible solution for energy management although it is very difficult to manage the energy consumption for the low powered sensor nodes. There are several other options from mechanical, thermal, and commercial energy harvester. Mechanical energy is generated from the movement or vibration of objects. One of the popular method of vibrational energy harvester is piezoelectric capacitor. Environmental vibration from bridges, roads, and rail tracks can also be used for this purpose. Thermal generators are also good source of energy harvesting and they live more than the vibration-based devices. There are some other issues in the sensor network related to Radio Frequency (RF) distribution channel. Concurrent charging and data transmission may corrupt data packets.

Our major concern in this paper is related to the energy replenishment for the sensor battery. Our approach works with a mobile charger deployed at the sensor network. Initially, the sensor nodes are spread uniformly over the experimental area. Then, the nodes are formed into clusters based on their location and the energy requirement. Landmarks are selected within each cluster based on the mobile charger's maximum frequency transfer range. More than one landmarks are selected for each cluster according to the intensity of energy requirement by the member nodes. Then, the mobile charger visits the landmarks one by one with the optimal traveling path using Hamiltonian cycle. It first visits the closer landmark and calculates the next nearest one. Then it forwards near the rest of the landmarks to ensure energy.

The remainder of this paper is organized as follows. In section II, we present the available RF energy harvesting techniques and their advantages and disadvantages. Section III describes concise overview of the related work done in this area. In section IV, we present the implementation details of this work. Section V and VI focuses on the simulation environment and simulation results, respectively. Finally, we conclude and suggest the future directions of this research in section VII.

II. Overview of Energy Harvesting Approaches

Energy harvesting is generally known as energy scavenging or power harvesting process through which energy is stored from external sources like solar power, thermal energy, wind, salinity gradients, vibration, and kinetic energy [2]. Energy can be obtained from these sources and stored in small devices to use in wearable computational devices, wireless sensor networks. In this paper, we focus on the ambient energy sources which are mainly based on radio frequency. Radio frequency energy can be obtained from the residual energy of other intermediate sources like television and radio broadcasting frequencies [3]. On the other hand, industries emit a lot of temperature, vibrations, and electromagnetic induction from the combustion and other sort of engines. These can be used as renewable energy sources for various purposes as well.

Ambient radio frequency energy harvesting needs to use certain frequency spectrum. To get the idea about how these frequency bands work, it is better to look at the GSM 900/GSM 1800/WiFi systems [4]. These frequency bands are present everywhere in the urban areas and are mainly used for telecommunication purpose. However, it is difficult for the capacitors to obtain the highest energy level in limited time if we want to use the energy gain from those frequency bands.

Radio frequency wave emitting devices convert microwave energy into direct electricity using rectifying antenna or rectenna. As there is no special regulations for the rectennas, it is wise to use the license-free ISM bands to avoid the conflict with existing ones. Radio Frequency IDentification (RFID) powered devices such as WSN nodes and mobile chargers can gain energy from these frequencies as well. Usage of sensor nodes are useful for the smart grids, smart homes, health monitoring devices, etc. Smart grid environment can have number of sensor nodes which need power to continue its operation without any interruption.

Wireless sensor networks are cost efficient as they need very less energy to transmit data over the wireless network. Sensor nodes participate to use low power media access control protocol for information sharing. The nodes replenish their batteries with replacement or recharging. Frequent battery replacement is not cost effective and impractical for mission critical applications. Thus, recharging becomes a realistic option. However, wireless charging technology is more challenging in case of radio frequency transmission. The quality of energy transfer is impeded by different issues, interference and noise can make less energy transmission from the actual. Thus, the energy modeling should take these challenges into account and keep some resource allocated. On the other hand, sensor nodes lifetime depend on the battery or own energy source. We could model the recharging option using solar power, but the drawback is the unavailability during night. Then, the smart grid can not be monitored due to inactive sensors. Thus, a better option would be using hybrid model, the mixture of solar and radio frequency energy transfer. However, the implementation of hybrid model is quite complex due to the cost and hardware requirements. As a result, we consider only radio frequency energy transmission throughout this paper. The energy used by a sensor consists of energy consumption by data reception, transmission, sampling, listening for data on the radio channel, being in sleep mode, etc.

III. Related Work

The design of networking protocols for ambient energy harvested wireless sensor networks are surveyed in [5]. The ambient energy harvested network eliminates the need to replace the batteries. But, it is very complex to store the energy with a sustainable solution without any interruption. The survey also indicated that the energy harvesting from environment has several factors affecting the overall performance. Their prime focus on the survey was comparing the key aspects between WSN and Wireless Sensor Networks Powered by Ambient Energy Harvesting (WSN-HEAP).

Ways of achieving timely and efficient charging of the sensor nodes are explained in [6]. The proposed technique includes Mobile wIreless Charger RObot (MICRO) for replenishing the battery of sensors. Minimum number of landmarks are used with location and energy replenishment requirements of the sensors. The research is focused on two main points; landmark selection, and visiting those landmarks using shortest possible path. This model will for sure help to reduce some energy consumption. Specific energy consumption model for the sensors are not mentioned in the paper. Additionally, the locations of the landmarks are static, the new ones are added by increasing the energy replenishment requirements. This may cause death for those sensors requiring urgent energy replenishment while unnecessary recharging for others.

Analysis about maximizing the energy consumption for the high priority nodes are discussed in [7]. The features used are power reception energy per priority nodes, and path traversal efficiency. High and low priority nodes are determined based on the energy requirements. The results are compared with their previous paper in [6] and found that SURESENSE [6] exploited better outcome than DRIFT [7].

An optimization problem on maximizing the battery lifetime of sensor nodes is detailed in [8]. They introduced the Wireless Charging Vehicle (WCV) which is similar in nature like the MICRO used in [6]. They optimized the vacation time and the traveling path for the charger using shortest Hamiltonian cycle. They provided that the optimal traveling path for the vehicle is the shortest Hamiltonian cycle when the objective is maximizing the ratio of the docking time over cycle time.

In [9], the authors studied the implications of recharge opportunities on sensor node operation and design of sensor network solutions. They focused on the battery power nodes and how these nodes meet the goals of lifetime, cost, data sensing reliability, transmission coverage, energy harvesting, and ambient to electrical energy conversion. They surveyed different aspects of energy harvesting sensor system architecture and storage technologies with examples.

The authors in [10] studied wireless rechargeable sensor network built from wireless identification, sensing platform, and RFID device. They mentioned that the wireless identification and sensing platform tags can harvest the receiving energy from the readers. They attended the issue of continuous operation for these wireless identification and sensing platform tags in indoor environment and referred to as energy provisioning issue. Their analysis reveals that their method reduces the number of readers significantly compared to those assuming traditional coverage models.

The authors in [11] highlighted the tradeoff among the number of chargers, the height of charging trees, and the total energy demand for multi-hop wireless network. They explored the multi-hop wireless energy transfer method to prolong the lifetime of low power networks. They developed optimization model for reducing the total number of chargers required using the energy demand and the total energy loss while transferring.

Active and passive protocols to harvest RF energy has been mentioned in [12]. One of them predicts useless messages from which RF energy can be captured passively. The other proposes a way to request RF energy emission and then harvest it actively. They compared both the schemes and found that neither of these two protocols change the other part of a wireless communication systems protocol stack, including the CSMA/CA mechanism and routing protocols.

Energy management scheme is proposed in [13] for residential usage called in Home Energy Management (iHEM). The paper focused on the demand supply balance and electricity expense reduction. They found that iHEM performs almost as optimization-based residential energy management.

In [14], the authors developed abstractions to characterize the issues of power management for energy harvesting sensor networks. They considered the harvesting opportunity from different nodes to align the workload allocation with the energy availability at the harvesting nodes. They also constructed a complete ambient RF-powered prototype for measuring temperature and light level and transmitted these parameters using wireless.

IV. Proposed Approach

Our experiment focuses mostly on the sensor energy harvesting process, and the efficient distribution of energy to the sensor nodes in periodic basis to prevent sudden network outage. In the following sections we describe the process with individual steps along with the mathematical description used in the simulation.

A. Region Selection

The whole network that are considered for this experiment is 100m×100m and divided into four equal regions which helps efficiently cluster the nodes. Each region is assigned to one **M**obile w**I**reless **C**harger **Car** (**MICCAR**) for charging purpose. Thus, the problem is divided into four subproblems each having its own energy consumption constraints. The **MICCAR** will have more docking time[1] compared to the cycle time[2] to recharge itself from its docking station, also the waiting time for the sensor nodes to get recharged in each cycles will be reduced.

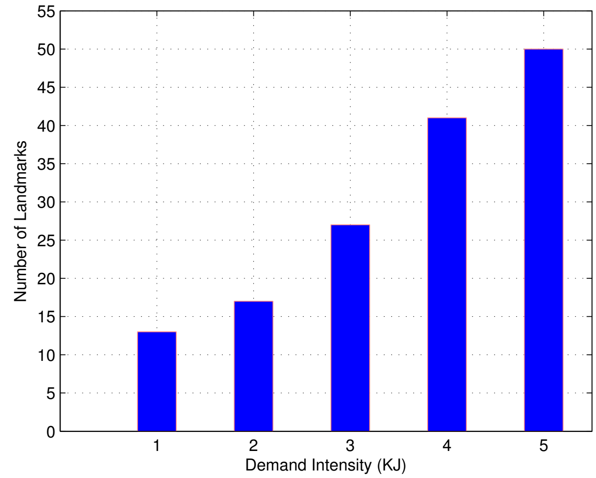

Fig. 1. Number of landmarks in the network based on energy demand [6].

B. Landmarks Selection

The landmarks are selected considering the energy requirement of the sensor nodes in the network. The landmarks increases with the energy demand increase, the worst case would be reserving a landmark for each sensor node which is equivalent to visiting every sensor node for recharging. The energy required for all sensor nodes on whole network is calculated using Equation 1.

$$E_{Req} = \sum_{i=1}^{N} E^i_{Bat} - E^i_{Rem} \tag{1}$$

where, E_{Req} is the total energy required for all sensor nodes, N is the total number of sensor nodes in the network, E^i_{Bat} is the capacity of the sensor i battery, and E^i_{Rem} is the remaining energy for sensor node i.

Although sensor nodes are categorized into both homogeneous and heterogeneous [15] considering the hardware and energy consumption, only the homogeneous sensors are used for the experiment. The total number of landmarks should be minimized in order to reduce the path length visited by the **MICCARs**. The number of landmarks is optimized using IBM CPLEX [16] and the result is mentioned in Figure 1.

The next issue is to assign the landmarks to each region. The landmarks are distributed according to the percentage of energy required by each region. The number of landmarks are

[1]Time required for a MICCAR to get recharged from the docking station.

[2]Time required for a MICCAR to complete a single pass in each cluster to ensure minimum node failure.

assigned in each region based on the percentage of required energy using Equation 2.

$$L_i = \left\lfloor L_{Dem} \frac{E^i_{Req}}{E_{Req}} \right\rfloor \tag{2}$$

where, L_i is the number of landmarks assigned to region i, L_{Dem} is the total number of landmarks in the network based on energy demand, E^i_{Req} is the total required energy at region i, and E_{Req} is the total energy required for all sensor nodes.

C. Location Discovery for Landmarks and Path Selection

As we get the number of landmarks required for each region, we choose the location for the landmarks from the nodes which require urgent energy. For example, if the number of landmarks required for region 1 is 3, we select 3 positions from the nodes requiring more energy compared to others.

Previously, energy distribution was done based on the high priority sensor nodes and for the subset of sensor nodes [17]. We used this method with minor changes to determine the exact location for the landmarks. We defined three levels of energy requirement; Urgent Level (U_L), Medium Level (M_L), and Normal Level (N_L). Our main objective is recharging maximum number of sensor nodes at urgent energy requirement level with maximum possible energy. Alternatively, it means keeping the distance as small as possible between these sensor nodes and **MICCAR**. Additionally, we ensured recharging maximum number of sensor nodes at medium level with high energy, and recharging maximum possible number of sensor nodes at normal energy requirement level.

Initially, the locations of urgent energy requirement level sensor nodes are selected as landmarks. Then, the **MICCAR** checks for a new location that can serve the initially attended node and any other closer node requiring energy, especially the sensor nodes at medium energy requirement level. This is done by advancing from the initial landmark to each point located within the radius of the quarter of the **MICCAR** wireless energy transfer range, R_C. For example, let's assume a **MICCAR** attends an urgent energy requiring node at point P_1 for a definite time. Then, the **MICCAR** finds a new location, P_2, within $R_C/4$ from point P_1 such that there is another node requiring energy, possibly with medium urgency. If any new energy requiring nodes are found from those locations, then that becomes the new landmark. The landmark remains unchanged if no energy requiring nodes are found within the wireless energy transfer range from new locations. Figure 2 shows the sensor nodes discovery process to select the best location of landmark, the distance $R_C/4$ is selected as the new radius for the discovery of prospective landmarks to keep the old urgent level nodes in its vicinity. We define the radius as $R_C/4$ from empirical results.

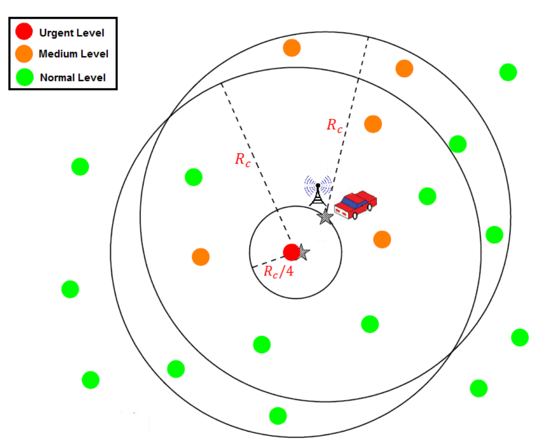

Fig. 2. Sensor nodes discovery process for selecting the best location of landmark, from the new location we are still recharging the sensor node at urgent level with high energy as the distance between this sensor node and the new location of landmark should be small.

Algorithm 1 : Location of Landmarks

L_i
$Nodes[\,] \leftarrow Nodes.sortAsc()$
for $i = 1 \rightarrow L_i$ **do**
  $Loc[\,] \leftarrow Nodes[i].Location$
end for
return Loc

Algorithm 1 describes the process of selecting the initial locations of landmarks according to the residual energy level from the nodes within the defined regions. All sensor nodes in the **MICCAR** defined region are sorted in ascending order, based on their remaining energy level. Then, the locations of the first L_i nodes, sensor nodes with the least residual energy, are selected to be the initial landmarks within their region.

Algorithm 2 defines the weight and priority of all nodes within the transfer range from the number of nodes at each level. It recieves all sensor nodes within $R_C/4$ range ($Nodes_{new}$), Urgent Weight (U_W), Medium Weight (M_W), and Normal Weight (N_W), respectively. It should be noted that *Urgent Weight* (U_W) gets the highest priority. Then, it counts the number of sensor nodes within each energy requirement level. Finally, the algorithm computes the total weight of all considered nodes within the **MICCAR** wireless transfer range.

Algorithm 2 : Weight for Prospective Nodes

$Nodes_{new}, U_W, M_W, N_W$
for $i = 1 \rightarrow length(Nodes_{new})$ **do**
  if $Nodes_{new}[i].Energy \leq U_L$ **then**
    $UL_n + +$
  else if $Nodes_{new}[i].Energy \leq M_L$ **then**
    $ML_n + +$
  else
    $NL_n + +$
  end if
end for
$W \leftarrow UL_n \times U_W + ML_n \times M_W + NL_n \times N_W$
return W

Algorithm 3 clarifies the usage of *eight* locations which are away from initial landmark by $R_C/4$ distance. Later,

Algorithm 3 : Landmark Location Update

```
L_i, U_W, M_W, N_W
Loc ← getLandmarks(L_i)
for i = 1 → length(Loc) do
    Loc_f ← Loc[i]
    for j = 1 → length(Nodes) do
        ED ← dist(Loc_f, Nodes[j].Location)
        if ED ≤ R_C then
            Nodes_new[ ] ← Nodes[j]
        end if
    end for
    W ← getWeight(Nodes_new, U_W, M_W, N_W)
    for j = 1 → length(Nodes_new) do
        if Nodes_new[j].Energy ≤ U_L then
            CUL_f ++
        end if
    end for
    N_L[ ] ← getEightLoc(Loc_i)
    for j = 1 → 8 do
        Loc_i ← N_L[j]
        for k = 1 → length(Nodes) do
            ED ← dist(Loc_i, Nodes[k].Location)
            if ED ≤ R_C then
                Nodes_n[ ] ← Nodes[k]
            end if
        end for
        CW ← getWeight(Nodes_n, U_W, M_W, N_W)
        for k = 1 → length(Nodes_n) do
            if Nodes_n[k].Energy ≤ U_L then
                CUL_i ++
            end if
        end for
        if CUL_i ≥ CUL_f  and  CW ≥ W then
            CUL_f ← CUL_i
            W ← CW
            Loc_f ← Loc_i
        end if
    end for
    Loc[i] ← Loc_f
end for
return Loc
```

these locations are tested as the next prospective landmark by serving the maximum number of urgent and medium level nodes. The landmark location update starts by selecting the initial locations of landmarks using Algorithm 1. Then, each of these initial locations are tested for better improvement, this is done by the following steps: **A)** The initial location is assumed to be the final location. **B)** All sensor nodes within the **MICCAR** wireless transfer range from the final location are collected. **C)** The weight of these nodes is calculated using Algorithm 2. **D)** The count of urgent level energy requiring nodes is computed. **E)** Eight locations from the final location are returned by dividing the transmission disk into eight equal regions. **F)** Each of these locations are tested as a possible landmark. Subsequently, the tested location is assumed to be the initial location. **G)** All sensor nodes within the R_C range from the initial location are collected. **H)** The current weight of these collected nodes is calculated using Algorithm 2. **I)** The current number of urgent level energy requiring nodes in the collected nodes is counted. **J)** The final location, the final weight, and the final number of urgent level energy requiring nodes are updated when the current weight and the current number of urgent level energy requiring nodes are greater than or equal to the final weight and the final number of urgent level energy requiring nodes, respectively. **K)** The initial landmark location will be updated by the final location after testing the eight possible landmarks locations. The same steps **(A-K)** are repeated for all initial landmarks locations for possible improvement. As we used different notations in three algorithms, Table I clarifies them in detail.

Later, the **MICCAR** visits its landmarks using the shortest Hamiltonian cycle to decrease the sensor nodes waiting time, and maximize the ratio of the docking time over cycle time according to the results obtained from [8].

D. Wireless Energy Transfer

MICCARs park at landmarks and emit radio signals which have different frequencies than those used for communication. In [18], the frequency band around 900 MHz is utilized for wireless charging of the WSNs whereas sensors communicate in the 2.4 GHz band.

Naturally, wireless energy transfer is limited to a certain range, R_C, since the radio waves attenuate as they travel from the transmitter to receiver. The source of signal strength loss has strong connection with the distance traveled by the signal itself. The signal strength looses its strength while going through the environment. The wireless energy transfer, using radio wave propagation in free space, is expressed using Friis transmission formula [19], [20] represented in Equation 3.

$$\frac{P_R}{P_T} = G_R G_T (\frac{\lambda}{4\pi d})^2 \tag{3}$$

where, P_R and P_T are the power available at the receiving antenna and the power supplied to the source antenna, respectively, G_R and G_T are the receiver and transmitter antenna gain, respectively, λ is the wavelength of the carrier, and d is the distance between the transmitter and receiver.

The gain of the antennas, usually measured in decibels, can be converted to power ratio using Equation 4.

$$G = 10^{(\frac{G_{dB}}{10})} \tag{4}$$

The wavelength of the carrier can be computed using Equation 5.

$$\lambda = \frac{c}{f} \tag{5}$$

where, c is the speed of light (3×10^8 m/s), and f is the frequency in Hz.

TABLE I. Variables, symbols, and functions used in Algorithm 1, 2, and 3.

Variables/Symbols	Description
$Nodes$	Global array stored at MICCAR for holding all the nodes within its region
$sortAsc()$	Function for sorting the nodes based on the remaining energy level
Loc	Array stored at MICCAR for holding the locations of landmarks
$Nodes_{new}$	Array of all sensor nodes within the radius of R_C from the current landmark
U_W, M_W, N_W	Weights of urgent, medium, and normal energy levels, respectively
U_L, M_L	Urgent, and medium remaining energy levels, respectively
UL_n, ML_n, NL_n	Count of urgent, medium, and normal remaining energy levels nodes, respectively
W	Weight or priority of prospective node
$getLandmarks()$	Function returns the locations of initial landmarks using Algorithm 1
Loc_i, Loc_f	Initial, and final locations, respectively
ED	Euclidean distance
$dist()$	Function for calculating the euclidean distance
$getWeight()$	Returns the weight of nodes using Algorithm 2
CUL_f, CUL_i	Count of final, and initial urgent level energy requiring nodes, respectively
$getEightLoc()$	Function for returning the eight locations from a node by diving the transmission disk into eight equal regions
N_L	Array for holding eight possible locations of landmarks
$Nodes_n$	Array of all sensor nodes within the radius of R_C from the tested landmark

The energy at each round is transferred to the nodes according to the energy requirement which changes with time. So, the energy distribution changes with each round for each region. Energy replenishment is done in such a way that no nodes become dead between two consecutive rounds.

E. Timing Constraints

We considered several variables to measure the round time, cycle time, docking time, and energy harvesting time for both the nodes and **MICCAR**. The relationship is defined using Equation 6.

$$D_t = R_t - (C_t + T_t) \tag{6}$$

where, D_t refers to the docking time for the **MICCAR** to recharge itself from the docking station, R_t is the round time which is constant at each round of the simulation, C_t is the cycle time for the **MICCAR** to traverse the landmarks, it depends on Hamiltonian path length and the speed of **MICCAR**, T_t defines the energy transmission time to the sensor nodes and depends on the amount of energy transmitted and the charging rate.

V. SIMULATION SETTINGS

The simulation environment is setup in Fedora 8 (Unix based operating system) with NS2 and LEACH [21]. The sensor nodes are uniformly distributed over the whole region. LEACH is a TDMA based MAC protocol which has clustering and routing protocol enabled for wireless sensor networks. This protocol is used to simulate the network for low energy consumption and create clusters to improve the lifetime of the network. By default, LEACH maintains the hierarchy for the nodes to transmit information between cluster head(s) and base station.

We used custom property to minimize the energy transmission with minimum waiting time for the sensor nodes to get recharged. The cluster heads are selected stochastically at each round with probability $1/P$. This refers that one cluster head cannot become cluster head in the next P rounds. Thus, it may create imbalance for the candidate sensor nodes to wear out the energy. So, we select the cluster heads using the energy consumption from all the sensor nodes of the whole network. In addition, four **MICCARs** are assigned to provide the charge for the sensor nodes according to the necessity of the network. In our simulation we used 50 sensor nodes uniformly deployed in the network area, the round time is 30 minutes, initial energy for each node is 10 Joule, the **MICCAR** energy is 200 Joules, the whole network area is 100 × 100 meters and divided into four equal regions. Table II summarizes the parameters used in the experiment.

TABLE II. Simulation parameters used in MICCAR scheme.

Simulation parameter	Description
No. of nodes in the network	5 (Min.), 50 (Max.)
Node distribution	Uniform
Area considered	100 × 100 $Meters$
Initial energy for nodes	10 $Joule$
Capacity of the sensor battery	10 $Joule$
No. of regions	4
Round time	30 $Minutes$
No. of MICCARs	4
MICCAR energy capacity	200 $Joule$
MICCAR wireless charging range	5-20 $Meter$
Energy consumption in free space	0.1 $nJoule/bit/m^2$
Urgent Level (U_L)	0-2.5 $Joule$
Medium Level (M_L)	2.5-7.5 $Joule$
Normal Level (N_L)	7.5-10 $Joule$

VI. RESULTS AND DISCUSSION

We focus on three different metrics in this section to evaluate the proposed approach: i) traveled distance or path length, ii) number of alive sensor nodes, and iii) remaining network energy.

A. Travel Distance

As the sensor nodes failure is considered as random event, the path from the **MICCARs** point to the event location is not necessarily the shortest by geographical distance. However, we measure the path length of **MICCARs** at each round considering maximum node recharge.

Figure 3 shows that the path length for the **MICCARs** to traverse at each round varies with the energy requirement by the sensor nodes as the landmarks locations are considered dynamic. In the first round, the required energy by all sensor nodes in the network was 225 Joules. Accordingly, there will be 19 landmarks in the network. The total length of the path to visit those landmarks by the four **MICCARs** is 576 meters. The required energy at round 6 and 7 were nearly equal 296 and 295 Joules, respectively. Thus, the number of landmarks in those rounds should be closer. According to [6], the path length should be the same for the previous case as they assumed static locations for each landmarks. However, the path lenght is quite different in our experiment as 600 and 649 meters, respectively. The major reason for this to happen is because we considered the landmarks as dynamic to be closer to urgent energy requiring nodes. Additionally, consideration was given on maximum number of sensor nodes to receive charge.

B. Alive Sensors

How many sensors are active at any moment is of utmost concern when it comes to mission critical applications such as electronic surveillance, security systems, health care monitoring, etc. It is necessary to know the status of each sensors periodically to ensure the sensor networks performance. We measure the sensors activity after every 30 minutes of round time and count the number of alive sensors. Figure 4 presents the number of alive sensors in the network after each round.

Number of alive sensor nodes becomes less at the end of each round, as represented in Figure 4. After that, energy is

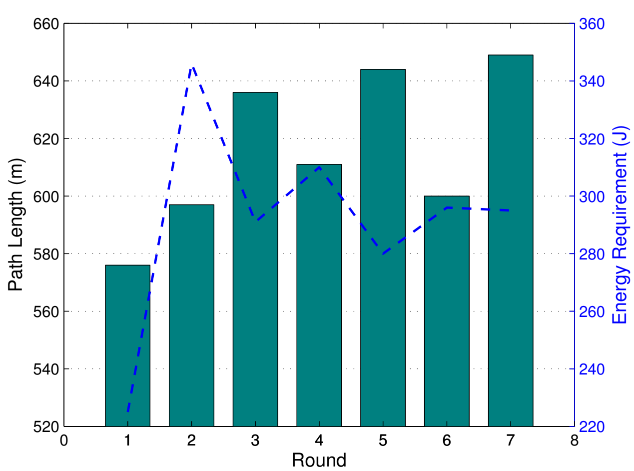

Fig. 3. The number of landmarks increase with the rise in energy demand. As a result, path length changes for the MICCARs to traverse at each round with three different level of energy requirement.

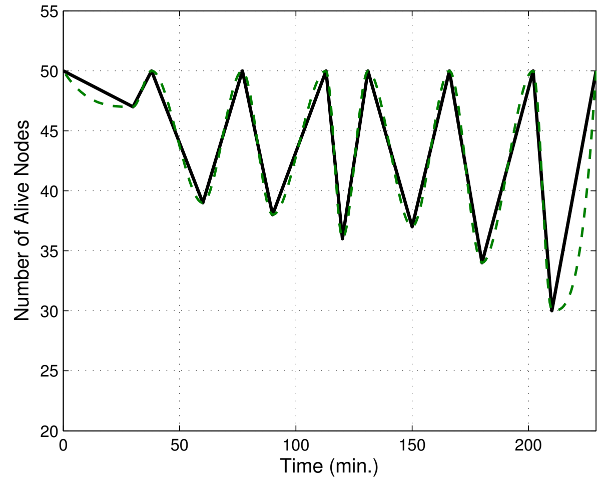

Fig. 4. Number of alive sensor nodes in the network with increase in the round time.

transmitted from the **MICCAR** to again make them alive. So, at each round the number of alive nodes remain same as the initial state. In our experiment, at the beginning of the first round there were 3 died sensor nodes. In order to recharge them and other urgent level sensor nodes, 19 landmarks were used with total of 576 meters path length. This process of recharging took around 8 minutes. However, during the third round there were 12 died sensor nodes. In order to recharge them and other urgent level sensor nodes, 26 landmarks were used with total of 636 meters path length. This process of recharging took around of 23 minutes. The time span of the recharging by **MICCARs** at the third round is much more than the time in the first round due to several factors. First, the number of landmarks to traverse in the third round are greater. Second, the path length and cycle time is greater in the third round. Finally, as there were 12 died sensor nodes in the third round and recharging was needed, the energy transmission time became higher compared to the case when 3 died sensor nodes needed recharging.

C. Remaining Energy

The remaining energy is computed at each round considering all the sensors in the network using Equation 7 and the result is shown in Figure 5.

$$Re_t = \sum_{i=1}^{N} E^i_{Rem}, \forall t \in \{1, 2, \ldots, T\} \tag{7}$$

where, Re_t is the remaining energy of the network at round t, E^i_{Rem} refers to the remaining energy of sensor node i, and T is the round time in minutes.

Energy is used by the network during the round time, so the energy becomes lower. When the **MICCAR** replenishes the sensors, the remaining energy increases over the each round trying to reach at the maximum level as shown in Figure 5. During the first 30 minutes, the sensors battery charge was

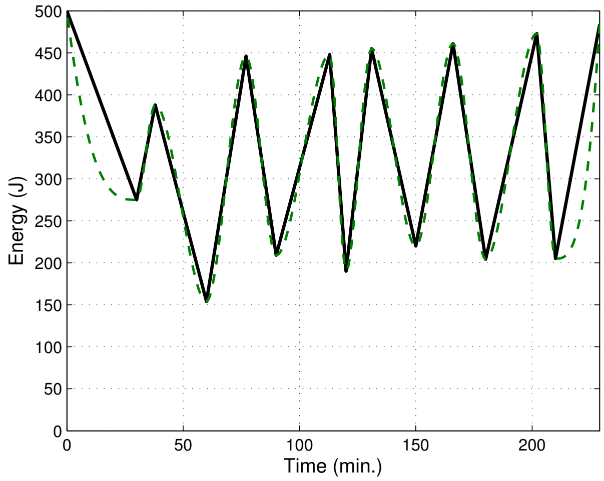

Fig. 5. Remaining energy in the network with increase in round time.

decreased by 45%. Then, the chargers work for 8 more minutes to put the networks remaining energy to 388 Joules which is much lower to the initial energy of 500 Joules. However, at the beginning of the second round, after 60 minutes of simulation, the network lost more than 69% of its energy. Then, 32 landmarks were used to quickly increase the network energy by recharging the sensors. It took 17 minutes for the **MICCARs** to increase the energy level to 446 Joules. The **MICCARs** stayed at the docking station for 22 minutes during the first round time to store energy in their batteries.

VII. Conclusion

Various energy recharging options are available to tackle different problem areas related to energy replenishment in wireless sensor network. In this paper, an approach is shown to ensure optimum energy distribution among all the nodes in a wireless sensor network by employing mobile chargers from several landmarks locations within each sensor cluster with time constraint. The mobile chargers mentioned in this paper visit the landmark and use radio frequency signals to transfer energy to the nearby nodes. An approach is presented to employ the chargers and use Hamiltonian cycle to ensure minimum time required to visit landmarks within the sensor network. As we consider both low cost, reliable, and secured solutions for energy replenishment at the sensor network, RF charging turns out to be the best fit. This scheme provides prolonged lifetime for the sensor battery, less waiting time for the sensor nodes to get recharged from the **MICCARs**, and also maximize docking time for the **MICCARs**.

Although our approach offers possible refinement in the area of RF energy harvesting in WSN, we find several improvement areas. For example, this paper does not consider the energy loss in the medium for RF signal propagation. The data communication between the charger **MICCAR** and the base station is also ignored. Additionally, the assumption of uniformly distributed node and ideal terrain can be changed into different node distribution and diversified surface model as the region of interest in the 3D world is not usually even.

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