Lighting IoT Test Environment (LITE) Platform: Evaluating Light-Powered, Energy Harvesting Embedded Systems

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***Abstract*—As interest in the Internet of Things (IoT) grows, so does the requirement for distributed sensing, computation, and communication. Some projections reach a scale of over a trillion wireless devices, which creates a battery replacement challenge that is unsustainable for both human resources (replacement effort) and the environment (disposal). One field of research that strives to meet this challenge is energy harvesting (EH) for self-powered systems. Photovoltaic (PV) cells enable EH capabilities and provide high energy density. They are also typically inexpensive, often making them the transducer of choice for self-powered systems. However, the performance of these EH nodes is rarely evaluated under realistic IoT environmental conditions, such as variable indoor lighting. Under low light, PV cells draw very little power and could place the self-powered system in a standby or even nonfunctional state. Most evaluations of EH systems in various lighting environments use software simulations to predict the behaviour of these nodes, but approximate models lack the exactness required to help with verification of hardware in real conditions. Another approach is user testing in the field, but this arduous solution would incur a variety of costs. This paper presents a third alternative: the Lighting IoT Test Environment (LITE) platform. The LITE platform is a tool that provides insight on how light-powered EH systems operate in low lighting environments. The LITE platform is able to physically emulate a variety of indoor and outdoor lighting sources with a novel mapping technique and provide time-series, environmental simulation of that source on a device under test (DUT). The light source emulation and time-series simulation capabilities are characterized with a worst case mean absolute percentage error (MAPE) of 3.2% and MAPE of 0.5%, respectively. By enabling engineers to accurately understand how these self-powered systems work under real world conditions, the LITE platform will better equip them to design, debug, and distribute fully functional and sustainable IoT nodes.**

Keywords*—energy harvesting, test platform, internet of things, embedded systems, verification, system on chip, photovoltaic

I. Introduction

Many recent IoT nodes in the literature incorporate energy harvesting, such as [1], which provides relief from the typical burden of extra cost, size, and replacement for batteries [2]. Photovoltaic cells, which powered the SoC in [1], are low cost and have high energy density per unit area of transducer. Given that light can often be found in many places, these three traits make PV cells commonly used for energy harvesting. Many times, however, PV cells encounter low lighting conditions leading to unpredictable device behaviours. For these EH devices, low light could leave a chip with insufficient power to operate. For example, the body sensor node SoC in [1] was measured at $6.45\,\mu\mathrm{W}$ demonstrating ultra low power operation. However, the variety and unpredictability of low lighting conditions, including the extreme case of complete darkness, that deployed nodes will encounter make it difficult to know whether or not the node will operate as intended.

Certain software models are capable of simulating node environments, systems, and networks to provide early intuition as to how they may behave [3]–[6]. These approaches have value in predicting the potential behaviour and performance of IoT systems, though they lack great detail. Chip components, such as power management units and boost converters, all play a part in the total behaviour of the EH SoC. The nanosecond time scale for circuit responses interconnected with the minute time scale for environmental changes makes modeling EH systems quite difficult. The limitations of software simulation prevent complete understanding of how a system will react to its environment. This implies that lab or usability based testing methodologies need to be employed. Physical testing on that scale, though, incurs large costs in many dimensions.

An alternative method could instead capture elements from both simulation and usability testing for fast and effective evaluations of PV based EH systems. This paper presents the Lighting IoT Test Environment (LITE) platform to achieve exactly this. The LITE platform performs both light source emulation and time-series simulation on an isolated, light-powered hardware system. The combination of these two capabilities enables realistic lighting profile re-creation. These profiles are based on low lighting in indoor and outdoor conditions. For network engineers, the apparatus can help reveal the delicate balance between node level and network level metrics. For hardware engineers and prototypers, the LITE platform can rapidly reveal the effectiveness of a harvesting circuit or commercial off-the-shelf (COTS) systems to demonstrate a proof of concept. By enabling engineers to evaluate, test, and develop systems with the LITE platform, they will be able to provide reliable and robust self powered designs.

This paper is organized as follows. Section II summarizes the existing related work. Section III describes the structure and components of the proposed LITE platform as well as the control mechanisms. Section IV details the mapping and data collection capabilities. Section V presents the results of the paper and Section VI provides the conclusion.

II. Related Work

The work in this paper relates in part to two particular themes found in the literature: 1) Simulating a theoretical IoT system through software modeling 2) Providing insight on energy harvester characteristics through physical platforms and testing methodologies. These two ideas are important to understand in their own contexts before considering how they come together in the LITE platform. And by learning about them individually, the motivation for the LITE platform can be better addressed.

A. Software Simulation

In the literature, several researchers proposed IoT related software simulators. These software tools try to predict IoT node states, such as lifetime, power consumption, and energy storage, under particular conditions. Users care about these simulators because trade-offs between design parameters can be weighed.

In [3], a Matlab and WSNet based simulator HarvWSnet was devised so designers could better understand the relationships between complex battery based models in conjunction with energy harvesting environments and network activity. The Matlab model describes the EH node state and links to the WSNet simulation that provides networking capabilities. However, it fails to incorporate any description of system behaviour, beyond modeling the power manager and battery, such as processor activity. Other simulators, such as COOJA, model the effects of deployment-ready software that would run on an IoT node. In [4], the SensEH tool adds capabilities to COOJA by optimizing simulations for either speed or accuracy. But this model is only available for a particular set of hardware nodes, such as the TI MSP430, preventing it from being useful to a wide range of designers. The researchers in [5] describe a simulation environment similar to [3], but written in SystemC-AMS. They offer a tiered and modular approach for modeling wireless sensor networks. Even though the layout was well thought out, little work was done to implement realistic models for components. This makes it difficult to evaluate any system as well as the simulator. Another software platform, different from the rest listed here, attempts to simulate a variety of IoT environments based using the Raspberry Pi computer with the NEMU emulator [6]. The idea was to provide rapid emulation of real IoT operating system level devices in software. The downside is that it is quite limited in its scope and can only simulate events on the network level, omitting circuit and physical level realities.

There are many IoT system simulators not listed in this paper, but the important idea remains that they can only provide a certain level of accuracy and precision. These tools help explore the design space, but are of limited use for hardware verification. This is because not all levels of system hierarchy can be expressed fully in software. The details matter when it comes to understanding how low power systems operate. The time it takes to provide accurate simulation is substantial, even when simulation capabilities are significant.

B. Harvester Characterization Platforms

The adoption of energy harvesting can greatly benefit an IoT system by prolonging its lifetime far beyond one charge of a battery or other energy storage unit. Realistically, this harvesting can come from a variety of transducers, such as photovoltaic (PV) cells, thermoelectric generators (TEGs), and piezoelectric transducers. Each of these harvesters have associated conversion efficiencies and energy densities that affect the end power retrieved from these devices. In the literature, researchers created numerous platforms for the purposes of characterizing these transducers under various environmental conditions. For example, the researchers in [7] designed a system that evaluates how a variety of photovoltaic cells would respond to static indoor, low lighting conditions. This approach only considered the effects of fluorescent light sources. Similarly in [8], the researchers investigated how four different types of indoor light sources affect photovoltaic cells across a range of light intensities. But characterization platforms are not unique to only PV cells. Other researchers devised systems for observing the behaviour of piezoelectric transducers by providing a robust physical framework and testing methodology [9]. A PV cell testbed is given in [10] which performs testing on light-powered, energy harvesting devices. The researchers developed the EnHANTs testbed to provide experimental control while conducting research on communication and networking algorithms for energy constrained nodes under lighting conditions. This approach, however, lacks one of the LITE Platform's main strengths, the ability to replicate a variety of lighting environments.

III. Platform and Control System

The LITE platform broadly consists of three components: the physical apparatus where simulations and measurements take place, the custom LED lighting array and control hardware circuitry that provides lighting capabilities, and the Energy Harvesting Data Collection (EHDC) platform previously designed by Fan et al. which acts as the master control system. [11]. High accuracy and repeatability were requirements for the platform to provide exact and consistent light profile simulations. Figure 1 shows a system block diagram of the platform proposed in this paper.

A. Physical Platform

Isolating the test space from external light is crucial for experimental control. A 1 x 1 x 1.2 cubic foot enclosure was designed to meet this requirement (see Figure 2). With the frame constructed from 8020 T-slotted aluminum beams, the left, right, and back side panels were covered in opaque, black acrylic sheets laser cut to size ensuring minimal leakage. The top and front of the platform were covered with thick fabric providing substantial light isolation as well as easy accessibility to the internals of the apparatus. A single piece of acrylic was used to support the LED lighting array and drivers. The acrylic sheet attached to the four vertical 8020 columns enabling the light source to be moved closer or further away from the DUT.

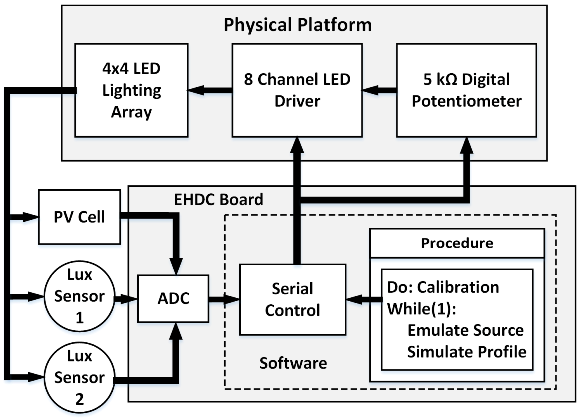

Fig. 1. System block diagram of the LITE Platform consisting of the EHDC board's hardware and software components, the physical LITE apparatus, PV cell (DUT), and lux sensors. The EHDC board shown here is a subset of the complete one. For the entire system, see [11].

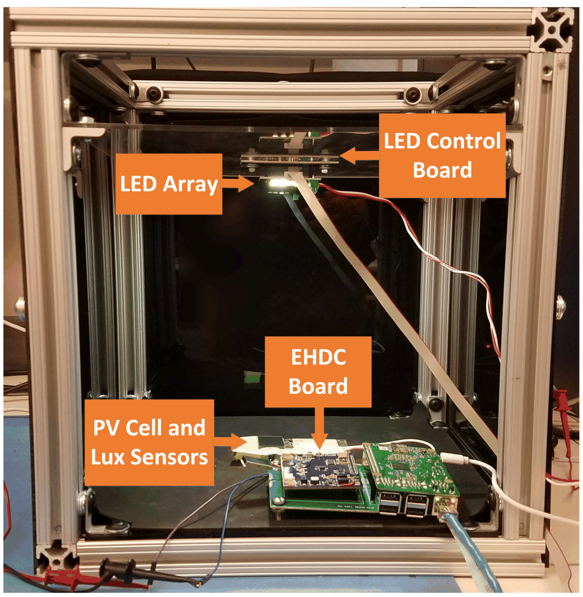

Fig. 2. Image of LITE platform implementation based on Figure 1.

B. Lighting Electronics

1) Lighting Array: The platform's lighting array consists of sixteen, 5000k cool white LEDs arranged in sets of two, which matches the number of current sinks provided by the driver. This array was designed with two sets of 1 x 8 sockets connecting the array to the driver board so other LEDs with different colors, temperatures, and sizes could be adopted onto the platform. This lighting array was typically operated at a height over 16 cm to provide a relatively distributed amount of light across the area where the sensors and PV cell were positioned.

2) Lighting Driver: The driver board comprises a TI TLC59108 LED driver and a Microchip MCP4261 $5\,\mathrm{k}\Omega$ digital potentiometer. The driver has eight constant current sink inputs requiring two LEDs per channel and communicates with the EHDC platform over an I2C interface. The digital potentiometer communicates via a SPI interface. The driver uses two separate lighting control mechanisms: inverse linear control of current through the digital potentiometer and piecewise linear control of current via control bits internal to the driver. A third possible light modulation technique under consideration was PWM. It was not implemented though because its modulated output generated undesired responses on the PV cell and lux sensors due to their RC time constants. A fourth possible technique was to turn off one or more of the eight driver channels, but this was simply not needed since enough control was already provided.

3) EHDC Board: The Energy Harvesting Data Collection platform was designed to profile, model, and predict energy harvesting environments for self-powered body sensor nodes [11]. It collects energy harvesting, environmental, and human behavior data in the real world. The EHDC platform consists of a Raspberry Pi computer and a custom header board with a) solar and thermal energy harvesting circuits with power management units, b) environmental and motion sensing circuits, and c) data logging and cloud computing capabilities. The platform collects and records data over time from sixteen sources simultaneously. Multiple Java programs provide this functionality. Two NOA1212 ambient lux sensors, set with different gains for indoor and outdoor lighting scenes, are used in conjunction with a $22\,\mathrm{mm}$ x $35\,\mathrm{mm}$ SLMD600H10L monocrystalline solar cell produced by IXYS. The sensors and PV cell were placed as close to one another as possible during the experiments.

C. Control System

The purpose of the control system is to generate any lux level in the apparatus requested by the EHDC board. There are two steps required for controlling the apparatus. Firstly, a calibration stage creates a regression-based profile that translates any desired input lux value to control bits for the driver board. Secondly, the time-series simulation program uses serial commands to communicate with the lighting electronics which create lighting scenes inside of the platform.

1) Calibration: The platform takes an input of desired lux values and outputs generated light with an equivalent value to the input. Control software is used to translate lux into driver control bits. To achieve this, the system is calibrated by selecting five LED driver gain bits and sweeping all potentiometer control bits for each gain. The resulting lux values are recorded in five curves. This mapping from control bits to generated lux is inverted such that the input is lux and output is control bits. Four of these calibration curves created for the LITE platform are shown in Figure 3. Out of these five inverted curves, a single piecewise function is created. These steps allow the apparatus' input and output to be in lux. Recalibration is required if the platform setup is altered. An alternative control mechanism for this apparatus could be a closed loop control algorithm, such as PID.

The calibrated, low light operating range is from 30 to 800 lux. The root-mean-square error (RMSE) between user input lux values and generated lux values collected from the lux sensor is 12.32 lux. Figure 4 illustrates the relative error across lux values from the piecewise calibration equation.

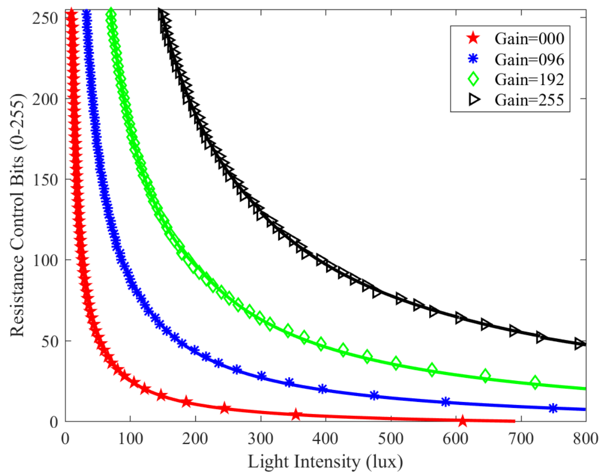

Fig. 3. These calibration plots show the relationship between input light intensity and LED driver board control bits. Five LED driver gains are selected, four of which are shown as examples in this figure.

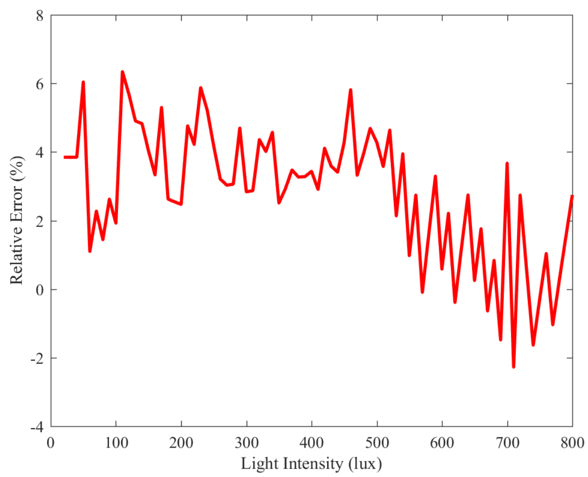

Fig. 4. Relative error between input (ideal) lux and output (generated) lux of the apparatus. The calibration equation turns an input lux stream into control bits, which in turn create real light that should match in value to the input.

2) Time-Series Profile Simulation: After calibration, the apparatus is capable of simulating time-series light profiles. The easiest source of lux data comes from the real world, but lux sequences could be generated in software. The Java based simulation program takes an array of lux values and a delay parameter as inputs. It then controls the LED array by sending control bits to the LED driver. In this experiment, $800\,\mathrm{ms}$ was used as the delay parameter.

IV. Enabling Light Profile Re-creation

A. Mapping

The LITE platform is primarily characterized by two functions which are the ability to provide time-series light simulation and light source emulation. The lux sequence generation capability was discussed in a previous section and is a rather straightforward problem to solve. Light source emulation on the other hand presents rather interesting problems. Trying to incorporate a variety of real light sources inside of the LITE platform would require multiple hardware modules and control schemes. Pursuing this approach could become quite costly. For example, the platform currently only hosts an LED rig, but if incandescent based, home lighting scenes were of interest then a unique, physical platform and control scheme would need to be devised to support it. This problem becomes unmanageable when one considers the variety of desirable light sources for testing, including the sun.

Another solution presents itself in the following way. If a set of light sources $L = \{L_1, L_2, ..., L_i\}$ are desired to be tested, use one light source λ to emulate any light source in set L. As a result of using λ, the DUT should be presented with an equivalent amount of power as if λ was in fact the light source of interest in set L. Two steps need be followed to accomplish this. Firstly, a relative set of equations describing the relationship between lux and power for PV cells must be made. This relationship will be denoted as a *lux power curve* or LPC. The measured LPCs for this apparatus are shown in Figure 5. Secondly, using those relationships a *mapping equation* must be created demonstrating how to effectively convert from the lux of any L_j to lux of λ in order to actually emulate the intended effect of L_j. In simpler terms, the mapping process can be thought of as rotating and shifting the LPC of λ either up or down to match the LPC of other light sources.

Concerning PV cell power, modern EH systems typically operate the cell at its maximum power point (MPP) to retrieve the most power possible under the immediate conditions. This assumption is important when considering mapping because changing the load will change the mapping equation. By bounding the scope to only consider nodes using MPP tracking (MPPT), far less information needs to be gathered from every light source. As a result, this was chosen as a reasonable assumption for the apparatus given its intended function.

This paper presents the mapping results for the following types of light sources in Figure 5: 5000k white LED, compact fluorescent lamp (CFL), fluorescent lamp, incandescent bulb, and the sun. Even though the lux range in Figure 5 was capped at 800 lux, some measured lux points exceeded this value ensuring that each LPC was accurate beyond the bounds of interest for this apparatus. But the accuracy of the sensors and measurements limited the lower bound of the range to approximately 30 lux. The MPPs were found using the IV curves under a set of steady light intensities. All IV curves were created using software to sweep current and measure voltage with a Keithley 2400 source meter.

B. Data Collection

The time-series simulation capability of the LITE platform requires discrete time, lux based datasets to operate. The EHDC board collected multiple environmental profiles for a variety of lighting sources that the platform can emulate. Two profiles in particular are highlighted in Figure 6. They are classified as a still sensor node under the shade outside and a moving body sensor node under fluorescent lighting, respectively. The moving body sensor node profile contains recorded lux data from a student working in a lab setting.

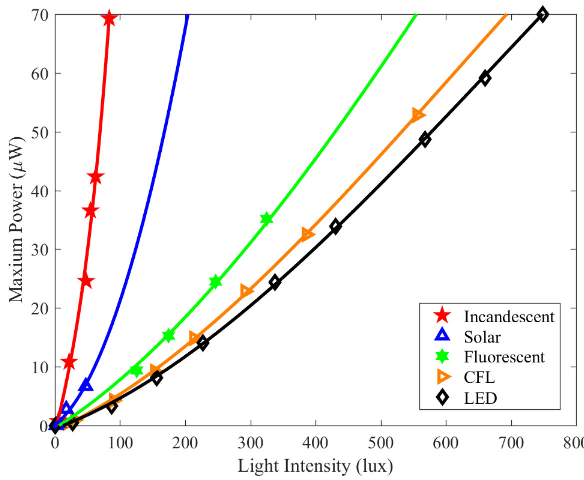

Fig. 5. Lux power curves (LPCs) showing the relationships between light intensity and maximum power obtained from the data of five typical light sources.

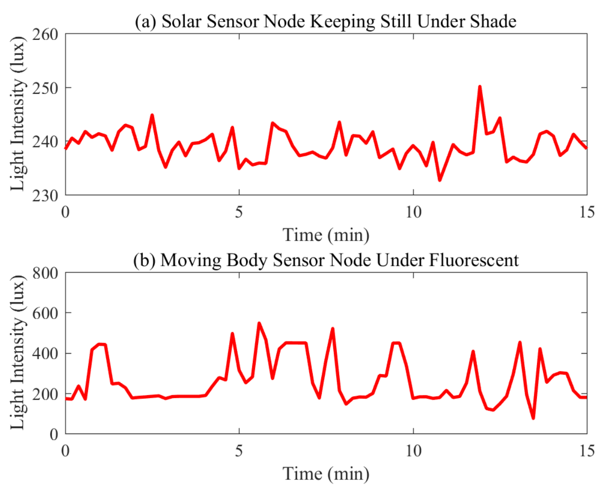

Fig. 6. Time-series lighting profiles from two applications: (a) still, solar sensor node under shade (b) moving body sensor node under fluorescent light

V. Platform Results

The first step in the platform's verification was to emulate the results found in Figure 5. This test is important because passing it would demonstrate the platform's readiness to emulate other light sources. The results of this test are found in Figure 7. The LPCs given in Figure 5 are the same as those in Figure 7, except for the omission of the LED LPC. The addition in Figure 7 is that the black, diamond symbol now represents the emulated LPC of the light source that the symbol is hovering over. In Figure 5, the diamond symbol represents the LITE platform's LPC curve. In Figure 7, the diamond still represents the LITE platform's LPC curve, but it has been modified in such a way that it completely acts like another source's LPC. This is the essence of mapping in this context. The mapping technique for this experiment was completed in three steps. Firstly, eight lux values associated with a particular source were chosen. Secondly, the MPPs associated with those lux values were derived and then used to solve for the equivalent LED lux that would produce that power. Thirdly, the LED lux values were applied to the platform's input generating the specific lux inside of the platform.

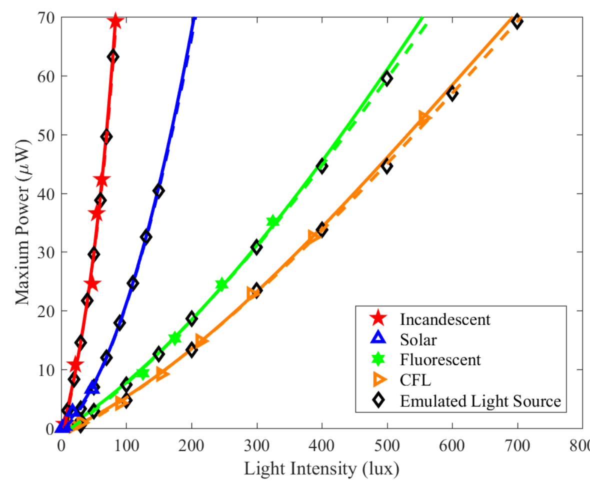

Fig. 7. Verifying mapping capability: the LITE platform can generate LPCs equivalent to the four other light sources.

There is visibly little error between the original LPC and its emulated counterpart. To demonstrate the actual error over each set, all four light sources' RMSE and MAPE values are given in Table 1. From this table, the data shows that the mapping functionality of the platform works very well over the given intensity range with the incandescent source having the greatest accuracy.

TABLE I. Mapping RMSE and Percent Error

	CFL	Fluorescent	Incandescent	Solar
RMSE	$0.828\,\mu$W	$0.804\,\mu$W	$0.780\,\mu$W	$2.423\,\mu$W
Percent Error	3.2%	2.5%	1.4%	2.1%

After confirming the mapping capabilities, another experiment combined both light source emulation and time-series profile generation. This experiment utilized the fluorescent lighting profile previously seen in Figure 6(b). In Figure 8, the profile from Figure 6(b) was passed through a mapping equation converting fluorescent lux to LED lux. Figure 8 represents a calculated, power-equivalent profile to that of the fluorescent profile, but using LEDs as the light source. This means that the profile can now be simulated in the LITE platform. The noticeable offset in lux between the two profiles in Figures 6(b) and 8 comes from matching the apparatus LPC to the fluorescent LPC by increasing the lux of the LED array. Figure 9 compares the ideal profile to be simulated, Figure 8, and the measurement of the real simulation for that profile. Figure 9 is a measure of relative error across time to provide an understanding of how accurate the time-series simulations are for the platform. This figure shows that the platform's generated light profile deviates very little from the calculated profile. The RMSE is approximately four lux and the MAPE is half a percent. The small error between the expected and measured light intensities effectively means the platform's performance does not vary over time.

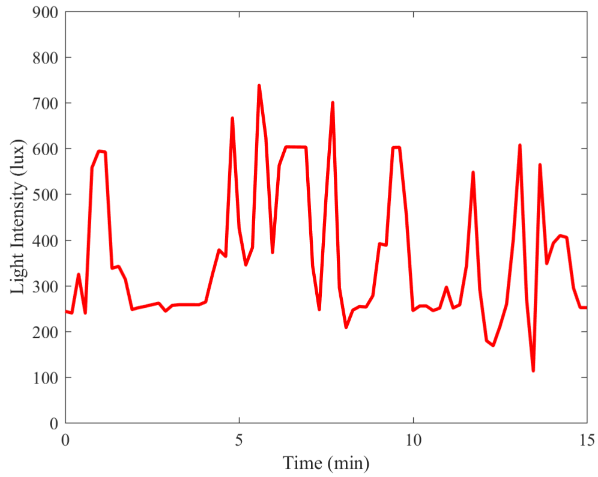

Fig. 8. This time-series data represents the power-equivalent LED lux profile of Figure 6(b).

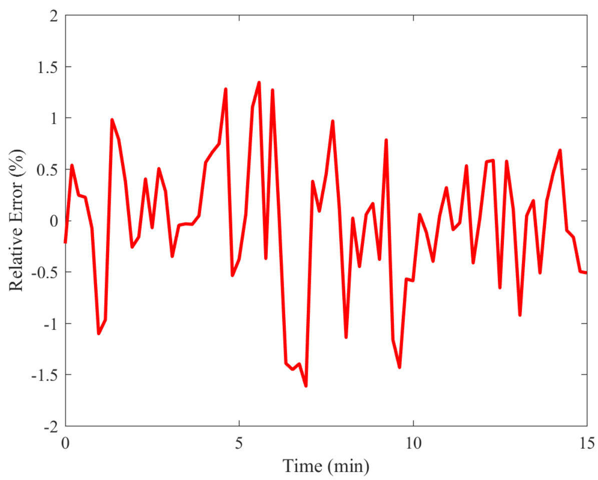

Fig. 9. Relative error between Figure 8 as an input light profile to the platform and the measured output profile simulated across a time span of fifteen minutes.

VI. Conclusion

While research on light-powered, EH nodes increases, little work has been completed to accurately understand how a physical node operates in realistic energy harvesting conditions. The LITE platform addresses this issue by providing a completely customizable, physically simulated lighting environment for testing these systems. The platform uses LEDs to emulate the behaviour of different light sources with a worst case MAPE value of approximately three percent. It simulates time-series lux data to replicate what a node would experience if immersed in a particular environment. It is able to do so with a MAPE value of half a percent, for the case of fluorescent lighting. Future work mainly includes expanding the emulation capabilities of the platform as well as improving accuracy of the system.

Acknowledgment

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