



EXPERIMENTAL ASSESSMENT OF A SUSTAINABLE DATA AND POWER TRANSMISSION SYSTEM

Murtadha B. Shlash¹ and Hassan K. Al-Musawi²

¹ M.Sc. student at Electronic and Communication Engineering Department, University of Kufa, Email: murtadhab.shlash@student.uokufa.edu.iq.

² Assist Prof. at Electronic and Communication Engineering Department, University of Kufa, Email: hasank.baqir@uokufa.edu.iq.

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ABSTRACT

Simultaneous Lightwave Information and Power Transmission (SLIPT) is an emerging technology that combines data and power transfer into an integrated optical link, capable of providing efficient and compact solutions for various clean energy interconnection applications relevant to IoT devices. This work reports an experimental study of an SLIPT system using commercial lasers and photovoltaic (PV) panels for synchronously transmitting information and power. An experimental testbed is performed to analyze SLIPT system prototypes transferring both data and harbored energy over a distance of 12m. The experimental results demonstrate that the Silicon (Si) PV panel can harvest up to 5.5% of laser power with a bit error rate (BER) of 1.32×10^{-4} . This pioneering approach opens up possibilities for low-cost, independent, and self-sustaining systems.

KEYWORDS

Energy harvesting, Optical communication, SLIPT, Photovoltaic detectors, Sustainable systems.



1. INTRODUCTION

Sensors work in conjunction with wireless devices that are part of the broader IoT ecosystem. These need a reliable and robust power supply, especially in cases where operation and communication with other intelligent systems are of utmost importance. Quality of Service (QoS) with respect to catering to their self-sufficient energy needs is paramount. Expressing the scientists' beliefs that some considerations offer the promise of reducing litter with regard to energy utilized over communication links is relevant in contemporary conditions ([Ghazi A. et al., 2021](#)). The aim behind the use of the SWIPT sensing system is to maximize collected transmitted power to satisfy the receiver portion's original transmission, thereby mitigating the wastage of energy from being consumed in other operations in the system. Lightwave transmission systems are also paired with low-power transceivers in a more effective power network, benefiting from improved quality of service ([Okuhara et al., 2020](#)). The concept of simultaneous lightwave information and power transfer (SLIPT) falls under the broader category of simultaneous wireless information and power transfer (SWIPT). Optical wireless communications (OWC), as noted by [Diamantoulakis et al. \(2018\)](#), herald a new dawn for the growth of the Internet of Things (IoT) and wireless sensor applications ([Kim et al., 2013](#); [Wang et al., 2014](#); [Wang et al., 2015](#); [Fakidis et al., 2020](#); [Htay et al., 2020](#)). They also offer considerable advantages over microwave methodologies, specifically in their high data rate transmission over longer distances ([Leeb et al., 2007](#)). Studies in health monitoring show that the SLIPT system can be of great help in a bid to allow continuous monitoring without battery replacement, as it supplies power for implantable medical devices ([Hasan, A., 2022](#)). In intelligent systems, SLIPT can supply power to specific sensors and devices and promote the power-efficient operation of such connections. This great feature is significant for situations when directive free-space optical links provide high bandwidth throughput and significant energy all at once.

[Kim et al. \(2013\)](#) and [Wang et al. \(2014\)](#) have shown the working of an optical SWIPT employing commercially available light-emitting diodes and silicon solar panels. The 3 Kbps data transmission implemented by [Kim et al. \(2013\)](#) is unsuitable for communication links that require a high data rate. The experimental setup by [Wang et al. \(2014\)](#) showed that with the aid of polycrystalline Si solar cells, the power harvested was 2.1 mW, which resulted in high data throughputs of 7 Mbps. Furthermore, [Zhang et al. \(2015\)](#) have demonstrated that organic solar cells can efficiently detect data at higher rates. The data rate of 34.2 Mbps was achieved by a 1-meter wireless optical link that harvests 0.43 mW of power. The transmitter employed was a red LD that had a wavelength of 660 nm. The SLIPT system underwent further improvements

made by different types of solar cells described by [Mica N.A. et al. \(2020\)](#) by deploying a triple junction perovskite solar cell at a receiver. Thus, they were able to use 50 mW optical power laser diodes of 660 nm with LD to achieve a data communication of 56 Mbps and energy harvesting of 3.3 mW in a 40 cm wireless link. Different photovoltaics include organic and gallium arsenide (GaAs) photovoltaic cells for light beam detection. Due to their small size, these devices have smaller capacitances than silicon-based solar cells. In that work, the researchers want to show that their experimental results demonstrate a high-rate SLIPT system. Utilizing a GaAs solar cell at the receiver achieved a data rate of 522 Mbps over a 2 m link with 42% optical-to-electrical power conversion efficiency.

This study introduces a conventional SLIPT system that employs commercial components such as a solid-state laser module and silicon solar panel to perform an experimental 12-meter FSO link in the laboratory. The solar panel can perform power conversion and data reception. The power received by the solar cells is recorded, while the bit error rate (BER) and eye diagram demonstrate the performance metrics for data transmission. The link enables data transfer while simultaneously charging the battery.

2. METHODOLOGY AND SYSTEM MODEL

In a system that uses lightwaves for simultaneous wireless information and power transfer (SWIPT), the transmitter, receiver, and inherent electrical characteristics are the main elements. [Fig. 1](#) illustrates these characteristics in detail. An optical beam is used to send data and power through a laser diode directly modulated in the transmitter. Optical elements are employed to shape and direct the laser beam towards the receiver.

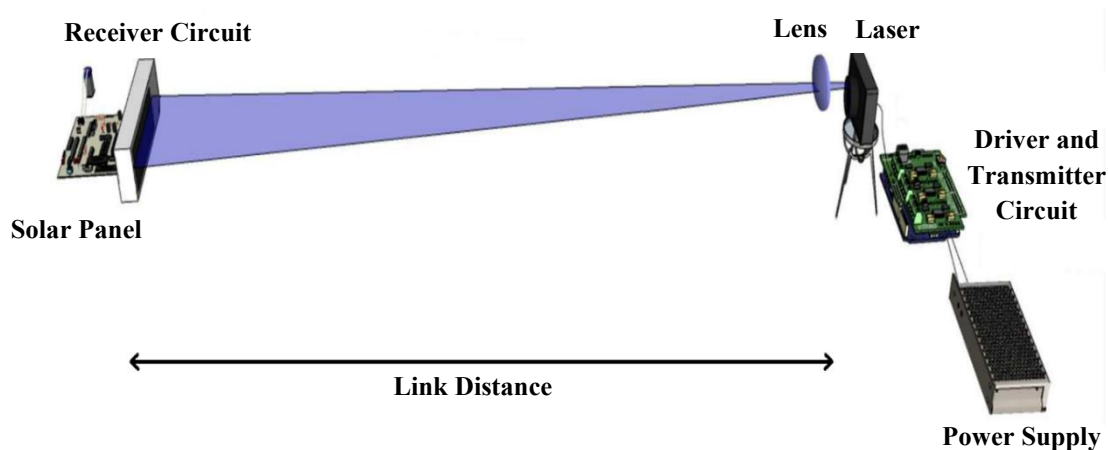


Fig. 1. The proposed lightwave-based SWIPT system.

The Free Space Optics (FSO) channel is utilized as the transmitting medium for the laser beam, making it possible to distribute energy and information wirelessly over a distance. The

photodetector converts incident laser light into electrical signals, allowing the receiver to decode, harvest power, and control energy for data circuit processing.

In optical transmission technology, modulation of the data signal onto the optical carrier is the crucial operation of an optical transmitter. The signal is transmitted to the receiver through free space. The most common optical source for operation is the laser diode. A laser diode, which may include solid-state and VCSEL lasers, is suitable for use by the transmitter. The optical transmitter in this system utilizes a blue-violet solid-state laser module that operates at a wavelength of 405 nm. This laser module is highly advantageous for achieving higher power capabilities and higher divergence angle (Hughes et al., 1992). It can also be effectively switched on and off and also biased with Direct Current (DC). The solar panel surface is illuminated evenly by a diverging optical ray that maintains a steady beam to adjust to any misalignment caused by atmospheric turbulence. Moreover, it is imperative to prioritize eye safety in the design of a wireless optical system (Bloom et al., 2003).

In terms of power and information conversion, PV cells show higher efficiency. Thus, the integration of optical communication systems with solar panels becomes relatively frequent. Their communication bandwidth must be taken into account during the manufacturing of these panels. While using solar panels for signal information reception, specific critical parameters should be considered, such as the electrical properties of the PV materials, illumination pattern incident on the panel, and other properties of the panel. The system process is shown in Fig 2. Subsequently, the microcontroller generates the necessary information destined for transmission as a payload. This data is then converted into a Pulse-Width Modulated (PWM) signal through the implementation of ON-OFF Keying (OOK) modulation. In this system, a switching circuit is employed to convert bit representations into analog signals, with the signal power on the transmitters consistently modulated in a high-low sequence. Concurrently, the modulation of the signal is achieved by varying the output intensity of the laser. At the receiving end, the solar panel is utilized to receive the transmitted optical signal while simultaneously harvesting energy. The power generated from the initial solar cell is directed to the charger controller circuit, which facilitates the charging of a lithium-ion battery. This configuration enables the battery to provide energy to the loads even in the absence of an external power source, thereby creating a self-sufficient system. Additionally, the detector samples the direct current output and converts it into an alternating current signal through the sampling process. The resulting signal is then transmitted to the microcontroller, where the time-driven signal is then converted back into a digital format, allowing for retrieval in its original representation.

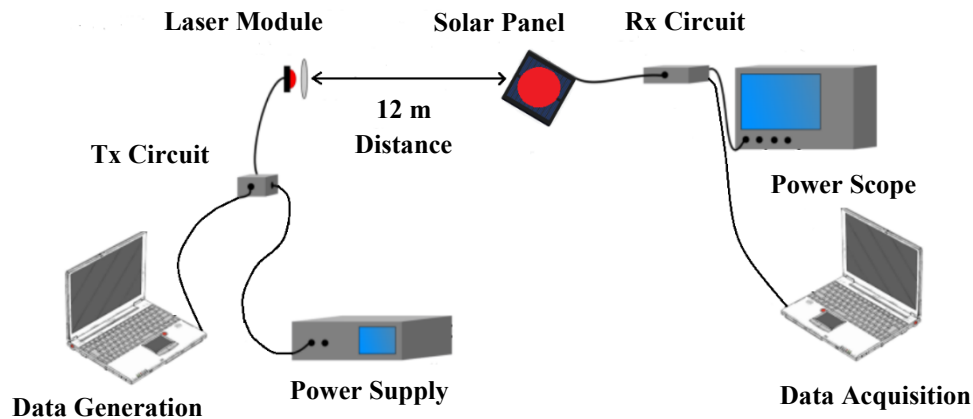


Fig. 2. Schematic of the proposed free space SLIPT system.

2.1. Transmission Circuit

The laser module included in the transmitter utilizes a laser diode that produces a light beam at 405 nm and optical power up to 200 mW. To drive the laser, the housing is equipped with a Printed Circuit Board (PCB) that contains a DC bias circuit for the laser diode. The housing also includes a lens mounted in front of the laser, as shown in Fig 3.

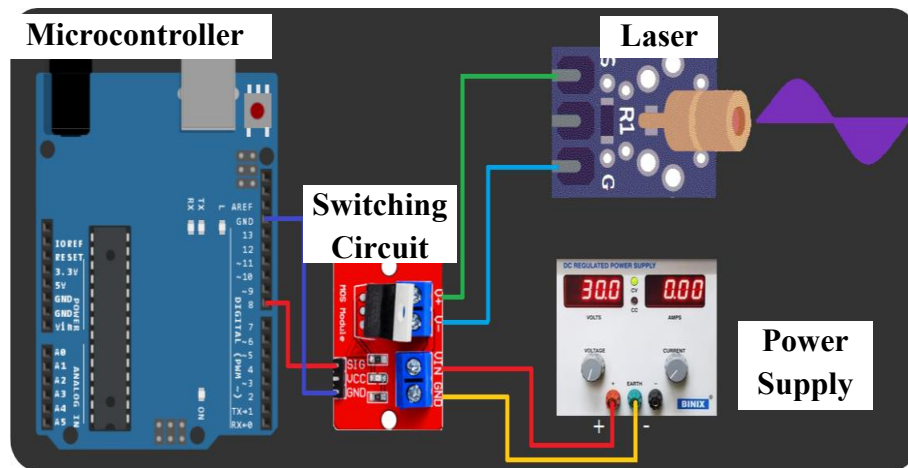


Fig. 3. The proposed transmitter circuit schematic of the system.

Modifying the lens ensures that the entire surface of the solar panel is illuminated at the required distance while maintaining the form and diameter of the traveled light beam. The incident light exhibits a horizontal divergence of 14° and a vertical divergence of 34° . By using OOK modulation scheme, the microcontroller transmits 8-bit ASCII characters as the information signal.

2.2. Information and power reception

Using the incident beam as a current source while maintaining a steady voltage between the PV cells is crucial to achieving the maximum bandwidth of the solar panel. The rapid change in light intensity that occurs when data is transmitted using OOK modulation results in variations depending on the speed of data transmission. To explain the demodulation process of the OOK,

a specific voltage threshold is used to compare the PV panel voltage. Bit-1 is represented in the received data when the voltage goes above the threshold, while bit-0 is represented when it goes below the threshold.

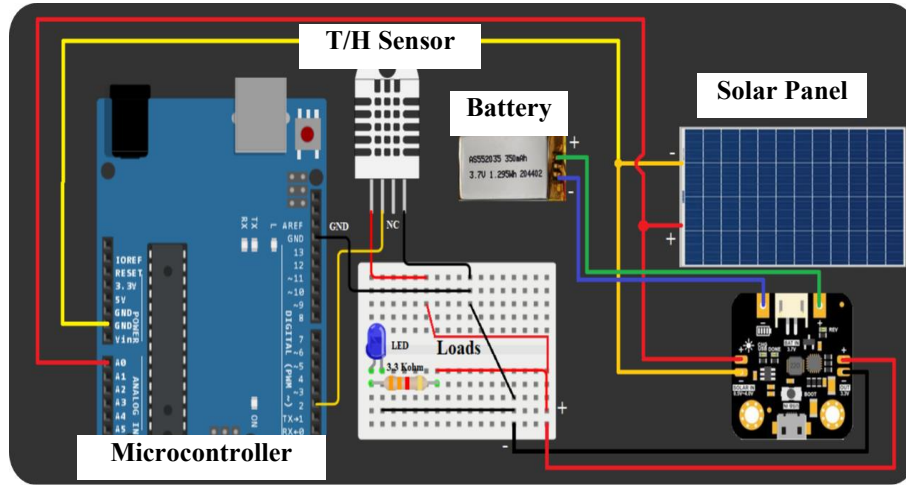


Fig. 4. The proposed receiver circuit schematic of the system.

The schematic of the receiver circuit is shown in Fig 4. The PV panel can convert optical power into electrical power and has dimensions of $37 \times 68 \text{ mm}^2$. The solar panel interface circuit in the receiver portion is responsible for separating DC power and AC signals by maintaining a steady voltage across the panels. The most effective way to harvest energy from solar panels that operate at their optimal operating point is by using Maximum Power Point Tracking (MPPT), which is considered the most effective method (Al-Jabari, A. et al., 2022). The I-V curve has a specific level that indicates the maximum power point of a solar panel, which operates at its highest efficiency and produces the highest output power. The solar charger controller is capable of performing MPPT, with solar input voltage ranging from 0.6-6 V and a maximum charging current of 50 mA. The charger controller is capable of charging the battery with a voltage of 3.7 V, such as lithium batteries. To ensure high-quality communication in real-time, it's essential to maintain a low level of complexity in digital signal processing. This requires a flat channel response without the need for any additional filters. The PV panel detects the variations in light intensity, which is connected to the microcontroller that decodes and displays the received data. The quality of the received signal can be measured using the BER.

3. EXPERIMENTAL RESULTS

The proposed SLIPT system, illustrated in Fig 5, is deployed for indoor implementation to evaluate the communication and power conversion capabilities. The communication link prototype is set to be 12m long (typical distance for indoor application) to be tested. The transmitter port consists of the microcontroller connecting to the switching circuit to operate a PWM-modulated laser module. The voltage-controlled current-driven laser module includes

the DC bias circuit, and the laser diode operates in the range of 12-24 V. The switching circuit supplies the laser module with the required voltage while switching at the time of information transmission.

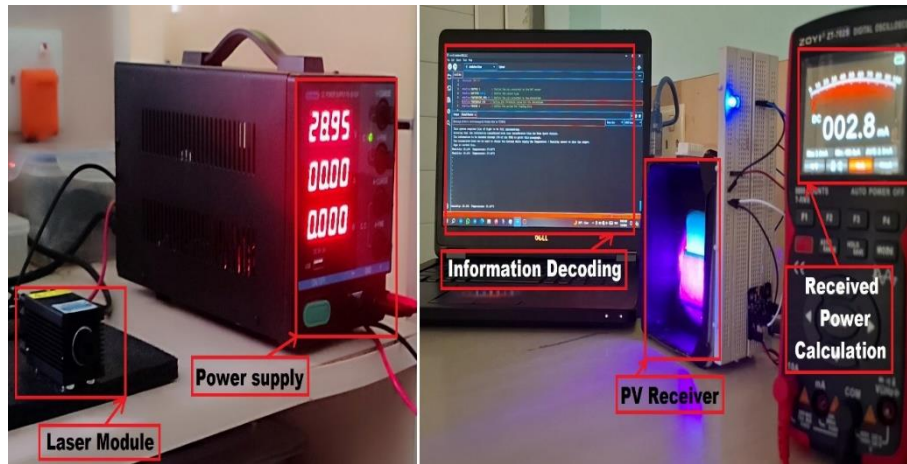


Fig. 5. The experimental setup of the proposed system.

3.1. BER analysis

When the incident signal is received by the PV panel connected to the microcontroller, the decoded data is converted into the corresponding original characters. Fig. 6 shows two different cases where the transmission signals undergo modulation and demodulation using MATLAB software, and the decoded data is plotted using the microcontroller.

In the first scenario, the laser module's maximum power, which is approximately 200 mW, is used to transmit the signal. Fig. 6(b) illustrates that the signal recovered is better than that of case 2, which transmits the signal with approximately half the maximum power depicted in Fig 6(c).

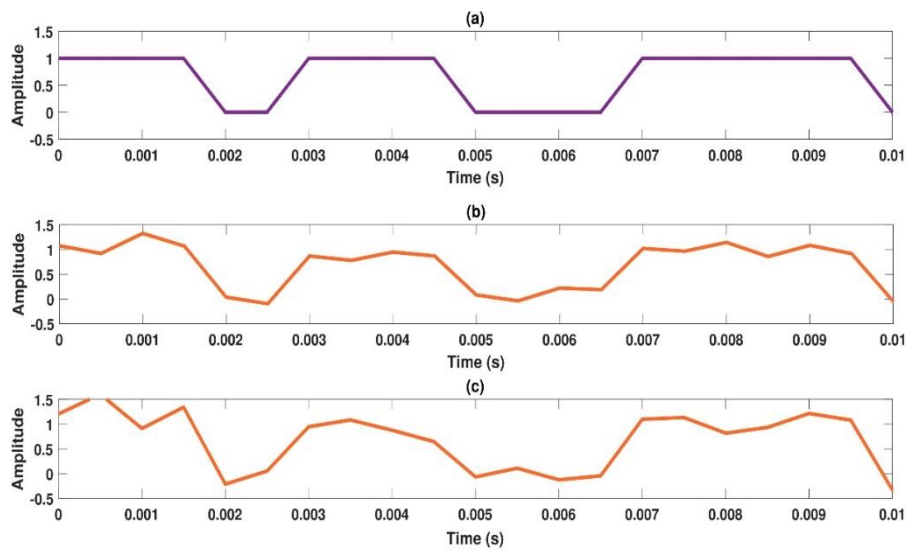


Fig. 6. Data transmission and reception process. (a) Transmitted signal; (b) Received signal with maximum transmission power; (c) Received signal with 50% of the maximum power.

The system's performance is evaluated by calculating the experimental model and comparing it with the simulation model. The BER resulting from the experimental system is measured using the mathematical relationship (Herbert T. et al. 1986).

$$BER = \frac{\text{No.of error bits}}{\text{Total transmitted bits}} \quad (1)$$

The theoretical BER can be calculated using the following expression (Aleš V. et al. (2016)).

$$BER_{OOK} = 0.5 \operatorname{erfc}\left(\frac{1}{2} \sqrt{\frac{Eb}{No}}\right) \quad (2)$$

The BER is estimated using a simulation model as well as practically by lab tests for the received signal from 1m to 12m with a 1m step. The received data is decoded and compared to the original transmitted signal to assess the BER values.

Under varying power conditions, the system's performance is described by the BER curve. Signal quality and data transmission errors are improved with a higher SNR. To evaluate the performance of the system for these two cases, the eye diagram is calculated in Fig 7. When the optical signal is transmitted with the highest possible power. The eye diagram reveals a well-defined and open “eye” shape. Indicating a minimal distortion in the received signal. A clear eye-opening suggests that the receiver can accurately distinguish between different logic levels (0 and 1). The eye diagram looks less open and highly distorted when the transmitted power is at 50% of its maximum. Due to noise, dispersion, or attenuation, the distinction of logic levels becomes more uncertain when the power is reduced. As illustrated in Fig 7, the bit error rate is higher because it becomes more challenging for the receiver to interpret the incoming data correctly with a power penalty of 1.1 dB compared to the theoretical implementation at a BER value of 10^{-3} , which is considered better signal quality (Proakis, J.G. et al. 2008).

According to the experimental results, the practical system closely follows the values in the simulation model, resulting in an accurate prediction of system behaviour. This alignment between simulated and theoretical values is crucial for validating the model's effectiveness and reliability. Furthermore, the combination of theory and practice allows engineers and researchers to identify potential discrepancies and address them proactively. By integrating theoretical models with practical simulations, designers can optimize communication systems to achieve higher performance, efficiency, and robustness.

3.2. Received power calculation

The PV panel is connected to the MPPT solar charger, which is designed to maximize the efficiency of the received power from the PV panel by continuously adjusting the electrical operating point of the solar module. A lithium-ion battery harvests the energy received by the solar cell. The hybrid sensor is connected to the output port of the MPPT as the system's load.

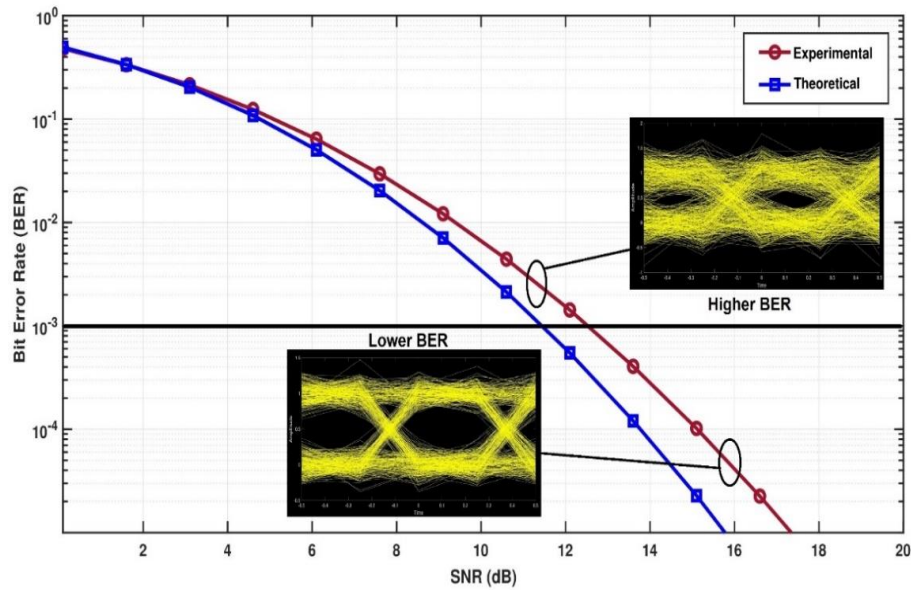


Fig. 7. BER vs. SNR comparison between theoretical and practical implementation.

Table 1 represents the electrical power harvested from the laser beam by the solar panel over a distance. The received power on the receiver side is calculated practically by lab tests for the received signal from 1m to 12m with a 1m step using lab equipment. The received electrical power is calculated using the power equation:

$$P_{ele} = V_{panel} \times I_{Load} \quad (3)$$

Initially, when the solar panel is close to the source, it can harvest most of the incident power. As the distance from the optical source increases, the received power decreases due to atmospheric turbulence, background, and reflected light from the solar panel protection layer.

Table 1. Experimental measurement of the power harvested by the system

Distance (m)	Harvested power (mW)
2	15.4
4	14.1
6	13.05
8	11.9
10	11.4
12	11.1

As the optical beam wavelength falls within the lower end of the responsivity range for Si solar panels, this corresponds to an acceptable power range and leads to an absorbance rate of approximately 16% at the transmitted wavelength. Atmospheric turbulence, light reflection from the panel's protective layer, and elevated solar panel temperatures were all forms of losses that the system encountered. Based on the analysis, MPPT's implementation makes it possible to transfer 94% of the detector's energy to the battery via the 12 m link. The panel's efficiency is measured at 16%, while the system's power harvesting capability is 5.5% of the transmitted power. These systems are considered self-sustained systems because they use the free energy

generated in the laser beam to reuse it in the receiver, which can be used in reverse communication and wireless sensor applications. Table 2 shows the recent works related to the SLIPT system implementation and their findings compared to this work.

Table 2. Overview of experimental SLIPT works

Reference	Environment	Transmitter Type	Receiver Type	Bit Error Rate	Harvested power (mW)
Kim, S.-M. (2013)	Outdoor	LED	Silicon solar panel	1.45×10^{-3}	1.02
Zhang, S. (2015)	Indoor	LD	Organic solar cell	4.08×10^{-4}	0.43
Fakidis, J. (2018)	Indoor	VCSEL	GaAs solar cell	2.2×10^{-3}	3.6
Tavakkolnia, I. (2021)	Indoor	LED	Organic solar cell	1.1×10^{-3}	10.9
This study	Indoor	Solid-State LD	Silicon solar panel	1.32×10^{-4}	11.1

4. CONCLUSIONS

This experimental study introduced a SLIPT system that adopted commercial lasers and PV panels. The experimental findings indicated that for a 12 m connection distance, the PV panel can harvest up to 11.1 mW of electrical power from the incident laser beam. The system also sustains communication links with a bit error rate of 1.32×10^{-4} . The system was tested to demonstrate its achievable performance in practical scenarios. The use of PV panels illustrated the capacity of power-efficient optical wireless communication networks to facilitate long-distance connections at a markedly lower cost than existing systems. The cost reduction is achieved by resource reutilization, diminishing the need for precise optical alignment, and minimizing the demand for energy supply infrastructure, all while preserving the intended outcomes of an energy-sustainable system.

Consequently, the system's efficiency and reliability are impacted by the need for Line of Sight (LoS), which requires various techniques to be enhanced, including adaptive tracking of the optical beam and mitigating aiming errors.

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