A Wireless Sensor System Supplied by a Solar Energy Harvester toward IoT Environmental Monitoring

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A Wireless Sensor System Supplied by a Solar Energy Harvester toward IoT Environmental Monitoring

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ABSTRACT

Harmful environments can cause seriously health problems to humans. Thus, it is should be develop a generation of wireless sensor systems that are energy self-powered to monitor physical parameters of an ambient environment in real-time and sending these parameters remotely to an IoT cloud service. In this paper, a wireless sensor system is proposed for an environmental monitoring. This system is based on two sensors and a NodeMCU board that includes a microcontroller with a Wi-Fi chip. This system is built to measure the ambient temperature, relative humidity, atmospheric pressure, and ultraviolet (UV) index. The power supply of the sensor system is a solar energy harvester, which consists of a solar cell, a DC-DC converter, and a rechargeable battery. This harvester is practically tested outdoors under direct sunlight. The wireless sensor system experimentally consumes an average power of 40 mW over one hour and the life-time of this system is 123 hours in active-sleep mode. The results demonstrate that the wireless sensor system has long-term and sustainable operation of the monitoring of an environmental data.

KEYWORDS

Wireless sensor system; Environmental monitoring; Solar energy harvester; Rechargeable battery; Internet of things (IoT)
1. INTRODUCTION

In the last decade, wireless sensor systems had a robust effect in environmental monitoring applications [1, 2]. These systems are extensively utilized to measure an environmental parameters in real-time [3-6]. Batteries are in often utilized to power the sensor systems, but they have a bounded life-time [7,8]. Energy harvesting (EH) methods are utilized to extend the life-time of the batteries [9-12]. These methods utilize various energy sources for instance solar [13], wind [14], thermal [15], mechanical [16], and radio frequency [17]. Solar energy is characterized by the high power density compared to other energy sources [18]. However, the illumination rates of solar energy are in instantaneous change. So, energy-storage elements and DC-DC converters are needed to store and regulate the power extracted via harvesting methods. Two storage-elements “a super-capacitor as well as rechargeable battery”, which are utilized as energy storages. Super-capacitors have lower energy densities than rechargeable batteries [19, 20]. So, in this paper, a battery is utilized. Moreover, a harvester depends on the solar was implemented to overcome the generic battery problem of the systems [21-25]. This proposed harvester grants the sensor system a more long-term life-time.

In the previous researches, different sensor systems were presented for environmental monitoring applications [26-28]. S. Senivasan et al. [26] implemented a harvester based on solar energy to power a wireless sensor network mote, which includes two NiMH batteries, a voltage regulator, and a temperature sensor, the power consumption was 94.29 mW; moreover, its lifespan of 38 hours, and the solar cell was large in the area. J. C. Lim et al. [27] developed a sensor system, has a rechargeable battery with a capacitance of 1500 mAh. This system had a ZigBee module and a temperature sensor, consumed a high power of 91.41 mW, as well as worked for forty hours. L. Joris et al. [28] introduced a sensor system has a sigfox module and a SHT21 sensor, the supplying was a 90 mAh battery, the system consumed power of 107.7 mW and the life-time was 20 hours.

This paper proposes a self-sustainable wireless sensor system for the perpetual monitoring of environmental parameters. The primarily goal of the proposed system is to prolong the life-time of wireless sensor systems. A low-power software algorithm is developed to enhance the system life-time to be 123 hours. Thereby, the proposed system could be work without changing the battery. Additionally, the system is
powered depending on a perpetual solar energy harvester to reach a higher life-time for the wireless sensor system. A rechargeable battery has high energy density-based the harvester. The system is implemented with the testing outdoors and consumes 40 mW. The sensor system measures the four physical parameters of ambient temperature, relative humidity, atmospheric pressure, and ultraviolet (UV) index. The data of the system are gathered by two sensors, monitored on a serial monitor application and sent to a cloud service via Wi-Fi. The primarily contributions of the paper are in two points:

- Development of a self-powered wireless sensor system for continuous monitoring of ambient temperature, atmospheric pressure, relative humidity, and ultraviolet index;
- Design a solar energy harvester to power the system depend on a solar cell and a rechargeable battery with saving the power consumption of the system using sleep commands and low-power hardware components;

The paper is organized as follows: Section 2 introduces the proposed architecture of the solar energy harvester and sensor system. The hardware implementation of the wireless sensor system with solar energy harvester is described in Section 3. The results are demonstrated in section 4. Section 5 discusses the proposed work. The conclusion of the paper is introduced in section 6.

2. PROPOSED ARChITECTURE

Fig. 1 demonstrates the proposed structure of the solar energy harvester as well as the wireless sensor system. This structure includes a solar cell to detect the sunlight irradiance. It also has a DC-DC converter to step-up the solar cell output and a rechargeable battery is used as energy storage and a NodeMCU board for processing the physical signals of two sensors: One to measure the humidity, temperature, and pressure, the other sensor to sense ultraviolet index. Further, a Wi-Fi to transmit an environmental data to a cloud service. Eventually, the environmental data of sensors are monitored on a serial monitor application. Fig. 2 illustrates the schematic diagram of the harvester with the sensor system. In this Figure, the utilized solar sell is a MPT 3.6-75, which is connected to the input of a LTC3105 DC-DC converter to charge a 18650 lithium-ion rechargeable battery. The used sensors are a BME280 and a GY1145, while the utilized NodeMCU board is a Gizwits WiFi Witty ESP-12F.
2.1 Simulation Model of the Solar Energy Harvester

The designed solar cell circuit and the DC-DC converter of the solar energy harvester is demonstrated in Fig. 3. The circuit is simulated by the LT-Spice software. The circuit consists of a solar cell phase to detect the sunlight of the voltage source \( V_1 \) as light source. At 1000 W/m\(^2\), the designed solar cell has a maximum voltage of 3.6 V and a current of 50 mA. The simulated output power from solar cell is 180 mW. These values of the simulated solar cell are selected based on considerations. The solar cell voltage is connected to power the LTC3105 chip, which has an input voltage range of 0.2-5 V. The power consumption of the LTC3105 is 24 µW and it was fabricated by linear technology\(^\circledast\). It is linked to \( R_1 \) and \( R_2 \) for fixing the converter output voltage \( V_{out} \). The computations of the \( V_{out} \) are obtained via Eq. (1) [26]. The required \( V_{out} \) to charge the rechargeable battery is 4.2 V. So, \( R_1 \) and \( R_2 \) are assumed as 837 k Ω and 200
k Ω, respectively. Also, $R_3$ is selected as 40 k Ω to capture the maximum photovoltaic voltage ($V_{MPP}$). The solar cell has maximum power point is based on the fractional open circuit voltage that was built-in the LTC3105. The $V_{MPP}$ is obtained via Eq. (2) [26]. Additionally, $C_3$ and $C_2$ are linked to the LTC3105 utilized to smooth the voltages of output and input, $L_1$ is a coil to charge the input current and the $V_{out}$ of the converter is fed to a suitable rechargeable battery.

\[ V_{out} = 1.004 \times (1 + R_1/R_2) \]  
\[ V_{MPP} = (1 \times 10^{-5}) \times R_3. \]  

\[ (1) \]
\[ (2) \]

**Fig. 3.** The designed solar cell circuit connected to the DC-DC boost converter.

### 2.2 Calculations of Energy and Lifetime

The life-time and energy consumption of the sensor system are theoretically calculated in case the no connection of energy harvester. Suppose the proposed system works in the active-sleep mode, and the process time cycle ($T$) of the system is chosen to be 60 minutes (3600 seconds), is comprised of 600 seconds active time ($t_{active}$) and 3000 seconds sleep time ($t_{sleep}$) and the operating voltage ($V$) of 3.3 V. Fig. 4 demonstrates a public power profile for the wireless system. The Active period $t_{active}$ is equal to ($t_{active} - 0$), the Sleep period $t_{sleep}$ is equal to ($T - t_{active}$), where $T = t_{active} + t_{sleep}$. 

![Diagram of solar cell circuit connected to DC-DC boost converter](image)
Suppose $I_{active}$ is the current consumption of the system is 72.5 mA in the active mode, while $I_{sleep}$ is 0.02 mA in sleep mode. Furthermore, $P_{avg}$ is the average power consumption of the system, which is obtained via Eq. (3). Thereby, $P_{avg}$ is 39.93 mW per hour. Hence, $E_{avg}$ is the corresponding average energy consumption of the system is roughly 143.748 Joules in 60 minutes, while the mean current is 12.1 mA.

\[
P_{avg} = \frac{1}{T} [V \int_0^{t_{active}} I_{active} \, dt + V \int_{t_{active}}^{T} I_{sleep} \, dt] \tag{3}
\]
\[
= \frac{1}{T} [V \times I_{active} \times t_{active} + V \times I_{sleep} \times t_{sleep}]
\]

The overall capacitance of the rechargeable battery is supposed to be 3800 mAh, the $V_{charge}$ is charging voltage for the battery is chosen to 4.2 V, and $V_{discharge}$ is the discharging voltage to be 3.3 V. The stored power ($P_{stored}$) for the utilized battery is calculated according to Eq. (4). Thereby, the $P_{stored}$ is reached to 15960 mW. So, the stored energy ($E_{stored}$) is equal 57456 Joules, where $I$ is the current in which the battery is providing to the sensor system. Let the life-time of the system is $T_{life}$; this value is calculated via Eq. (5). Thus, $T_{life}$ is equal to 399 hours. It is suitable life-time for powering the wireless sensor system.

\[
P_{stored} = I \times V_{charge} \tag{4}
\]
\[
T_{life} = \frac{P_{stored}}{P_{avg}}. \tag{5}
\]

From the solar cell, the average energy $E_{PV}$ is obtained via Eq. (6). $W$ is the sunlight irradiance, $\eta$ is the solar cell efficiency, $A$ is the area of the solar cell, it is supposed 0.00432 m², and $t_{PV}$ is the time that the solar cell is giving energy. Let, the cell efficiency is 7 %, the solar cell operates for six hours/day, and the irradiance of 1000 W/m².

**Fig. 4.** Power profile of the wireless system.
Thereby, the $E_{PV}$ of the solar cell is 6531.84 Joules. Additionally, the charging time ($T_{\text{Charge, PV}}$) from the solar cell to battery is 0.022 days (0.52 hours), as obtained via Eq. (7). So, the discharging time of the system will be higher than the charging time of the harvester. Thereby, the solar cell of harvester is perpetual for the sensor system.

\[ E_{PV} = A \times W \times \eta \times t_{PV} \]  

(6)

\[ T_{\text{Charge, PV}} = \frac{E_{\text{stored}}}{E_{PV}}. \]  

(7)

3. IMPLEMENTATION OF THE WIRELESS SENSOR SYSTEM

3.1 Hardware Implementation

The setup of wireless sensor system with energy harvester is demonstrated in Fig. 5. It is implemented using the following hardware components “solar cell, DC-DC converter, rechargeable battery, BME280 sensor, GY1145 sensor, and NodeMCU board”. The system includes a low-power BME280 sensor, chosen from BOSCH® for sensing an environment’s ambient temperature, relative humidity, and atmospheric pressure. This sensor has range of the ambient temperature is from - 40 to 85 °C, it has range of the relative humidity is from 0 to 100%, and the atmospheric pressure range from 300 to 1100 hPa, practically, it draws a current (3.6 µA) [29]. The ultraviolet sensor was GY1145 for measuring the ultraviolet (UV) index, it draws a current of 1.4 µA [30]. The brain of the system is a NodeMCU board from Espressif Systems®, which has a small dimensions of 29.9 mm × 31.5 mm. Moreover, the NodeMCU board is utilized for processing the environment’s data. The board consumes a low-current of 2.5 mA, and 3.3 V its operating voltage. A Wi-Fi chip transmits these data to a cloud service. This Wi-Fi chip range is 400 meters, while the current consumption of 70 mA [31].

The harvester contains a solar cell was founded from Sundance Solar® and its dimensions is 7.2 cm × 6.0 cm; the cell is a thin-film, amorphous MPT 3.6-75, it gives power of 180 mW at 1000 W/m² irradiance. The cell can convert light into electric power. The utilized solar cell has specifications: a maximum current and voltage of 50 mA and 3.6 V, respectively [32]. Depending on calculations, the utilized MPT3.6-75 cell is chosen. The solar cell was connected in series to power the DC-DC converter, which is utilized to fix the solar cell output voltage. The converter is depend on a LTC3105 [33]. In other words, this converter charges one battery as a backup energy source. Therefore, this battery would has 3800 mAh overall capacitance, a 4.2 V
voltage, and it has an area of 11.7 cm$^2$. A MCP1700 low dropout voltage regulator is used [34] to fix the battery voltage to 3.3 V, due to the NodeMCU works at this value. The BME280 and GY1145 sensors, as well as Wi-Fi chip are fixed on a breadboard. This board has total area of 3.0 cm $\times$ 7.0 cm.

**Fig. 5.** The setup of the wireless sensor system with energy harvester.

### 3.2 Software Implementation

The flowchart of the wireless sensor system is described in Fig. 6. It comprised of sequential steps. The BME280 and GY1145 sensors are configured, then I$^2$C communication protocols are initialized for the mentioned sensors. Then, an initialization is carried out to the Wi-Fi, then, the NodeMCU is identified on the Ubidots platform. The NodeMCU of the system working in two modes: active and sleep. So, the sensor system is worked in the active mode. Then, the sensor system verify a connection of the network of Wi-Fi, if its status is equal to one, the NodeMCU continuously reads the environmental data of the utilized sensors. After sending these data to the Ubidots platform for 10 seconds through the Wi-Fi and then, the sensors are turned off, the Wi-Fi goes into sleep, then, the NodeMCU board is transferred into the sleep mode for a duration of 50 seconds. A serial monitor application is used for monitoring the data, which was received from the system. In active mode, the BME280 and GY1145 sensors are configured and I$^2$C protocols are initialized to these sensors. The NodeMCU board also is configured. Finally, the cloud service receives the data and also the serial monitor application is used to display the ambient temperature,
relative humidity, atmospheric pressure, and ultraviolet (UV) index.

Fig. 6. The flowchart of the wireless sensor system.

3.3 Wireless Communication

The Wi-Fi chip type “ESP8266MOD” is utilized. The performance of the Wi-Fi chip depends on many factors for instance, data rate, energy consumption, and security. The Wi-Fi has power consumption of 70 mA at active mode, as well as its data rate is 72.2 Mbps. The Wi-Fi is secure in transmission for certain data from a device to others. It provides multi security modes in authentication and data encryption and authentication. The operating frequency of the Wi-Fi is 2.4 GHz. It is a wireless protocol convenient for wireless systems [35].

In the proposed system, the utilized Wi-Fi is version 5.8, and it can save energy; the Wi-Fi is experimentally tested and the measured current consumption was 0.2 mA at sleep mode, thereby, the Wi-Fi protocol is efficient. Moreover, the utilized Wi-Fi is so suitable for energy harvesting (EH) systems and convenient with wireless systems including sensors. Wi-Fi chip compatible with ASCII commands, which is utilized in configuring communications. The utilized protocol in the Wi-Fi was depend on the
IEEE 802.11 b/g/n. additionally, the data of utilized sensors connect to the NodeMCU board of the wireless sensor system through I²C protocols.

4. RESULTS

From the simulation of the solar energy harvester, Fig. 7 demonstrates the I-V characteristic curve of the solar cell under direct sunlight irradiance of 1000 W/m². The sunlight is utilized to represent the source of illumination in order to validating the electrical characteristics of utilized solar cell. It is clear that the maximum current of the solar cell is 50 mA at a voltage of 3.6 V.

![I-V characteristic curve of the solar cell under 1000 W/m².](image)

Fig. 7. I-V characteristic curve of the solar cell under 1000 W/m².

Also, Fig. 8 illustrates the P-V characteristic curve of the solar cell at straight sunlight irradiance be 1000 W/m². This Figure shows that the solar cell maximum power (MPP) is 180 mW at a 3.6 V voltage. Practically, the voltage and current of the solar cell was measured via a number of various resistors and 2 multi-meters (One multi-meter to measure the current and the other to the voltage). The irradiance rate is measured on a sunny day, via a solar power meter.
Fig. 8. P-V characteristic curve of the solar cell under 1000 W/m².

Fig. 9 demonstrates the discharging curve of 3800 mAh rechargeable battery for the system in active-sleep mode. Therefore, in this mode, the battery takes roughly 123 hours for discharging from 4.2 to 3.3 V. So, the sensor system is powered without the harvester for 123 hours. The voltage of the battery stops at 3.3 V during discharging operation, because of the working voltage of the NodeMCU of the system works at this value. Thereby, the system was not run if its voltage less than 3.3 V. The voltage measurements for the battery are taken via a multi-meter.

Fig. 9. The discharging curve of 3800 mAh battery.

Fig. 10 demonstrates the charging and discharging voltages from the solar cell and the battery over 539 hours. The charging experiment was executed outdoors with 1000 W/m² and was started at 12:00 pm on 11 June-2021 (sunny day). The discharging experiment is terminated at 539 hours. It is clear that the sensor system operates during different periods for discharging and charging the battery. A longest period for the
wireless sensor system was tested to be 246 hours. Eventually, the results demonstrate that the wireless sensor system is supplied using solar energy harvester that can sustainably operate.

![Graph showing charging and discharging voltages for the battery.](image)

**Fig. 10.** 539 hours of the charging and discharging voltages for the battery.

Fig. 11 reveals a screenshot of the displayed environmental data on a serial monitor application, which is conducted for monitoring an environmental status of an ambient environment during the active period (600 seconds/hour) of the system. The monitored environmental data are instantaneously visualized on the application for every active period of the system. An environmental information based on the monitored data “relative humidity, ambient temperature, atmospheric pressure, and ultraviolet index”. From this perspective, one can notice the environmental information by a direct method. In the First, the ultraviolet index reading of an environment is shown to be 0.00. Also, the relative humidity reading is 31.79% and the ambient temperature reading of an environment is monitored at 36.56 °C. In addition, the atmospheric pressure is 1008.28 hPa. Then, the ultraviolet index, and relative humidity, ambient temperature, and atmospheric pressure are 0.00, 31.71%, 36.60 °C, and 1008.26 hPa, respectively. So, these data would be changed continuously. Thereby, this app provides humans information for an environmental status of an ambient environment over the time.
Table 1 illustrates comparisons between recent wireless sensor systems. In the proposed work, the developed system has 2 sensors (BME280 and GY1145), but the systems in [26-28] have only one sensor. Numbers of physical parameters of the proposed work is 4, while the systems parameters in [26-28] were less. The utilized Wi-Fi technology has a higher range than the technologies in [26, 27]. Additionally, the life-time of the system is the highest compared to researches [26-28], as well as the system power consumption is fewer than works in the literature [26-28]. Various trade-offs in these systems for example, energy storages types “super-capacitors and batteries” which have difference in energy density, size, and charging cycles. Also, a challenge among amount of environmental data sent and power consumption from the
system and a trade-off among various wireless technologies to send environmental data whether in long or short range as well as the power consumption of these technologies.

6. CONCLUSION

This paper introduces a perpetual solar energy harvester for supplying a wireless sensor system towards environmental monitoring. The solar energy harvester is designed to stretch the life-time of the wireless sensor system from 2 to 123 hours. The power consumption of the system is 40 mW. The sensors’ data of the system are instantaneously monitored on the serial monitor application. The system provides a strolling solution for sustainable monitoring of an ambient temperature, relative humidity, atmospheric pressure, and ultraviolet index. In the future, we will consider a battery has a higher capacity than 3800 mAh. Further, testing the power performance of the solar cell at different bending angles. Additionally, a product of the wireless sensor system could be manufactured using a printed circuit board.

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Data availability The paper has no associated data.

Table 1. Comparisons between recent wireless sensor systems.

| Reference | Sensors         | Numbers of Physical Parameters | Wireless Technology      | Life-time of System (Hrs) | Power Consumption (mW) |
|-----------|-----------------|--------------------------------|--------------------------|--------------------------|------------------------|
| [26]      | Temperature     | One                            | MICAz 2.4 GHz 75 m       | 38                       | 94.29                  |
| [27]      | Temperature     | One                            | Zigbee 2.4 GHz 100 m     | 40                       | 91.41                  |
| [28]      | SHT21           | Two                            | Sigfox 2.4 GHz 10 km     | 20                       | 107.7                  |
| The Proposed Work |              | Four (Relative Humidity, Ambient Temperature, Atmospheric Pressure, and Ultraviolet Index) | Wi-Fi 2.4 GHz 400 m       | Perpetual, and 123 with no harvester | 40                     |

Table 1. Comparisons between recent wireless sensor systems.
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