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Lifetime enhancement of wireless sensor network using solar energy harvesting technique

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Abstract
The finite energy of batteries associated with wireless sensor networks is a major constraint, which limits its lifetime. One of the methods to overcome this major limitation is the energy harvesting (EH) systems. There are many energy sources available nowadays, but solar energy is flexible, mature and is an external power source; so, it is broadly utilised for EH in the wireless sensor network to enhance the life of the network. The solar EH technique along with the low energy adaptive clustering hierarchy protocol is applied. The charging and discharging curves of the battery and energy status of the nodes are propounded. The simulation results demonstrate that the lifetime of the battery and the network gets augmented after applying the solar EH technique.

1  |  INTRODUCTION

In this era, the wireless sensor network (WSN) is one of the popular and foremost used networks in the world. WSN consists of the sensor nodes that are capable of monitoring the different environmental conditions and forwards the data to the sink where it transfers further for processing.

A WSN node is frequently powered by the batteries. Batteries can be rechargeable or non-rechargeable. The non-rechargeable batteries limit the life span of the WSN and also affect the performance of the network, which is a critical issue. As a consequence, rechargeable batteries must be used. Since most of the WSN applications are situated in an inhospitable area, consequent replacement of the batteries would be inconvenient. Hence, it is strenuous to enlarge the life span of WSNs under a finite power of the device. Therefore, energy harvesting (EH) technologies could be utilised to prolong the life span of the WSN, and the supreme familiar sources are solar, wind, vibration, radio-frequency (RF), and thermal [1] that are used for EH.

Different EH techniques are available nowadays for the WSN, but solar EH technique is extensively used because solar cells give the highest power density of 15 mW/cm². Hence, it is adequate to fulfil the power needs of the WSN [2]. The different power densities of EH sources are given below in Table 1.

Solar energy is one of the greenest technologies. The periodic availability of solar energy makes it feasible for the WSN and enhanced the life span of the network. So, we used solar EH technique to enhance the life span of the network. Solar energy can be harvested through a photovoltaic conversion technique [1]. The photovoltaic panel consists of different cells; cells are either attached in series or parallel to meet the requirements of power while adjusting the values of the current and voltage supplied by these cells [3]. The cells are made according to different technologies such as polycrystalline silicon, amorphous silicon, monocrystalline silicon, and thin films [3].

The study is organised as follows: Section 1 elucidates the introduction. Section 2 recounts the related work. Sections 3 and 4 designate about the solar cell, its model and about the rechargeable battery, respectively, which we utilised during the simulation, whereas performance evaluation is given in Section 5 and finally section 6 draws the conclusion.

2  |  RELATED WORK

In recent years, researchers make efforts to use renewable energies as a power source for WSN such as the solar energy, wind, thermal, vibration and RF. Several researchers propound different harvesting models. Minami et al. [4] designed a solar biscuit, which is a battery-less wireless system for the surveillance of the environment. Simjee et al. [5] presented a supercapacitor operated solar-powered wireless sensor node, called Everlast. Yin et al. [6] designed an intelligent solar EH system using maximum power point tracking (MPPT) for WSNs.
Another study deals with solar-powered WSN and introduces distributed routing schemes for energy management in Reference [7]; balanced energy allocation scheme [8], energy estimation and forecast scheme [9] and adaptive learning enforced broadcast policy [10] with solar-powered WSN also exist in the literature. Abbas et al. [11] proposed an EH model for solar-powered WSN along with the energy management system. They also described the analytical behaviour of the model. Numerical simulations were also performed to show the current-voltage (IV) and photovoltaic (PV) characteristics of the solar cell. Qi and Zhu [12] proposed a one-diode equivalent circuit-based versatile simulation PV model in the form of a masked block. The model can also work with MPPT. The IV characteristics of the PV module were also simulated with different combinations. In Reference [13], Jaitawat and Singh demonstrated the imperfections of the battery and supercapacitors. By varying the different channel conditions, they find out which imperfection of the supercapacitor and the battery is a bottleneck in system performance. The numerical results of the analysis are also given. In Reference [14], the authors offered a hybrid EH model that exploits solar energy and electromagnetic energy. They also developed a mixed-integer programming method that is used to lessen the energy dissipation of the sensor nodes. They also noted the impact of the mixed-integer programming on a hybrid EH system and transmission power control on energy-saving nodes. Frohlich et al. [15] explicates the analysis on the efficiency of the low power and low voltage solar harvesting circuits. Two experiments based on the maximum power point of solar panel were implemented and demonstrate that more work is to be done on such solar harvesting circuits. In Reference [16], the energy efficient grid-based routing algorithm for the sensor network to enhance the lifetime of the network was proposed. They apply the fuzzy rules to find the appropriate route to reduce the number of hops in routing to save energy. Imededdin et al. [17] minimise the power consumption by presenting a WSN node with methods and made the node feasible to be used with the EH system. The design, implementation and measurements were also proposed.

In the related work, the authors designed the solar nodes and applied different EH techniques in WSN. They also deliver the energy management schemes. Different methods to minimise the power consumption methods are also available in the literature. Solar EH technique is used along with MICAz nodes and the Low energy adaptive clustering hierarchy (LEACH) protocol is used to reduce the power consumption of the nodes. The solar EH technique is utilised to surge the lifetime of the network. 

**Table 1** Power densities of harvesting techniques [2]

| S.No. | Methods          | Power density |
|-------|------------------|---------------|
| 1.    | Solar cells      | 15 mW/cm²     |
| 2.    | Piezoelectric    | 330 µW/cm²    |
| 3.    | Vibration        | 116 µW/cm²    |
| 4.    | Thermoelectric   | 40 µW/cm²     |
| 5.    | Acoustic noise   | 960 nW/cm²    |

**Figure 1** Harvested energy stored in battery [1]

### 3 | SOLAR ENERGY HARVESTING IN THE WSN AND THE SOLAR CELL

#### 3.1 | Solar energy harvesting in the wireless sensor network

The energy from the sources is converted into electrical energy by using an appropriate hardware. Due to the expansion of the technology, it is practicable to coordinate the energy harvesting module in pint-sized and dense sensor nodes, and such types of nodes frequently are alluded as EH sensor nodes [1]. EH sensor nodes comprise of every fundamental constituent that is needed for executing the tasks and operations with a summation of EH unit, which can transform the surrounding energy into an electrical form [1]. The transformation method applied into the EH relies on the kind of energy source. This method not only will surge the lifetime of the network but also lessen the need for battery replacement. The harvested energy can be used directly in a network, that is the power unit directly utilises the harvested energy to run the network, or it can accumulate the harvested energy in batteries for current and later use [1]. Figure 1 below demonstrates the EH module used for the storage of harvested energy.

Solar energy is broadly used for harvesting energy because of its high power density. Solar energy is a renewable, flexible, mature and unlimited source of power. The harvesting module used for harvesting the solar energy is the solar cell, which is explained in the Section 3.2.

#### 3.2 | Solar cell

This section elucidates the model of the solar cell. Using the photovoltaic effect, the solar cell converts light rays into electrical energy to bestow power to the WSN. A basic photovoltaic (PV) system entails of a solar panel, each encompasses of a number of solar cells that produce electricity [18]. Diffused
silicon p-n junction and several other materials such as monocrystalline, polycrystalline, amorphous, cadmium telluride and copper indium gallium selenide/sulphide [19] are used as semiconducting materials in PV cells.

The output current of the solar cell is directly proportional to solar irradiation and voltage [11]. The equivalent circuit of the solar cell is presented in Figure 2.

The Ideal solar cell's equation [12], which makes an ideal model, is given as follows:

\[
I = I_{pb} - I_{o} \left[ \exp \left( \frac{V}{AVt} \right) - 1 \right] \tag{1}
\]

where ‘\(I_{pb}\)’ is the photocurrent [in amperes (A)], ‘\(I_{o}\)’ is the reverse saturation current (A), ‘\(V\)’ is the diode voltage (V) ‘\(Vt\)’ is the thermal voltage, \(A\) is the diode ideality factor.

The thermal voltage is specified in the subsequent equation [12]:

\[
Vt = kT/q \tag{2}
\]

Here ‘\(k\)’ is Boltzmann's constant, and its value is \(1.38 \times 10^{-23}\), whereas ‘\(T\)’ is solar cell's temperature (in Kelvin) and ‘\(q\)’ is the charge of an electron, \(1.6 \times 10^{-19}\) C.

The temperature of the solar cell which is described in Equation (2) is given as [12]:

\[
T = 3.12 + 0.25 \times G/G_{ref} + 0.899 \times Ta - 1.3W/s + 273 \tag{3}
\]

In the above Equation (3), ‘\(G\)’ is the irradiance intensity (\(\text{W/m}^2\)), ‘\(G_{ref}\)’ is the reference irradiance intensity, ‘\(Ta\)’ is the ambient temperature and ‘\(W/s\)’ is the local wind speed (m/s).

The ‘\(I_{pb}\)’ in Equation (1) depends upon the cell temperature, and the irradiance intensity is stated as follows [12]:

\[
I_{pb} = \frac{G}{G_{ref}} \left[ I_{sc, ref} + \mu I_{sc} (T - T_{ref}) \right] \tag{4}
\]

Here ‘\(I_{sc, ref}\)’ is the short circuit current of the solar cell at the reference condition, \(T_{ref} = 25\)°C and ‘\(\mu I_{sc}\)’ is the short-circuit temperature coefficient of the solar cell.

The reverse saturation current [12] of the solar cell is

\[
I_{o} = I_{o}, \text{ref} \left( \frac{T}{T_{ref}} \right)^{3/A} \exp \left[ qE_g \left( \frac{1}{T_{ref}} - 1 \right) / T \right] / kA \tag{5}
\]

\[
I_{o}, \text{ref} = I_{sc, \text{ref}} / \left[ \exp \left( \frac{V_{oc, \text{ref}}}{AVt} \right) - 1 \right] \tag{6}
\]

In the former Equation (6), ‘\(V_{oc, \text{ref}}\)’ is the solar cell's open-circuit voltage, and ‘\(E_g\)’ is the energy bandgap whose value is 1.12–1.15 eV [12].

The I–V characteristic equation [12] of the solar cell, which comprises series resistance (\(R_s\)) and shunt resistance (\(R_{sh}\)), is stated as:

\[
I = I_{pb} - I_{o} \left[ \exp \left( \frac{V + IR_s}{AVt} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \tag{7}
\]

Furthermore, with the addition of cells in series (\(N_s\)) and parallel (\(N_p\)), the above Equation (7) becomes [12]:

\[
I = N_p I_{pb} - N_p I_{o} \left[ \exp \left( \frac{V + IR_s}{N_p AVt} \right) - 1 \right] - \frac{\left( \frac{N_p}{N_s} \right) V + IR_s}{R_{sh}} \tag{8}
\]

The P–V characteristic equation [12] is specified as:

\[
P = I \cdot V \tag{9}
\]

### 3.2.1 MSX-005F solar panel

However, there are numerous parameters which are required to be brought into thought while choosing the solar panel. These aspects comprise of an open circuit current, short circuit current, maximum power point and the IV characteristic curve. Moreover, except these measures, the solar panel has to be lasting to resist the exposure to out-of-doors conditions to lessen the monetary value of substituting them. Taking all these parameters into consideration, we choose the MSX-005F solar panel from the BP solar [20] for simulation. This panel is cheap and small in size. The dimensions of the MSX005 F solar panel are 114.3 mm × 66.8 mm×3 mm, and its characteristics [20] are specified in Table 2.

### 4 RECHARGEABLE BATTERY

Primarily there are two types of energy storage devices in WSNs, and those are batteries and supercapacitors. Generally, rechargeable batteries are utilised in the solar harvesting system. This method is more matured and has high gain densities as compared to a supercapacitor. Some rechargeable batteries
are a lead-acid battery, a nickel-cadmium battery, a nickel-
hydrogen battery, lithium-ion battery, and a lithium-polymer
battery. In this proposed work, we utilised a lithium-ion battery
with a capacity of 730 mAh, which is enough to support the
system after recharging. The Lithium-ion battery has a nominal
voltage of 3.7 V. The time required to charge the battery is
given in the following equation [21]:

\[
\text{charge time} = \frac{\text{battery capacity(mAh)}}{\text{produce energy(mA)}}
\] (10)

The time required to discharge the battery is given in the
following equation [21]:

\[
\text{Discharge time} = \frac{\text{battery capacity(mAh)}}{\text{current draw(mA)}}
\] (11)

5 | PERFORMANCE EVALUATION

5.1 | Flow chart of proposed work

5.2 | Simulation setup

All the implementations of the proposed work are done using
MATLAB R2013b to obtain successful results. We use the
solar EH technique along with LEACH, which is a MAC
protocol. LEACH is the first hierarchy network protocol in
which the nodes transfer the data to the cluster head, and the
aggregated data of the cluster heads communicate directly with
the sink (base station) [22].

The assumptions that are taken into consideration while
implementing the proposed technique are: the nodes are
randomly deployed in the sensor field, all nodes have the same
initial energy, the next round of the LEACH will come after
1 s, our network is deployed in the sunlight area and the solar
radiation is neither blocked by any clouds nor by any objects,
the solar energy is available from 6 am to 7 pm, the value of
current at a particular time of the day is assumed based on the
radiation intensity and the MICAz sensor nodes are used in the
network. The simulation parameters for WSN are given in
Table 3.

We considered that the MICAz nodes are deployed in the
sensor field. These nodes are working in three different states:
active state, idle state and sleep state. In the active state, the
nodes are able to transmit or receive data, while in the sleep
state, some parts of the sensor node circuitry are turned off,
that is, they cannot take part in network activity, whereas in the
idle state, the nodes do not transmit or receive the data [24].
The current consumption of nodes in these different modes is
presented in Table 4.

| Parameter | Value |
|-----------|-------|
| Open circuit voltage (Voc) | 4.6 V |
| Short circuit current (Isc) | 160 mA |
| Maximum output power (Pmax) | 500 mW |
| Voltage at maximum power (Vmp) | 3.3 V |
| Current at maximum power (Imp) | 150 mA |
| Surface area | 36 cm² |

| Input parameters | Description |
|------------------|-------------|
| Network coverage | 100 × 100 m² |
| Number of nodes | 100 |
| The initial energy of sensor nodes | 0.7 J |
| Energy for transmission (ETx) | 50 nJ |
| Energy for the reception (ERx) | 50 nJ |
| Energy for data aggregation (EDA) | 5 nJ/bit/signal |
| Sink location | (50,50) m |
| Data packet size | 3000 bits/s |

Abbreviation: WSN, wireless sensor network.
5.3 | Results and discussion

First of all, we determine the number of rounds performed by the LEACH protocol. Next, we evaluate the PV characteristics of solar panel to know how many watts of energy we could extract from solar cell. Then, charging and discharging curves of the battery are also displayed when the sensor nodes are in active, sleep and idle modes after which the, energy status of

| Type of mode | Current value |
|--------------|---------------|
| Active mode  | 18 mA         |
| Idle mode    | 8 mA          |
| Sleep mode   | 15 μA         |

**TABLE 4 Power consumption of MICAz nodes [25]**

**FIGURE 3** Operating nodes per round before applying the solar energy harvesting technique

**FIGURE 4** The output power of MSX-005F solar panel
the nodes at particular rounds of the LEACH after furnishing the solar energy to the WSN are proffered. Lastly, we compare the lifetime of the network before and after applying the solar EH technique on the basis of the number of rounds. The more the number of rounds, the greater will be the lifetime of the network.

Figure 3 given below shows the lifetime of the WSN in terms of rounds without applying the solar EH technique. All the nodes become dead after 3665 rounds.

Now, we will compute the solar power by using MSX005 F solar panel. The MSX005 F solar panel's maximum output power is 500 mW at the irradiance intensity of 1000 W/m². The voltage given to this panel is 3.3 V. The open-circuit voltage of the panel is 4.6 V, and short circuit current is 160 mA. The series resistance is 0.45 Ω. The assumed value of the parallel resistance is taken as 21.35 Ω. The power-voltage characteristics of the solar panel are also calculated which are displayed in Figure 4.

The PV characteristics of the solar panel at different irradiance intensities are given in Figure 5. The solar panel delivers its maximum power at 1000 W/m² and its minimum power at 250 W/m². At 750 W/m², it delivers 0.28 W of power, and at 500 W/m² the power is 0.13 W.

**FIGURE 5** Photovoltaic (PV) characteristics of the solar panel at different irradiance intensities

**FIGURE 6** Irradiance against the time of a day
The power of the solar cell depends on the intensity of the solar cell. As the sun’s irradiance intensity varies from morning to evening, therefore, at noon, the solar panel offers maximum output. In the morning and evening time, the solar panel delivers the minimum output.

The plot of irradiance intensity [11] against the time of the day is shown in Figure 6.

The plot in Figure 6 also shows that we can achieve maximum current when the irradiance intensity is maximum that is, during the noon. Based on this plot, we assume that the solar panel gives a maximum current of 150 mA at noon. The sunny day starts at 6 AM and ends at 7 PM. So, the value of the current at different times of the day is given in Table 5.

| Time of a day | Value of Current (mA) |
|---------------|-----------------------|
| 6 AM          | 16.6                  |
| 7 AM          | 33.2                  |
| 8 AM          | 66.4                  |
| 9 AM          | 83                    |
| 10 AM         | 99.6                  |
| 11 AM         | 116.2                 |
| 11:30 AM      | 132.8                 |
| Noon          | 150                   |
| 1 PM          | 132.8                 |
| 2 PM          | 116.2                 |
| 3 PM          | 110                   |
| 4 PM          | 99                    |
| 5 PM          | 66.4                  |
| 6 PM          | 33                    |
| 7 PM          | 16.6                  |

5.3.1 Charging and discharging curves of the battery

The harvested energy from the solar panel is used to recharge the lithium-ion battery of 730 mAh capacity. The MICAz nodes consume 28 mA of average current while performing the communication. Figure 7 depicts the plot of charging the discharging curve of the battery.

In Figure 7, the blue line depicts the charging of the battery from the solar panel. The red line portrays the discharging of the battery, and the green line illustrates that the battery life surged with the addition of harvested energy from the panel. First of all, as shown in Figure 7, the battery gets discharged in 26 h. The discharged time of the battery is calculated using the formulae indicated in Equation (11). Increase in the current consumption while performing the communication is accompanied by decrease in the battery capacity. With the addition of the harvesting energy in the battery, its capacity is increased. Now after getting recharged, the battery will be discharged in approximately 130 h, and this harvested energy prolongs the battery life. Consequently, the green line in Figure 7 illustrates the lifetime enhancement of the battery.

Furthermore, we have taken the three scenarios in which the nodes are working in different states to display the charging and discharging curve of the battery. These scenarios are (1) when nodes are in the active state, (2) when nodes are in an idle state and (3) when nodes are in the sleep state. The charging and discharging time of the battery is calculated using the Equations (10) and (11), respectively.

In the first scenario, Figure 8a, the nodes consumed 18 mA of current in the active state. The discharging of the battery is shown by a red line, the blue line represents the charging from the solar panel at the particular time of the day, and the green line represents the increment in the life of the battery. Figure 8b represents the second scenario. It demonstrates the process of charging and discharging when nodes are in an idle state. In the idle state, the nodes consume 8 mA of current. In this scenario, the battery discharges in 91 h. The third scenario is displayed in Figure 8c, and in this scenario, the nodes consume 15 µA of current. The outcomes in these figures confirm that the battery life is prolonged with recharging.

![charging and discharging curve of the battery](image-url)
5.3.2 | Energy status of nodes

In the present section, we demonstrate the energy of the nodes after different rounds of LEACH before and after applying the proposed technique. Before applying the proposed harvesting technique, it took 3665 rounds for the network to become dead, and the first node dies at the 1777th round. The depletion of energy after the 500th round in the form of the stem plot is displayed in Figure 9.

As the number of rounds increases, the energy of the nodes decreases. Consequently, the energy of the nodes was also checked after the 1500th and 2500th rounds and displayed

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**FIGURE 8** (a) Charging and discharging curves when nodes are in the active state. (b) Charging and discharging curves when nodes are in an idle state. (c) Charging and discharging curves when nodes are in the sleep state

**FIGURE 9** Stem plot of energy after 500th round
in Figures 10 and 11, respectively. Afterwards, at the 2500th round, as exhibited in Figure 11, almost all nodes become dead and only few nodes remain alive.

Furthermore, in Figure 12, we display the leftover energy of the nodes along with harvested energy supplied to the nodes. The blue-coloured data represent the energy consumed by nodes, the green-coloured data represent the harvested energy from the solar panel and the brown one represent the energy of nodes after recharging. The magnified view of Figure 12 is displayed in Figure 13.

In Figure 13 also, the green colour bar shows the harvested energy from the sun, which is given to the nodes after every round. The blue colour bar shows the energy consumed by the nodes and the brown colour bar shows the energy of nodes after recharging. The nodes from 65 to 74 and 76 to 100 are dead, and after providing them the harvested energy they turn alive. Previously, these nodes had no energy and were dead. Therefore, after recharging, these nodes obtained amount of energy and can again contribute to the network, which enhances the life of the network.
5.3.3 | Lifetime calculation after applying the proposed technique

The results are given in terms of the number of rounds. The lifetime of the network is directly proportional to the number of rounds. The more the number of rounds, the larger will be the lifetime of the network. When we supply the harvested energy to the network, its lifetime becomes virtually double. The lifetime of the network before and after applying the proposed technique is illustrated in Figure 14 and of the operating nodes per transmission in Figure 15.

On comparing the lifetime of the network, it can be concluded that the results obtained after applying the proposed technique are superior. Looking at Figure 14, formerly applying the solar EH technique, all the nodes become dead at the 3665th round, but after furnishing solar energy to the same nodes, their lifetime surged twice. Now, all nodes become dead after the 7352th round. With the implementation of the proposed technique, the network survives for a longer period. The network's lifetime gets more prolonged by harvesting the energy day after day.
6 | CONCLUSION

In recent times, though, the energy of environs comes as an attainable addition to the network's battery in WSN through the EH systems. One of the novel techniques to extend the WSN lifetime is the solar EH technique. As the manual restoring and recharging of batteries is not pragmatic, the sun is the most reliable source of energy used for the EH system. Therefore, the solar EH technique is utilised to prolong the lifetime of the WSN. We also used a low energy adaptive clustering hierarchical protocol. The simulation results are obtained by using MATLAB 2013b. The charging and discharging curves of the battery and the energy status of the nodes are also propounded. The evaluation of the work is done, and results are given in terms of number of rounds. The lifetime of the network is directly proportional to the number of rounds; the more the number of rounds, the larger will be the lifetime of the network. The comparison of the lifetime of the network in terms of rounds and transmissions are also presented. Primarily, the WSN becomes dead after performing 3665 rounds, but afterwards on implementing the solar EH technique, the network lifetime nearly gets doubled, and network becomes dead after performing 7352 rounds. Thus, the results of the proposed solar
EH technique demonstrates that the lifetime of the battery and the network is increased.

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