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A contemporary outlook on wireless sensor networks for solar power harvesting

Perspectiva actual de las redes de sensores inalámbricos para la captación de energía solar

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ABSTRACT

Key words:

Embedded Systems, Internet of Things, Renewable Energy, Solar Power Harvesting, Wireless Sensor Networks.

While solar energy has been an emerging source of renewable energy for many years now with various studies delving into building more robust and compact solar cells, their use as a power source for mobile and small machinery such as Wireless Sensor Networks (WSN) is less discussed. However, with increasing global efforts in subsidizing more sustainable technology and energy, many studies have emerged in the past decade on building solar power based wireless sensor networks. The combination of novel harvesting circuits, mechanisms to obtain maximum possible power, smart power management algorithms and improving energy technology has provided the necessary framework for self-powered WSN nodes that have much longer lifetime. This paper reviews the newer proposed technology that aids the development of Solar Energy Harvesting Wireless Sensor Networks.

RESUMEN

Palabras claves:

Sistemas embebidos, Internet de las cosas, energías renovables, captación de energía solar, redes de sensores inalámbricos.

Aunque la energía solar es una fuente emergente de energía renovable desde hace muchos años, con varios estudios que profundizan en la construcción de células solares más robustas y compactas, su uso como fuente de energía para maquinaria móvil y pequeña, como las redes de sensores inalámbricos (WSN), es menos discutido. Sin embargo, con el aumento de los esfuerzos mundiales para subvencionar tecnologías y energías más sostenibles, en la última década han surgido muchos estudios sobre la construcción de redes de sensores inalámbricas basadas en la energía solar. La combinación de novedosos circuitos de recolección, mecanismos para obtener la máxima potencia posible, algoritmos inteligentes de gestión de la energía y la mejora de la tecnología energética ha proporcionado el marco necesario para que los nodos de las WSN se autoalimenten y tengan una vida útil mucho más larga. En este artículo se revisa la nueva tecnología propuesta que ayuda al desarrollo de las redes de sensores inalámbricos con captación de energía solar.

1.Introduction

A recent emerging technology, wireless sensor network (WSN) is the backbone of many advances in the Internet of Things (IoT). The applications of these networks have ranged from disaster management, ecological studies, medical monitoring systems, and air quality metrics [2]. One of the major functions of WSNs currently is environmental monitoring which is characterized by its function to transmit data over a large area wirelessly to the gateway node. Amongst the notable standards for wireless sensor networks commonly researchers cite ZigBee, Z-wave, WiFi, and Bluetooth [2-3]. The novel and inviting features of WSNs are their reliability which gives the system a large operational lifetime, especially when flexible architectures such as wireless mesh are utilized. At the heart of the performance of any WSN are the wireless sensor nodes and their specifications.

At their core, ever wireless sensor node is characterized by its size, stand-alone power supply, its transmission latency and its sensory accuracy. Over the recent years, sensors have become increasingly accurate at miniscule sizes, therefore it can be deduced that the primary bottleneck in the size of a wireless sensor node is its powering mechanism or the size of the battery. It is observed that a significant correlation exists between the useful life of the individual nodes and their duty cycle as well as the volume of data flow within the system. While there are IoT objects that use high power per unit time, these tend to be less sustainable, therefore it is a standard practice to maintain a design constraint of being powered by a readily available source such as 1.5V IEC 60086 size R6 batteries [2]. Though WSNs are mainly low

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power systems that do not need large batteries, Inherently the use of batteries applies a limit on the operational time of the network after which the system will have to be taken out of service to recharge or replace the batteries. This process interrupts the operation where the wireless sensor is being used and in cases where the network is spread over several kilometers the replacement can be time intensive and impractical. Therefore, a source of energy is needed that provides energy at the place of operation itself without the need for interrupting service, human intervention, or connection to grid. Some such viable technologies are stated in the Table 1.

Table 1. Energy Resources viable for use in Wireless Sensor Networks

Energy Source	Available Power	Approximate Efficiency	Smallest Size of Harvester
Vibration Energy	100 $\frac{\mu W}{cm^2}$	1%–10%	<1-10 cm³
Thermal Energy	100 $\frac{mW}{cm^2}$	1%–10%	2-3 cm³
Radio Frequency	0.3 $\frac{\mu W}{cm^2}$	50%	2-3 cm³
Solar (Photovoltaic) Energy	0.1 $\frac{mW}{cm^2}$ (Indoor) 100 $\frac{mW}{cm^2}$ (Outdoor)	5%–30%	Few nanometers (under development)

Source: [1] and [4]

From Table 1 it can be noted that solar power demonstrates the optimal trade-off between efficiency and power density amongst other comparable sources of energy. Furthermore, it should be noted that the size of harvesters of solar energy are becoming smaller by the day, recent cells using nanotechnology have been manufactured in the order of nanometers. The growing market for solar panel manufacturers also provides ample investment and resources for its integration with WSNs. Maurya et al. have stated that near about 15 mW/cm3 of photovoltaic power can be harvested from solar energy for wireless sensors [2]. Converters are used to transform this energy to the DC that drives the internal circuitry of the WSNs. Additionally, advancements in storage technology allows the system to function in conditions that are not favorable for harvesting solar energy. The advantages of solar energy that make them optimal for powering WSN nodes, which are given as follows [1]:

- From a theoretical perspective the output from harvesting solar energy is inexhaustible.
- Solar power tends to show a superior power density than other quotidian renewable energy resources.
- Apart from the production of the solar cells, the pollution and carbon footprint of solar energy is null.
- Solar energy shows compatibility with a most devices having diverse ranges rated power characteristics.
- Photovoltaic harvesters are silent, more durable, and less location restricted than other harvesters.

The major objective of this critical review is to extensively encompass the features of a Solar Energy Harvesting based Wireless Sensor Node, to illustrate the known and potential shortcomings faced by such systems, and review in detail the solutions proposed in various recent studies to improve this technology or extend its application. The remaining portion of this paper is organized as follows: Section II aids in a more comprehensive overview of Solar Energy Harvesting Wireless Sensor Networks and provides an outline of the components involved in such a system. Section III provides the problem description or major considerations in designing an optimal system. Section IV reviews literature which proposes new technology to optimize the designs with respect to the considerations in the previous section. Section V provides some simulation platforms developed to aid in analyzing performance of the Photovoltaic Harvester. Section VI gives the overall summary of the review along with the author’s insight into the most efficient technologies in every domain.

2. Major components of solar energy harvesting wireless sensor network

a. Photovoltaic Harvester Subsystem
   - Photovoltaic panel/ Solar cell.
   - DC Boost Converter.
   - Mechanism for Maximum Power Point Tracking (MPPT).
   - Addition Intelligent Mechanism for Energy Forecasting.
   - Storage Media.

b. Sensory Array
   - Sensor Development/Interface Board (SENSORPUCK, FLORA, Thunderboard Sense).
   - Analog to Digital Converter.

c. Computing and Processing Unit
   - CentralMicrocontrollerDevice(TIMSP430F1232, STM32F103, Atmel ATmega328).
   - Analog to Digital Converter.

d. Communication Unit
   - Transceiver Module (Zigbee, LoRa, etc).

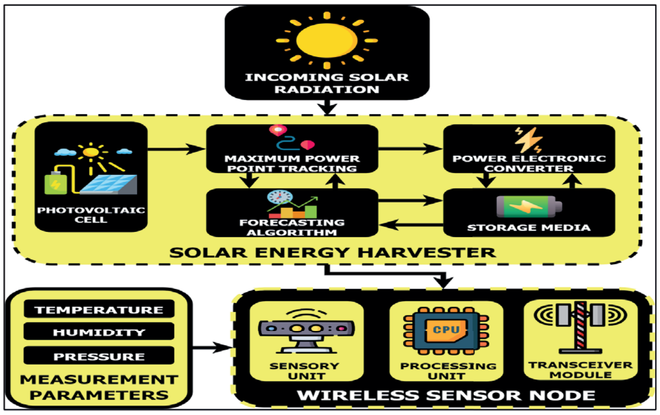

Figure 1. Schematic Diagram of a Solar Harvesting WSN

The sensor unit performs as the central instrumentation platform which detects physical quantities like temperature, light, humidity, or pressure, see Figure 1. The computational unit then processes this data to useful markers that would provide the system with decision making feedback. As per the mesh architecture these data packets of useful information are relayed to nearby nodes until it reaches the central database or gateway node. The end user can then access this information or it can be used to autonomously drive a control system. The energy harvesting unit, which is a unique feature of this build of WSNs, supply stable power at the operating voltage (3V) to the WSN node to allow continuous supply of energy and uninterrupted service.

3. Modern Wireless sensor mechanisms for solar power harvesting

The following section covers the literature survey related to the key aspects of Solar Energy Harvesting Wireless Sensor Networks where the key obstacles lie and can lead to gross optimization improvements in existing systems.

a. Storage Technologies for Wireless Sensors

Solar energy can be continuously collected and utilized directly by the WSN node, which is known as battery-less operation. This reduces the cost of the solar energy harvesting WSN as well as battery related maintenance. However, it creates contingency issues as power through the sun may become erratic or insufficient in certain environmental conditions. Recent advancements in high efficiency storage devices have promoted supercapacitors to the primary media for SEH storage, whereas traditional batteries are now often only integrated in these systems as a contingency [1]. various media for energy storage in solar energy harvesting wireless sensor node have been summarized from various studies in Table 2.

Table 2. Storage Technologies Used in Solar Energy Harvesting Wireless Sensor Nodes

Sr.No	Storage Technology Used	Author	Average Recharge Cycles	Features
1	Nickel Metal Hydride (NiMH) NM15 battery	Chien et al. (2016)	2,000	High energy density although life cycle is lower. Can be charged through trickle method, using low current.
2	Taiyo Yuden LIC1235RS3R8406 supercapacitor (40 F)	De et al. (2018)	500,000	Very fast charging rate and high operational range of temperatures, though less energy density and higher self-discharge rates
3	7.4V Li-Po battery	Ibrahim et al. (2017)	5,000	Higher weight-energy rate, long lifespan and low discharging rate
4	Autonomous Battery Less Sensor	Estrada-López et al. (2019)	-	Larger useful life, virtually free of maintenance, and cost-effective performance.

b. Maximum Power Point Tracking

Maximum power point tracking (MPPT) has often been availed in solar energy harvesting in order to ensure the maximum amount of power that can be harnessed through the solar panels may be collected. The maximum power point refers to the to the constant voltage level that provides peak power levels being produced in the photovoltaic cell. In most new designs of solar power systems and charge controllers, some version of the MPPT technique is employed. At its core, MPPT technique aims to make the solar module's resistance equal to that of the load of the circuit or the battery. Generally, MPPT can boost energy generation by 20%–30% [9-13]. All MPPT algorithms fall into the following wide classifications:

- Perturbation and observation (P&O): This method alters the operational parameters directly to try to achieve the MPP. This algorithm can be very complex and has been modelled to have optimal performance in various studies but essentially it boils down to the sequence shown in Figure 2a.
- Incremental conductance: This algorithm has been visualized in Figure 2b. Essentially it operates by comparing the incremental conductance of solar energy harvester to the instantaneous conductance. Depending on the feedback, which is either a positive or a negative value, it varies the voltage until a

stopping condition (MPP) is reached. Unlike the first method once the stopping condition is met there are no further alterations in the voltage.

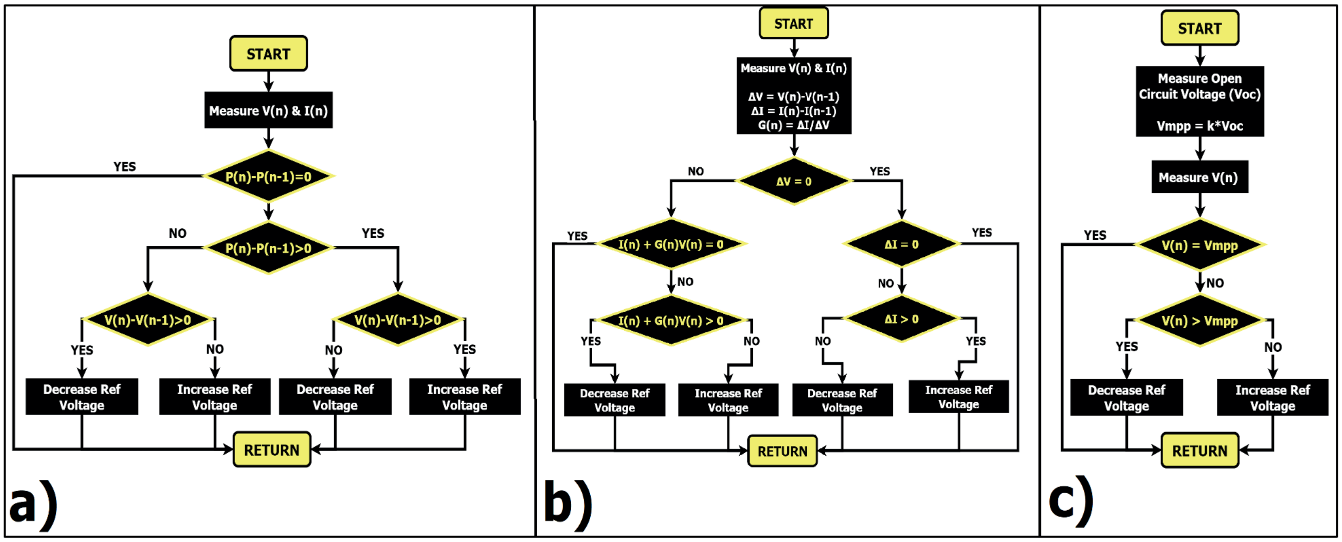

Figure 2. MPPT Techniques a) Perturbation and Observation. Fuente. [9] b) Incremental Conductance. Fuente. [9] c) Fractional Open-Circuit Voltage. Fuente. [10]

c. Solar Tracking for Wireless Sensors

As mentioned in the earlier sections of this paper, the main constraint with respect to WSN nodes is their size. Therefore, until recent times tracking, which is common in many commercial PV systems, was not used as the energy used by the tracker would be more than the energy harvested by the system overall. This would put the design into an energy debt and therefore was mostly deemed infeasible. However, many studies in recent literature have proposed trackers that ensures minimal energy is lost with low power consumption which are ideal for WSN nodes. Some of these studies are highlighted in Table 4.

Table 3. Novel Solar Trackers in recent literature

Sr.No	Tracking Mechanism	Author	Description	Error
1	Single axis online solar tracker with IoT.	Pulungan et al. (2020)	A sensor array is interfaced with an embedded microcontroller control system and a ThingSpeak enabled cloud database to give the resultant model.	0.8%
2	Knowledge-Based Sensors PV Tracker.	Canada-Bago et al. (2020)	The method implements a synchronous IoT architecture using a fuzzy-rule based system in tandem with the controller.	1.2%
3	Lightweight Adaptive Solar Tracker	Jackson et al. (2017)	The method amalgamates a flexible energy generation framework with intelligent and computationally lightweight program to adapt and optimize the energy production.	0.9%

Fuente. [12-14]

4. Overall summary with highlights of best noted technologies in every domain

Finally, the Table 7 summarizes the domains of literature studied as part of this survey on solar energy harvesting for wireless sensor nodes. Overall, the main features that have led to development in more efficient, long-lasting and compact solar energy harvesting nodes have been storage technologies, maximum power point tracking, solar tracking, intelligent algorithms and developed simulation platforms. The table summarizing this information also provides a critical evaluation of the most optimal and novel technology that has been studied in literature (as per analysis by the author). The reasoning as to why this particular technology has been chosen is also provided.

Table 4. Overall Summary of Review with Critical Analysis

Sr.No	Domain of Interest	Contribution to SEH-WSNs	Ideal Technology from literature	Remarks by author	Issues to be considered for future studies
1	Storage Technologies	Allows uninterrupted operation of each node even during periods where harvesting is infeasible. Gives an overall longer lifetime to the system.	Supercapacitors De et al. (2018) [6]	In the future if it is intended to deploy WSNs with close to unlimited lifetime, the storage source may not be limited to a few thousand recharge cycles. Supercapacitors are hence ideal.	Low capacity of supercapacitors compared to batteries. Hybrid combinations to be explored further.
2	Maximum Power Point Tracking	Provides ability to maximize power harvested from solar cells. Improves system efficiency.	Perturb & Observation Sharma et al. (2018) [12]	Highest efficiency stability balance. The technique inherently provides much more flexibility between reviewed methods and thus holds scope for improving accuracy further.	The voltage does not remain constant after MPP thus using more computational resources.
3	Solar Tracking	Various improvements in performance such as increased power harvesting and improvements to system cost-efficiency	Single axis online solar tracker with IoT Pulungan et al. (2020) [13]	The low-cost simple execution of this tracker makes it mass producible and its compatibility with the IoT framework make it a novel solution.	A custom platform for database collection would streamline operations.
4	Energy and Power Management Algorithms	Adapting power consumption profile to energy harvested and forecasting future power demands prevents from unexpected system failure	Reinforcement learning; Q-learning Fraternali et al. (2019) [15]	The approach provides high accuracy along with a large and versatile range of predicted parameters. One of the more systematic uses of RL for energy harvesting.	Using a larger sample set with more data points can boost the accuracy of the model.
5	Simulators for Energy Harvesting	Analysis of system design provides essential information for evaluating its probable performance on prototyping. Saves funds and resources of building faulty designs.	GreenCastalia Benedetti et al. [19]	The framework is based on Castalia which is custom built for WSNs making it ideal for SEH-WSNs. The open-source build has been most comprehensive and refined.	The extension of the program for customized use is left to the end user. Would be more useful with built-in features.

Fuente: [1-19]

5. Conclusion

Solar Energy harvesting continues to make its way into the market as the energy resource of the new age. The use of solar power for niche applications such as for powering WSN nodes, proves its versatility as a power source even for smaller machines. This survey provides the following contributions. The fundamental concepts and components of a Solar Energy Harvesting based WSN system have been detailed. This is followed by a review of the challenges and design considerations that are currently experienced in building such systems. Finally, efforts at tackling these challenges made in recent notable literature have been reviewed comprehensively. The future scope of Solar Energy Harvesting based WSN systems is very promising in the field of smart homes, smart cities, ecological monitoring, process control and automation in industries, and IoT applications. This survey is aimed at serving as a reference for future engineers, researchers, and scientists while designing and manufacturing improved Solar Energy Harvesting based WSNs.

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