

Article

Design of a Distributed Long Range Wide Area Network Passive Grain Carton Temperature and Humidity Detection System Based on Light Energy Harvesting

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Abstract

Temperature and humidity monitoring in grain-carton warehousing is essential for quality assurance, yet fixed wiring is difficult under frequent stacking and battery-powered tags require routine maintenance. This study proposes a distributed passive monitoring sensing system that combines high-efficiency light energy harvesting with low-power long-range wide-area network (LoRa) communication. The key novelty is a carton-oriented separated architecture: an external photovoltaic harvester is wired to internal sensing/communication modules, mitigating stack-induced shading and enabling reliable operation for sensors embedded inside densely stacked cartons; an occlusion-tolerant multi-tag reporting strategy is further adopted. The tag integrates (i) an energy management module based on the bq25570 with a monocrystalline light cell and energy storage for low-light/intermittent illumination, (ii) a LoRa transceiver optimized for long-range and occlusion-tolerant data delivery, and (iii) a temperature–humidity sensing module for reliable microenvironment measurements. A hardware layout with an external photovoltaic panel and internal core modules mitigates carton-induced shading, while low-power scheduling and a lightweight protocol ensure robust sensing and transmission. Experiments show that the energy management module achieves > 60% charging efficiency at a 1.3 V input. After penetrating three layers of grain cartons, the LoRa link maintains a stable range of 500–800 m with $\leq 1\%$ packet loss under concurrent multi-tag transmission. The measurement errors are within $\pm 1^\circ\text{C}$ and $\pm 3\%$ relative humidity (RH) in the experimental setup. The proposed system eliminates fixed bus wiring and routine battery replacement, offering a scalable solution that enables maintenance-free monitoring in densely stacked warehousing environments.



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Keywords: light energy management; LoRa communication; passive monitoring; low-power consumption design; temperature and humidity detection tag; grain-carton warehousing

1. Introduction

Food security underpins social stability and sustainable economic development [1]. It also remains a strategic priority worldwide [2]. In the farm-to-table supply chain, warehousing and logistics connect production to consumption; their efficiency and safety largely determine grain quality and supply assurance [3]. Grain cartons (e.g., paper cartons, wooden crates, and plastic turnover bins) are widely used in grain processing enterprises, strategic reserve depots, and short-term storage, because they are flexible and convenient for mechanized handling and stacking [4]. However, grain in cartons continues aerobic respiration, releasing heat and moisture and thereby altering the local microenvironment within the pile [5]. At moderate temperatures (15–30 °C) and high relative humidity (>65–70%), microorganisms and storage pests can proliferate [6]. Such biological activity may trigger heating, condensation, mildew, and toxin contamination during storage [7], which ultimately contributes to post-harvest losses [8]. In some regions of China, mildew-related losses associated with insufficient environmental monitoring have been reported to reach 3–5% [9], posing economic and food-safety risks. Therefore, long-term, accurate, and reliable in situ monitoring of temperature and humidity inside grain cartons is essential for early warning and timely interventions to preserve storage quality [10].

In response to this urgent demand, traditional grain condition monitoring technology solutions prove inadequate in practical large-scale, dynamic warehousing scenarios, exposing numerous insurmountable bottlenecks. Wired monitoring systems based on industrial buses (e.g., the RS-485 serial bus and the Controller Area Network (CAN)) offer stable data links [11]. However, in grain-carton warehousing, they are often impractical, because frequent stacking and relocation make cabling difficult [12], cables restrict handling operations, and connectors may oxidize or loosen in dusty environments, resulting in intermittent communication and reduced reliability [13]. Battery-powered wireless sensor networks can simplify deployment and improve flexibility [14]. For example, battery-managed designs based on ZigBee have been reported for monitoring applications [15]. However, their lifetime is constrained by limited battery capacity under 24/7 monitoring requirements [16]. For large deployments (hundreds to thousands of cartons), battery replacement becomes labor-intensive and difficult in densely stacked warehouses [17]. It may also introduce safety risks and battery waste, which conflicts with low-carbon and sustainable warehousing goals [18]. Therefore, a monitoring solution that avoids both fixed cabling and routine battery maintenance is needed for long-term, low-intervention grain-carton storage.

To overcome the energy constraint of conventional WSN tags, passive sensing based on environmental energy harvesting has attracted increasing attention in both academia and industry [19]. In grain storage, sensor networks are commonly used to monitor key parameters such as temperature, humidity, and gas concentration (e.g., CO₂) [20], enabling coordinated assessment of grain condition at multiple locations [21]. Energy-harvesting tags scavenge ambient energy (e.g., solar, thermal, vibration, and radio-frequency energy) and convert it into electrical power to support sensing, processing, and wireless communication [22]. This approach can reduce or eliminate battery dependence and enable long-term operation with minimal maintenance [23]. Among these sources, light (solar) energy is particularly attractive, because photovoltaic harvesting is mature, relatively energy dense, and cost-effective [24], and it can be supported by either natural daylight or indoor illumination in warehousing environments [25].

For data delivery from inside densely stacked cartons, the wireless link should provide long range, low power consumption, and strong penetration through carton materials and stacking layers [26]. LoRa, a representative low-power wide-area network technology, is well suited to these requirements [27]. LoRa adopts Chirp Spread Spectrum (CSS) technology. At the same transmit power, its communication range far exceeds that of

conventional short-range wireless technologies such as ZigBee and Bluetooth. Moreover, it provides good link robustness, enabling reliable communication in complex warehousing environments involving carton bodies and multiple stacked layers. This has been reflected in engineering applications such as a LoRa-based irrigation system [28], further discussed in the design and data-delivery scheme of a LoRa-based wireless sensor network [29], and validated in a temperature–humidity monitoring and communication system deployed in complex propagation environments such as coal mines [30]. In addition, its ultra-low receive current and deep-sleep modes allow efficient power matching with passive power-supply systems [31].

Combining light energy harvesting with low-power LoRa communication is a promising approach for building distributed, low-maintenance monitoring systems and has been explored in several application domains [32]. Prior work has demonstrated the feasibility of solar-powered LoRa sensing in outdoor infrastructure monitoring (e.g., waterlogging detection and drainage control) [33] and has investigated power-management strategies for energy-harvesting WSN tags [34]. Comprehensive surveys have also summarized the opportunities and challenges of passive sensing for IoT applications [35]. In parallel, LoRa has been adopted for agricultural monitoring and other long-range low-power deployments. Hong and Zhang reported a smart agricultural monitoring system based on LoRa, illustrating its applicability to long-range monitoring deployments [36]. Yuan discussed the application and optimization of LoRa wireless communication technology in low-power IoT devices, providing design-oriented considerations for such deployments [37]. Energy management for smart warehousing tags has also been addressed, highlighting the importance of duty cycling and energy-aware scheduling in practical deployments [38].

Despite the progress in energy-harvesting sensing and LoRa-based monitoring, a practical distributed passive monitoring system tailored to densely stacked grain cartons remains challenging. Key issues include the following: (1) energy availability under shading: stacking and occlusion reduce illuminance at the tag, requiring an architecture that mitigates shading and an energy-management strategy that can harvest, store and regulate power efficiently under low-light and intermittent illumination; (2) sensing representativeness and reliability: sensors must be placed to reflect the true microenvironment inside cartons while maintaining low power consumption and long-term stability, and their operation must be coordinated with the energy budget and communication schedule; (3) penetrating communication and multi-tag access: multi-layer cartons introduce severe attenuation and multipath effects; therefore, the achievable link margin and range must be verified, and a lightweight protocol is required to support concurrent multi-tag reporting with low packet loss and clear tag identification.

In this work, this study designs and validates a distributed passive grain-carton temperature and humidity monitoring system that integrates light energy harvesting with low-power LoRa communication. The proposed system adopts a separated architecture with an external photovoltaic panel and internal sensing/communication modules to mitigate carton-induced shading. A bq25570-based energy-management unit with maximum power point tracking (MPPT) is employed to enable efficient harvesting and regulated power delivery under low-light conditions. The tag further integrates an SHT31 temperature–humidity sensor and an E22-400T22S LoRa transceiver to support accurate sensing and robust long-range data transmission in stacked-carton environments.

The main contributions are summarized as follows:

- (i) A hardware architecture that decouples energy harvesting from in-carton electronics, improving energy availability under stacking/occlusion.
- (ii) A low-power operating strategy and lightweight communication protocol for reliable multi-tag reporting.

- (iii) Experimental validation of energy harvesting efficiency, link performance through stacked cartons, and sensing accuracy, demonstrating maintenance-free operation without fixed wiring or battery replacement.

2. Design of a Distributed LoRa Passive Temperature and Humidity Detection Tag for Grain Cartons

This work targets the requirements of long-term and distributed monitoring in grain-carton warehousing and designs a low-cost LoRa-based passive monitoring system enabled by light energy harvesting and bq25570 power (Texas Instruments, Dallas, USA) management. The tag integrates three functional modules: (i) a light energy harvesting and power-conditioning module, (ii) a temperature–humidity sensing module, and (iii) a LoRa communication module. Together, they support the full monitoring chain of energy harvesting → data acquisition → wireless reporting. The harvesting module acts as the system’s energy hub; using the bq25570 MPPT function, it improves energy conversion and regulates storage and power delivery under low-light and intermittent illumination, thereby reducing dependence on fixed wiring and routine battery replacement.

The architecture of the proposed distributed passive monitoring system is illustrated in Figure 1. Each sensor tag is divided into two parts based on its location: the core module and the external photovoltaic (PV) module. The core module comprises a LoRa antenna, a core control/communication circuit, an energy management module, and a temperature–humidity sensing module. The PV panel is placed outside the stacked cartons to reduce shading, while the sensing and communication electronics are deployed inside the target carton to capture the local microenvironment. Interfaces and routed wiring enable flexible placement of sensing modules, supporting distributed measurements within densely stacked carton arrangements.

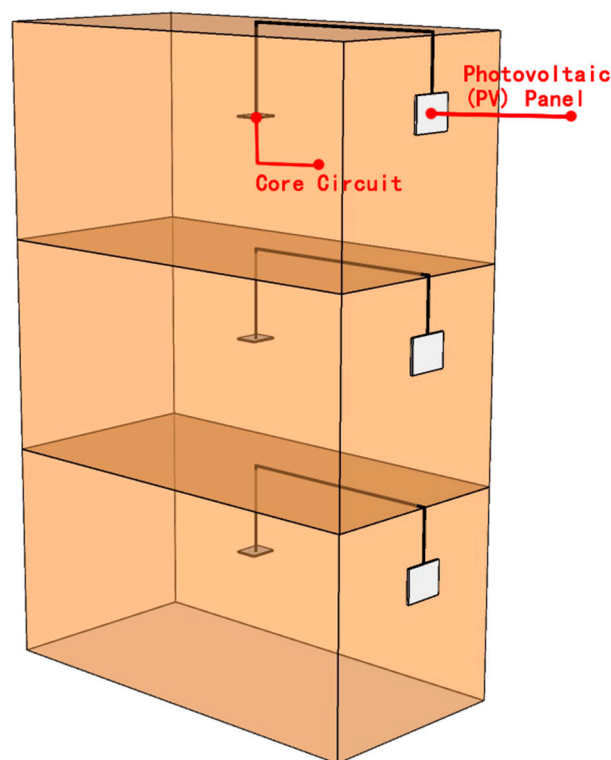


Figure 1. Application of the distributed LoRa passive sensing tag.

Figure 1 illustrates the application scenario, where the prisms denote stacked grain cartons (grain carton outer size: $3.0 \times 1.5 \times 1.0$ m). The core module is placed inside the carton,

used to collect local temperature and humidity data and transmit it via LoRa, whereas the PV panel is routed to an unshaded external position via wiring to maximize light exposure. This configuration improves deployability in dynamic stacking environments and avoids the constraints of bus wiring. Leveraging LoRa's penetration capability, the tag can report measurements from cartons located near the center of a stack, facilitating early detection of adverse storage conditions. The external-PV/internal-electronics layout also simplifies tag installation and removal during routine warehousing operations. This design improves system reliability in stacked-carton scenarios and supports long-term passive monitoring of in-carton temperature and humidity in practical warehousing.

The tag adopts a passive power supply chain of light energy harvesting–power management–low-power delivery to enable long-term operation. A 30×20 mm monocrystalline micro-photovoltaic panel harvests light energy under low-illuminance conditions. Power management is implemented using the bq25570 having a conversion efficiency above 60%, which applies MPPT to adjust the PV operating point and achieve a conversion efficiency above 60%. The harvested energy is stored in a 3.3 V, 0.1 F thin lithium capacitor with overcharge and over-discharge protection. To match the harvested-energy budget, the firmware uses duty-cycled operation: after data acquisition and LoRa reporting, the tag enters sleep mode and is awakened periodically or by interrupts. In sleep, the total current consumption is $\leq 10 \mu\text{A}$, enabling on-demand energy use.

The system follows an accurate sensing–lightweight processing–reliable transmission workflow (Figure 2). The tag uses an SHT31 sensor for temperature and humidity measurement; within the typical grain-storage range ($15\text{--}30^\circ\text{C}$), the temperature accuracy is $\leq \pm 1^\circ\text{C}$. A low-power MCU performs data processing and duty-cycled scheduling. Once the storage voltage reaches the bq25570 enable threshold, the MCU triggers sensing and initiates LoRa transmission. The gateway then forwards the received data to a cloud management platform via Ethernet for storage, visualization, and threshold-based alarms.

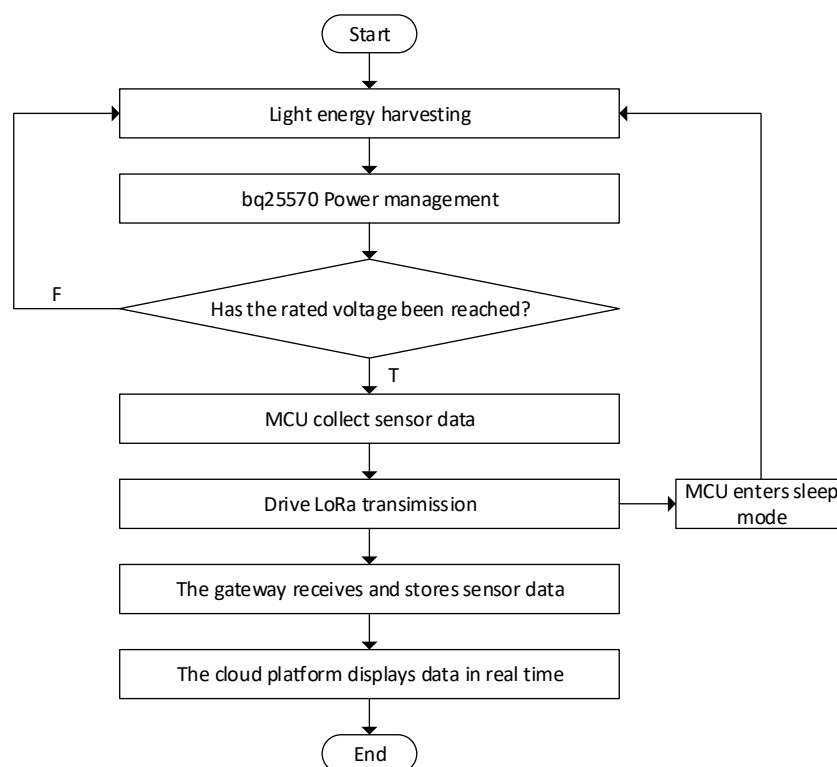


Figure 2. Circuit architecture and sensing module of the distributed LoRa passive sensing tag.

The proposed distributed LoRa passive monitoring tag is designed for grain-carton warehousing and addresses the practical constraints of dense stacking and frequent re-location. Compared with wired bus-based solutions, the tag eliminates fixed cabling and simplifies deployment. The sensing module is compact and can be placed inside cartons, while the photovoltaic panel is positioned externally and connected via wiring, thereby mitigating stack-induced shading and improving energy availability. This external-harvester/internal-sensing layout enables reliable long-term monitoring of the in-carton microenvironment and enhances the practicality of large-scale deployment in grain and fodder storage.

3. Design of Functional Modules for the Distributed LoRa Passive Grain Carton Temperature Detection Tag

To enable long-term operation of the proposed passive monitoring tag in grain-carton warehousing, the tag is organized into three functional modules: (i) light energy harvesting and power management, (ii) temperature–humidity sensing, and (iii) LoRa communication. These modules are co-designed to balance energy availability, measurement accuracy, and reliable data transmission in stacked-carton environments. The PCB layout is shown in Figure 3; the design passes DRC verification, and the board size is 37×28 mm.

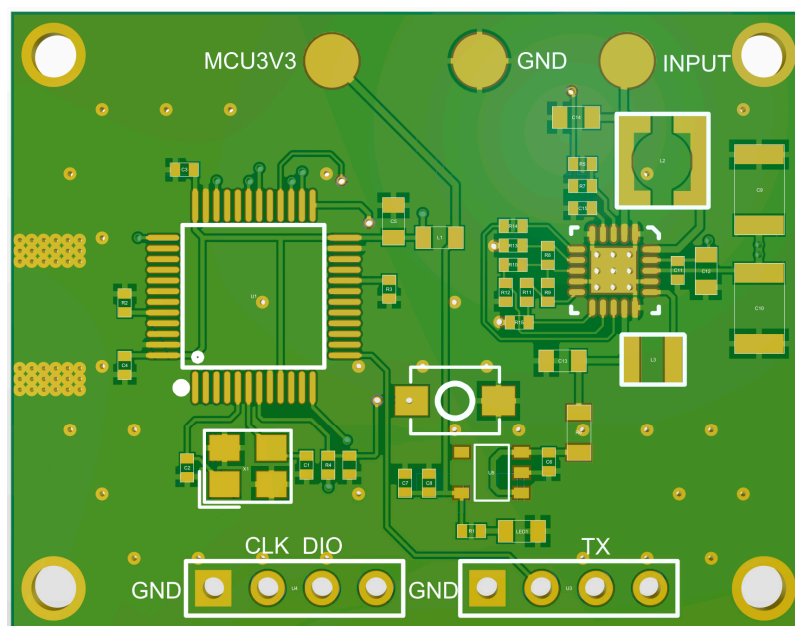


Figure 3. Temperature and humidity acquisition tag circuit PCB.

Figure 4 shows the voltage-regulation stage, which provides a stable 3.3 V supply for the tag. The regulator (U5), together with the decoupling capacitors, suppresses ripple and high-frequency noise to improve supply stability. This 3.3 V rail powers the LoRa module and the temperature–humidity sensing module; therefore, its stability directly affects measurement accuracy and wireless communication reliability.

3.1. Light Energy Harvesting and Processing Module

The bq25570 is an energy-harvesting power-management IC designed for ultra-low-power applications. It supports cold start under very low illuminance, converts energy captured by micro photovoltaic panels into regulated DC power and charges an energy-storage element to supply the tag electronics, including the MCU, the SHT31 sensor, and the LoRa module. Owing to its low start-up voltage, high integration, and high

conversion efficiency, the bq25570 is well suited to low-light and intermittent-illumination warehousing conditions.

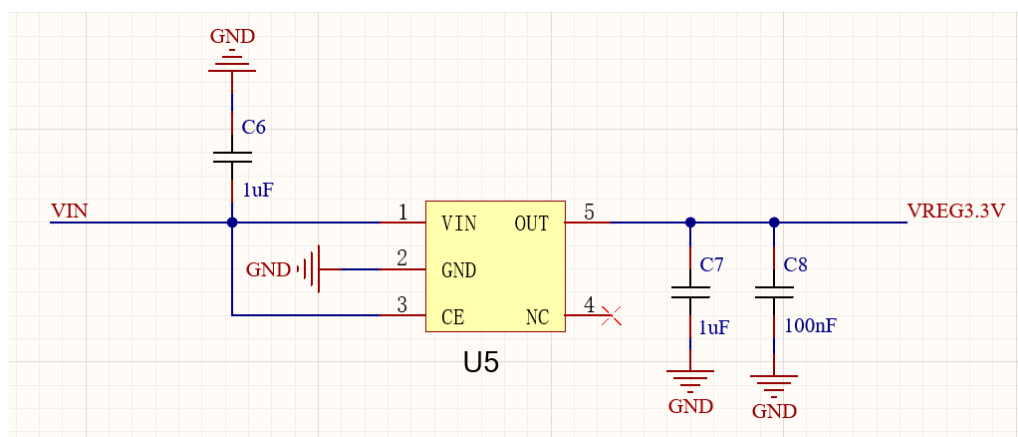


Figure 4. Circuit voltage regulation module schematic diagram.

Figure 5 (adapted from the bq25570 datasheet) illustrates the charging efficiency of the bq25570 when the input current is fixed at $I_{IN} = 100 \mu A$ and the input voltage V_{IN_DC} is swept from 0.1 to 3.0 V. Here, charging efficiency refers to the fraction of input electrical power that is converted and delivered to the energy-storage node. V_{IN_DC} represents the equivalent DC voltage of the photovoltaic source, which characterizes the available input-voltage level under low-illumination conditions, whereas V_{STOR} denotes the storage-node voltage, reflecting the voltage state of the storage capacitor/battery. The plotted parameter range is representative of μW -level indoor harvesting, demonstrating that the bq25570 can sustain high conversion efficiency even with microcurrent input, thereby enabling effective conversion of limited indoor light into usable electrical energy for the tag.

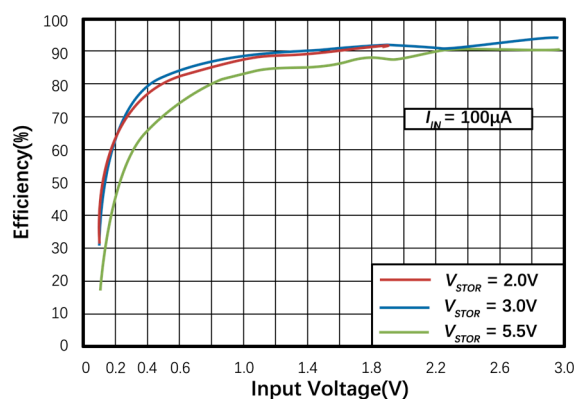
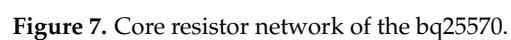
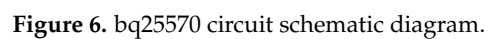


Figure 5. bq25570 charging efficiency diagram.

The circuit schematic is shown in Figure 6. Harvested energy is accumulated in the storage element; once the voltage reaches a predefined threshold, the on-chip power stage (LDO/DC–DC) is enabled to provide a stable supply to the load.

As shown in Figure 7, the core resistor network controls the operating procedure of the bq25570 through four configurable parameters, namely V_{BAT_OV} (the rising threshold voltage of the capacitor), $V_{BAT_OK_PROG}$ (the falling threshold voltage of the capacitor), $V_{BAT_OK_HYST}$ (the threshold voltage at which the device starts discharging), and V_{OUT} (the output voltage).


$$V_{BAT_OV} = \left(\frac{3}{2}\right) \times V_{BIAS} \times \left(1 + \frac{R_{OV2}}{R_{OV1}}\right) \quad (1)$$

$V_{BAT_OK_PROG}$ can be calculated as follows:

$$V_{BAT_OK_PROG} = V_{BIAS} \times \left(1 + \frac{R_{OK2}}{R_{OK1}}\right) \quad (2)$$

Substituting the resistor values into the equation yields $V_{BAT_OK_PROG} \approx 2.9$ V for the tag. When the storage-capacitor voltage falls below 2.9 V, the discharge (i.e., power delivery to the load) is disabled to prevent further voltage drop.

$V_{BAT_OK_HYST}$ can be calculated as follows:

$$V_{BAT_OK_HYST} = V_{BIAS} \times \left(1 + \frac{R_{OK2} + R_{OK3}}{R_{OK1}} \right) \quad (3)$$

Substituting the resistor values into the equation yields $V_{BAT_OK_HYST} \approx 4.8$ V for the tag. During the charging process, once the storage-capacitor voltage exceeds 4.8 V, the system enables power delivery to the load.

V_{OUT} can be calculated as follows:

$$V_{OUT} = V_{BIAS} \times \left(1 + \frac{R_{OUT2}}{R_{OUT1}} \right) \quad (4)$$

Substituting the resistor values into the equation yields an output voltage of $V_{OUT} \approx 3.3$ V, which satisfies the supply-voltage requirement of the tag electronics.

3.2. Temperature and Humidity Sensing Module

The temperature and humidity sensing module uses an SHT31 digital sensor to meet the requirements of high accuracy, low power consumption, and compact size for grain-carton warehousing. The SHT31 provides a temperature range of -40 to 125 °C and a humidity range of 0–100% RH, with typical accuracies of ± 1 °C and $\pm 3\%$ RH, respectively. These specifications support reliable detection of microenvironment variations inside cartons caused by grain respiration and moisture accumulation. In terms of power consumption, the SHT31 draws ~ 1.5 μ A in typical measurement mode and ~ 0.2 μ A in standby, which is suitable for the harvested-energy budget of the proposed passive monitoring tag. The module integrates a minimalist front-end, including supply protection and filtering, and operates from the 3.3 V rail to reduce sensitivity to supply fluctuations.

For duty-cycled monitoring, the sensor is triggered by the MCU wake-up event and supports configurable sampling intervals (5–10 min in this work), allowing the average current to be reduced to the microampere level when combined with MCU sleep scheduling. Data are read via the UART serial interface, and the measurement procedure is summarized in Figure 8. The SHT31 features fast response and an IP67-rated metal package, which improves robustness against dust and trace moisture in practical storage environments. A cyclic redundancy (CRC) check is applied during data transmission to prevent missing or corrupted readings.

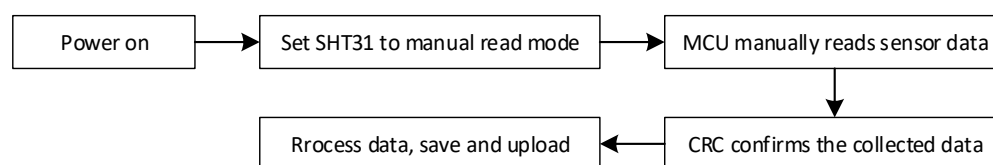


Figure 8. Temperature and humidity sensing data collection flow chart.

In a three-layer stacked paper-carton scenario, the sensing module is suitable for embedded deployment inside cartons due to its compact form factor, without reducing usable storage density. Its ultra-low power consumption, combined with the light energy harvesting and power-management unit, supports long-term operation under either natural daylight or warehouse lighting. Moreover, the specified operating ranges and robust circuit design help maintain consistent temperature–humidity measurements under day–night

fluctuations, seasonal changes, and spatial microenvironment variations within stacked cartons, including the middle and bottom layers.

3.3. LoRa Transmission Module

The tag integrates an E22-400T22S LoRa transceiver module. The module adopts a 26×16 mm SMT package with a 1.27 mm pitch stamp-hole footprint, facilitating compact integration within the tag electronics. As shown in Figure 9, the VCC pin is powered from the 3.3 V rail, and the UART interface is connected to the MCU via RXD/TXD, avoiding additional level-shifting circuitry. The M0 and M1 pins are used to select the operating mode (configuration, normal transmission, and sleep). An external antenna is employed to improve the link budget and transmission range in stacked-carton environments.

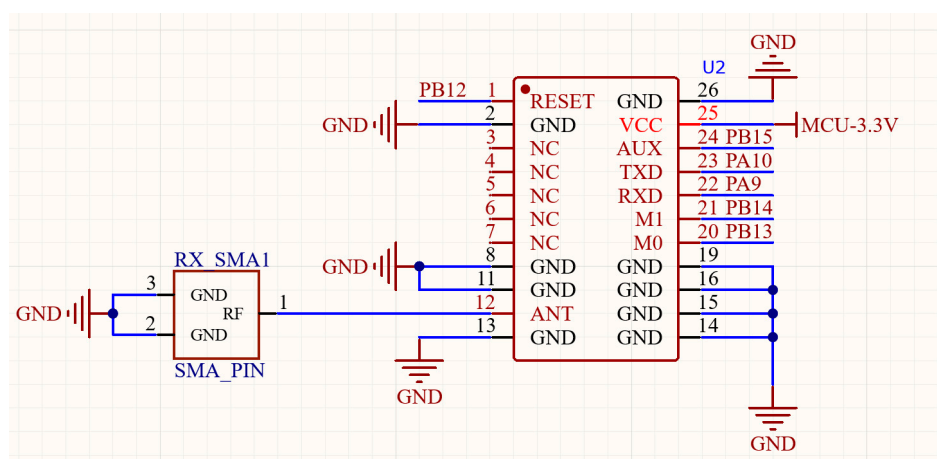


Figure 9. LoRa module circuit diagram.

The E22-400T22S LoRa module is designed for long-range communication with low duty-cycle operation. At a transmit power of 22 dBm, the tag maintains a communication range on the order of 100 m in a warehouse environment even with attenuation caused by three layers of stacked paper grain cartons, supporting practical coverage in large storage areas. The measured current consumption is 15 mA in receive mode, 110 mA during transmission, and 3 μ A in deep-sleep mode. When combined with MCU duty cycling and timed wake-up, the average daily current of the communication subsystem can be reduced to the microampere level, which is compatible with the harvested-energy budget of the proposed passive monitoring tag. The module also supports non-volatile parameter retention, allowing configuration via a host computer and immediate operation after power restoration without firmware reprogramming. The operating flow is summarized in Figure 10.

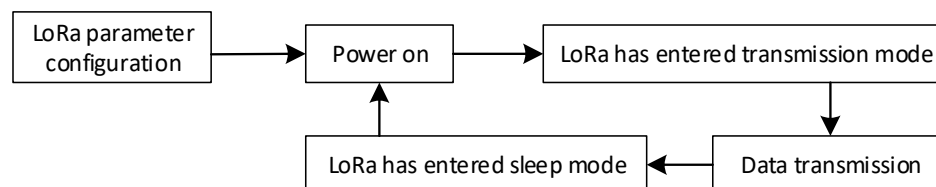


Figure 10. LoRa module working flow chart.

To improve the reliability of temperature–humidity data delivery, a lightweight communication protocol is implemented (Table 1). The gateway address and channel fields determine the destination, while the frame header and tail facilitate robust packet delimitation and parsing. A frame header and trailer are used for packet delimitation and

gateway-side parsing, enabling reliable detection of message boundaries and payload extraction. Addressing is defined by a hierarchical identifier comprising tag (slave) address + channel identifier, which uniquely distinguishes measurements from different cartons, locations, and stacking layers under dense deployment. This addressing scheme reduces data mix-ups across tags and facilitates subsequent cloud-side monitoring and management.

Table 1. Frame format of the lightweight LoRa communication protocol.

Byte	2	1	2	2	1
	Gateway Address	Gateway Channel	Frame Header	Slave Address	Slave Channel
1	1	1	1	2	2
Temperature High Byte	Temperature Low Byte	Humidity High Byte	Humidity Low Byte	CRC Check	Frame Tail

The protocol includes a CRC field to verify the integrity of transmitted payloads (e.g., temperature–humidity data) and addressing information. CRC checking enables the receiver to detect packet corruption that may occur under attenuation and interference in stacked-carton warehousing environments, thereby improving data reliability for storage-condition assessment. In addition, the fixed frame structure with well-defined fields standardizes LoRa data exchange and simplifies parsing. On the tag side, the frame can be assembled efficiently (e.g., using pre-defined arrays), and only the sensor payload needs to be updated after each measurement. On the gateway side, the standardized format supports fast decoding and storage, improving end-to-end data throughput in the monitoring pipeline. Overall, the protocol enhances robustness and efficiency for long-term passive monitoring in grain-carton warehousing.

4. Test of the Distributed LoRa Passive Grain Carton Temperature Detection Tag

To validate the performance and practical applicability of the proposed distributed passive monitoring tag in grain-carton warehousing, a set of laboratory and scenario-mimicking experiments was conducted. The evaluation includes the following: (i) module-level tests to characterize the energy harvesting, sensing accuracy, and RF output; and (ii) system-level integration tests to verify end-to-end sensing, LoRa uplink, and gateway-side parsing for multiple tags. In addition, scenario-mimicking tests were performed using stacked cartons and representative attenuation conditions to assess communication robustness under occlusion. This evaluation links component characterization to system performance and provides evidence under deployment-relevant conditions.

4.1. Module-Level Testing

To evaluate the energy-harvesting and power-delivery performance of the bq25570 under indoor illumination, waveform measurements were performed at an illuminance of approximately 230 lux. The evaluation included two stages. First, a DC power supply was used to emulate the photovoltaic input, allowing verification of the bq25570 configuration and the correctness of its regulated outputs. Second, under indoor lighting (226 lux), the charging efficiency was measured to assess the chip's harvesting and power-management capability under low-input conditions.

Figure 11 shows the waveforms of a complete charge–discharge cycle of the bq25570 module. The discharge phase is enabled when the storage-capacitor voltage reaches 4.76 V, and it is disabled when the voltage decreases to approximately 2.9 V, consistent with the thresholds programmed by the resistor network.

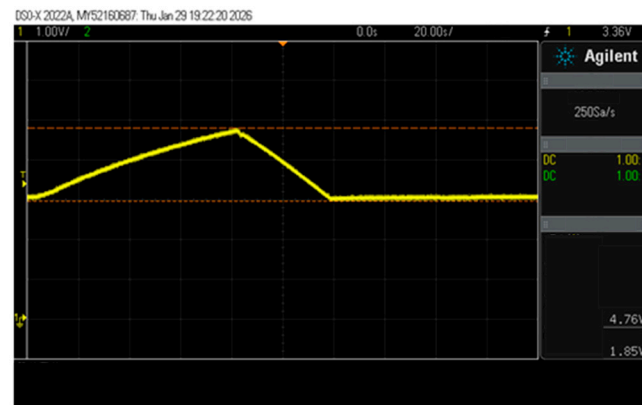


Figure 11. Waveforms of a complete charge–discharge cycle of the bq25570 module.

Figure 12 shows the measured output voltage V_{in} of a monocrystalline silicon photovoltaic (PV) panel (15×5 cm) under indoor illumination (226 lux). With a $15 \text{ k}\Omega$ load, the output current can be estimated as $I_{in} \approx 91 \text{ }\mu\text{A}$, yielding an input power of $P_{in} = \frac{V_{in}^2}{R} \approx 125.4 \text{ }\mu\text{W}$.

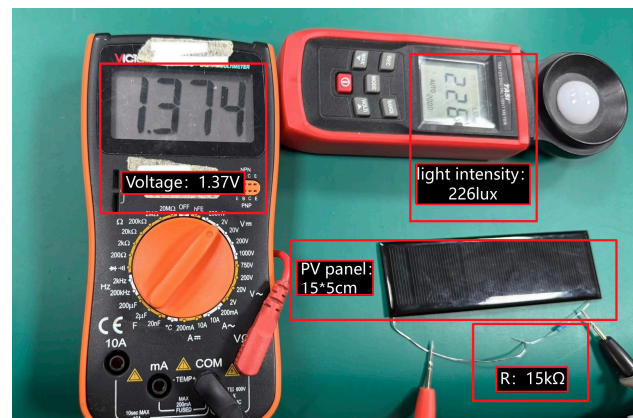


Figure 12. PV output voltage at 226 lux.

Figure 13 shows the measured voltage waveform of the bq25570 storage capacitor ($700 \text{ }\mu\text{F}$). Over a 10 s charging interval, the capacitor voltage increases from 3.553 V to 3.874 V.

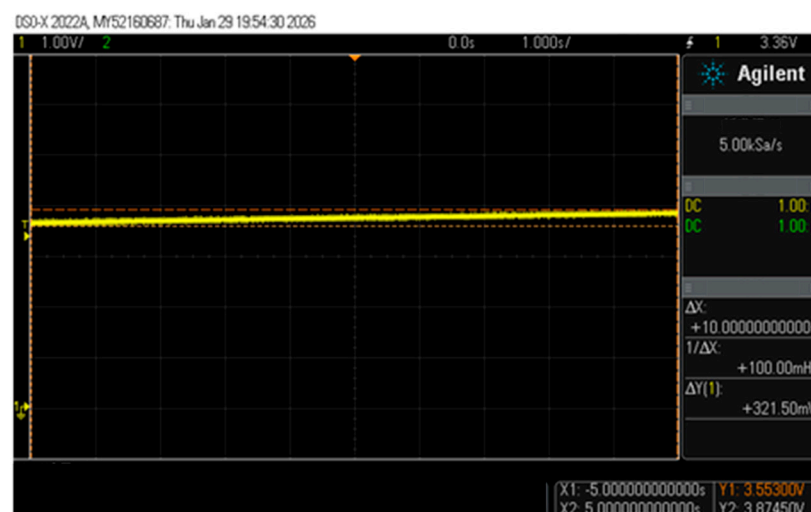


Figure 13. Measured charging waveform of the bq25570 under indoor illumination (226 lux).

The corresponding net increase in stored energy can be calculated as:

$$\Delta E = \frac{1}{2} \times C \times (V_2^2 - V_1^2) = \frac{1}{2} \times 700 \times 10^{-6} \times (3.874^2 - 3.553^2) \approx 8.3 \times 10^{-4} \text{ J} \quad (5)$$

The average stored power P_{stor} can be calculated as:

$$P_{stor} = \frac{\Delta E}{\Delta t} \approx \frac{8.3 \times 10^{-4}}{10} = 8.3 \times 10^{-5} \text{ W} = 83 \text{ uW} \quad (6)$$

At this operating point, the charging efficiency of the bq25570 can be estimated as:

$$\eta = \frac{P_{stor}}{P_{in}} \approx \frac{83}{125} = 66.4\% \quad (7)$$

Experimental results confirm that the bq25570 can be programmed via the resistor network and delivers the expected outputs. Under indoor illumination, the device successfully completes energy accumulation, threshold-based decision-making, and regulated power delivery, demonstrating robust adaptivity to low and intermittent input power. The measured charging efficiency reaches approximately 66%, enabling reliable system powering and efficient energy harvesting and management.

It should be noted that this value represents a net stored-energy efficiency, and it does not explicitly account for capacitor leakage, the system's standby consumption during the test, or the bq25570's internal operating losses. If these factors are included, the effective input power and total conversion losses can be refined through longer-duration measurements or component-level (separated) characterization.

Table 2 shows the performance of the SHT31 temperature–humidity sensing module. In a short-term response test, the measured humidity changes from 72.6% RH to 86.5% RH and the temperature increases from 29.6 °C to 33.6 °C, indicating that the sensor can track rapid microenvironment variations. In a temperature-cycling damp-heat chamber test over −10 to 40 °C, the SHT31 readings remain close to the reference values. The temperature error is within ±1 °C and the humidity error is within ±3% RH, supporting reliable environmental monitoring for the proposed passive monitoring tag in grain-carton warehousing.

Table 2. Sensing module data acquisition.

Time	Original Data	Humi	Temp
15:17:12:367	R:072.6RH 029.6 °C	72.6% RH	29.6 °C
15:17:16:365	R:078.3RH 031.2 °C	78.3% RH	31.2 °C
15:17:20:389	R:086.6RH 033.6 °C	86.6% RH	33.6 °C

Figure 14 presents the measured RF output of the LoRa module under a 3.3 V supply using a 20 dB attenuator. The transmit spectrum is centered at 433 MHz, and the output power is approximately 20 dBm. In open outdoor conditions, 433 MHz LoRa links are commonly reported to achieve communication distances on the order of hundreds of meters. In grain-carton warehousing with severe attenuation due to three-layer stacked paper cartons and multi-row arrangements, the effective range is reduced; nevertheless, the expected communication distance of 500–800 m is sufficient for cross-area reporting from distributed tags to gateway units in large-scale warehouses.

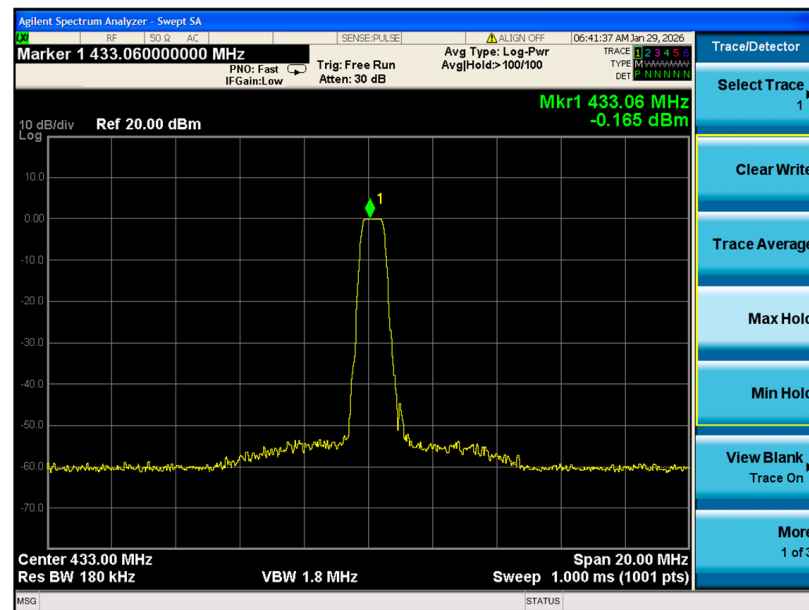


Figure 14. LoRa power output diagram under 3.3 V power supply.

4.2. System-Level Integration Testing

After validating each core module, the LoRa transceiver, bq25570 power-management unit, and SHT31 sensor were integrated into a prototype tag PCB. System-level integration tests were then performed to verify end-to-end operation between an ESP32-based gateway/host and multiple tags. The evaluated pipeline was data acquisition → LoRa uplink → gateway reception and parsing. Figure 15 illustrates the experimental setup.

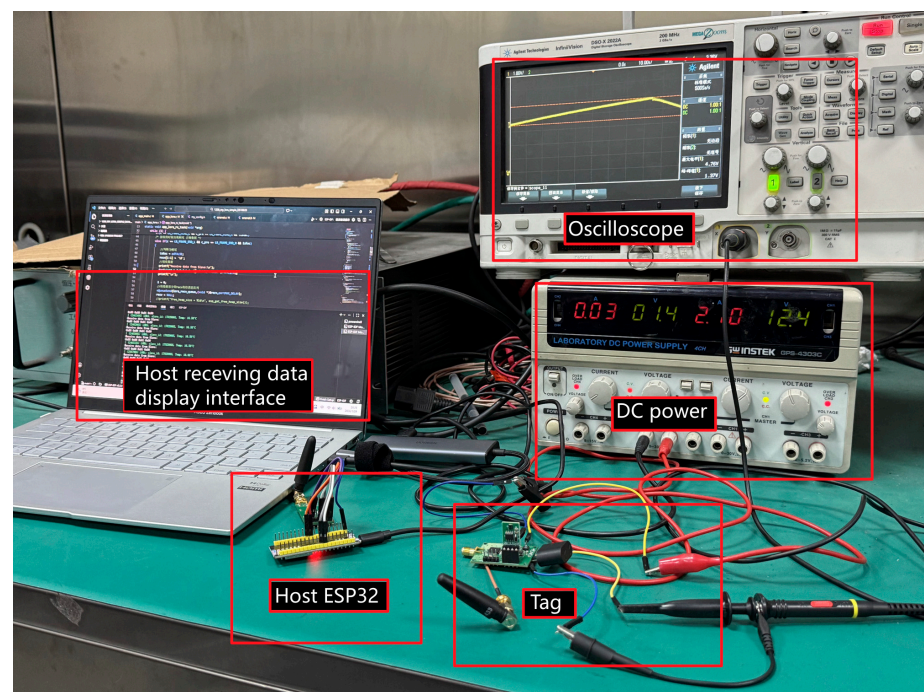


Figure 15. Experimental setup for the system integration test.

Specifically, to speed up testing, a DC power supply was used to emulate the light-harvesting input. The bq25570 harvests and regulates the incoming energy and stores it in the storage capacitor. Once the capacitor voltage reaches the programmed output threshold, power delivery to the load is enabled: the slave tags boot up, and each tag

measures temperature and humidity, transmits a framed payload via LoRa and then enters sleep mode to reduce energy consumption. The ESP32 gateway receives the packets and parses the frame fields to recover the tag ID and sensor readings.

As shown in Figure 16, three tags were deployed in different environments and successfully reported to the gateway. The host received multiple replies, for example, tag ID 0d020002 reporting 49.0% RH and 28.2 °C; other tags followed the same framing logic. The decoded tag IDs and measurements matched the transmitted frame contents, indicating stable multi-tag communication and reliable centralized parsing. These results satisfy the system requirement of low-power sensing, reliable transmission, and centralized gateway-side processing for grain-carton warehousing.

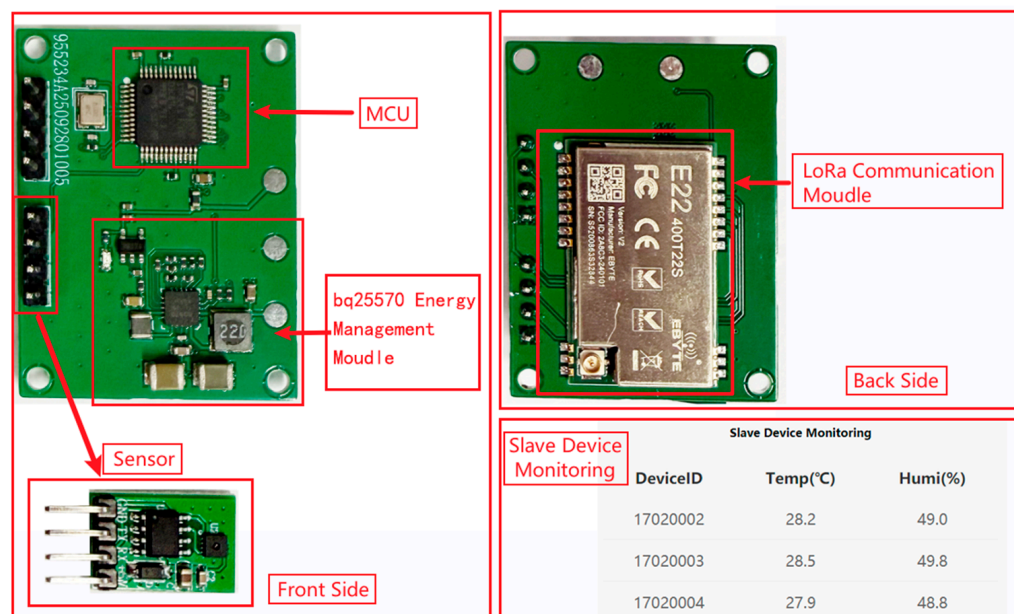


Figure 16. Photograph of the tag prototype and the host-PC test results.

5. Conclusions

The proposed distributed LoRa passive monitoring system for grain-carton temperature and humidity sensing is enabled by light energy harvesting and power management, integrating bq25570-based energy management, SHT31 sensing, and LoRa communication. The main performance results are summarized as follows. The bq25570 achieves a charging efficiency of >50% under low warehouse illuminance and, together with a 0.1 F storage element, supports continued tag operation. The SHT31 provides measurement errors within ± 1 °C (temperature) and $\pm 3\%$ RH (humidity) at room temperature. With a transmit power of ~20 dBm under a 3.3 V supply, the E22-400T22S LoRa module is expected to provide an effective transmission range of 500–800 m after penetrating three layers of stacked grain cartons. Compared with wired monitoring systems, the proposed approach eliminates bus wiring, allowing tags to be embedded directly into cartons and improving deployment flexibility under dynamic stacking. Compared with battery-powered solutions, light-powered operation avoids routine battery replacement; the tag enters deep sleep with a current of ~3 μ A, reducing maintenance effort. Overall, the system provides a scalable and reusable solution for long-term passive monitoring in warehousing and logistics applications.

This study has several limitations. First, the experimental validation was mainly conducted under laboratory and scenario-mimicking conditions; therefore, the long-term stability and robustness in operational warehouses with varying illumination, stacking patterns, and environmental disturbances still require further verification. Second, the penetration and communication performance was evaluated with three-layer stacked

cartons and a limited number of prototype tags; larger-scale deployments with more tags and diverse carton materials/stack geometries should be examined to fully characterize multi-tag access performance and link reliability. In addition, the reported transmission range after carton penetration is currently based on the present test setting and is expected to be further confirmed in real warehouse layouts.

Field deployment in operational warehouses and long-term stability evaluation will be conducted in future work. To further enhance practicality under harvested-energy constraints, this study will evaluate alternative sensing elements with lower standby and measurement currents, while maintaining the required accuracy for grain-storage monitoring. Moreover, LoRa parameters will be tuned for specific warehousing scenarios (e.g., stack height, carton density, and gateway placement) by jointly optimizing spreading factor, bandwidth, coding rate, and transmit power to reduce airtime and energy consumption. These improvements are expected to increase robustness and extend operating time under low-light and intermittent illumination.

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