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Advancements in Energy-Autonomous Wireless Sensor Networks: Integrating Simultaneous Energy Harvesting and Ambient Light Sensing Systems

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***Abstract*— Wireless Sensor Networks (WSNs) are widely used for surveillance applications, including detecting moisture and temperature in intelligent structures, automating industries, and predicting crop health. Sensor nodes are strategically placed in distant locations to detect and gather data from the surrounding environment, which is then sent to the Base Station (BS). When a sensor is depleted of power, it cannot fulfill its function without a replacement energy source. Nevertheless, the constrained energy capacity of a sensor's battery hinders the sustained operation in such applications. To address the energy constraint without altering the dimensions of the sensors, scientists have suggested using energy harvesting to replenish the battery's capacity via power supply. Hence, it is essential to implement effective power management to maximize the advantages of harnessing supplementary environmental energy. Furthermore, changing the power sources of the sensors and redeploying them incurs significant costs in terms of both time and cost. This paper presents a wireless sensor platform that addresses the need for Internet-of-Things (IoT) applications requiring numerous maintenance-free, affordable wireless sensor nodes. The proposed platform features a Single Photovoltaic Transducer (SPVT) that serves the dual purpose of Energy Harvesting and Ambient Light Sensing (EH-ALS). This dual functionality enables the employment of smaller and more affordable nodes that do not rely on an additional power source, resulting in decreased components. The device utilizes Bluetooth Low Energy (BLE) technology for communication and can collect and detect interior light conditions with a detection threshold of 210 LUX. The Light Intensity (kLUX) readings show a distinct pattern from 10:00 AM to 11:00 AM for the Simultaneous EH-ALS system with SPVT. Between 10:00 AM and 10:08 AM, the light intensity gradually increases and reaches its maximum at 12 kLUX.**

Keywords*— *Autonomous, Wireless Sensor Networks, Energy Harvesting, Ambient Light Sensing, Bluetooth Low Energy, Photovoltaic Transducer.

I. INTRODUCTION

WSNs have significantly impacted the industry for testing multi-hop wireless networks. This is due to its potential use in preservation and operational structures for security and community wellness monitoring. The fundamental aspects of this model include the design of transmission procedures, localization techniques, tracking methods, and controlling energy [1]. Hedge systems based on the IoT have shown a beneficial impact on solar energy output. Current techniques, such as localization, optimal aggregation, and ML algorithms [2], primarily concentrate on mitigating risks associated with edges. A wide range of solar radiation options are available to hedge against the potential risks of low exposure for photovoltaic investment. The models for forecasting using edges yielded a Pearson's correlation coefficient of 0.92 and an R-squared score of 0.83. WSNs were motivated by technical priorities, such as the preservation of biodiversity and their conversion into energy. Typically, the WSN nodes are powered by batteries.

The system is deemed "depleted" when its power is fully used; batteries may be substituted or reenergized in small-scale applications. Replacing or recharging is often characterized by sluggishness and high expenses, leading to a decline in network efficiency. However, it is an unavoidable need. Consequently, other approaches have been proposed to postpone the decline in battery life, such as implementing energy management and session-based operations in routing [3]. These technologies sometimes use low-current wireless transceiver approaches, whereby the components may be deactivated to conserve power. When the device enters the energy economical phase, its output is considerably reduced compared to when it is turned on [4]. However, the device cannot transmit or identify the payload while in a state of dormancy. The task cycle terminates following the duration that the device is operational, alternating between active and idle states until ultimately shutting down. Utilizing low-power procedures appears to be a plausible rationale that aligns with the durability of WSNs.

The many kinds of ambient energy comprise nuclear power, natural, electrical, mechanical, and others, as mentioned in reference [5]. Both of these power suppliers should be accessible for energy collection. Additionally, a complementary transducer is required to convert electrical energy. Power gathering uses energy to generate power without relying on another energy source. The excavators need financial commitment and are advantageous when using traditional energy sources like grid power or batteries becomes excessively costly and unfeasible. The energy harvester must provide power on demand rather than just when it is accessible. It is advisable to prioritize the need for energy storage [6].

Multiple types of energy can be used for EH-ALS. These include radiation, heat, and physical (including prospective and fluid) [7]. Cosmic radiation, pressure in the atmosphere change, and solar atomic neutrinos are abundant, although they possess little energy. The harvesting device entirely depends on its position and the choice of suitable forms when different energy fields are available. Typically, just a few suitable solutions are available for a certain location.

Detecting the ideal temperature and vibration variations is a significant challenge. Illumination systems, such as calculators, can provide sufficient interior energy for low-power purposes. Furthermore, the gadget may use waves and temperature radiation for business reasons in situations involving high temperatures and strong oscillations that follow a predictable pattern. Ensuring data security and protecting information privacy are significant obstacles when it comes to performing sensitive calculations using IoT devices and sensors [8].

This study examines the latest advancements in WSNs with a specific emphasis on reaching self-sufficiency in energy. The combination of concurrent EH-ALS systems gives an innovative method to improve the sustainability and efficiency of WSNs. The suggested system tries to overcome the limitations of standard sensor nodes by using ambient light as a viable energy source. The progress made in this study not only helps to overcome limitations in power supply but also creates opportunities for more resilient and self-sufficient WSNs. Incorporating these technologies has a significant potential for advancing sensor networks, allowing them to function independently while delivering dependable and uninterrupted surveillance under various environmental circumstances.

II. RELATED WORKS

The literature study explores current progress in energy harvesting technologies, including a range of topics from self-powered sensors to their use in the IoT and other areas. The chosen articles investigate several facets of energy harvesting, providing insights into the methodology, implementations, output values, and corresponding benefits and constraints.

Liu et al. (2021) performed a thorough examination, consolidating current advancements in energy-collecting technologies. The output values provide a comprehensive summary of the domain, offering crucial insights into the status of self-powered sensors and their use in the dynamic realm of the IoT [9]. The benefit resides in the extensive scope, yet possible constraints may arise from the difficulty of treating every subtle feature.

In their study, He et al. (2021) specifically examined energy harvesters that have the potential to thrive in future body sensor networks. They placed equal importance on individual and simultaneous energy sources [10]. The output values offer particular observations into developing energy harvesters for wearable gadgets. The benefit lies in the intense concentration, providing comprehensive expertise. Nevertheless, constraints may arise if certain advancements are not addressed.

In their publication, Moloudian et al. (2024) thoroughly examined RF energy harvesting methods, presenting detailed knowledge on the use of wireless sensing without the need for batteries, as well as its applications in Industry 4.0 and the IoT [11]. The output values consist of a combination of RF energy harvesting methods and their respective applications. The benefit comes in the specific concentration on RF energy harvesting, which is especially helpful for IoT applications.

In their study, Nwalike et al. (2023) examined RF energy harvesting systems comprehensively, offering valuable insights into energy use for wearable devices [12]. The generated numbers thoroughly comprehend RF energy harvesting technology for wearable devices. The benefit is in the concentrated viewpoint, offering a valuable understanding of technical progress. Limitations may arise if the evaluation fails to include the most up-to-date advancements.

In their study, Sarker et al. (2021) conducted a comprehensive analysis of the influence of power converters on circuits that gather electromagnetic energy [13]. They specifically focused on the factors that must be considered when designing such circuits for independent sensor applications. The output values provide a thorough comprehension of the effects of power converters on energy harvesting. The benefit stems from the precise concentration on this crucial element, enabling a thorough comprehension.

In their publication, Shokoor and Shafik (2023) comprehensively analyzed energy harvesting techniques designed to sustain WSN [14]. The output values provide a comprehensive perspective on the sustainability factors in energy harvesting for sensor networks. The benefit is in its comprehensive comprehension, serving as a significant asset. Limitations may occur if there is a lack of coverage on particular aspects or recent advancements.

Kanoun et al. (2021) extensively analyzed energy-conscious system designs for self-governing wireless sensor nodes. Output values provide a comprehensive comprehension of energy-conscious system designs [15]. The benefit lies in concentrating on system design concerns providing useful perspectives. Limitations may occur if certain subtopics or recent advancements are not addressed.

La Rosa et al. (2021) presented a study on the approach describing the process of simultaneously harnessing energy and detecting ambient light and how they are integrated. This document provides a comprehensive overview of the implementation, including the specific technical aspects involved in the design and testing of the sensor [16]. The output values provide information on the efficiency and abilities of the energy-autonomous sensor. The benefit stems from incorporating two distinct capabilities, resulting in increased adaptability. Limitations may arise if certain technological intricacies or obstacles are not thoroughly resolved.

To summarize, the literature analysis sheds light on the wide range of energy harvesting technologies, including their use in wearables and body sensor networks and energy harvesting and design factors for WSNs. Every study provides vital knowledge, and while the reviewed literature provides a thorough grasp, it is acknowledged that the area is always changing, requiring continued investigation to keep up with the current advancements. The chosen articles gave a detailed and subtle viewpoint on the current advancements in energy harvesting, serving as a basis for future research and advances in this rapidly evolving field.

III. Single Photovoltaic Transducer (SPVT) for Energy Harvesting and Ambient Light Sensing (EH-ALS)

The SPVT is an advanced technology developed to harvest energy and sense ambient light simultaneously. This system integrates the properties of an SPVT, which captures energy from surrounding light sources, with the features of an atmospheric light sensor. The PVT is capable of harnessing electricity from accessible light sources and also can detect and respond to the surrounding ambient light levels. This makes it a highly adaptable and energy-efficient option for various applications. Integrating Energy Harvesting (EH) and Ambient Light Sensing (ALS) into a single device, SPVT simplifies EH procedures and simultaneously offers up-to-the-minute information on ALS. This technology has significant potential for advancing the design of independent WSN, IoT devices, and other technologies that need EH and ALS. The SPVT demonstrates the capacity to make substantial contributions to the progress of energy-autonomous systems via its dual-use capability.

The system described in this study is shown in Fig. 1. The system is practically self-sufficient due to a SPVT that generates power and detects light using a communication protocol operating in the temporal domain.

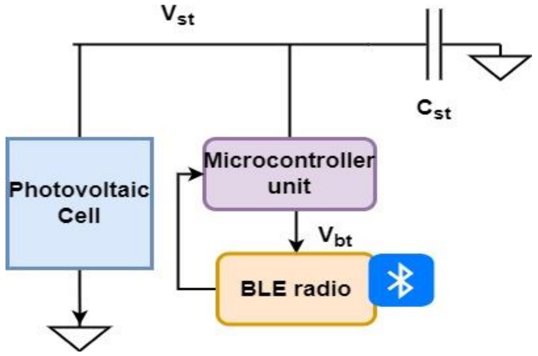

Fig. 1. Block diagram of SPVT

Fig. 2 depicts the functioning of the structure, demonstrating its alternating process between an EH phase and the data transfer phase. During the EH phase, the PVT collects ALS and stores it in the C_st capacitor. In the information transfer phase, the saved energy is utilized to power the BLE radio. Throughout the EH phase, the PV cell generates an electric current which powers the capacitor C_st and results in an accumulation of voltage V_st. The microcontroller unit (MCU) monitors this voltage throughout this phase while operating in halt function to achieve ultra-low power usage. Once the voltage V_st approaches its highest point, V_h, the system transitions into the information transfer phase. In this phase, the MCU increases the voltage V_bt on one of its main input/output (MIO) pins, which supplies energy to the BLE radio. Throughout the communication phase, the C_st The capacitor has to provide a current to the network in the mA range, which is much higher than the collected current in the tens of microampere range. This disparity results in a decrease in V_st. Once the BLE radio completes its wireless operation, it initiates the "BTH" signal, which activates the Finite State Machine (FSM) of the MCU to turn off the BLE station by restoring the V_bt signal. This occurrence prompts the system to recommence the process of gathering resources.

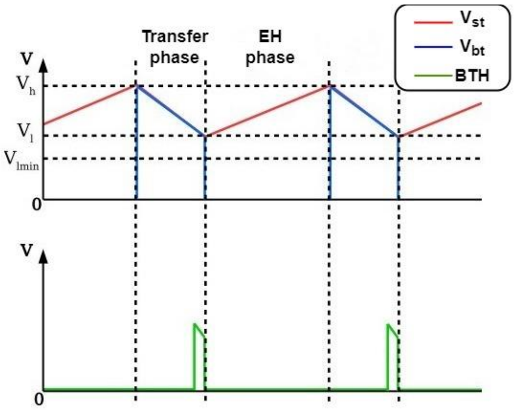

Fig. 2. Operation of the EH-ALS system

The primary design problem of an Energy-Aware Wireless Sensor Network (EAWSN) is to regulate the very constrained energy resources effectively. Therefore, the MCU, known for its ultra-low power consumption, was chosen as the optimal option for the automation and energy conservation module. When choosing the link unit, the main factor to examine is its energy consumption since it accounts for most of the system's power use. The BLE protocol for communication has been chosen because of its low power usage, suitable connection budget, and widespread adoption of mobile devices.

To prevent the network from being overwhelmed with beacons, which might negatively affect other BLE devices operating within its range, it is necessary to restrict the number of radio occurrences occurring within a certain period. The EAWSN switches between the transfer phase and a standby phase, with the time interval (T_stb) shown in Fig. 3.

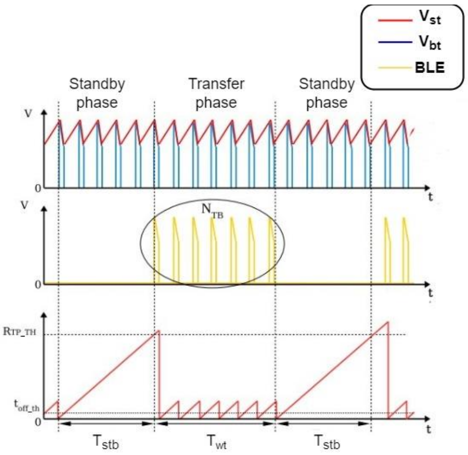

Fig. 3. Switching of EAWSN between the transfer phase and a standby phase, with the time interval (T_{stb})

During the transfer phase, the EAWSN emits a quantity N_{TB} of signals. In the standby phase, it is essential to prevent the voltage V_{st} from beyond the permitted level V_h. Hence, it is necessary to augment the present level of system utilization. To include this functionality, the BLE radio is activated and set up only to acquire bytes to configure the EAWSN, namely to adjust the parameters wirelessly T_{stb} and N_{TB}. The transfer window period (T_{wt}) is much less than T_{stb} in a typical usage scenario.

An additional factor to consider in developing the EAWSN is optimizing the conversion rate of gathered energy, which relies significantly on selecting the SPVT. The sensing threshold is a crucial characteristic for evaluating the efficiency of light intensity in PV cells since they are also used for ALS. The effectiveness of the power conversion and the Highest Energy Point (HEP) at the lowest required light intensity of 210 LUX are crucial because of their impact on weight, dimensions, and other criteria. A PV generator's Maximum Power Point (MPP) is the optimal operating situation when the power transmission from the energy source to the load is the greatest.

To provide a certain level of flexibility and reduce the impact of parameter fluctuations in the elements of the proposed framework, a 24 µF capacitor has been selected for this use case. The total energy harvested has been given as follows:

$$E_{harvest} = C_{st}.(V_h^2 - V_l^2)/2 \qquad (1)$$

V_h and V_l are the highest and the lowest values of C_{st}.

IV. RESULTS AND DISCUSSION

Fig. 4 displays the aerial perspective of the printed circuit board (PCB) used to collect empirical data. The aerial perspective displays the readily accessible, pre-made equipment used in constructing the system. The BLUENRG module is used for Bluetooth-low-power communication in BLE radio. The STM32L0 MCU achieves ultra-low energy consumption and great system performance using a meticulous collaborative design of software and hardware components. Additionally, the MCU is responsible for managing the WSNs.

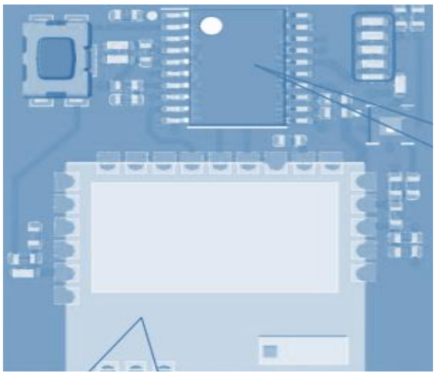

Fig. 4. Aerial perspective of PCB with SPVT for EH-ALS

The term "Quality of Communication (QoC)" encompasses the comprehensive evaluation of communication efficiency, dependability, and proficiency inside a given system, network, or application. It involves several elements contributing to the effective and efficient data transmission among units or parts. Within the "Simultaneous EH-ALS Systems framework," the notion of QoC has special significance in guaranteeing the optimal operation of devices that concurrently gather energy and detect surrounding light.

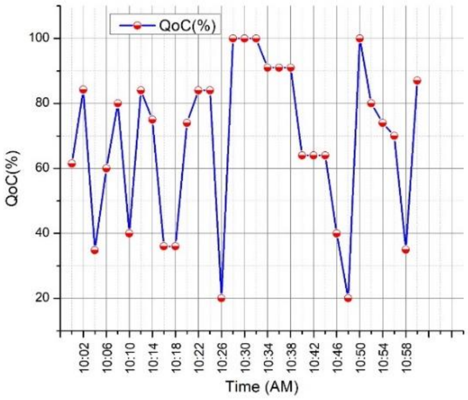

Fig. 5. QoC (%) in the time interval between 10:00 AM and 11:00 AM for EH-ALS with SPVT

The QoC for the Simultaneous EH-ALS system with SPVT varies between 10:00 AM and 11:00 AM, as shown by the dynamic QoC (%) values. The Fig. 5 illustrates variations in communication efficacy within the designated time frame. Significantly, at 10:28 AM, 10:30 AM, and 10:32 AM, the Quality of Communication (QoC) hits its maximum level of 100%, suggesting very efficient and dependable communication throughout these periods. In contrast, the QoC decreases to 20% precisely at 10:26 AM, indicating a momentary deterioration in data transfer quality. These variances indicate that the system undergoes fluctuations in circumstances or external variables that affect the dependability of communication during the designated period. Examining these QoC metrics offers an essential understanding of the time-based fluctuations in communication effectiveness for EH-ALS using SPVT. This analysis enables focused enhancements and optimizations in the system.

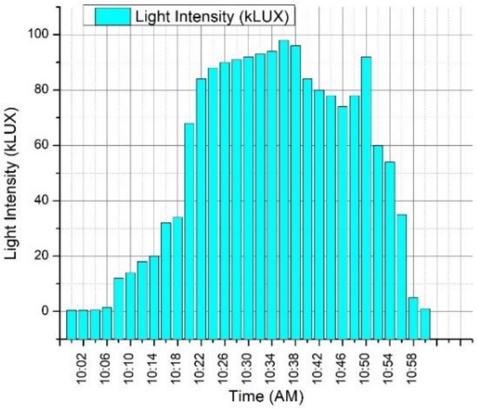

Fig. 6. Light Intensity (kLUX) in the time interval between 10:00 AM and 11:00 AM for EH-ALS with SPVT

Fig. 6 depicts the Light Intensity (kLUX) in the time interval between 10:00 AM and 11:00 AM for EH-ALS with SPVT. The Light Intensity (kLUX) readings show a distinct pattern from 10:00 AM to 11:00 AM for the Simultaneous EH-ALS system with SPVT. Between 10:00 AM and 10:08 AM, the light intensity gradually increases and reaches its maximum at 12 kLUX. Following that, between 10:10 AM and 10:36 AM, there is a notable increase in the brightness level, reaching its highest point at 98 kLUX at 10:36 AM. This time frame exhibits high ambient light levels, favorable for efficient energy collection and light detection capabilities. However, starting at 10:38 AM, there is a progressive decline in light intensity, ultimately reaching one kLUX at 11:00 AM. The decrease in performance may affect the system, suggesting a possible difficulty in low-light situations. Examining these light intensity measurements provides useful insights into the relationship between fluctuations in ambient light and the effectiveness of EH-ALS with SPVT.

V. CONCLUSION

This article introduces a WSN platform that caters to the requirements of IoT applications that need many low-maintenance, cost-effective, wireless sensor nodes. The suggested platform incorporates an SPVT that fulfills the twin functions of EH-ALS. This dual capability allows for smaller, more cost-effective nodes that do not need an extra power source, reducing the number of components. The gadget uses BLE technology for communication and can gather and identify indoor light conditions with a detection threshold of 210 LUX. At 10:28 AM, 10:30 AM, and 10:32 AM, the Quality of Communication (QoC) hits its maximum level of 100%, suggesting very efficient and dependable communication throughout these periods. Light Intensity (kLUX) values show a clear pattern between 10:00 AM and 11:00 AM for the Simultaneous EH-ALS system with SPVT. From 10:00 AM until 10:08 AM, there is a progressive rise in light intensity, eventually reaching its peak at 12 kLUX.

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