A Battery-free and Sensor-less Photovoltaic Tag for Real-time Indoor Light Illuminance Evaluation

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***Abstract*—As the number of Internet of Things (IoT) nodes exponentially increases, replacing or recharging batteries for these end devices limits the working lifetime and space span of ubiquitous IoT. This paper introduces a battery-free IoT tag for indoor light illuminance estimation and evaluation. Utilizing the relationship between the light intensity and the interval between transmitted Bluetooth low energy (BLE) packets, the proposed system assesses the current indoor lighting conditions without using an additional sensor. Owing to their battery-free characteristics, these maintenance-free tags can be easily installed in a very wide range. The cost of this proposed tag is low, only a few discrete components enable the energy to slowly buffer and rapidly release after fully charged. The on/off voltage thresholds can be handily reconfigured. The compact prototype, whose size and cost are only 32x20 mm^2 and US$1, respectively, is fabricated and tested. It is capable of grading light levels above 30 lux. Field tests prove the feasibility and performance of this design. It gives a new insight into the future of pervasive sensing.**

***Index Terms*—Battery-free IoT, sensor-less device, photovoltaic, light illuminance evaluation, pervasive sensing**

I. INTRODUCTION

Nowadays, wireless sensor networks (WSN), an important part of the Internet of Things (IoT), provide a robust infrastructure for building automation. The primary objective is to enhance environmental comfort by continuously monitoring environmental parameters such as humidity, light intensity, and noise level. The efficiency of energy utilization might be concurrently improved toward a low-carbon lifestyle [1], [2].

Until now, the most prevailing energy supply for remote sensing devices remains chemical batteries [3]. The frequent replacement or recharge of batteries becomes labor-intensive, particularly when a large amount of IoT nodes are sparsely distributed. The disposal of batteries after their service life also imposes a severe environmental impact. Therefore, the power issue is one of the major obstacles against the further spatial and temporal expansion of IoT networks. Battery-free sensing techniques are considered a promising solution to overcome the difficulty of pervasive power supply [4]–[6].

Some studies have explored the feasibility of self-powered WSN [7]–[9]. Yet, most require additional sensors and a chemical battery to support intermittent heavy power consumption. A new sensing and harvesting paradigm is necessary to get rid of both the additional sensors and the large-volume and environmentally unfriendly batteries.

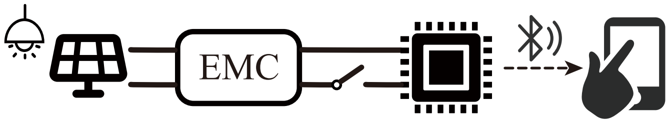

Fig. 1. System architecture.

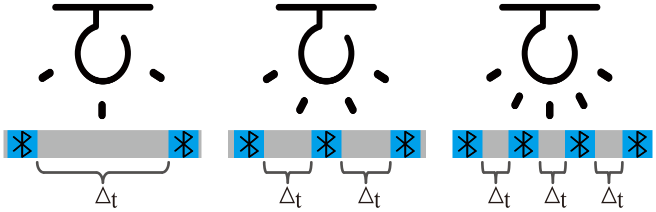

Fig. 2. Illuminance estimation according to the transmission intermittence under varying ambient light conditions.

This paper proposes a concise battery-free and sensor-less photovoltaic tag for ultra-low-cost indoor light illuminance evaluation. The proposed low-cost system further achieves distributed and real-time light intensity evaluation within the illuminance of 30 lux to 600 lux.

II. SYSTEM OVERVIEW

The block diagram of the proposed illuminance assessment system is shown in Fig. 1. An amorphous silicon photovoltaic panel is used for capturing ambient indoor light and converting it into direct current. The generated current is fed to the energy management circuit (EMC) for further conditioning. Once the accumulated energy reaches a specific level, which is sufficient to power an IoT task, the EMC releases the stored energy to power up the digital electronics to fulfill the task. The Bluetooth low-energy (BLE) system on chip (SoC) can subsequently use up the stored energy to broadcast wireless data packets. The receiver edge devices, such as smartphones or microcontroller units (MCUs), collect the data packets and calculate the time intervals of the adjacent data packets.

The operational principle of this design is illustrated in Fig. 2. As ambient light illuminance increases, the self-powered IoT tags progressively reduce the transmission intervals between two Bluetooth data packets. Consequently, the edge receiver can infer the ambient light intensity around the remote tag in real-time according to the packet intervals.

III. Design

A. Solar Panel

According to the classical I-V curves of a photovoltaic panel, at those output voltages below the maximum power point (MPP), the output current is approximately proportional to the solar irradiance level [10]. In many energy harvesting applications, the maximum power point tracking (MPPT) scheme is utilized to enlarge energy income. In this design, we utilize the aforementioned proportional relation between output current and solar irradiance to get some rough information about local illuminance in the same process of energy extraction. Since this design works in a way of generation and then immediate utilization, no large storage device is needed for accumulating much energy. A complicated MPPT module is not necessary either. Getting rid of the MPPT module might violate common sense to harvest as much energy as possible under the same illuminance. Yet, it lowers the power consumption and cost. Since information rather than energy is the final purpose of this indoor low-irradiance application, more harvested energy is not considered the priority.

There are two major difficulties in refining the solar panel's simultaneous sensing capability during the energy harvesting process. One is to make sure this PV tag can work properly under weak illuminance in the indoor environment. The other is to enhance the resolution within a wide range of illuminance variations. The first problem is solved by utilizing an amorphous silicon PV panel, which is more capable of harvesting energy under weak illuminance. Even if it is not as efficient as its monocrystalline and polycrystalline counterparts, it is a good choice for the indoor environment. To simplify the implementation of the energy management circuit (EMC) to the furthest extreme, a boost converter circuit to convert a low-voltage PV source to an applicable digital voltage should be avoided. We chose a PV panel, which stacks eleven internal cells, as the PV source in this design. The photovoltaic panel selected is the TRONY SC-2237-9 model of amorphous silicon solar panel, capable of reaching 5.5 V voltage and 10 μA current under 200 lux. The 5.5 V open-circuit voltage covers most of the digital voltage levels. For the second problem, since the illuminance level is proportional to the output current magnitude, by setting a specific constant threshold for triggering each energy release action, the charging speed can be regarded as inversely related to the intermittence of energy release actions.

B. Energy Management Circuit

The EMC plays a key role in ensuring the energy buffer and release mechanism (EBRM) [11], in particular, in a trickling power scenario. This design uses a concise three-transistor energy management (3T-EM) circuit to fulfill this task by referring to [12]. The 3T-EM can be successfully started up with only 0.4 μA input current. The on/off threshold voltages can be easily adjusted to a specific tailor-made energy requirement by revising the resistor network. Easy voltage regulation is also implemented by the 3T-EM circuit by ingeniously using a depletion-mode MOSFET. Since the IoT task in each energy release moment is very simple, the 3T-EM circuit gives the most economical way to balance the temporal power mismatch between the PV source supply and IoT SoC power demand.

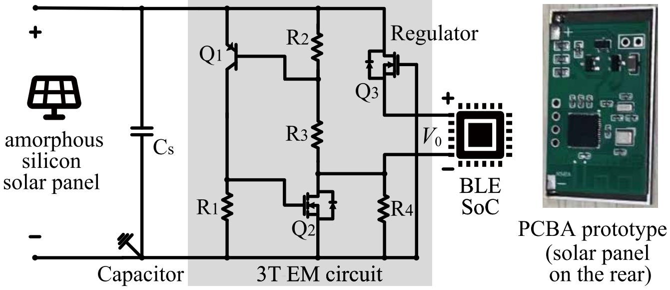

Fig. 3. 3T-EM circuit topology and its PCB prototype for the battery-free sensor-less PV tag.

Fig. 3 shows the topology and the printed circuit board assembly (PCBA) prototype of the 3T-EM circuit. During the ON state, Q_3 is biased in the saturation region. The drain current satisfies

$$I_{ds,3} = K_{p,3}\frac{W}{L}\left(V_{gs,3} - V_{th,3}\right)^2, \tag{1}$$

where $I_{ds,3}$ and $V_{gs,3}$ are the drain-to-source current and gate-to-source voltage of Q_3, respectively; $K_{p,3}$, W, L, $V_{th,3}$ are the process constant, width, length, and the threshold voltage, which can be found in its SPICE model. These parameters cannot be fetched directly. We can extract the relationship between the drain current and gate voltage in the saturation region from the datasheet. Denoting a specific saturation drain current as $I_{ds0,3}$ and the corresponding gate voltage as $V_{gs0,3}$, we have

$$K_{p,3}\frac{W}{L} = \frac{I_{ds0,3}}{(V_{gs0,3} - V_{th,3})^2}. \tag{2}$$

Denoting V_0 and $I_0 = I_{ds,3}$ as the load voltage and current, respectively, from (1) and (2), the output voltage during the ON state can be solved as follows

$$V_0 = -V_{th,3} - \sqrt{\frac{I_0}{I_{ds0,3}}}(V_{gs0} - V_{th,3}) \tag{3}$$

For the depletion-mode NMOS Q_3, the threshold voltage is negative. So, when the load current I_0 is low, the output voltage

$$V_0 \approx |V_{th,3}|. \tag{4}$$

Previous study [12] shows that the simple 3T-EM can supply a relatively constant voltage within an acceptable digital level. It can support an output current of up to 35 mA, which is sufficient for powering most low-power SoCs.

IV. Experimental Evaluation

The PV panel used in this tag device is a thin-film amorphous silicon solar panel, whose size is 37×22×1.1 mm^3. A BLE SoC (nRF52832 by Nordic Inc.) is used to send out an iBeacon packet when a sufficient amount of energy is accumulated. The size of the PCBA prototype is 32×20×1.5 mm^3. The PCBA is attached and soldered on the rear of the solar panel, making the entire device as thin as about 3 mm.

The sent-out iBeacon packets are received by either a smartphone or a specific receiver. The intermittence analysis is realized with the receiver-side software for illuminance estimation.

A. *Single-tag Evaluation*

The power generated by the PV panel is usually not sufficient to directly drive the MCU, in particular, under weak illuminance. The trickling power must be efficiently accumulated and released in an intermittent mode. In each round of intermittent operation, we must ensure a sufficient amount of energy is ready before kicking off to fulfill a complete IoT task. Besides ensuring a nonstop operation during a task, a stable supply voltage must be also provided. In some previous studies [4]–[6], the energy conditions were monitored by the MCU, which controls the operation with the software instructions. In this design, all the energy buffering and release procedures are controlled by the EMC design. Since this is a full hardware solution, the software part can be more efficiently realized.

To get to know the appropriate amount of energy from the storage capacitor C_s for executing a successful IoT task, it is necessary to measure how much energy the system consumes during a complete operational cycle. After downloading the program code to the MCU, energy consumption measurements are conducted. According to the measured results, the energy consumption in a round of initialization and BLE iBeacon broadcasting is approximately 105 μJ and 69 μJ, respectively. Denoting the total energy consumption as E_c, according to the energy formula of a capacitor

$$E_c = \frac{1}{2} C_s \left(V_{\text{on}}^2 - V_{\text{off}}^2\right); \qquad (5)$$

therefore, the harvested energy in each round can be handily designed considering the energy gap between the on/off thresholds as well as the power conversion efficiency of the EMC. The energy balance between supply and demand is critical for the reliable and robust operation of battery-free IoT systems. In this design, on/off threshold voltages are ultimately adjusted to 4.5 V and 2 V, respectively. Given that a 22 μF energy storage capacitor C_s was utilized for energy buffering. Therefore, each round of energy release can give about 179 μJ of energy. It is slightly higher than the energy demand of each iBeacon broadcasting task.

Fig. 4 shows the testing setup for evaluating the performance of the proposed PV tag. A desk lamp, which can smoothly adjust the light intensity, serves as the primary light source. An oscilloscope is employed to show the storage voltage across C_s in the experiment. The illuminance near the PV panel, connecting to the prototyped PCB, is measured by a handheld illuminometer. The picture of energy buffering and release intermittence under three illuminance intensities are shown in Fig. 5. The light illuminance changes twice from 99.1 lux to 193.3 lux, then to 404.3 lux. The illuminance-changing moments are marked by red dashed lines in the picture. By gradually adjusting the light source to increase illuminance, it can be observed that the time interval for charging C_s from V_{off} to V_{on} decreases. The two steep voltage drops after a full charge correspond to the energy consumption of the processes of chipset initialization and one round of BLE packet transmission, respectively.

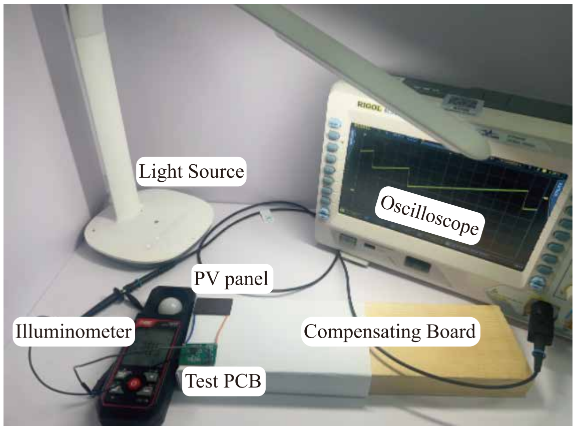

Fig. 4. Testing setup.

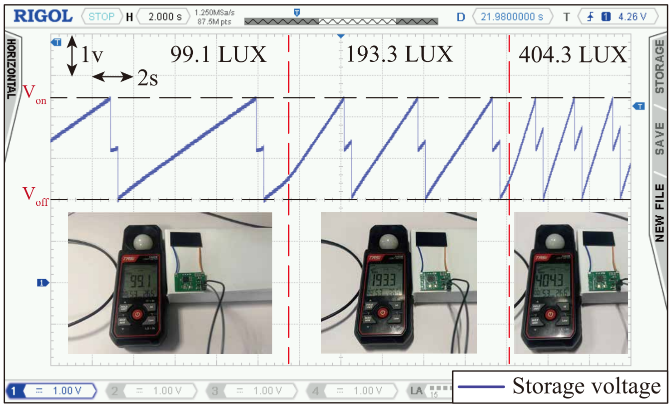

Fig. 5. Transmission intermittence under different illuminance intensities.

B. *Field Test*

Field tests are carried out to evaluate whether passive IoT tags could, to a certain extent, replace illuminance sensors in distinguishing different levels of ambient light intensity. The experimental procedures include: placing the tag in real-world environments with different illuminance conditions; scanning the Bluetooth data packets using a receiver; and recording the moments when the Bluetooth data packets were received, i.e., the time stamp. This timestamp information is then used to calculate the time intervals between each Bluetooth data packet emitted by each tag under specific illuminance conditions. In practical applications, Bluetooth data packet transmission is subject to interference from environmental factors such as electromagnetic interference and physical obstacles. Therefore, to determine whether the passive IoT tag can partially replace

TABLE I
COMPARISON BETWEEN DIFFERENT SCHEMES

	Additional sensor	Dimension	Undervoltage lockout	Sleep-mode current	Lowest illuminance
WSNP [6]	Yes	8.6×5.4 cm^2	software	3 μA	100 lux
ALCS [5]	No	2×2 cm^2	software	1 μA	200 lux
This design	No	3.2×2 cm^2	hardware	0.4 μA	28.8 lux

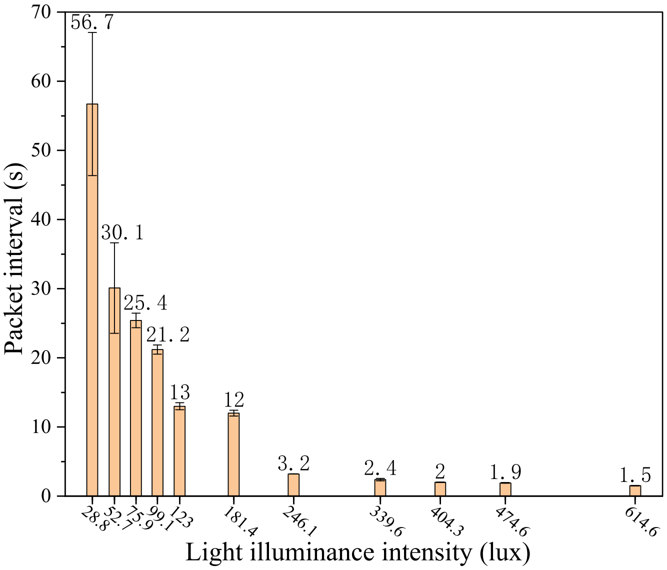

Fig. 6. Relationship between light intensity and packet interval.

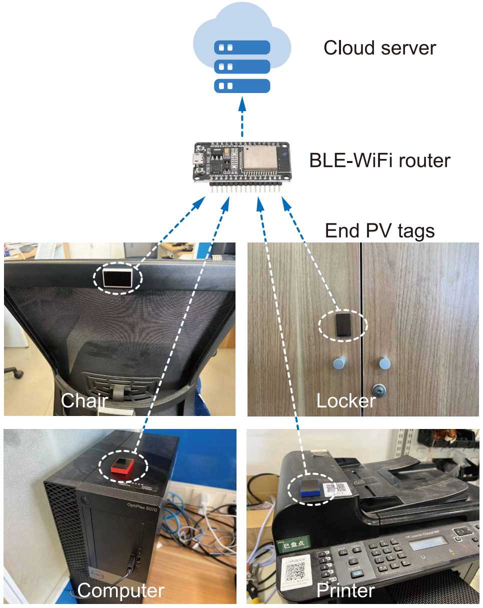

Fig. 7. Practical application scenarios.

an additional sensor cannot rely solely on measuring the performance of the transmitting end device with an oscilloscope. Instead, it requires evaluating the actual reception of Bluetooth data packets by an end receiver and corresponding software for data analysis.

The end receiver and software used in this experiment are an MI 8 smartphone and the nRF Connect software. The transmitted BLE packet can be received within 20 meters. Fig. 6 shows the recorded packet intervals under different light illuminance intensities. An inversely related trend between illuminance intensity and packet interval can be observed. The variation is more significant under the low-light range. In the higher illuminance range, the rate of change decreases. Moreover, there is a large standard deviation of the packet intervals as we can observe from Fig. 6. This might be attributed to the relatively large variation of charging speed at low-light conditions, which requires more scrutiny in the future study. Recently, we use the measure packet intervals in different cases to roughly categorize the indoor lighting conditions into three general zones: dark, low light, and bright.

The passive IoT tags can be conveniently positioned in various locations within an indoor environment to monitor the lighting conditions around the distributed objects. The send-out information from these end tags is collected by an edge device, such as an ESP32 module. Given its BLE and WiFi communication capability, the ESP32 module acts as a lightweight BLE-WiFi gateway. It uploads the collected data to the cloud server for further analysis and decision-making. This practical application scenario is illustrated in Fig. 7.

Table I gives a comparison to other relevant works. It shows that the proposed design exhibits the lowest standby power consumption. It is capable of working under a lowest illuminance condition, compared with other cutting-edge designs. Therefore, it is more suitable for deployment in the indoor environment.

V. CONCLUSION

This paper introduced a battery-free and sensor-less photovoltaic IoT tag designed for indoor light illuminance monitoring. It is capable of operating stably under low-light conditions, to the lowest extreme of 28.8 lux. The system utilizes the relationship between the light intensity and the packet interval in self-powered wireless transmission to achieve a battery-free and sensor-less evaluation of ambient light illuminance. Compared with other relevant works, our design exhibits the lowest standby power consumption and a broader working condition. The exceptionally low standby power and manufacturing cost contribute to the possible application of massive edge nodes in an indoor environment. Based on the data collected by the ultra-low-cost tags, we can carry out more complex analysis, data mining, etc. on the cloud server to realize some future applications, such as item tracking, localization, and comprehensive indoor environmental monitoring.

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