A LoRa-Based Energy-Harvesting Sensing System for Living Environment

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***Abstract*—Recent years have witnessed rapid deployments of low-cost, low-power devices in living environment to support various Internet of Things (IoT) based monitoring systems and sensing applications. As an emerging Low-Power Wide-Area Network (LPWAN) technology, LoRa provides a low-cost wireless solution that supports long-range data collection for low data rate applications. Although LoRa offers many new opportunities to provide fine-scale measurements in living environment, it is often very costly to run cables to power those sensing devices. Recently, equipping LoRa networks with solar energy harvesting capability is attracting more and more attention, because solar panels are cost-effective, easy to deploy, and provide renewable energy for sensors without the need to run cables. However, there have been very few studies looking into the reliability of powering the LoRa devices for sensing in living environment through solar energy harvesting. We develop a new LoRa-based energy-harvesting sensing system and leverage it to perform a series of real-world experimental studies. Experimental results not only demonstrate the feasibility of using solar energy to power LoRa devices for sensing tasks in living environment but also reveal important challenges on supporting the applications with high sampling rate requirements.**

***Index Terms*—Internet of Things, sensing in living environment, prototype, LoRa, energy-harvesting**

I. Introduction

Recent years have witnessed rapid deployments of low-cost, low-power devices in living environment to support various Internet of Things (IoT) based monitoring systems and sensing applications. As an emerging Low-Power Wide-Area Network (LPWAN) technology, LoRa provides a low-cost wireless solution that supports long-range data collection for low data rate applications. Over the past decade, LoRa networks have been deployed in 153 countries to support various applications, such as smart city, smart energy, and smart home [1]–[9]. For example, 19,821 LoRa devices and 100 gateways have been deployed in an urban area in China to support 12 kinds of smart city applications, such as gas meter monitoring, water meter monitoring, and gas alarming [1]. LoRa offers many new opportunities to provide fine-scale measurements in living environment. Unfortunately, it is often very costly to run cables to power those LoRa devices.

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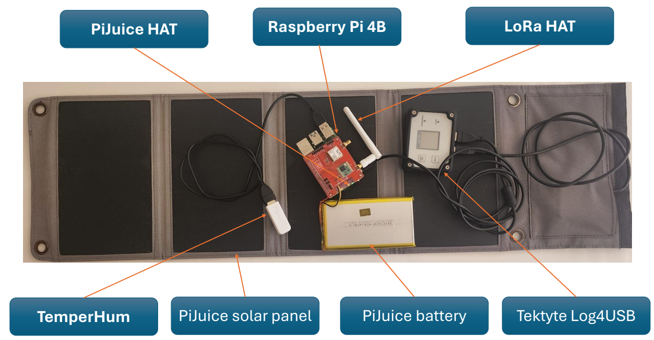


Fig. 1: LoRa-based sensing platform hardware.

Recently, equipping LoRa networks with solar energy harvesting capability is attracting more and more attention, because solar panels are cost-effective, easy to deploy, and provide renewable energy for sensors without the need to run cables. However, there have been very few studies looking into the reliability of powering the LoRa devices for sensing in living environment through solar energy harvesting. We develop a new LoRa-based energy-harvesting sensing system and leverage it to perform a series of real-world experimental studies. Experimental results not only demonstrate the feasibility of using solar energy to power LoRa devices for sensing tasks in living environment but also reveal important challenges on supporting the applications with high sampling rate requirements.

Our paper is organized into the following sections. Section II introduces our LoRa-based sensing platform. Section III presents our experimental study. Section IV reviews the related work. Section V concludes this paper.

II. Sensing System in Living Environment

In this section, we present the hardware design of our LoRa-based sensing platform and the software design of our sensing system.

A. Hardware Design

Figure 1 shows the hardware of our sensing platform. Our platform is built by integrating several Commercial Off-the-shelf (COTS) hardware modules, including

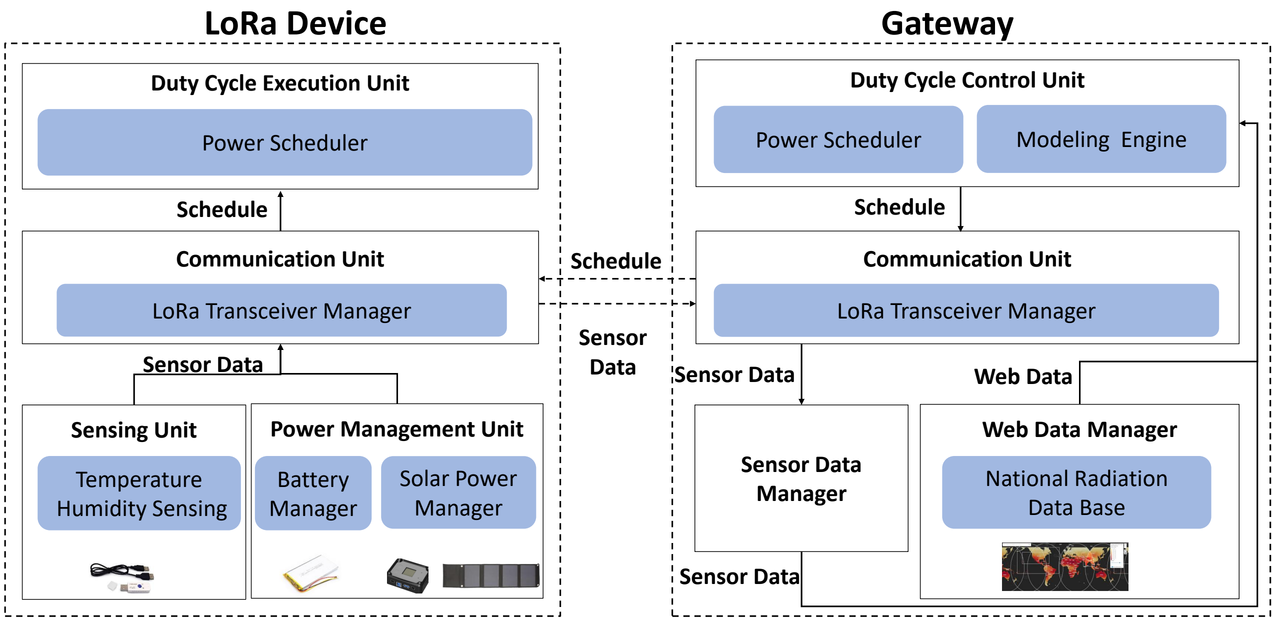


Fig. 2: Software architecture of our sensing system.

a Raspberry Pi computer, a hygrometer, a LoRa GPS Attached on Top (HAT), a PiJuice HAT, a PiJuice solar panel, a PiJuice battery, and a multi-meter. The Raspberry Pi 4 Model B [10] serves as the core computation unit and manages all sensing and communication functions. The TemperHum hygrometer [11] generates the temperature and humidity readings. Other sensors can be integrated to our platform based on the application's needs. The Dragino LoRa GPS HAT [12] equipped with a Semtech SX1276/SX1278 LoRa transceiver [13] supports LoRa communication. The PiJuice HAT [14] and the PiJuice solar panel [15] harvest solar energy and store the excess power stored in the PiJuice battery [16]. The Tektyte Log4USB multi-meter [17] measures the solar panel's energy output. Our platform supports the sleep mode, which reduces the power consumption from seven watts (active mode) to nearly zero. The total hardware cost is $506: $55 for the Raspberry Pi computer, $32 for the hygrometer, $32 for the GPS module, $69 for the power module, $112 for the solar panel, $35 for the battery, and $171 for the multi-meter.

B. Software Design

The software architecture of our sensing system is depicted in Figure 2. There are two pieces of software: one running on each LoRa device and the other running on the gateway. The software that runs on the LoRa device consists of four main units: Sensing, Power Management, Communication, and Duty Cycle Execution. The Sensing Unit manages temperature and humidity sensors. The Power Unit monitors the battery level of the onboard battery and the solar panel's current generation. Such readings together with temperature and humidity measurements are collected and forwarded to the gateway by the Communication Unit. The Duty Cycle Execution Unit periodically puts the platform into sleep mode to reduce its energy consumption based on the schedule created by the gateway.

The software that runs on the gateway consists of two units: the Communication Unit, and the Central Control Unit. The Communication Unit receives sensor data from the LoRa devices and forwards them to the cloud for analysis. The Central Control Unit allows the application to specify the sampling rate for each LoRa device and generates the operation schedule (active-sleep) accordingly.

III. Experimental Study

We perform a series of experiments to explore the feasibility of using solar energy to power LoRa devices for sensing tasks in living environment. We first perform a 50-day real-world measurement to examine the capability of our system to provide reliable temperature measurements in an urban environment. We then perform a set of controlled experiments to investigate the performance of our sensing system when it uses different sampling rates. Finally, we investigate the effect of weather on the performance of our sensing system.

A. Sensing Performance

We have implemented our sensing system system and deployed the LoRa devices and gateways in Miami, Florida. We first perform a 50-day real-world measurement to examine the capability of our system to provide reliable temperature measurements. We put the LoRa device in a

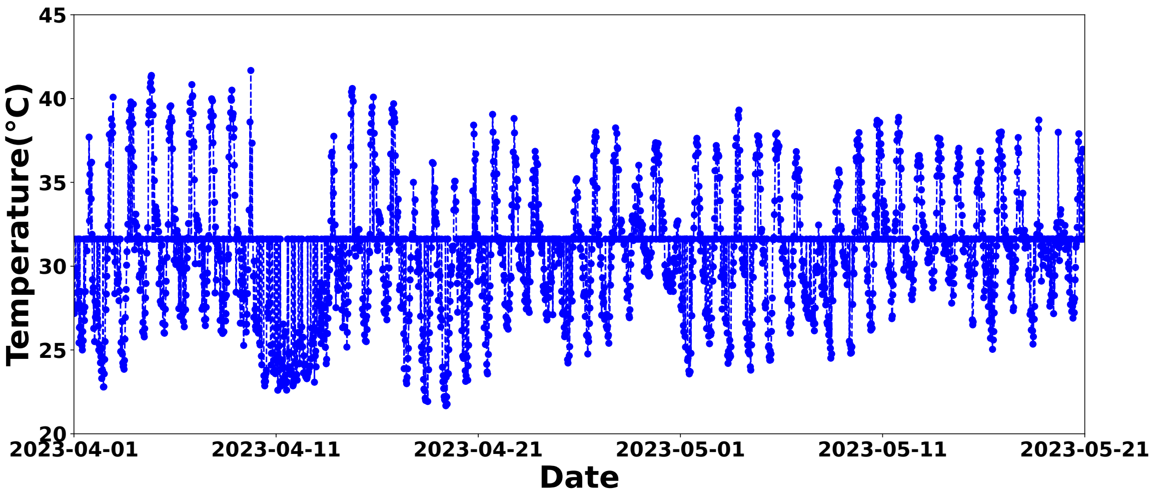
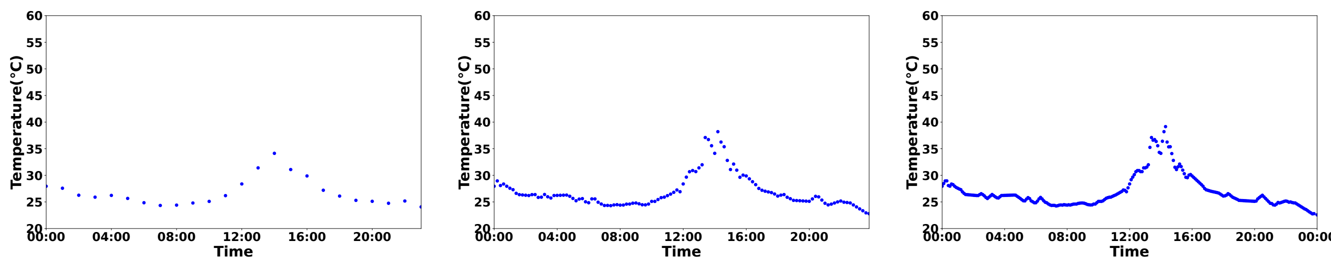


Fig. 3: Temperature measurements over 50 days.



(a) Day 1: One sample per hour.

(b) Day 2: Five samples per hour.

(c) Day 3: Ten samples per hour.

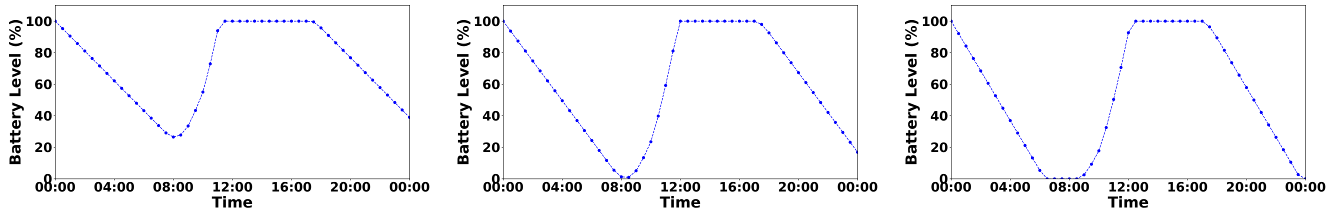
Fig. 4: Temperature measurement with different sampling rates.

weatherproof box for outdoor deployment and configure it to generate two samples per hour. Figure 3 plots the temperature measurements collected from April 1 to May 20, 2023 (50 days). The temperature in April ranges from 21.4°C to 42.0°C and the one in May varies from 23.3°C to 39.4°C. Our sensing system successfully delivers all readings generated by the LoRa device with a 100% delivery rate.

We then perform a set of controlled experiments to investigate the performance of our system when the LoRa device generates data at different rates. We configure the LoRa device to generate one sample per hour during the first day, increase the sampling rate to five samples per hour during the second day, and double the sampling rate for the third day. Figure 4 plots the temperature measurements over those three days. As Figure 4 shows, more temperature variation details are captured by our system when the LoRa devices employ a higher sampling rate. More importantly, Figure 3 and Figure 4 demonstrate the flexibility of using solar energy to power our LoRa-based sensing platform to provide reliable measurements in a real-world living environment.

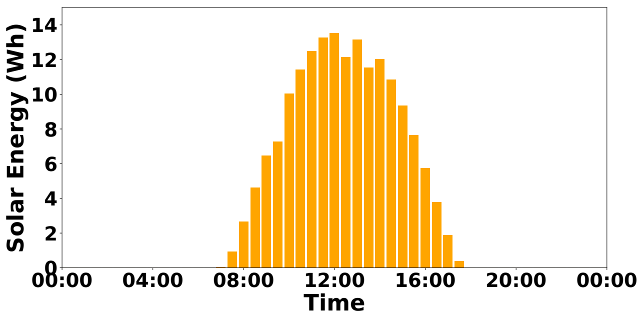
B. *Effect of Weather*

We further investigate the effect of weather on the performance of our sensing system. Figure 6a plots the solar energy produced during a sunny day and Figure 6b shows the precipitation of that day. We divide 24 hours into 48 half-hour time periods and report the amount of produced solar energy during each time period in Figure 6a. As Figure 6a shows, the distribution of produced solar energy follows a bell-shaped curve and peaks at noon when the maximum solar irradiance presents. The maximum solar energy produced in each time period is $13.54Wh$. The produced solar energy is 0 before sunrise and after sunset. Figure 5 plots the battery level of the LoRa device over 24 hours on that day when using different sample rates. As Figure 5a shows, the battery level gradually decreases from 100% to 33.8% before sunrise at $7AM$ when the LoRa device generates 34 samples per hour. The battery level increases sharply and reaches 100% before noon. The battery is full until sunset at $6PM$. As Figure 5b shows, the battery level shows a similar pattern when the LoRa device generates 46 samples per hour. Our sensing system experiences a 30-minute service interrupt during $8AM$ and $9AM$ when the LoRa device runs out of battery before

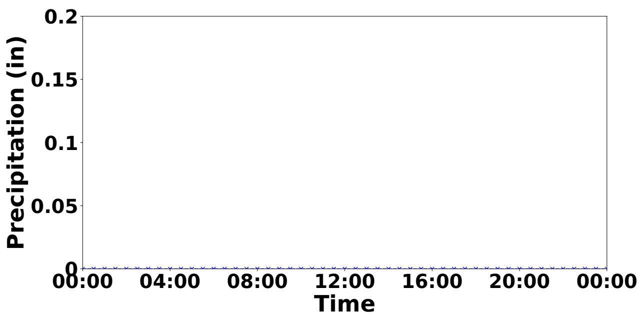


(a) Sampling rate: 34 samples per hour. (b) Sampling rate: 46 samples per hour. (c) Sampling rate: 58 samples per hour.

Fig. 5: Battery level of the LoRa device when using different sampling rates during a sunny day.

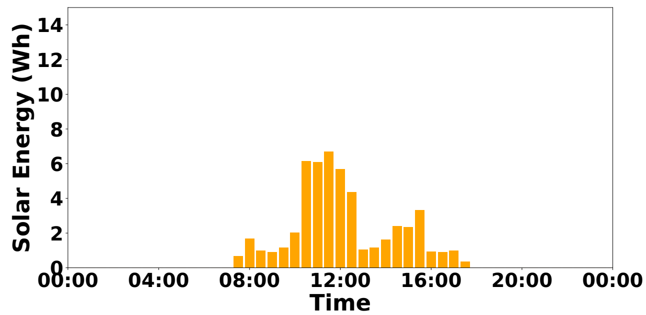


(a) Solar energy generated over 24 hours.

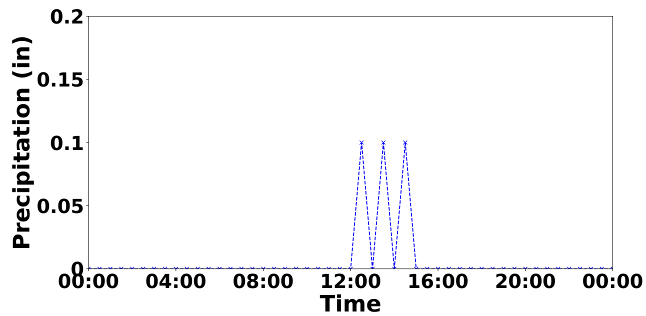


(b) Precipitation.

Fig. 6: Solar energy produced during a sunny day.



(a) Solar energy generated over 24 hours.



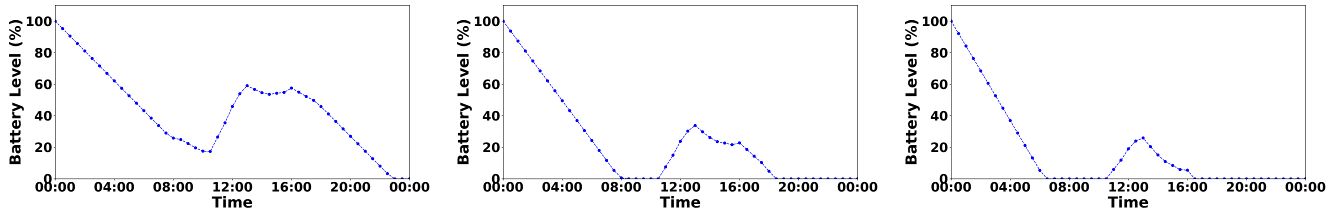
(b) Precipitation.

Fig. 7: Solar energy produced during a cloudy day.

sunrise. The service interrupt increases to 150 minutes when the LoRa device generates 58 samples per hour.

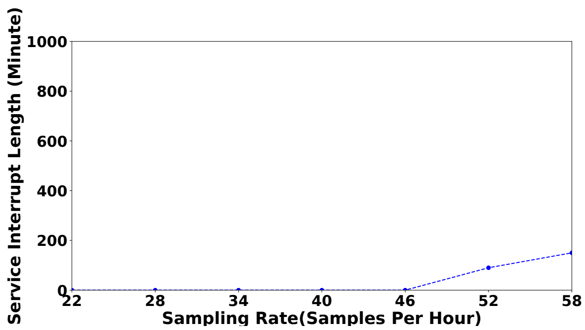
Figure 7a plots the solar energy produced during a cloudy day and Figure 7b shows the precipitation of that day. By comparing Figure 6a and 7a, we observe that the solar energy produced during a cloudy day is much less than the one generated during a sunny day. The maximum solar energy produced within a time period during that cloudy day is $6.70Wh$, $6.84Wh$ less than the one generated during the sunny day. As Figure 7a shows, there was a rainfall between $12{:}30PM$ and $3{:}30PM$. The amount of solar energy generated during the rainfall is small (ranging from $1.04Wh$ and $4.38Wh$ per time period). Figure 8 plots the battery level of the LoRa device over 24 hours on that cloudy day when the LoRa device employs different sample rates. As Figure 8a shows, when the LoRa device generates 34 samples per hour, the battery level gradually decreases from 100% to 43.2% before sunrise and further reduces to 17.3% until $11{:}30AM$. The battery level reaches its maximum at $2{:}00PM$ (59.1%) and varies from 17.3% to 59.1% before sunset. The sensing system stops working at $10{:}30PM$ when the LoRa device runs out of battery. Figure 8b and Figure 8c show similar patterns with longer service interrupts, when the LoRa device runs out of battery at $6PM$ and $4PM$, when it samples at the rates of 46 samples per hour and 58 samples per hour, respectively.

Figure 9 plots the lengths of service interrupts when the LoRa device uses different sampling rates and faces different weather conditions. As Figure 9a shows, our sensing system provides reliable service without any interrupts when the LoRa device generates less than 46 samples per hour during a sunny day. The length of service interrupt increases when the LoRa device generates samples at higher rates. As Figure 9b shows, our sensing system starts to experience service interrupts when the LoRa

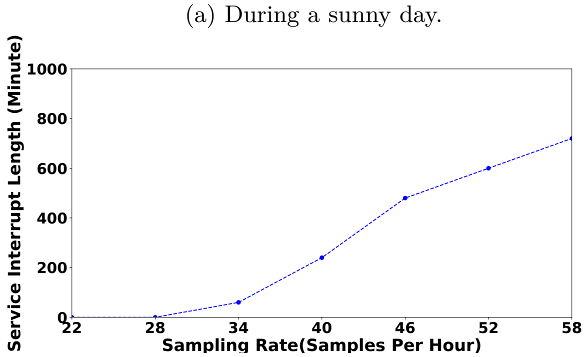


(a) Sampling rate: 34 samples per hour. (b) Sampling rate: 46 samples per hour. (c) Sampling rate: 58 samples per hour.

Fig. 8: Battery level of the LoRa device when using different sampling rates during a cloudy day.



(a) During a sunny day.



(b) During a cloudy day.

Fig. 9: Length of service interrupt when using different sampling rates.

device generates more than 28 samples per hour during the cloudy day. The lengths of service interrupts are 150 minutes and 720 minutes when the LoRa device generates 58 samples per hour during the sunny day and the cloudy day, respectively. The differences between the curves in Figure 9a and 9b present the effect of weather on the performance of our sensing system. The results highlight the important challenge on supporting the applications with high sampling rate requirements. We plan to develop a new solution that maximizes the samples collected during a day by dynamically adjusting the sampling rate of the LoRa device based on weather conditions.

IV. Related Works

The effectiveness and efficiency of using IEEE 802.15.4 based Wireless Sensor Networks (WSNs) for various sensing applications have been extensively studied in the literature. For example, Haefke et al. developed a WSN to collect temperature, humidity, and light measurements and leveraged those readings to create a remote weather station [18]. Endy et al. proposed to use WSNs to monitor indoor and outdoor temperature [19]. Cheick et al. presented a study that examines the performance of WSNs, which are used for precision agriculture [20]. Although IEEE 802.15.4 based WSNs work satisfactorily most of the time thanks to years of research, they are often complex and difficult to manage once the networks are deployed. Moreover, the deliveries of time-critical messages suffer long delay, because all messages have to go through hop-by-hop transport.

Recent studies show that using the LPWANs can effectively overcome such limitations, because network management and time-critical messages can be exchanged directly between LoRa devices and gateway through long-distance links. As an emerging LPWAN technology, LoRa provides a low-cost, low-power wireless solution that supports long-range data collection for low data rate applications [21]. Over the past decade, LoRa networks have been deployed in 153 countries to support various applications, such as smart city, smart energy, and smart home [1]–[9], [22]–[30].

Solar power harvesting is appealing for use for sensing applications because solar panels are relatively inexpensive and easy to deploy, and they provide a renewable power source to operate sensing platforms in locations that are remote, hard to reach, or simply difficult or expensive to run electrical wires or replace batteries. For example, Dutta et al. presented a sustainable wireless network that consists of self-sustaining solar-powered devices [31]. Anzola et al. [32] and Lee et al. [33] developed prototypes of fully renewable wireless sensing platforms powered by solar energy. Bolte et al. introduced a low-power device with a solar panel array and a lithium polymer battery [34]. However, there have been very few studies looking into the reliability of using solar energy to power LoRa-based sensing platforms. This paper aims to provide a real-world experimental study that explores the feasibility and identifies the challenges along such an important research direction.

V. Conclusions and Future Work

This paper details the design of a new LoRa-based sensing system with energy-harvesting capability. Leveraging such a system, we perform a series of real-world experimental studies to explore the feasibility of using solar energy to power LoRa devices for sensing tasks in living environment. Experimental results show that solar energy can effectively power our LoRa-based sensing system to meet the requirements of those applications with low or moderate sampling rates, such as living environmental monitoring, occupancy detection, and water metering. However, the maximum number of samples that can be collected by the solar-power platform largely depends on the weather conditions. Such an observation presents a critical need for new weather-based scheduling methods for those applications with high sampling rate requirements. We plan to address this important issue in our future work.

Acknowledgment

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