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Self-Powered 6LoWPAN Sensor Node for Green IoT Edge Devices

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Self-Powered 6LoWPAN Sensor Node for Green IoT Edge Devices

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Abstract— In this paper, a simulation model and practical testbed for green Internet of Things (IoT) edge devices are proposed based on solar harvester with constant voltage-maximum power point tracking (CV-MPPT) technique. Billions of connected edge devices represent the essential part of the IoT through the IP-enabled sensor networks based on IPv6 over Low power Wireless Personal Area Network (6LoWPAN). In traditional IoT edge devices, the stored energy in the non-rechargeable battery determines the node lifetime while it is being depleted with time. Therefore, purchasing billions of such batteries is costly and must be disposed of efficiently. This paper is aimed at simulating and implementing a new class of green IoT edge devices that can report data wirelessly and powered perpetually using clean energy. The developed edge device utilizes solar energy harvesting mechanism through photovoltaic (PV) module, this approach will avoid periodical battery replacement and hence, the energy supplied to the sensor mode is not limited anymore. The implemented testbed is based on open-source hardware and software platforms while the simulation environment is based on MATLAB/ SIMULINK 2019a. The effects of temperature and solar irradiance on the performance of the developed approach are examined in order to confirm the leverage of the proposed methodology scheme. The lifetime of the developed green IoT device is predicted based on the device's activities, current consumption, and energy storage capacity. The obtained results showed that the battery lifetime is extended by 38-49% when the edge device runs on an independent power source.

Keywords—6LoWPAN, Energy Harvesting, Green Energy, IoT, Self-Powered Node, Solar Energy, WSN.

1. Introduction

In recent years, there has been growing recognition of the vital links between the technologies and markets related to the Internet of Things (IoT). The term IoT will be used in its broadest sense to refer to all Internet-connected devices such as wireless sensors, smartphones, software, smart vehicles, actuators, consumer electronics and computers [1].

Wireless sensor network (WSN) composed of hundreds to thousands of small-embedded devices called sensor nodes. These sensors are capable of capturing the environmental conditions in real-time and report the data wirelessly to remote base stations (sink nodes). The role of WSN in IoT has received increased attention across a number of disciplines in recent years by industrial researchers and academic scholars. One advantage of the WSN is that it avoids the problems of wire connection in traditional networks. Another advantage of using WSN is that it is capable to work in applications where harsh environmental conditions existed such as smart buildings, bridge monitoring, healthcare, agriculture, and coal mining. Despite these promising features of the WSN, there are still many unanswered questions about its challenges and need to be addressed [2] [3].

Wireless sensor nodes play an essential part in broadening the sensing layer of the IoT architecture. These embedded devices are grouped together to build what it is called WSN assisted IoT network [4]. There are wide ranges of sensors that can be equipped to wireless sensor nodes to measure different phenomena like toxic gases, atmospheric pressure, temperature, humidity, geographical position, illumination, stress, motion, flow rate, etc.

The action in IoT architecture located at its edge device where the sensors and actuators existed. The edge devices of the IoT are also known as end-devices or end-points because they include end-user appliances and equipment. The end devices can interconnect with other networks and/or other devices to exchange real-time data, activate an actuator or execute a command [5].

In general, the main building blocks of the WSN is the sensor node, which is consisted of four main units as depicted in Fig. 1: a power unit, a processing unit, a sensing unit and a communication unit. The sensor node is battery-powered device and hence it has a limited lifetime and finite energy capacity. Accordingly, the power unit suffers from a significant issue. Moreover, conventional battery performance has not ameliorated much enough when compared to the increment of electronic devices power consumption. When the battery depletes its energy, it is an expensive task to recharge or replace the battery especially when the sensor node is inaccessible in a remote area [6].

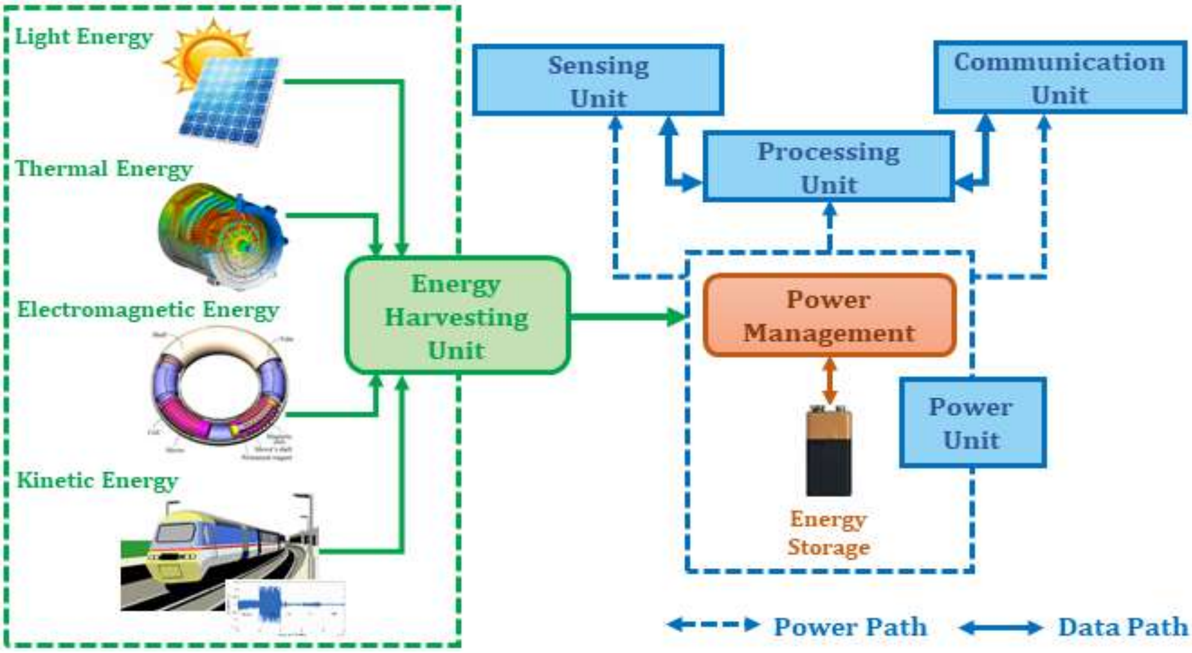


Fig. 1: Wireless sensor node architecture with energy harvesting device

Prolonging the sensor node lifetime is a crucial issue in many applications that adopted WSN architecture [7]. There have been active research efforts that tried to conserve the sensor node energy and extend the network lifetime. These efforts included topology control techniques [8], Medium Access Control (MAC) mechanisms [9], and managing the node duty-cycle (sleep and active periods) [10][11], which prolonged the network lifetime to some extent. However, these contributions are unable to change the fact that the node energy is still limited. Despite these intensive research efforts, the network lifetime and efficient energy consumption of a sensor node remain a network performance bottleneck. As days proceed, the batteries used to power the sensor nodes lose their stored energy and subsequently the node get isolated from the network.

In order to overcome the aforementioned challenges of the limited power source, a new class of sensor nodes is required by harvesting the energy from the surrounding environment. These new sensor nodes are capable of changing the ambient energy like vibration, light, sound, movement, and heat to usable electrical energy [12].

Energy scavenging, energy harvesting or power harvesting is a mechanism that harvests the abundant free ambient energy and transforms it into usable electrical energy. Many different forms of free ambient energy existed in nature or as wasted energy in man-made systems, such as:

- Light energy (outdoor sunlight or indoor lamps) [13].
- Thermal energy (industry or human body) [14] [15].
- Radio frequency energy (antenna) [16].
- Kinetic energy (rotation, vibration and motion) [17].

Unfortunately, most of the available energy harvesting techniques are not suitable for IoT devices because of the following reasons: (i) system components and redevelopment costs, (ii) size and weight of the energy scavenger module, and (iii) the availability of an ambient energy source to produce sufficient energy. This paper will focus on the technologies that can be integrated directly to IoT devices and harvest a considerable amount of energy from the surrounding environment.

The rest of the paper is organized as follow: Section II surveys the recent research topics that are existed in the literature and related to the proposed approach. In Section III, the detailed explanation of the proposed approach is presented. Section IV provides a comprehensive discussion about the obtained results. Finally, the paper is concluded in Section V.

2. RELATED WORKS

In the last decade, industrial researchers and academic scholars showed their interest in developing energy-efficient mechanisms to reduce the consumed energy by the sensor odes using different approaches through routing, MAC layer and

physical (PHY) layers. Although with extremely energy-efficient routing techniques, once the finite energy storage of the sensor node is depleted, the sensor node will be isolated and no longer contribute to the network operation.
This section focuses on the researchers that explored energy harvesting technologies from natural and man-made resources. The related work section reviews the recent researches from energy storage perspectives. Accordingly, the literature classifies the IoT edge devices into three different categories: battery-based storage, supercapacitor- based storage, and hybrid storage.

1) Edge device with battery storage: the battery-operated sensor nodes characterized by high charge-discharge capacity and immense energy density. Therefore, the node size can be minimized. However, this type of nodes experienced capacity loss that shorten the lifetime of the sensor node. Heliomote [18] was the first efforts that targeted the area of sustainable energy. The sensor node was based on Mica2 platform [19] and powered using two NiMH batteries. The maximum power point tracking (CV-MPPT) technique was not utilized but undercharge protection and overcharge protection were equipped with the rechargeable batteries. Yue and Ying [20] developed a PV-powered sensor node with battery storage for water quality monitoring application. Different sensors were used to measure the water quality and send the data to a sink node using IEEE 802.15.4 as a communication protocol. The authors argued that the developed system consumed little power and flexible to be deployed in different regions easily. Alippi *et al.* [21] proposed a monitoring system deployed in Queensland, Australia in order to observe the temperature and underwater luminosity for the coralline barrier. The developed monitoring framework relied on battery operated WSN that equipped with solar energy harvester. The authors argued that their developed approach was adaptive, robust and could be used to monitor the marine environment efficiently. González *et al.* [22] developed a self-powered sensor node prototype called Open-WiSe mote. The hardware and software components of the implemented mote were described. The mote depended on solar energy harvester to prolong its lifetime in addition to sleep and wake-up strategy. The obtained results validated through experimental scenarios. Abbas *et al.* [23] introduced a schematic and analytic model for solar harvester with proper energy management an MPPT technique. Abbas provided a complete analysis and simulation results at various levels of solar irradiance. The developed model capable of harvesting the energy from the sun and depleted it wisely to guaranty network connectivity. Shin and Joe [24] introduced an energy prediction mechanism with a transmission interval algorithm for indoor IoT applications. Their work was experimentally tested in an indoor environment and based on fluorescent lamps intensity to estimate the amount of the harvested energy accurately. Then, the optimal transmission interval was adjusted based on the node residual energy (battery) and the harvested energy. Nguyen *et al.* [25] proposed an energy-harvesting aware routing algorithm (EHARA) for heterogeneous IoT networks. The authors argued that the introduced algorithm capable of prolonging the battery-operated network lifetime under changeable traffic load and various environmental conditions in addition to improving the network's quality-of-service (QoS).
2) Edge device with supercapacitor storage: the supercapacitors distinguished by exceptional life cycle (≈20 years with millions of charge/discharge cycles) [26]. Dondi *et al.* [27] proposed an optimization methodology with an MPPT technique for WSN that adopted solar energy harvester with supercapacitors. A simplified mathematical model was used for the PV panel in order to estimate the immediate power generated by the attached panel. The experimental results were conducted to demonstrate the impact of the proposed approach in which a maximum efficiency of 85% achieved by using discrete components. Liu and Sinencio [28] developed smart nodes for IoT networks that harvest the solar irradiance to prolong the node lifetime. The hill-climbing MPPT was used to provide maximum energy under different illumination levels in order to be stored in supercapacitors. The authors argued that the obtained results from their approach enhanced the efficiency of self-sustainability and characterized by an ultra-low-power operation.
3) Edge device with hybrid storage: the batteries have higher energy density (30-200 Wh/kg) than supercapacitors (2-30 Wh/kg) [29] and hence the battery required less space. In addition, the supercapacitors have high self-discharge rate compared to batteries that makes the energy waste nonnegligible. Accordingly, a hybrid storage for the harvested energy is demanded. Prometheus [30] is the pioneer hybrid energy storage approach for sustainable sensor nodes. The work described the key challenges, implementation issues and proposed an energy management system for solar energy harvesting embedded systems. The sensor node was based on TelosB platform and its main goal was to store abundant amount of energy in order to extend the node lifetime with least leakage current. Qian *et al.* [31] focused on introducing an unprecedented category for battlefield sensing applications. The proposed sensor node had the ability to send the data wirelessly and harvest the energy from the ambient environment to run its components. The authors argued that the self-powered feature would enable the sensor node to be deployed real battlefields or war game areas. There proposed approach utilized ultra-capacitors and rechargeable chemical batteries without adopting any MPPT technique. Qi *et al.* [32] introduced a rule-based adaptive energy management strategy for self-powered WSN nodes. There proposed approach composed of solar panel, supercapacitor, battery, and energy management strategy. The authors aimed at prolonging the network lifetime and eliminating the limited battery problem. The authors argued that their proposed approach was robust and succeeded in extending the node lifetime to several years instead of several days. Deng *et al.* [33] developed a hybrid energy harvesting system for WSN nodes that were deployed in an IoT environment. The nodes capable of harvesting energy from different sources: wind, solar, and thermal. The experimental results illustrated that the proposed approach enhanced the network lifetime regardless of the weather conditions.

Finally, Liu *et al.* [34] provided a clear understanding regarding energy solutions and key challenges in green IoT networks. They concluded their work by providing three steps to achieve green power solution for IoT applications:

1. Self-powered IoT devices that harvest the energy from the surrounding environment by adopting dual-battery architecture;

2. Green base stations that are powered by green energy and emitted radio frequency to charge the surrounding IoT devices wirelessly;
3. Corporate balancing energy strategy that mitigates the disparity between the harvested and the wirelessly transferred green energies.

This paper was motivated by the prompt integration of small-scale energy harvesting mechanisms with embedded devices and the energy consumption challenge in IoT edge devices. Accordingly, this paper aimed at designing and developing a new class of IoT edge devices that can report data wirelessly and powered perpetually by harvesting the energy from the surrounding environment. While the main contributions of this work are as follow:

1. Designing and simulating a new class of self-powered sensor node for green IoT applications using MATLAB/ SIMULINK 2019a. The developed simulation environment is dynamic and can be initiated with different solar irradiance and temperature values that helps the designer to study the effectiveness of attaching solar module to the sensor node or not before deploying the IoT edge device;
2. Implementing a real-time testbed to investigate sensor node sustainability and demonstrate the effectiveness of the proposed approach. The sensor node built using opensource hardware and software platforms to reduce testbed implementation cost and enable future amendments;
3. Integrating the energy-harvester with the constant voltage-maximum power point tracking (CV-MPPT) controller in order to maximize the output power from the attached PV module as well as reduces the steady-state oscillation at low-power consumption. The CV-MPPT was chosen due to its simplicity, inexpensive implementation and it works efficiently even in low solar irradiation conditions.

3. SELF-POWERED 6LOWPAN SENSOR NODE

The number of connected objects is tremendous in IoT and generates an immense energy requirement. Accordingly, the green IoT environment needs to utilize energy sources efficiently. Limited energy replenishment is the major constraint influencing the performance of the IoT network in which most IoT edge devices are battery-driven. There have been several ways to alleviate the negative effect of the energy limitation in sensor networks. The energy harvesting technique is used to transform different forms of energy into electrical energy as a power source for the sensor node. In the literature, there were several modules that had been proposed to harvest ambient energy, including solar, wind, and vibration energies. The proposed approach in this paper focuses on solar energy because it is the most abundant renewable energy source and provides long-term solutions.

The work presented in this paper aimed at simulating and implementing a new class of IoT edge devices that can report data wirelessly with self-power capability. Therefore, this paper proposes a new solar energy harvesting scheme to alleviate the inherited battery problems in sensor networks. The proposed scheme is built-up on the principle of PV effect by focusing on maximizing the efficiency of the energy harvesting device in transferring solar irradiation from the solar panel to the rechargeable battery. Also, an MPPT controller is used to increase the amount of harvested energy from the PV source for a given environmental condition.

The Internet Engineering Task Force (IETF) working group developed the 6LoWPAN in 2007; it provides direct integration of IPv6 over the IEEE 802.15.4 standard. The 6LoWPAN network consists of many embedded wireless devices that are characterized by a power-constrained, low-cost, low-data rate with limited memory [35]. In this paper, various simulation scenarios are conducted and a real-time testbed is developed in order to verify and validate the effectiveness of the developed approach. Hence, the IoT edge devices are stationary, running full 6LoWPAN protocol stack [36] and unaware of their geographical location. The 6LoWPAN is chosen because it enables the edge devices to have ubiquitous connectivity and accesses the Internet through a border gateway at a cheap cost. Hence, new interconnected services can be achieved by emerging IP-connected devices (i.e. actuators sensors, and intelligent objects).

3.1. Simulation Model

In this paper, green IoT edge device based on 6LoWPAN is modeled and simulated using MATLAB/SIMULINK to study the solar energy harvesting strategy for prolonging the network lifetime. Equipping the sensor node with renewable energy source will eliminate the regular battery replacement which is impractical in some applications. Since the acquired environmental energy is quite limited. Therefore, before modeling an energy harvesting platform for green IoT network, the energy consumption of the node components needs to be investigated in addition to the ambient energy profile to add more real conditions to the developed model.

The developed model is based on a simple sensing application, as explained in experimental testbed section, in which the edge device senses the temperature of the surrounding environment and reports it wirelessly to the based station using 6LoWPAN technology. In addition to the node power bank, the node harvests the solar energy to produce additional energy for node lifetime expansion. The solar irradiation alters through the day and through the seasons. Accordingly, the renewable energy source of the node will depend mainly on the PV module. The logged data from the experimental testbed that include temperature and solar irradiance are fed to the simulation environment in order to add more reliability to the developed simulation model.

The proposed approach is shown in Fig. 2 and developed using a MATLAB/SIMULINK 2019a. The developed model is based on solar cell equivalent circuit that includes a light dependent current source, a diode, a shunt resistor and a series resistor. The developed model is capable of predicting the actual behavior of a solar cell under different environmental conditions because electrical specifications of the practical PV module are considered. The electro-magnetic interference (EMI) filter is used to eliminate high frequency undesirable electrical signal that generated either by electrical conductors or radiated emissions. While the power management unit consists of three main blocks: CV–MPPT, buck converter and battery charging control. The green IoT edge device modeled as variable resistive load with time to imitate the sleep/active periods.

3.2. Experimental Testbed

In developing an IoT edge device for green IoT applications, three main factors must be considered: (i) low-cost components, (ii) cheap and reliable wireless communication module, and (iii) high-performance power management system. Fig. 3 shows the developed sensor node in which the Arduino Uno board [37], an open-source hardware platform, is chosen as a processing platform for the sensor node. The sensor node has three additional components: the XBee module, light-dependent resistor (LDR) and digital temperature sensor (DHT11) for wireless radio transmissions and sensing functionality, respectively. The sensor node is powered by Lithium-Polymer battery (5000 mAh) and solar harvesting module as an additional power source. A 3W PV panel is attached to the node's power unit with 9V open-circuit current and 333 mA short circuit current. The developed sensor node also has an SD card in order to log the sensed value for simulation result verification.

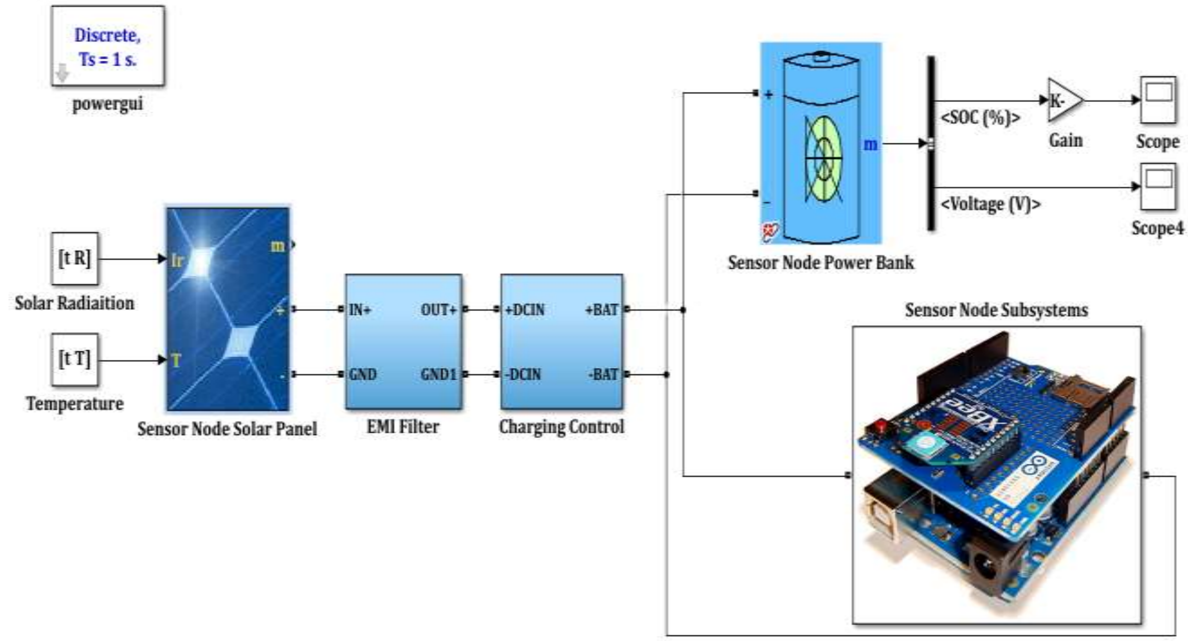


Fig. 2: The proposed self-powered model for green IoT edge device

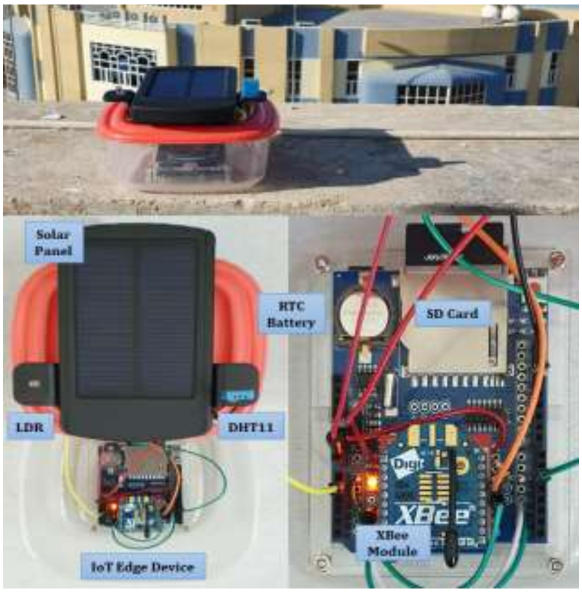


Fig. 3: Developed IoT edge device with PV module

Different battery types are commercially available for IoT sensor networks. Alkaline and Lithium-Thionyl-Chloride (Li-Th-Cl) are not rechargeable, which means that such batteries have a limited lifetime and cannot be integrated with the proposed solar harvesting system. On the other hand, a wide range of rechargeable batteries also exists Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH), and Lithium batteries [38][39]. The developed testbed is based on Lithium-Polymer batteries to store the harvested energy because of the following reasons: (i) it has various shapes and sizes to fit different devices; (ii) it is smaller and more efficient than other batteries with equal energy capacity; and (iii) it has higher power density than other batteries.

Due to the limited size and hardware complexity of the IoT edge device, the proposed solar harvester adopts CV–MPPT techniques among the available approaches (perturb-and-observe (P&O), incremental conductance (IncCond), ripple correlation control (RCC) and intelligent MPPT) for the following reasons:

- It is the fastest algorithm to retain PV operating point close to its maximum value;
- It is the easiest algorithm to implement because it neglects the influence of temperature and solar irradiation fluctuation by assuming a constant reference voltage which is equal to MPP;
- It does not need further calculation to measure PV output power but rather, it measures the PV output voltage. Therefore, there is no computation burden is added to the sensor node;
- It is inexpensive and has high efficiency even under low solar irradiation;

The flow chart of CV–MPPT is shown in Fig. 4 in which the output voltage of the PV panel is needed to be read at the commencement of the operation. The reference voltage (V_{ref}) is kept constant to be close to the MPP. The first reading of V_{PV} is used to setup the duty-cycle (D) of the DC-DC converter. During the algorithm execution, the duty-cycle is amended if there is a difference between V_{PV} and V_{ref} . When the VPV is less than V_{ref}, the duty-cycle is increased in the following step or vice-versa.

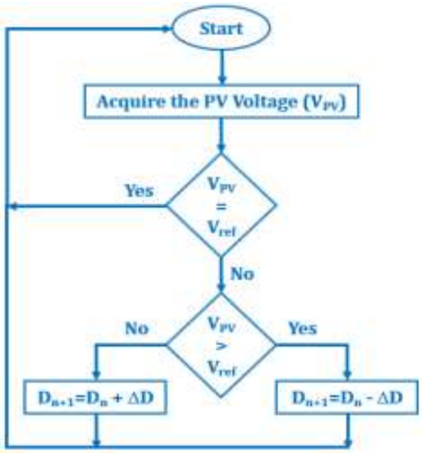


Fig. 4. The CV–MPPT Algorithm [40]

In addition, the battery-charging controller is integrated within the system in order to regulate the charging/discharge processes and avoid battery drainage. In the IoT edge device, a buck converter is used to adjust the output voltage of the PV module under variable weather conditions. It regulates the duty-cycle of the step-down converter with a voltage-mode controller to apply constant output voltage. Even with the existing of the solar harvesting module, the 6LoWPAN node lifetime also affected by its duty-cycle and the amount of sensed and transmitted data. The Arduino Uno board may draw a significant amount of current compared to other existing platforms. However, the advantages of this selection appear in shorten the experimental/simulation times and the integration of lightweight IP-enabled nodes in green IoT applications.

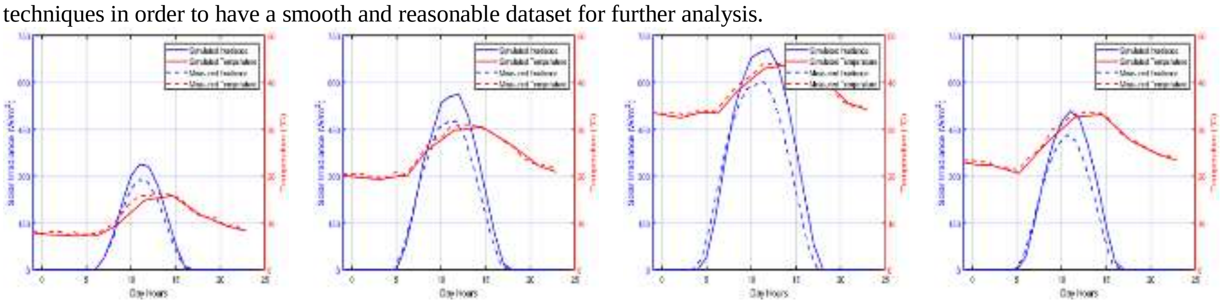
4. RESULTS AND DISCUSSIONS

As stated earlier in this paper, the developed green IoT edge device and its simulation model deployed in an IoT environment that executes a simple sensing application. The sensor node is responsible for sensing the surrounding phenomena and transmitting the sensed data in a timely manner while being prudent about its energy consumption. The IoT edge device integrated with solar energy harvester that recharges the node battery. To validate the proposed model, it is simulated using MATLAB/SIMULINK and several scenarios are conducted under different solar irradiance conditions.

The node equipped with a digital temperature sensor (DHT11) and a light-dependent resistor (LDR) to measure the ambient temperature and solar irradiance respectively. The LDR measures the light intensity in foot-candles using the open-source library that is available in [41]. The foot-candles value is converted to Watt using the formula given in Eq. 1 and then divided by the surface area of the LDR in order to have the solar irradiance in W/m^2. This approach is used to estimate the amount of solar energy available where the green IoT edge device deployed.

$$Light_{Watt} = Light_{FootCandel} \times 0.01609696 \tag{1}$$

The testbed was built at Al-Iraqia University while the green IoT edge device was deployed at the roof of the college of engineering building in Baghdad-Iraq. Fig. 5 shows the solar irradiance and temperature values for different months of the year. The dataset was collected during four months in order to have a comprehensive result and analyze the proposed approach from different perspectives. It is clear from Fig. 5(a) to Fig. 5(d) that there are some deviations in solar irradiance and temperature values between the practical measurements and the simulation due to the sensor's error and environmental interference. In addition, there are some extremes in the obtained dataset or missing values and these issues were solved using interpolation techniques in order to have a smooth and reasonable dataset for further analysis.



(a) January (b) April (c) July (d) October

Fig. 5: Solar irradiance and temperature value for different months of 2019

The experimental dataset is redrawn in Fig. 6 in which it is easy to observe that January has the lowest amount of solar irradiance while July has an abundant amount of solar irradiance among the other months. Therefore, the analysis in this paper was conducted based on July dataset.

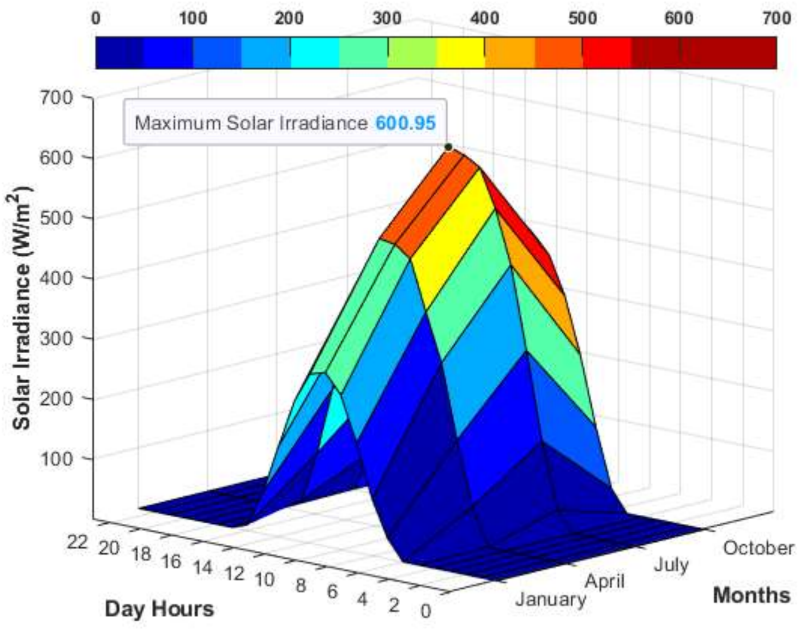
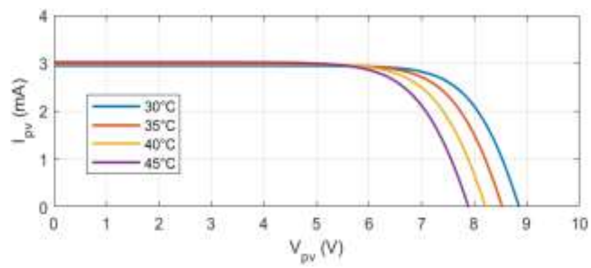


Fig. 6: The experimental dataset for 2019

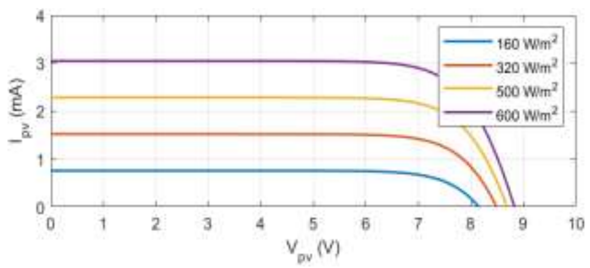
A simple voltage-divider circuit is used to measure the voltage and current generated by the attached PV panel at different temperature values and variable solar irradiance. Fig. 7a and Fig. 7c shows the effect of temperature on the PV panel performance while the solar irradiance assumes to be constant. The temperature has a negative influence on the PV power when the temperature increases the output power of the PV panel decreases. While Fig. 7b and Fig. 7d illustrates the impact of solar irradiance fluctuation of the PV panel performance. When solar irradiance increases the generated current and the output power increase. Therefore, the MPPT technique is used in order to have maximum power despite temperature variation and irradiance fluctuation.

The solar PV panel generates non-linear electrical energy due to the variation in weather conditions, energy harvesting time and the node deployment location. Fig. 7 showed the current, voltage and power curves for the attached solar module. When the PV module subjected to a light load, the output voltage approaches to the open-circuit voltage. Therefore, current and power are simultaneously very small. The power gradually increases as the load become heavier until it reaches the peak value before being gradually declined. Accordingly, The entire sensor node lifetime depends on the rechargeable battery lifespan.

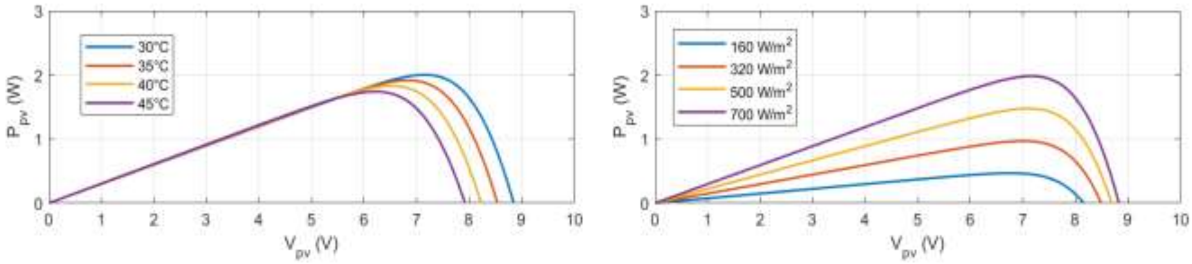
To begin with battery lifetime analysis, simple scenarios are considered in which the IoT edge device will wake-up every particular period by its internal timer to read the sensor information, process the sensed data and send it to the personal area network (PAN) coordinator. Once the transmission is finished, the IoT edge device goes back to sleep mode. Accordingly, the green IoT edge device exhibits two different operational states: active and sleep. In the experimental scenarios, the sleep period is changed from 2 to 58 seconds. According to the practical current drawn by 6LoWPAN node's component and the corresponding operational time, Fig. 8 depicts the monthly energy usage of the developed green IoT edge device versus different sleep periods. The developed 6LoWPAN sensor node may consume a significant amount of energy compared to other microcontrollers, which means that this setting will facilitate studying the impact of the proposed solar energy harvesting scheme. The energy usage analysis was conducted using the approach provided by Farahani in [42], when the sleep period increases the node's duty-cycle decreases and therefore, the node lifetime increases accordingly. It is clear that the battery lifetime depends on the node's hardware performance and network operation efficiency.



(a) I-V characteristics (variable temperature)



(b) I-V characteristics (variable irradiance)



(c) P-V characteristics (variable temperature) (d) P-V characteristics(variable irradiance)

Fig. 7: The temperature effect of PV performance

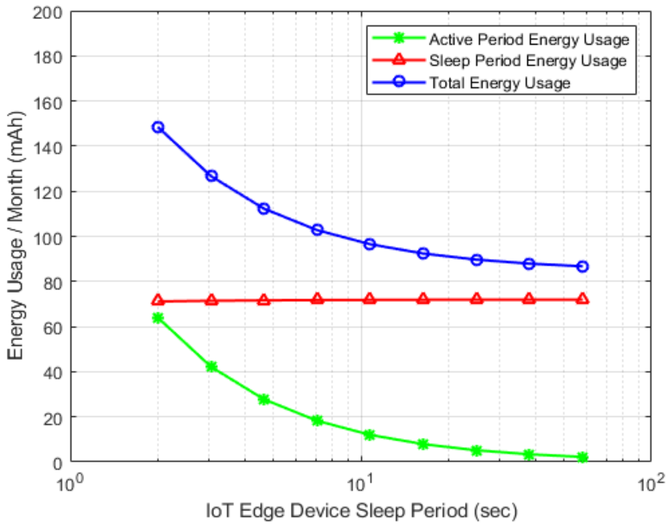


Fig. 8: Energy usage of the developed green IoT edge device

Fig. 9 depicts the IoT edge device lifetime as a function of the sleep period for both non-rechargeable and rechargeable 6LoWPAN sensor nodes. The term "non-rechargeable" stands for the 6LoWPAN sensor nodes that do not utilize any energy harvesting techniques. On the other hand, the term "rechargeable" stands for the 6LoWPAN sensor nodes that equipped with energy harvester. The analysis was conducted based on the practical dataset during July 2019. The lifetime calculation was determined for one week then it multiplied by 52.143 to get an approximate one-year value. For simplicity, the efficiency of the rechargeable battery was assumed to be constant for different sleep periods and the battery efficiency was considered to be 50%. The IoT edge device will use solar energy for sensing the surrounding environment, processing the sensed data and send the processed data to the sink while using battery power during the absence of solar radiation. In other words, the solar harvester compensates the energy depleted by the sensor node during the night or when there is no solar irradiance in cloudy or dusty weather conditions. In summary, there is a significant positive correlation between sleep period current and battery lifetime especially in IoT applications that utilize extremely low-duty-cycle.

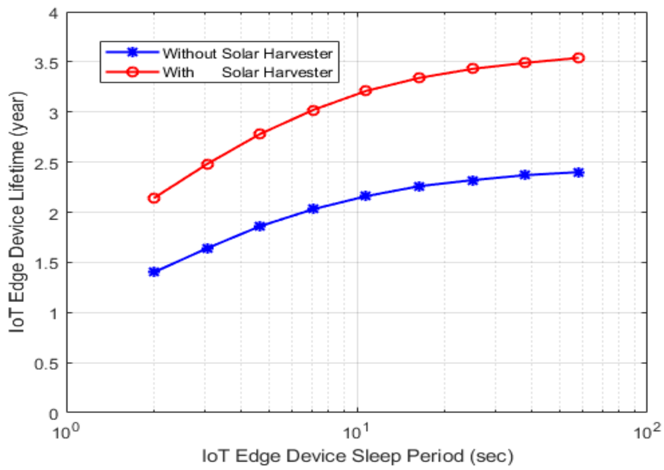


Fig. 9: Green IoT edge device lifetime

The proposed approach of the green IoT edge device will eliminate periodic battery replacement and succeeded in prolonging the network lifetime by approximately 38-49% depending on the node's duty-cycle as shown in Fig. 9. In theory, a renewable harvesting system should enable the sensor node to have an infinite lifetime. However, the ambient energy is intermittent in nature, and hence it may not satisfy the energy demand of the sensor node for some outdoor applications. As shown in the obtained simulation and practical results, the proposed approach succeeded in prolonging the battery lifespan and hence the sensor node lifetime. The lifetime expansion depends on the availability of sufficient illumination and the current consumption of the sensor node. It is worth noting that the methodology presented in this paper is not limited to a self-powered Arduino Uno boards; it can be implemented in any Arduino based or other embedded systems to maximize the stored energy lifespan of the system.

5. CONCLUSION

Most of the existing sensor nodes are battery-driven, which is relatively inexpensive and suitable for many applications. However, for long-term operation, the battery-powered sensor nodes are not feasible as the battery needs to be replaced or recharged. Therefore, this paper demonstrated the development and modeling of renewable harvesting sensor nodes based on solar energy. This is because the harvested solar energy could be used to power the IoT edge devices for years without any human intervention to replace the node's battery. The developed green IoT edge device also adopted the integration of 6LoWPAN technology in the sensor node architecture to illustrate its impacts in IoT applications. In addition, the CV-MPPT technique was used to maximize the harvested energy by the attached PV panel. The practical testbed and simulation results depicted that using the solar harvesting module succeeded in prolonging the network lifetime and opened a new horizon for the self-powered sensor networks. The developed scheme substantially prolonged the IoT edge device lifetime by approximately 38-49% compared to the traditional battery powered sensor node. Furthermore, the main advantages of the introduced approach represented in reducing the network maintenance costs and averting the environmental contamination due to non-rechargeable batteries. Finally, using an open-source hardware platform will facilitate the approaching popularity and make it available in a wide range of daily life activities.

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