

An Energy-Harvesting Shield and Solar Testbed for IoT: LoRa Performance Insights and Power Measurements

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Abstract

Designing firmware for energy-harvesting (EH) IoT devices requires testing under realistic and repeatable conditions, yet most simulation tools abstract away critical physical constraints, and field testing is often impractical or non-reproducible. This paper presents a two-part platform to address this challenge: (i) a modular shield for the STM32 NUCLEO development boards that integrates a solar panel, energy harvesting power management, environmental and motion sensors, GPS, and flash memory; and (ii) an indoor testbed that reproduces real-world solar irradiance using programmable dimmable lamps driven by recorded sunlight traces. Together, these tools enable reproducible experimentation on energy-aware firmware, including runtime adaptation and energy budgeting strategies. Furthermore, we analyze real-world LoRa communication performance and highlight a lesser-known phenomenon where higher spreading factors, while theoretically robust, experience signal degradation due to synchronization loss. Our platform provides a practical foundation for long-term, realistic evaluation of EH-powered IoT systems.

Keywords

Energy harvesting, Solar-powered IoT, LoRa communication, Indoor testbed, Wireless sensor networks

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1 Introduction

In recent years, energy harvesting (EH) has emerged as a promising solution to power Internet of Things (IoT) devices deployed in remote or hard-to-reach environments such as wildlife monitoring, environmental sensing, or smart agriculture. By harvesting ambient energy—e.g., solar, thermal, kinetic, or RF sources—these systems can operate without battery replacement or wired power, enabling long-term autonomous deployments [1–3]. Solar energy harvesting, in particular, is among the most efficient sources for outdoor deployments, offering high energy density and widespread availability. However, designing and validating energy-aware algorithms for such devices is challenging [4]. Unlike traditional systems with stable power supply, EH-based devices must adapt to unpredictable, non-stationary energy availability, which depends on environmental conditions that fluctuate over time and space. This creates a significant obstacle for evaluating energy management strategies and optimization algorithms, such as those for sampling frequency, duty cycling, or data transmission [5, 6].

Simulation-based approaches often abstract away physical constraints and require synthetic or over-simplified models of energy input [7]. On the other hand, field experiments are time-consuming, weather-dependent, and difficult to control or replicate [8]. In this paper, we present two complementary contributions aimed at advancing the development and validation of energy management algorithms for solar-powered IoT devices. First, we introduce a custom shield designed to be mounted on a NUCLEO development board [9], extending its capabilities with multiple sensors, a solar panel, and an energy harvesting power management system. This board is designed to support experimentation with adaptive firmware and energy-aware protocols. Using this platform, we experimentally characterize LoRa by combining power consumption profiling with a field campaign measuring link



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quality (RSSI/SNR) and reliability over different spreading factors and distances. The results show how energy usage scales with configuration and reveal that, at high spreading factors, synchronization drifts can degrade post-correlation SNR, impacting link robustness. Second, we describe a flexible indoor testbed that enables long-term simulations of energy harvesting algorithms under controlled yet realistic solar conditions. The testbed reproduces solar irradiance using programmable dimmable lamps driven by real-world irradiance traces.

2 Related Work

2.1 IoT Development Boards

Several development platforms have been proposed to support experimentation with energy-harvesting IoT systems. Notably, Texas Instruments offers the *TIDA-00488 Solar Energy Harvester for MSP430* kit, a reference design built around the MSP430 microcontroller, equipped with an energy harvester and designed for outdoor solar applications [10]. Silicon Labs provides the *xG22-EK8200A Energy Harvesting Explorer Kit*, which supports dual-source energy harvesting (photovoltaic and kinetic) using e-peas PMICs and is aimed at real-world IoT deployments [11]. Other kits include the Microchip *PIC24F16KA102 XLP Energy Harvesting Development Kit*, which integrates a Cymbet energy harvester and solid-state battery to demonstrate solar-powered operation both indoors and outdoors [12]. Texas Instruments further offers the *eZ430-RF2500-SEH Solar Energy Harvesting Kit*, which combines an MSP430 sensor node with a IXOLAR KXOB25-04X3F solar panel and EnerChip battery modules for long-term field deployment [13].

These platforms enable power management experimentation, but often lack a complete sensor-radio-logger integration suitable for firmware-level evaluation. Our shield extends this landscape by offering a cohesive integration of harvesting, sensing (including GPS), storage, and sub-GHz LoRa communication suitable for adaptive and energy-aware firmware research.

2.2 Solar Energy Harvesting Platforms

Some platforms are specifically optimized for outdoor deployment. PowerFilm, in collaboration with e-peas, developed a rugged energy harvesting kit that combines outdoor-capable solar panels, supercapacitors, and PMICs to power ultra-low-power IoT electronics in exposed environments [14]. Analog Devices and STMicroelectronics also offer outdoor-optimized PMICs, such as the ADP5090 and SPV1050, which support Maximum Power Point Tracking (MPPT) and high-efficiency solar harvesting at low voltage levels [15]. Additionally, EnOcean technology provides batteryless wireless sensor modules for building automation and industrial settings, relying

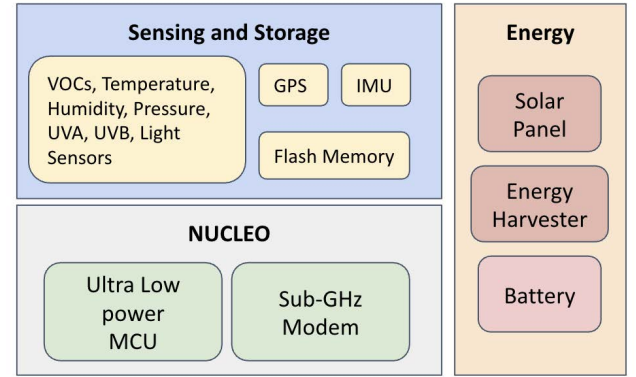


Figure 1: Functional block diagram of the RESTART system architecture.

entirely on environmental energy sources like indoor light, thermal gradients, or mechanical motion [16].

While these outdoor-capable solutions prioritize reliability and efficiency in energy collection, they rarely include integrated sensing or communication subsystems tailored for energy-aware experiments at the firmware level.

3 RESTART NUCLEO Shield

The RESTART board is a hardware extension (“shield”) designed specifically for the STM32 NUCLEO development boards. Its purpose is to provide all the necessary peripherals to evaluate energy harvesting strategies and energy-aware firmware in long-term IoT deployments.

3.1 Hardware architecture

The RESTART board architecture, depicted in fig. 1, is organized into three key domains: sensing and storage, computation and communication, and energy supply.

On the sensing side, the shield integrates a diverse set of environmental sensors, including Volatile Organic Compounds (VOCs), temperature, relative humidity, absolute pressure, acoustic sensor, UVA, and UVB light sensors. It also includes an Inertial Measurement Unit (IMU), a GPS receiver, and NOR flash memory for local data storage. These components are optimized for low-power operation and support a variety of energy-aware application scenarios.

At the core, the STM32 NUCLEO-WL55JC board provides an ultra-low power microcontroller and a sub-GHz LoRa modem, enabling programmable control and long-range wireless connectivity.

The energy subsystem includes a solar panel as the primary power source, an energy harvesting circuit based on the BQ25504, and a rechargeable battery for storage and regulation. This setup enables autonomous operation under

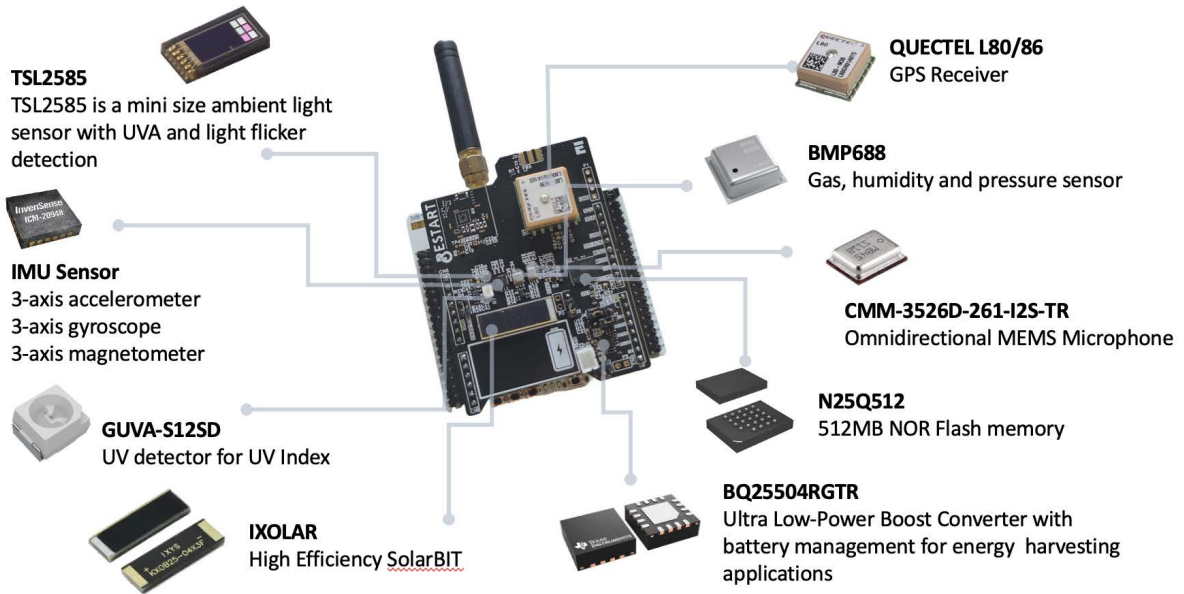


Figure 2: RESTART board and major components. The image highlights key sensors, energy harvesting circuitry, storage, and communication modules integrated on the shield.

intermittent energy availability, making the platform suitable for real-world, long-term deployments in outdoor and energy-constrained environments.

3.2 Hardware Components

The RESTART shield has been designed to equip the NUCLEO-WL55JC board with all the necessary components for realistic experimentation in energy-harvesting IoT scenarios. An exploded view with the major components is shown in fig. 2. It integrates three functional domains: energy harvesting and regulation, environmental and inertial sensing, and localization and data storage.

The power subsystem is based on a high-efficiency IXOLAR solar panel, with compact dimensions (22 mm x 7 mm x 1.8 mm) and maximum power output of 22 mW, is capable of providing energy even in low-light conditions. Energy harvested from the panel is regulated and stored using the Texas Instruments BQ25504 IC, a widely used ultra-low-power boost converter and power manager. This component supports cold-start operation from input voltages as low as 330mV, and implements maximum power point tracking (MPPT) to dynamically adapt to solar irradiance conditions. The energy is stored in a rechargeable lithium battery, enabling the system to operate autonomously even in periods of low or no sunlight. Output voltage can be regulated to match the requirements of the NUCLEO board and attached peripherals.

For sensing capabilities, the shield integrates a rich set of low-power environmental and motion sensors that allow developers to emulate realistic workloads across various applications. The TSL2585 provides ambient light measurement, UVA sensitivity, and flicker detection, making it particularly suitable for light-aware duty cycling or solar calibration tasks. UV exposure is further characterized by the GUVVA-S12SD sensor, which provides UV index readings. Motion and orientation are captured using the ICM-20948, a 9-axis Inertial Measurement Unit (IMU) that combines a 3-axis accelerometer, gyroscope, and magnetometer, enabling activity recognition, movement classification, or animal behavior tracking. Atmospheric conditions are monitored by the Bosch BME688, a compact sensor that simultaneously measures gas concentration (for VOC detection), temperature, humidity, and barometric pressure. Additionally, an omnidirectional MEMS microphone (CMM-3526D) allows for acoustic event detection and ambient sound profiling, which can be relevant in wildlife monitoring scenarios.

In terms of localization and storage, the board integrates a Quectel L80/86 GNSS receiver, enabling geolocation features for mobile nodes or GNSS-triggered events. To support energy-aware data logging and autonomous operation over long periods, the shield includes a 512Mbit NOR flash memory (Winbond N25Q512), which offers persistent storage for sensor readings, energy status, and internal decision metrics. This component enables local buffering in scenarios with

intermittent connectivity or strict power budgets that delay communication.

All components have been selected for their low power consumption and high integration, making the shield suitable for evaluating dynamic trade-offs between sensing, communication, and energy availability. The modular architecture also facilitates firmware-controlled peripheral activation, allowing fine-grained energy-aware strategies to be implemented and validated.

4 Board testing

The NUCLEO-WL55JC [9] board used in this work integrates the STM32WL microcontroller, which supports multiple sub-GHz communication protocols operating in the 868MHz ISM band, including proprietary FSK, GFSK, and standard stacks. For the remainder of this paper, we focus on the LoRa and LoRaWAN protocols, due to their widespread adoption in low-power long-range IoT applications.

4.1 LoRa Communication Overview

LoRa (Long Range) is a low-power wide-area network (LP-WAN) modulation scheme based on Chirp Spread Spectrum (CSS) technology. It is widely used in energy-constrained IoT deployments thanks to its long-range capabilities and low transmission power. One of the core parameters of LoRa is the *Spreading Factor* (SF), which controls the trade-off between data rate and communication robustness. Higher SF values (e.g., SF12) result in longer transmission time and increased receiver sensitivity, allowing packets to be decoded even at very low signal-to-noise ratios (SNR). Conversely, lower SFs (e.g., SF7) enable faster transmissions with reduced energy cost but shorter communication range.

LoRa devices typically operate in either transmission (TX) or reception (RX) mode, each with distinct energy profiles and timing behavior. These modes, combined with adaptive data rate (ADR) mechanisms, allow for dynamic tuning of communication parameters based on link conditions and energy availability. A detailed description of LoRa PHY and MAC layer behavior is beyond the scope of this work; we refer the reader to [17] for an in-depth treatment.

4.2 Measurement Setup

To accurately characterize the power consumption of LoRa transmissions on our board, we employed the Nordic Power Profiler Kit II (PPK2) as showed in Fig. 3. This tool enables high-resolution current measurements with sampling rates up to 100kHz and is well suited for capturing fast transients typical of wireless communication events. The board was powered at different voltage levels (3.6V, 3.8V, and 4.0V) to reflect varying battery states in real-world solar-powered devices.

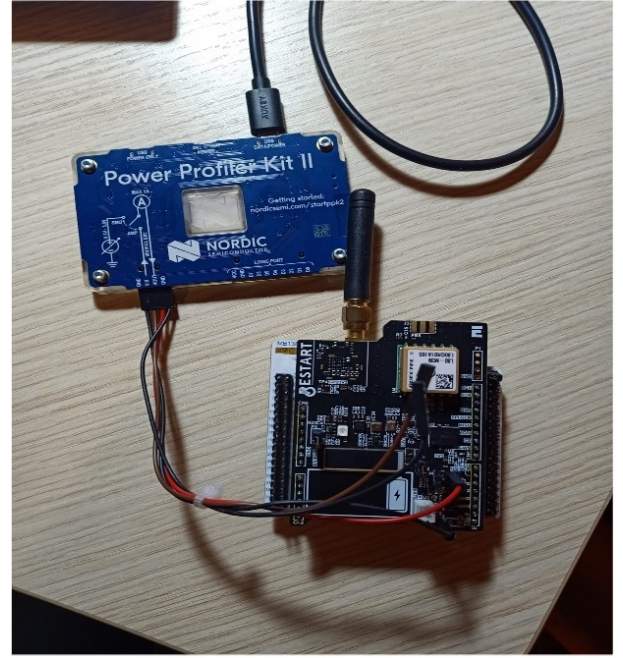


Figure 3: Power measurement test with PPK2

4.3 Current Profile and Analysis

Figure 4 shows the current trace captured during a complete LoRa transmission at spreading factor SF12. The profile highlights five distinct phases:

- **Initialization:** A short peak (up to ≈ 60 mA) associated with wake-up, internal checks, and sensor polling.
- **Activation:** A plateau between 20 and 40 mA as the radio is powered and configured.
- **Transmission (TX):** A sustained high-current interval (35–45 mA) corresponding to packet transmission, with occasional sharper peaks due to power amplifier ramp-up.
- **Reception (RX):** Moderate current draw (10–15 mA) while the radio is actively listening for downlink packets.
- **Idle/Sleep:** Return to the baseline state (< 1 mA), where only minimal leakage and background tasks are active.

The entire event lasts about 18.2 s, with an average current of 13.37 mA and a peak of 62.2 mA. The measured charge consumption is 243.25 mC, which corresponds to an energy expenditure that scales with the chosen supply voltage. This trace clearly illustrates how duty cycling and radio activity dominate the energy budget of LoRa devices.

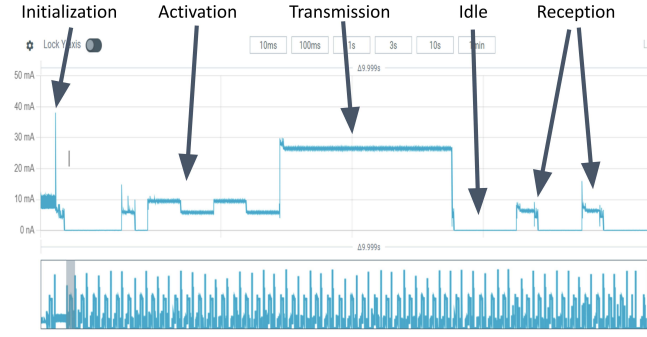


Figure 4: Current consumption profile during a LoRa SF12 transmission.

4.4 Energy Consumption Results

Table 1 reports the average energy required to transmit and receive a single packet at SF7 and SF12 across three supply voltages. Each value is the mean of ten independent measurements, estimated from the current profiles and supply voltage. The results confirm that higher spreading factors significantly increase the energy cost per packet, both due to longer transmission time and to extended reception windows.

The results clearly show that energy consumption increases slightly with supply voltage, due to higher absolute current levels. SF12 transmission requires over 20 times more energy than SF7 because of the increased duration of the transmission interval. More in detail, every transmitted symbol in LoRa can carry a number of coded bits equal to the spreading factor; nevertheless, it is recommended [18] that transmissions lasting more than 16.38 ms enable the low data-rate optimization (LDRO) mode, resulting in two fewer coded bits per symbol. Since the symbol duration is proportional to 2^{SF} , the transmission time at SF12 is $7/10 \cdot 32 = 22.4$ times longer than at SF7, which matches the measured energy ratio. Reception is cheaper than transmission in both cases, but SF12 still doubles the energy compared to SF7. In our measurements, the instantaneous power in reception is roughly one third of that in transmission, so the overall energy cost in RX is mainly determined by the reception window duration rather than by the power level itself. In the following discussion, we consider the case where no acknowledgment (ACK) is expected; in such a scenario, the reception time is determined solely by the preamble and payload of the incoming packet. If an ACK were present, the total reception time would also depend on its size and the corresponding transmission duration from the peer device. In the no-ACK case, the duration of the reception depends mainly on the SF, the expected timing error, and the minimum number of symbols required for correct reception. The most influential parameter is the SF: the higher it is, the

Table 1: Energy consumed per LoRa transmission/reception at different voltages.

Voltage Applied	TX SF7 (J)	TX SF12 (J)	RX SF7 (J)	RX SF12 (J)
3.6 V	$1.12 \cdot 10^{-2}$	$2.5 \cdot 10^{-1}$	$2.2 \cdot 10^{-3}$	$5.0 \cdot 10^{-3}$
3.8 V	$1.20 \cdot 10^{-2}$	$2.7 \cdot 10^{-1}$	$2.3 \cdot 10^{-3}$	$5.3 \cdot 10^{-3}$
4.0 V	$1.24 \cdot 10^{-2}$	$2.8 \cdot 10^{-1}$	$2.5 \cdot 10^{-3}$	$5.6 \cdot 10^{-3}$

longer it takes for the device to receive a single symbol, so the reception window must be longer. For example, at SF7 a symbol lasts about 1 ms, while at SF12 it can last over 30 ms. Another important factor is the timing error, i.e., the uncertainty about when exactly the packet will arrive; assuming an error of 20 ms, the window must be wide enough to cover that interval in advance and delay with respect to the expected time. The minimum number of symbols to be received, typically six, also affects the calculation.

5 LoRa Radio Field Test

We conducted a LoRa measurement campaign to evaluate the device's performance and build quality.

Five locations near the Department of Electronic Engineering at the University of Rome Tor Vergata (see Figure 5) were selected based on a decreasing gradient of RSSI (Received Signal Strength Indicator) values. At each point, the device was placed on the ground, and 100 packets were sent to a RAK Wireless WisGate Connect Gateway installed on a nearby building and equipped with a 5.8dBi Fiberglass Antenna. The packets were evenly split: 50 packets using DR0 (Data Rate 0), with a bandwidth (BW) of 125 kHz and a spreading factor (SF) of 12, and 50 packets using DR5, with the same bandwidth but a lower spreading factor of SF 7. This configuration allowed us to evaluate the device's performance under different signal strength conditions and transmission rates, clearly indicating its reliability and data transmission capabilities in real-world scenarios.

The measurement results are shown in Figures 6 and 7, which report the average RSSI and SNR (Signal-to-Noise Ratio), respectively. In Figure 6, the average reported RSSI values for SF12 and SF7 decrease as the distance from the gateway increases. Although the two curves are quite similar, at certain positions (e.g., P2 and P3), SF7 shows slightly more variation than SF12, likely due to its reduced robustness. No value is reported at P5 for SF7, as no packets were received, i.e. the desired signal strength resulted below the receiver sensitivity, for that spreading factor. Note that LoRa is designed to work well even below the noise power level, so the RSSI measurements plateau when the desired signal power falls below the noise level. A noise floor of -112dBm

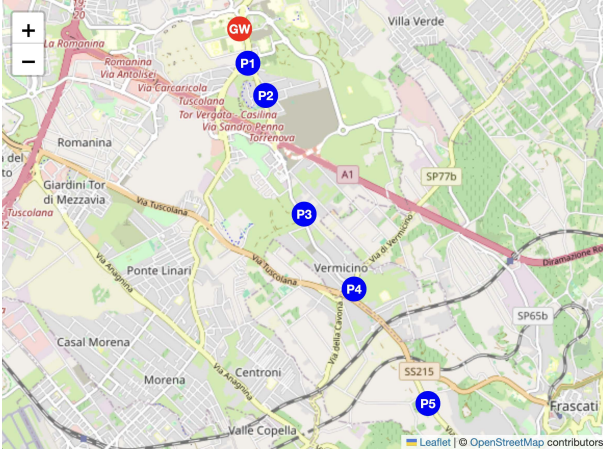


Figure 5: Transmitting locations

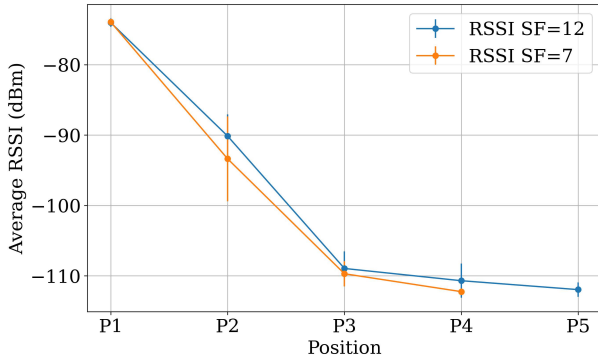


Figure 6: Average RSSI vs. distance for SF12 and SF7

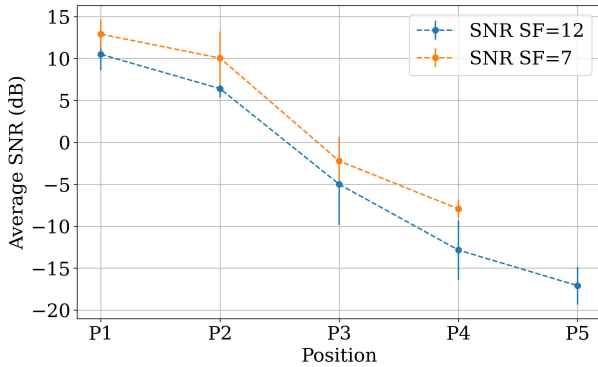


Figure 7: Average SNR vs. distance for SF12 and SF7

corresponds to an equivalent receiver noise figure of approximately $F=10$ dB, for a nominal bandwidth of 125 kHz and $T=300$ K.

Figure 7 shows the measured post-correlation signal-to-noise ratio (SNR), as reported by the device. A first comment

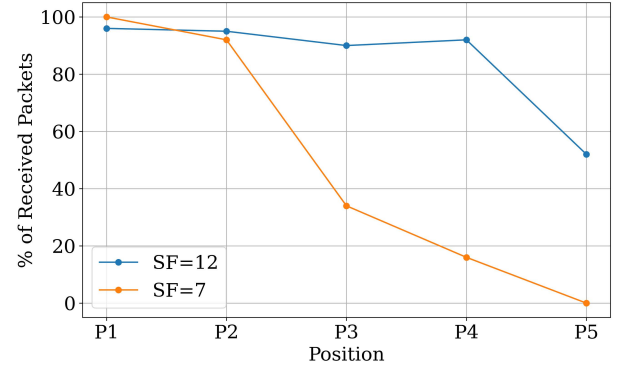


Figure 8: Transmission reliability vs. distance for different SFs

is that, while showing the same decreasing behavior as the RSSI, the SNR yields a seemingly more reliable estimate, and we attribute this phenomenon to the SNR being obtained post-correlation, i.e. later in the receiver chain, while the RSSI is obtained based on a measure of the incoming power.

A second comment is that the two SNR plots in fig. 7 were expected to be overlapping, with a minimum required SNR of -7 dB for SF7 and -19 dB for SF12. This is not the case in our experimental results, as a loss of almost 4 dB is observed. We attribute this discrepancy to the effect of timing offset drifts between the transmitter and the receiver. According to the ST Nucleo-WL55JC specifications, the board features an external high speed 32 MHz crystal oscillator with a typical speed error within ± 10 ppm. Note that communication with high spreading factors results in very long symbol transmission durations, and even small sampling clock drifts result in significant degradation of the SNR. Indeed, Semtech recommends [19] some crystal oscillator error compensation in their application notes, and the LRDO option is enabled by default for higher SFs, just for the purpose of sampling time error tracking with low complexity.

Due to the structure of the synchronization preamble in LoRa, the effects of timing drifts are more relevant in large payload packets, where the timing drift cumulates during the reception of the frame, and is less sensitive for smaller frames. In our evaluation we used packets with a payload of 45 bytes, lasting 1.87 s with LDRO, which would require a clock drift lower than 2.7 ppm in order to be received with a negligible SNR loss and not require enabling the LDRO option (in order to cumulate a timing error lower than half a chip duration). The clock reference stability could be improved, without impacting the low power consumption of our design, substituting the external XO with a temperature-compensated crystal oscillator (TCXO).

Figure 8 highlights that higher spreading factors improve data transmission reliability over longer distances, albeit at

the cost of increased energy consumption. For this device, SF12 — the highest permitted spreading factor for the deployment region — was selected to ensure full coverage across the test area.

6 Solar Irradiance Emulation Platform

6.1 Testbed Structure

The indoor testbed is based on one or more RESTART boards placed under dedicated dimmable AC lamps. The purpose is to emulate solar irradiance conditions using controlled artificial lighting, enabling reproducible testing of energy-harvesting firmware. The vertical distance between each lamp and board is set to approximately 40–50 cm, based on empirical testing to ensure uniform illumination across the solar panel. This physical layout allows for flexible configurations, ranging from single-board experiments to parallel multi-node setups.

6.2 Lamp Control and Irradiance Reproduction

Each lamp is driven by a ROBOTDYN AC dimmer [20] controlled via phase-angle modulation, with a pulse-width modulation (PWM) signal generated by an ESP32 microcontroller [21]. The ESP32 receives the target irradiance values from preloaded time-series traces and maps them to dimmer settings through a calibrated lookup table, ensuring a smooth and monotonic change in brightness. Although the spectral output of the lamps does not perfectly match the AM1.5G standard, adopting standardized solar simulator lamps would allow a more accurate spectral reproduction and improve the reliability of optical sensor measurements on the RESTART board. The system supports two timing modes. In the basic configuration, the ESP32 maintains time with its internal clock starting from a predefined reference. In the networked configuration, it synchronizes periodically over Wi-Fi using the NTP protocol, ensuring alignment with real-world time during long-term experiments.

6.3 Solar Irradiance Datasets

The irradiance traces used to drive the lamps are derived from the U.S. National Solar Radiation Database (NSRDB) [22]. This database provides high-resolution solar resource data for thousands of locations, generated through a combination of satellite imagery, weather models, and ground-based measurements. For our experiments, we selected the “PSM v3” dataset for Miami (Florida) covering a 10-day period in July 2012, representative of typical summer conditions with high and stable irradiance.

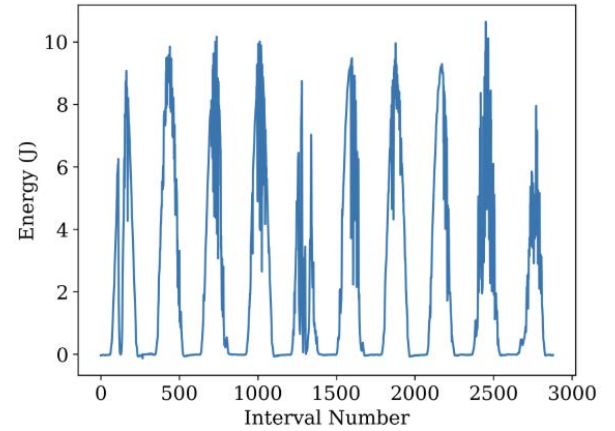


Figure 9: Example of solar irradiance profile over ten days in Miami, FL.

The dataset, downloaded in CSV format via the NSRDB Data Viewer, includes timestamp, Global Horizontal Irradiance (GHI, in W/m^2), and location metadata. The GHI values, sampled at 5-minute intervals, are linearly normalized to a 0–100% range before being fed to the lamp control system. No filtering or smoothing is applied so that short-term variability, such as cloud cover or haze, is preserved. The same trace can be replayed cyclically to evaluate firmware behavior under repeatable yet realistic energy input conditions. Figure 9 shows a typical GHI profile used in our experiments.

6.4 Calibration of Artificial Illumination

The photovoltaic cell integrated in the RESTART shield is used as a reference sensor to calibrate the indoor light sources. By measuring its short-circuit current under sunlight, a baseline is established that reflects the maximum charging capability of the device. The same measurement is then repeated under the testbed lamps at different distances and dimmer levels, allowing us to determine the fraction of solar input reproduced indoors. In this way, the dimmer setting corresponding to the measured target current defines the maximum charging condition for experiments, while intermediate values are scaled accordingly. This procedure links the datasheet specification, the outdoor reference, and the artificial illumination into a coherent method for reproducing realistic solar-powered operating conditions in the laboratory. It should be noted, however, that the calibration remains relative, since the spectral distribution of artificial lamps differs from that of sunlight and thus affects the photovoltaic response. This limitation is acceptable for our target scenario, as devices are rarely exposed to direct sun and typically harvest energy under shaded or attenuated light conditions.

7 Firmware Simulation and Validation Potential

One of the key advantages of the solar testbed is that it enables a structured workflow for the development and evaluation of energy-aware firmware. When designing new algorithms for energy management, the first step typically involves building a simplified energy model of the device. This model defines the different operational states—such as sensing, communication, and sleep—and associates each of them with an energy cost, often measured empirically on the actual hardware.

Based on this model, a state machine is defined that governs how the device should behave under varying energy conditions. Transition rules can take into account both the energy level stored in the battery and external factors such as the time of day or recent activity history. Once the state machine is designed, its performance can be explored through simulation, using realistic solar input data over long time periods. A notable example of such an approach is presented in [23], where energy traces from real irradiance datasets are used to simulate device behavior and evaluate firmware strategies. At this point, the testbed becomes a critical tool. By reproducing the same solar irradiance profile that was used in the simulation, the testbed allows the developer to run the real firmware on real hardware, under controlled but realistic energy conditions. This makes it possible to directly compare the simulated behavior with the actual one, and to validate or refine the design choices made during the modeling phase.

7.1 Conclusions

The proposed testbed offers a reproducible environment for evaluating solar-powered IoT devices. Based on the RESTART shield—featuring a photovoltaic cell, energy management, LoRa radio, and sensors—it has been used to characterize communication energy costs and link quality across spreading factors and distances. By combining the board with programmable lighting and irradiance datasets, the system supports realistic long-term indoor experiments. This bridges simulation and practice, providing a solid basis for adaptive energy management and communication strategies under realistic solar-powered conditions.

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