Towards Sustainable Greenhouses Using Battery-Free LiFi-Enabled Internet of Things

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***Abstract*—As the world faces a changing climate, agriculture needs to develop more efficient and sustainable food production systems. Traditional farming methods consume considerable amounts of energy and are largely manually controlled, which leads to sub-optimal production. Greenhouses, which enable year-round crop growth, can play an important role in efficient food production. Leveraging the need for artificial light in greenhouses when the natural sunlight available is not sufficient, we envision that recent progress in Internet of Things (IoT) technology, together with novel Light-Fidelity (LiFi)-based methods have the potential to significantly reduce energy and resources used in food production. In this paper we describe our work towards sustainable and precision greenhouses by using LiFi-enabled IoT. Here we present a battery-free wireless network of IoT sensor nodes that exploit LiFi for both communication and power harvesting, while monitoring environmental conditions for optimal greenhouse operation and plant production. We highlight the research challenges and the way forward to integrate LiFi to monitor and control greenhouses, as well as a proof-of-concept LiFi-enabled IoT system for a real-world greenhouse.**

***Index Terms*—Battery-free, IoT, LiFi, precision greenhouses, sustainable greenhouses.**

I. Introduction

With increasing anthropogenic pressure on global ecological systems, the world needs to develop sustainable agricultural systems that reduce land area requirements, and consumption of water, fertilizer, and fossil fuels. Greenhouses enable year-round plant growth that is resilient to weather effects on yield and crop quality. These enclosed systems provide a means to reduce water and fertilizer needs via recycling or closed-loop control systems that use sensors to monitor greenhouse conditions and adjust them as needed, e.g., turning on sprinklers, turning on/off heating/cooling, etc.

The primary challenge to widespread adoption of precision greenhouse is the significant energy demands for temperature control, supplemental lighting, and other systems control functions, as well as the additional investment cost with respect to more traditional farming. Nevertheless, greenhouse production of food is widespread in several parts of the world, and provides a massive opportunity to embed sustainability and contribute to local food production, reducing greenhouse gas emissions from the global food transportation system. These challenges have motivated work on improving greenhouse efficiency [1].

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In particular, addressing the need for artificial light in greenhouses when natural sunlight is not available or sufficient, low-cost, light-emitting diodes (LEDs) have been shown to provide illumination that benefits photosynthesis, contributing to plant growth even in indoor scenarios with artificial lighting [2]. As such, there are systems that automatically adjust the light power in greenhouses, such as the one proposed in [3] or commercial products such as LumiGrow, GrowWise LEDs from Philips, Heliospectra products or GrowFlux. Artificial lighting in agriculture enables a whole new set of techniques and strategies for growing crops, such as controlled-environment agriculture (CEA) and vertical farming. These practices bring reductions in water usage of up to 99% compared to traditional agriculture techniques, improve yield per square meter and reduce labor hours [4]. The worldwide vertical farming market is today twenty times larger than only seven years ago [5]. However, smart lighting systems mentioned above focus on changing light hue and power for optimal plant growth, but do not exploit LED's recently discovered communication capabilities: the light they emit can be modulated at very high speeds not perceived by the human eye. This technology is named Visible Light Communication (VLC), or Light-Fidelity (LiFi) when used in networked systems.

In this paper, we leverage our previous work on enabling battery-free Internet of Things (IoT) nodes using a combination of LiFi and RF backscatter technology [6] and propose the use of this technology to enable battery-free, LiFi-enabled IoT deployments to monitor and control next-generation greenhouses to attain efficient production while reducing greenhouse resource footprint. In addition, in this paper we also discuss the research challenges raised by greenhouses monitored and controlled by Li-Fi enabled IoT, as well as how LiFi enabled IoT systems are dimensioned to effectively and efficiently monitor and control smart greenhouses. Then, we propose to leverage the versatility of LED technology as a way to equip next-generation greenhouses to provide:

- low-power, yet efficient and flexible illumination;
- communication to the IoT tags deployed to monitor the environmental conditions of the greenhouse;
- energy sources to power the IoT tags so that they can operate without batteries for sustainable operation.

Data gathered from the IoT tags is then used to control greenhouse irrigation, lighting, ventilation, humidity, etc. The benefits of the LiFi-enabled IoT system for sustainable greenhouses are many-fold: (1) because of its low cost, the deployment can be as dense as needed for effective greenhouse control; (2) in addition to its low cost and low power, the LiFi-enabled IoT system's battery-free operation is environmentally sound and consistent with its sustainability goals; and, as a result, (3) it requires lower maintenance and human intervention as there are no batteries that have to be replaced or hard-wire data download requirements.

The remainder of this paper is structured as follows. We discuss greenhouse monitoring requirements in Section II. Our LiFi-enabled IoT approach for greenhouse monitoring and control is detailed in Section III, while networking-related issues raised are discussed in Section IV. The dimensioning and preliminary performance evaluation of our current proof-of-concept prototype is described in Section V in terms of illumination provided for crop growth, and in Section VI in terms of illumination provided for harvesting. Finally, Section VII concludes the paper with a discussion of ongoing work and future directions.

II. Lighting and monitoring conditions in greenhouses

Greenhouse conditions are driven largely by incoming solar radiation that creates the internal energy balance. In many locations, greenhouses are coated seasonally to reduce incoming solar radiation, which can reduce plant stress and energy required to keep the glasshouse at a set temperature range [7]. Greenhouse conditions are often measured in one or a few locations, and monitored by a co-processor that can adjust heating or cooling elements to keep air temperature within optimal plant growth ranges. Cooling elements can include fans, adjustable louvers or roof panels, blowers, swamp coolers and air conditioners. Heating can be accomplished by smudge pots or AC heaters, and is often tied into building HVAC (heating, ventilation and air conditioning), especially in larger commercial or institutional (e.g., university) glasshouse complexes with steam heat. Newer or retrofitted glasshouses can be monitored with digital systems that provide multiple loci of measurement and control.

Lighting metrics considered in agriculture are the normalized difference vegetation index (NDVI), the leaf area index (LAI) and daily light integral (DLI). For the sake of simplicity, in this work we focus on DLI: Plants rely on *light quantity* (Photosynthetically Active Radiation; PAR, 400-700 nm) and *light quality* (in multiple wavelengths) for proper growth and development [8]. Light quantity powers photosynthesis that produces sugars, the building blocks for plant growth. Light quality helps determine development of structures that become leaves, flowers, or other plant features. The metric used to measure the amount of photons within the PAR region that are delivered in a specific area over a full day period is DLI, whose unit is $\text{mol}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, where 1 mol is equivalent to $N_\text{A} \approx 6.022\cdot 10^{23}$ (Avogadro's Constant) of photosynthetically active photons. The DLI metric is very useful for describing the light conditions of plants, thus it is one of the key target parameters in our LiFi-based IoT system.

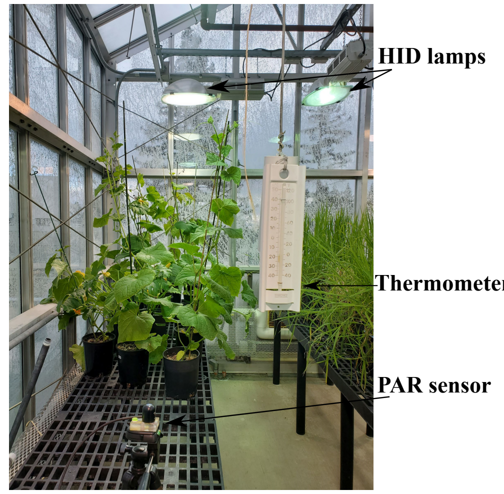


Fig. 1. A greenhouse at UCSC campus showing how greenhouses are traditionally instrumented.

Glasshouse light levels are affected by shading from their own roof infrastructure, neighboring buildings, clouds, and trees. Ambient light quantity and quality also vary seasonally. Therefore, it is common for plants in greenhouses to be provided with supplemental lighting. For many decades such lighting was provided from ballasted fluorescent or high-pressure lamps, as the ones shown in Fig. 1. Toxic components, energy demand, and evolving technology have made such systems obsolete, and increasingly LEDs are being used for supplemental lighting of greenhouse and other grow environments.

Other important greenhouse conditions that affect plant growth include soil moisture levels, humidity, air movement, and the concentration of carbon dioxide (pCO_2). Soil moisture can be measured with resistive or capacitive sensors and can operate with relays that turn on watering systems in a feedback manner. Excess humidity and standing water can facilitate the growth of plant pathogens. In such cases dehumidifiers (or humidifiers in arid regions) can help moderate extremes. Exposure to wind is necessary for development of strong plant stems, and air movement can help keep greenhouses free of pests and pathogens [9]. The next generation of greenhouses will take advantage of novel IoT solutions to monitor the aforementioned parameters, couple with cloud computing and big data to tune greenhouse environments to the best growth conditions of plants.

III. LiFi-enabled IoT for greenhouses

Our vision for next-generation, sustainable greenhouses leverages LED technology's low cost and versatility to provide not only supplemental illumination, but also communication and energy harvesting capabilities. In addition to low cost, energy efficiency and longer lifetimes, LED technology has a number of features that make it beneficial for greenhouse use:

- LED illumination can be controlled according to greenhouse illumination requirements. LED lighting can be dynamically adjusted by simply controlling the amount of current fed to LEDs. Most lights in greenhouses provide

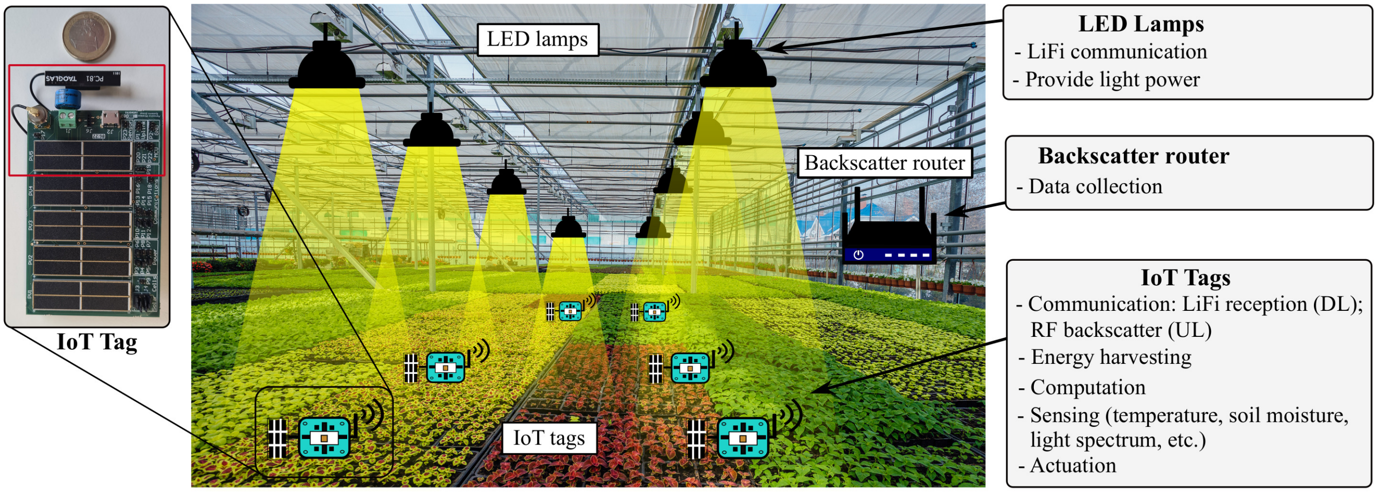


Fig. 2. System architecture: Battery-free IoT tags receiving LiFi data and transmitting sensed data with RF backscatter to a router.

visible wavelengths, where RGB LEDs are the most flexible as they use three diodes in red, green and blue to produce a variety of different colors. Infrared LEDs are not usually used in greenhouses unless there is the need for keeping plants warm on cold nights;

- Leveraging LiFi technology, LEDs can be retrofitted and utilized for power-efficient data transmission and control to IoT tags. Light emitted by LEDs can be modulated for data transmission;
- LEDs can also be employed as energy harvesting sources that power the IoT tags deployed in the greenhouse. Harvesting energy from LEDs and natural light allows the IoT tags to operate without batteries.

Based on the above observations, we illustrate the proposed architecture of the LiFi-based IoT enabled greenhouse in Fig. 2. LEDs are deployed pervasively in the greenhouses, and IoT devices equipped with relevant sensors (e.g., temperature, humidity, soil moisture, etc.) are distributed around the greenhouse to carry out harvesting, communication, computation, sensing and actuation tasks. Data gathered from the IoT tags are transmitted to an edge device, in this case a router that can be used to remotely control greenhouse conditions. We describe each of the functions performed by the IoT system below.

A. Communication

We use LiFi in downlink. Data from LEDs is usually actuation commands that facilitate managing, adjusting, and tuning the IoT tags (e.g., request data from specific tags, modify sampling rate, system upgrades, selection of sensor, etc.). LED emission patterns may be adjusted to specific greenhouse areas in order to achieve the required illumination (e.g., depending on crops, current sun exposure) by either selecting the corresponding LEDs and/or using external optical devices such as collimators or diffusers.

In our current prototype, we opt to use commercial and small-sized solar cells in the IoT tags to serve as the power harvester from light sources. Some current research efforts also use solar cells as LiFi receivers in IoT tags by either using different solar cells (one for receiving data and other for energy harvesting) [10], or employing the same solar cell(s) for both purposes [6]. It should be noted that one of the limitations of using solar cells as LiFi receivers is their relatively lower bandwidth by comparison to photodiodes. The reason for this choice is that solar cells are passive devices, while photodiodes need an active amplification stage, which significantly increases the tag's power consumption. Besides, with today's technology achievable data rates are in the range of hundreds of kb/s when white LEDs are used as transmitters, which is adequate for greenhouse IoT applications given their low bandwidth communication requirements.

For the uplink, we use the low-power transmission technique termed *RF backscatter*, which absorbs and reflects RF signals present in the environment for modulating data passively [10] [6]. The backscatter router on the right side of Fig. 2 sends an RF signal that is absorbed and reflected back by the tags according to sensed data.

B. Battery-free operation of IoT tags

Our system avoids the use of batteries, that currently are largely based on Lithium. This chemical component is difficult to extract, can be found only in a few regions of the planet and can have a significant harmful environmental impact, especially at the time of their disposal. Besides that, the demand for batteries keeps increasing, further increasing extraction of raw materials and their environmental impact. We instead store the energy harvested in the electric field of a capacitor, which then powers the IoT tag circuitry. Capacitors can store less energy than batteries, yet it is much easier to recycle them.

C. Computation

Extremely low-power microcontrollers are used to minimize energy consumption. Additionally, we use an event-driven, interrupt-based implementation approach for additional power savings [10]. Unpredictable energy source variations which may impact the system's energy harvesting capabilities can

TABLE I
COMPARISON OF OUR PROPOSAL AGAINST OTHER WIRELESS COMMUNICATION TECHNOLOGIES FOR IOT APPLICATIONS

Technology	Range	Data rate	Power consumption
WiFi	Tens of meters	∼Mb/s	880.6 mW (TI WL1801MOD)
ZigBee	Up to 100 m (LoS)	∼ kb/s	192 mW (AT86RF215)
BLE	Up to 100 m (LoS)	∼Mb/s	30.03 mW (CC2651R3)
LoRa	∼km	∼kb/s	128.37 mW (RN2483)
NB-IoT	∼km	∼kb/s	847.4 mW (Quectel BG96)
Our proposal	Up to 305 m LOS @17 dBm RF carrier	300-500 b/s @305 m 2.9 kb/s @160 m	3.8 μW

be mitigated by using non-volatile memory technology which will prevent loss of data in the event of power failures [11].

D. Sensing

Greenhouse IoT tags will be equipped with multiple sensors, e.g., temperature, humidity, soil moisture, CO_2, etc. to monitor relevant environmental- and plant conditions. Some recent sensing technologies are noteworthy including RFID-based soil moisture sensors [12] (which however operates at very short distances of 1-2 meters, and requires a movable robotic arm to collect sensed data) and biodegradable sensors [13]. Data collected from the embedded sensors are processed by the tag's microcontroller and transmitted through the uplink.

E. Actuation

Tags receive actuation commands through the downlink to manage and control the IoT operation, including sensor sampling rates, maintenance checks, etc. Through a closed-loop control approach, automatic actuation commands to the greenhouse control system, e.g., to increase ambient temperature or activate an irrigation system, can be issued based on the current measurements reported by the IoT. Note that the system can be deployed such that control can be customized to the specific needs of different areas of the greenhouse.

F. Implementation and experimental results

We build upon our prior work on PassiveLiFi [6], where we presented the first battery-free tag combining LiFi for downlink and low-power RF-backscatter for long-range uplink communication. In the downlink, we achieve a data rate of up to 280 kb/s. In the uplink, we offload the clock from the tag to the LiFi infrastructure for additional energy savings, and we use *chirp spread spectrum* (CSS) signals in the backscatter channel, which lets us decode even below the noise floor, increasing communication range (hundreds of meters) at very low power. The performance of our PassiveLiFi tag's uplink in terms of communication range, data rate and power consumption is summarized in Table I and compared against state-of-the-art communication technologies. Note that while neither high data rates nor very high communication ranges are required by IoT services in precision greenhouses, the key metric for self-sustainable greenhouse systems is energy consumption. Our communication solution consumes at least

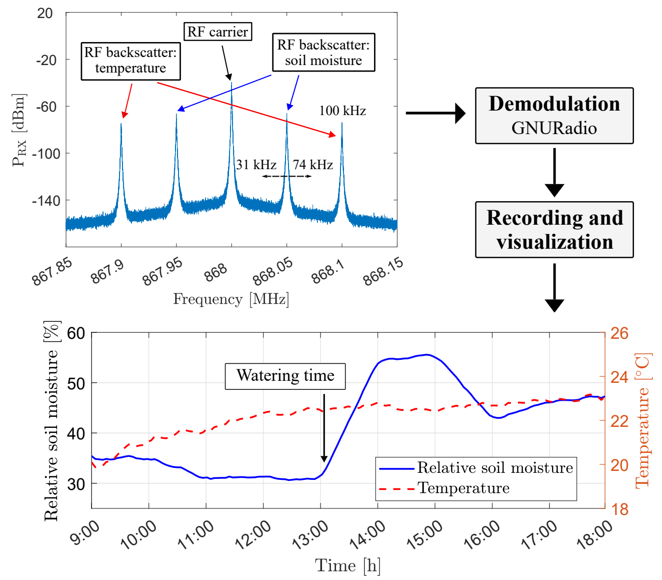


Fig. 3. Spectrum of received signal and experimental results of temperature and soil moisture monitoring in a plant pot. Sensors employed: MAX6577ZUT+T for temperature and DFRobot-Gravity SKU:SEN0308 for soil moisture.

4 orders of magnitude less than the state-of-the-art. We have prototyped our system as shown in Fig. 2. Note that, differently from [6], PassiveLiFi is now integrated in a single PCB to make it more practical to use in real-world deployments. The red rectangle highlights the final tag size including a single solar cell, obtained from the study made in Section VI. Additionally, we have integrated temperature and soil moisture sensors to the IoT tag and have been able to monitor soil moisture in- and temperature around a plant pot for several hours as shown in Figure 3. Figure 3 also plots the spectrum of the received signal, where each sensor data is received in a different frequency. We are currently working on scaling our prototype to include multiple IoT tags, which raises various networking challenges, which we discuss in Section IV below.

IV. NETWORKING

LiFi-enabled battery-free IoT poses a number of networking research challenges. In particular, how to address the system's power and bandwidth limitations while capitalizing on its unique features such as low-power operation and energy harvesting capabilities. The networking protocol suite needs to account for the type of uplink and downlink used to transmit, respectively, data sensed in the IoT tags as well as information from the infrastructure sent to the IoT tags. In the case of deployments with one bulb per tag, the downlink from the bulb will be dedicated to the tag. However, some scenarios may require denser IoT deployments resulting in a number of tags sharing the same downlink. In this case, the bulb will need to communicate with individual tags via unicast communications. The networking protocols should also support broadcast or multicast communications so that commands can be sent to a subset or all the tags covered by the bulb. For uplink via RF backscatter, depending on the tags-per-router ratio, tags will have to share the uplink. Access to the shared uplink can be regulated, e.g., using a low-power, collision-free, scheduled-access approach controlled through the downlink LiFi channel.

V. Dimensioning LiFi-Enabled Greenhouses: Illumination Requirements

This section describes an example of how a battery-free LiFi-enabled IoT system would be dimensioned for a real-world greenhouse environment while providing enough lighting for crop growth. Note that in this example, we assume a worst-case scenario where there is no natural light and the system relies only on artificial lighting from the LEDs. These scenarios happen in the real world, e.g., in vertical farms or during the night in traditional greenhouses. As the LiFi transmitter, we leverage our open-source and open-hardware OpenVLC platform (http://www.openvlc.org/). We then need to ensure that OpenVLC is able to satisfy the illumination requirements for farming. We use the same LED model as in OpenVLC1.3, whose light emission pattern is set by a collimator leading to a Lambertian index of $m = 13.91$ [14]. The Lambertian index m of the LED defines the radiation pattern width. To guarantee a sufficient amount of light, we install an array of 3 LEDs per bulb, each of them fed with a forward current of 700 mA, which leads to a total output luminous flux per bulb of $\phi_{\mathrm{V}} = 2494\,\mathrm{lm}$. We assume a greenhouse of 6 m x 10 m (which is the dimension of one of the greenhouses at the UCSC campus) and a vertical distance from the lighting infrastructure to the crop that may be $h = 0.5$, $h = 1$ or $h = 1.5$ m. We consider a grid of bulbs with a distance of 0.5 m among them, which leads to a total number of 209 bulbs distributed along the whole scenario. We analytically manage our lighting deployment, which allows us to know beforehand the lighting performance and to adjust the fixtures locations accordingly, saving installation time and cost. To do so, we focus on the DLI and illuminance, which are two key metrics for crop growth and lighting, respectively.

Knowing the output luminous flux per bulb and the scenario geometry, we can compute the illuminance (measured in lux and denoted by E) at every location by using the well-known free-space channel path-loss of VLC [15]. Then, we compute the DLI metric employed in farming, formulated as DLI = $E{\cdot}\eta$, where η is ratio between the photosynthetic photon flux (PPF), measured in mol·s^{-1} (or mol·day^{-1} knowing the number of lighting hours per day), and luminous flux, measured in lm (or lux·m^2). Both can be computed using the spectral radiant flux of LEDs. The DLI obtained when we illuminate for 24 hours, and the greenhouse dimensions and parameters are those described above, is the one shown in Fig. 4. We also show the corresponding illuminance values. Note that the distance between the LEDs and crop is crucial for the level and homogeneity of the DLI in the crop. When distance is short ($h = 0.5$ m), the DLI provided is very unbalanced, i.e., DLI levels can go from less than 10 mol·m^{-2}·day^{-1} (sufficient for some flowers and seedlings) to up to 30 mol·m^{-2}·day^{-1} (satisfying needs for growing cucumber, capsicum, eggplant, tomatoes, etc.). This could mean restricting certain types of plants to distinct locations within the greenhouse, but allows

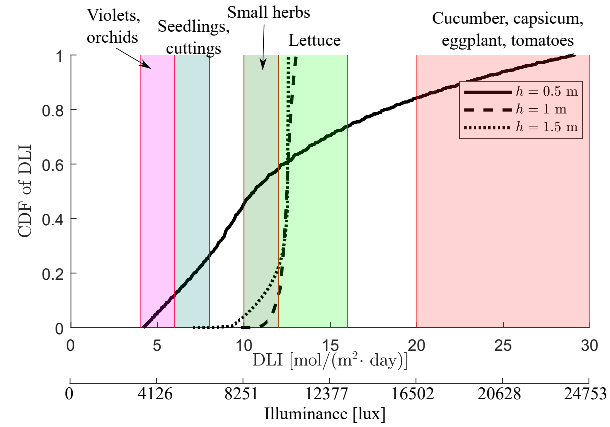


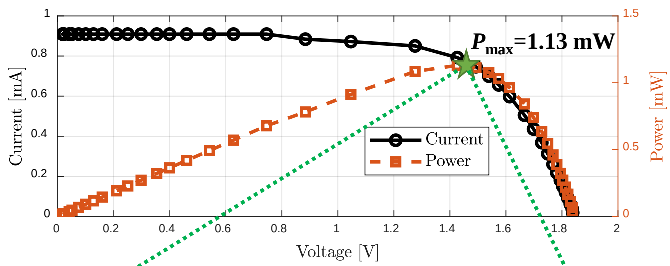
Fig. 4. DLI and illuminance in a 6x10 m greenhouse with a total number of 209 lighting fixtures of 2494 lm each distributed in a square grid with 0.5 m of distance among fixtures. Cumulative density function (CDF) is represented for different vertical distances.

for more diversity of plants. With distances of $h = 1$ m and $h = 1.5$ m the DLI levels provided are quite uniform, which would promote consistent conditions for plant growth. When $h = 1$ m, most of the loci achieve DLI values larger than 12 mol·m^{-2}·day^{-1}, which is within the range for several crop categories (e.g., lettuce: 12-16), and it is achieved with an average DLI of 12.42 mol·m^{-2}·day^{-1}. It is worth noting that the LiFi system can be re-arranged depending on the required DLI levels, e.g., we can adjust the height, location, light power, LED type, etc.

VI. Dimensioning LiFi-Enabled Greenhouses: Energy Harvesting Requirements

Not only must the illumination provide good lighting conditions for enhancing crop growth, but it must also guarantee enough power to support battery-free operation of the IoT tags deployed around the greenhouse. We use our PassiveLiFi [6] system as a battery-free IoT tag, and the OpenVLC platform used as the LiFi transmitter must secure the operation of PassiveLiFi in a battery-free manner. As formulated in Section V, the average 12.42 mol·m^{-2}·day^{-1} DLI level at $h = 1$ m computed leads to an average illuminance value of $E = 10249$ lux. This high illuminance allows solar cells to harvest a large amount of energy, and then reduce the size (or number) of solar cells employed by the IoT tags. We then use a single solar cell, namely the SLMD121H04L, instead of 5 as in PassiveLiFi [6], which results in a footprint reduction by a factor of 5, to a final size of the IoT tag of around 43x14 mm.

In order to compute the amount of power harvested by the solar cell, and then verify if the IoT tags can be battery-free, we characterize the solar cells under the lighting conditions derived in Section V by experimentally computing the current versus voltage (I-V) curve. We show the result in Fig. 5. This I-V curve has been measured experimentally by connecting a variable resistor after the solar cell and varying its load, then measuring the current through this load and the voltage across it. Note that the maximum current I_{sc}=0.91 mA is obtained in short-circuit mode, while the maximum voltage V_{oc}=1.84 V is obtained in open circuit mode between the solar cell terminals.



IoT tag operating mode	Idle	DL	UL	Sensing
Power consumption [μW]	0.2	240.5	3.8	585.9
Remaining power [%]	99.98	78.72	99.66	48.15

Fig. 5. Experimental current versus voltage curve (solid line) measured for one SLMD121H04L solar cell, under lighting conditions of 10249 lux with XHP35B-00-0000-0D0HC40E7 LED and TINA-M collimator models. Dashed line represents the harvested power. Considering the maximum harvested power and the power consumption of the tag, we also represent the remaining power to be dedicated for additional tasks.

Figure 5 also plots the resulting electrical power captured by the solar cell which depends on the load connected after the cell. The maximum power that the solar cell is able to harvest is $P_{\max}$=1.13 mW, which is obtained with a load of 1.8 kΩ. A power harvesting chip can be used to adjust the load automatically and ensure that the solar cell always operates in the maximum power point [6].

Figure 5 further shows the power consumption in the four operating modes of the IoT tag (Idle, Downlink (DL), Uplink (UL) and Sensing). Considering the maximum power harvested (1.13 mW) we compute the power remaining to be dedicated for additional tasks such as actuation. In the DL mode, the duty cycle for packet decoding is assumed to be 100%, which is the most power inefficient case (worst case) and, in practice, it may require a lower duty cycle with lower power consumption. The consumption in sensing mode has been experimentally measured considering the three sensors integrated into the IoT tag, namely: temperature sensor with a nominal consumption of 378 μW, soil moisture sensor with a consumption of 10.8 mW, and light sensor with a consumption of 540 μW. If sensors operate according to a 5% duty cycle (since we do not need to keep measuring continuously), the total consumption is: 18.9 μW + 540 μW + 27 μW = 585.9 μW. The margin in harvested power provides us with the opportunity to extend the functionality of the IoT tag, e.g., adding more sensors, scaling up the sampling frequency, data rate, transmission range, etc.

VII. Conclusion

We presented our vision towards next-generation sustainable greenhouses that use low-cost, low-power LED technology for greenhouse illumination, and we showed a proof of concept. Additionally, LEDs serve as energy harvesting sources and provide downlink communication to power and control battery-free IoT tags deployed around the greenhouse to autonomously monitor current greenhouse conditions. Illumination must be large enough for crop growth (satisfying the minimum DLI required per plant) and for energy harvesting (satisfying the minimum required for autonomous operation of IoT devices). Leveraging passive RF backscatter technology for uplink communication, IoT sensors continuously report their readings that are used by greenhouse controls to regulate cooling, irrigation, ventilation, etc. The proposed battery-free LiFi-based IoT system will enable sustainable and precision greenhouse operation by seamlessly monitoring and controlling greenhouse conditions.

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