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Plan de Recuperación, Transformación y Resiliencia

E3. Initial report on novel low-power communication technologies and energy harvesting

Project: RISC-6G

PROGRAMA DE UNIVERSALIZACIÓN DE INFRAESTRUCTURAS DIGITALES PARA LA COHESIÓN
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Deliverable information

Description: Initial specification of low-power wireless communication technologies with specific focus on energy harvesting for 6G networks.

Due date: 30/06/2023

Responsible: IMDEA Networks

Partners involved: IMDEA Networks

Work Package 4 (WP4): Low-power Communication Technologies in 6G networks

Activity 9: Wireless harvesting for 6G networks (IMDEA)

Description: We propose a combination of LiFi and RF backscatter technology to enable battery-free Internet of Things (IoT) in future 6G deployments, enabling LiFi-enabled IoT deployments such as in the monitoring and control of next-generation greenhouses. Leveraging LiFi and RF backscatter technology in our work would provide next-generation greenhouses with low-power, yet efficient and flexible illumination.

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

In the scope of this task, we focus on utilizing LiFi-enabled Internet of Things (IoT) technology to introduce sustainable and precise greenhouse methods. We anticipate that by leveraging the advancements in IoT technology and incorporating innovative Light-Fidelity (LiFi) techniques, we can achieve substantial reductions in energy consumption and resource utilization within the realm of food production. *This work has been published in the IEEE Communications Magazine [1].*

Building upon our previous research in [2], which focused on enabling battery-free Internet of Things (IoT) nodes through the integration of LiFi and RF backscatter technology, we extend the application of this technology to facilitate battery-free, LiFi-enabled IoT deployments in monitoring and controlling advanced greenhouses. Our aim is to achieve efficient production while minimizing the environmental footprint of greenhouse resources.

In addition, we discuss the research challenges associated with the implementation of Li-Fi-enabled IoT in monitoring and controlling greenhouses. We will explore topics such as the efficient dimensioning of Li-Fi-enabled IoT systems to ensure effective monitoring and control of smart greenhouses. By delving into these aspects, we aim to develop a comprehensive understanding of the potential hurdles and effective strategies for deploying Li-Fi technology in the context of smart agriculture.

Our proposal capitalizes on the versatility of LED (Light-Emitting Diode) technology to equip next-generation greenhouses with the ability to offer the following benefits and functionalities:

- 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

Lighting and Monitoring conditions in Greenhouses

The internal energy balance of greenhouses is primarily influenced by incoming solar radiation. This radiation/ligthing plays a significant role in shaping the environmental conditions within the greenhouse. In agriculture, several lighting metrics are taken into consideration to assess and monitor the growth and development of plants. These metrics include the Normalized Difference Vegetation Index (NDVI), which quantifies the health and vitality of vegetation; the Leaf Area Index (LAI), which measures the extent of leaf cover and canopy density; and the Daily Light Integral (DLI), which quantifies the total amount of photosynthetically active radiation received by plants over a day. These metrics serve as valuable indicators in understanding the lighting conditions and optimizing the cultivation environment for efficient crop growth. Given its significance in plant growth and development, the DLI metric serves as a key target parameter in our LiFi-based Internet of Things (IoT) system.

Greenhouse light levels are influenced by various factors, including shading from the greenhouse roof structure itself, neighboring buildings, clouds, and trees. Additionally, the quantity and quality of ambient light vary with the changing seasons. To address these fluctuations and ensure consistent and optimal lighting conditions, supplemental lighting is commonly provided to plants in greenhouses. This supplemental lighting helps to maintain adequate light levels throughout the year, compensating for any deficiencies caused by external factors and ensuring consistent growth and productivity of the plants.

Traditionally, ballasted fluorescent or high-pressure lamps, as depicted in Figure 1, have been used for greenhouse lighting purposes for several decades. These lighting technologies have been widely employed to provide the necessary supplemental lighting to support plant growth in greenhouses. However, with advancements in lighting technology, new options have emerged that offer improved efficiency, control, and flexibility in meeting the lighting requirements of plants in a greenhouse setting. Other important greenhouse conditions that affect plant growth include soil moisture levels, humidity, air movement, and the concentration of carbon dioxide (pCO2).

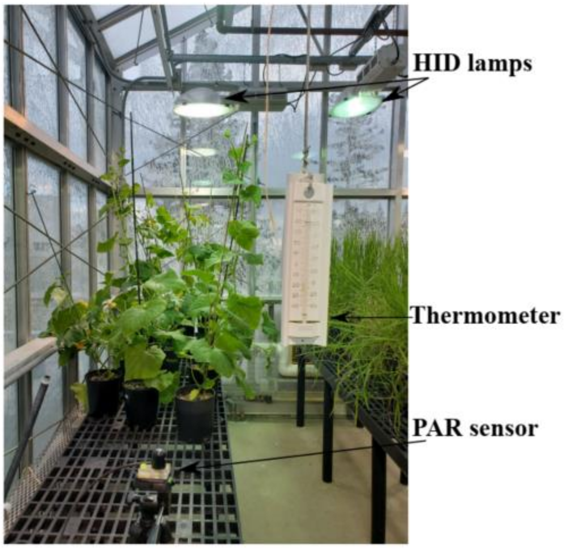


Figure 1: Example showing how greenhouses are traditionally instrumented

The next-generation of greenhouses will embrace innovative Internet of Things (IoT) solutions to monitor the parameters mentioned earlier. These solutions will be combined with cloud computing and big data analytics to fine-tune greenhouse environments and create the optimal growth conditions for plants. By leveraging IoT technologies, greenhouse operators will have access to real-time data on lighting, temperature, humidity, and other relevant factors. This data can be processed and analyzed using cloud-based platforms, enabling the application of advanced algorithms and machine learning techniques to optimize and personalize the growth environment for each plant species or variety. This integration of IoT, cloud computing, and big data holds tremendous potential for maximizing productivity, resource efficiency, and crop quality in modern greenhouses.

LiFi-enabled IoT for Greenhouses

Our vision for the future of sustainable greenhouses revolves around harnessing the low cost and versatility of LED (Light-Emitting Diode) technology. In addition to serving as a source of supplemental illumination, we envision LEDs playing a multifaceted role by providing communication and energy harvesting capabilities.

By integrating communication capabilities into LED lighting systems, we can enable seamless connectivity within the greenhouse environment. This opens up possibilities for various applications such as remote monitoring, control systems, and data exchange between different components of the greenhouse ecosystem. Moreover, LED technology can be utilized to harvest energy from the ambient environment, such as solar or thermal energy. This energy harvesting capability can help reduce the reliance on external power sources and enhance the sustainability of greenhouse operations.

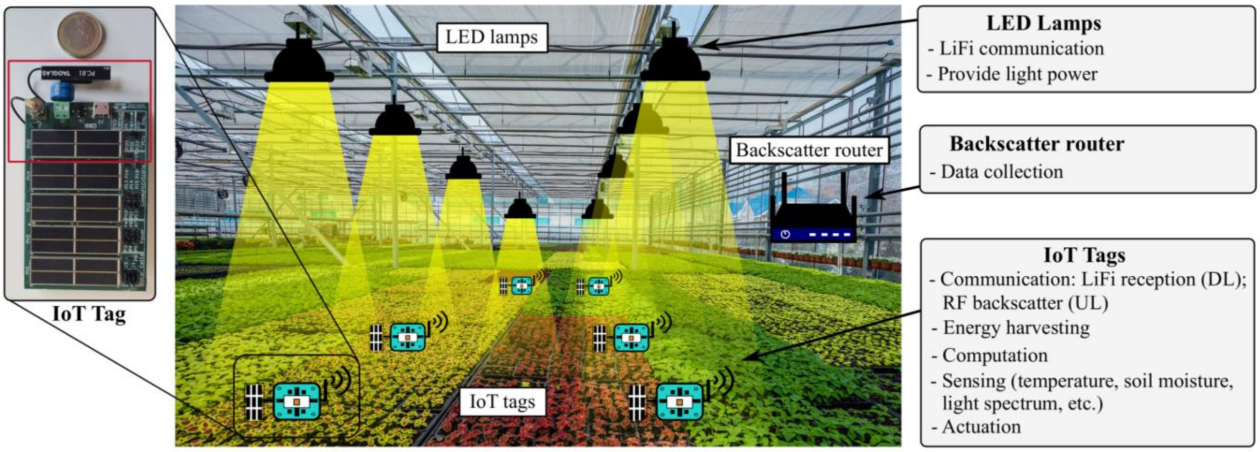


Figure 2: System architecture: Battery-free IoT tags receiving LiFi data and transmitting sensed data with RF backscatter to a router

We have developed a proposed architecture for a LiFi-based IoT-enabled greenhouse, which is depicted in Figure 2. In this architecture, LEDs are strategically deployed throughout the greenhouse to provide pervasive lighting. The IoT devices within the greenhouse are equipped with various sensors, such as temperature, humidity, and soil moisture sensors, to collect real-time data on environmental conditions. These IoT devices are distributed across the greenhouse to efficiently carry out tasks related to energy harvesting, communication, computation, sensing, and actuation.

In our proposed system, the data collected from the IoT tags, which are equipped with various sensors, is transmitted to an edge device. In this case, the edge device is a router that serves as a central hub for data processing and remote control of greenhouse conditions. We describe each of the functions performed by the IoT system below

- Communication: In our setup, we utilize LiFi technology for the downlink transmission. The data transmitted from the LEDs primarily consists of actuation commands, which are used to facilitate the management, adjustment, and optimization of the IoT tags within the greenhouse. These commands enable actions such as requesting specific data from certain tags, modifying sampling rates, performing system upgrades, and selecting appropriate sensors. In the uplink transmission, we employ a low-power technique called RF backscatter. This technique involves the absorption and reflection of RF signals present in the environment to passively modulate data [2]. As depicted on the right side of Figure 2, the backscatter router sends out an RF signal that is then absorbed and reflected back by the tags based on the sensed data. This enables the tags to transmit information without requiring their own active RF transmission capability.
- Battery-free operation of IoT tags: Our system is designed to eliminate the need for batteries, which are predominantly based on Lithium. Lithium extraction is challenging as it is only available in limited regions of the planet, and its extraction and disposal can have significant negative environmental consequences. By removing the reliance on batteries, our system aims to reduce the environmental impact associated with their use and disposal. Instead of using batteries, we store the harvested energy in the electric field of a capacitor, which powers the IoT tag circuitry. This approach allows us to minimize the environmental impact associated with energy storage and disposal by utilizing a

more recyclable component.

- Computation: To minimize energy consumption, we employ extremely low-power microcontrollers in our system. Additionally, we utilize an event-driven and interrupt-based implementation approach, which allows the system to respond to specific events or triggers, conserving power by only activating the necessary components when needed.
- Sensing: In our greenhouse IoT system, the tags are equipped with a variety of sensors to monitor important environmental and plant conditions such as temperature, humidity, soil moisture, and CO2 levels. These sensors provide valuable data for understanding the greenhouse environment and optimizing plant growth. To collect and process the data, the tags utilize their embedded microcontrollers. The microcontrollers analyze the sensor readings and perform necessary computations to derive meaningful insights. Once the data is processed, it is transmitted through the uplink channel of the system.
- Actuation: In our greenhouse IoT system, the tags receive actuation commands through the downlink channel, enabling the management and control of various aspects of IoT operations. These actuation commands can include instructions for adjusting sensor sampling rates, performing maintenance checks, and other relevant tasks. By employing a closed-loop control approach, the IoT system can automatically issue actuation commands to the greenhouse control system based on the real-time measurements reported by the IoT tags. This allows for dynamic control and optimization of greenhouse conditions. For example, based on sensor readings, the system can adjust the ambient temperature or activate an irrigation system to maintain optimal growing conditions for the plants.

Implementation and experimental results

Our work builds upon our previous research on PassiveLiFi [2], which introduced a battery-free tag that combines LiFi for downlink communication and low-power RF-backscatter for long-range uplink communication. In the downlink, we achieved a data rate of up to 280 kb/s using LiFi technology.

For the uplink communication, we optimized energy efficiency by offloading the clock synchronization to the LiFi infrastructure. Additionally, we employed chirp spread spectrum (CSS) signals in the backscatter channel, allowing us to decode signals even below the noise floor. This significantly increased the communication range of our system to hundreds of meters while maintaining low power consumption.

To summarize the performance of our PassiveLiFi tag's uplink, we provide a comparison in Table I against state-of-the-art communication technologies. This comparison includes factors such as communication range, data rate, and power consumption, highlighting the advantages of our approach in terms of energy efficiency and long-range communication capabilities.

Table 1: 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

It is important to note that in the context of self-sustainable greenhouse systems, the focus is primarily on energy consumption rather than achieving high data rates or long communication ranges. The goal is to design an IoT solution that operates efficiently with minimal energy usage. Our communication solution consumes at least 4 orders of magnitude less than the state-of-the-art.

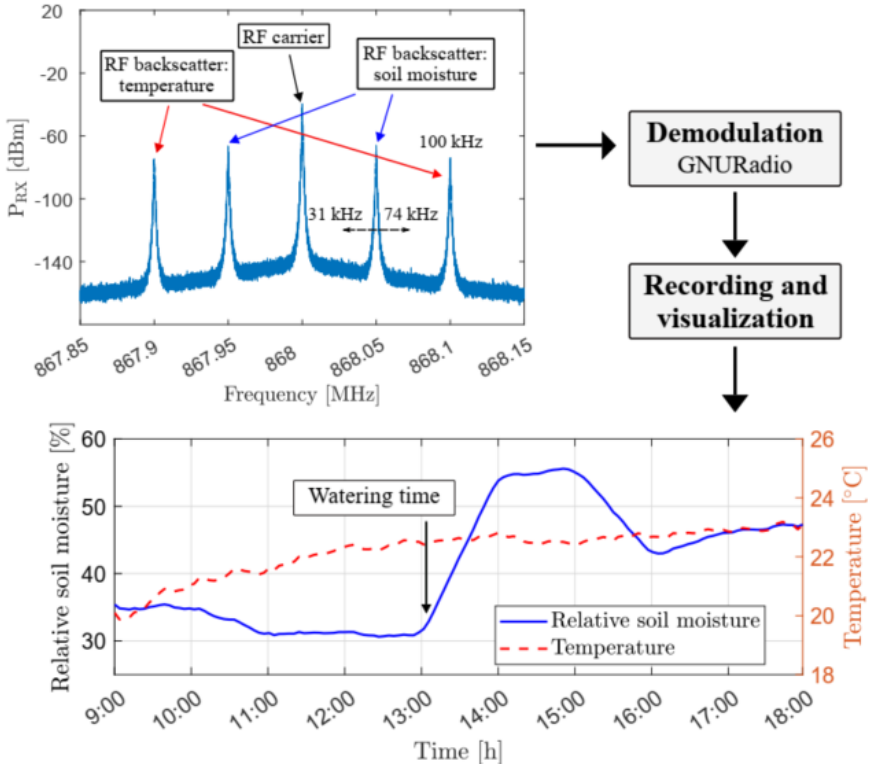


Figure 3: Spectrum of received signal and experimental results of temperature and soil moisture in a plant pot.

Additionally, we have successfully incorporated temperature and soil moisture sensors into our IoT tags, allowing us to monitor soil moisture levels and temperature in the vicinity of a plant pot over an extended period of time, as depicted in Figure 3. The spectrum of the received signal is also displayed in Figure 3, illustrating that each sensor's data is transmitted at a distinct frequency.

Activity 10: Low-power communication (IMDEA)

Description: We design a new modulation scheme based on On-Off-Keying (OOK) and Pulse Width

Modulation (PWM). The modulation scheme is simple, low cost, and yet efficient as it exploits the densification of artificial lighting, using both visible light and infrared spectrum. We created an enhanced version of OpenVLC open-source project (led by IMDEA Networks) as a prototype for our solution, and we empirically demonstrate its reliable performance in communication across various dimming scenarios. We also make the implemented system openly accessible to the research community.

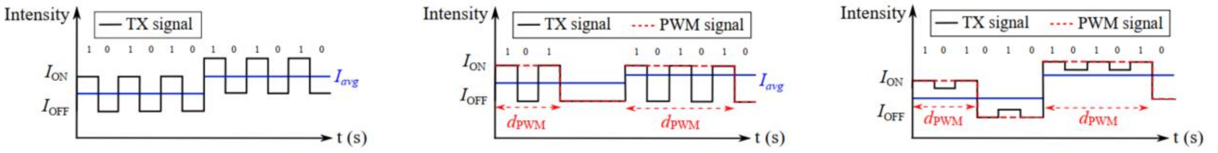
Visible light or infrared? Modulating LiFi for dual operation in the visible and infrared spectra

In this study, we anticipate that forthcoming LiFi systems will operate in both the visible light and infrared ranges, harnessing the benefits of both spectra to ensure reliable communication. From a technological perspective, LED bulbs commonly consist of numerous compact Surface Mounted Device (SMD) LEDs. In the coming years, it is conceivable that certain SMD LEDs may operate within the visible light range, while others function within the infrared range. Consequently, it would be straightforward to enhance the capabilities of LED bulbs to operate in both spectra. Our solution also capitalizes on the fact that conventional photosensitive devices are responsive to both visible light and infrared spectra. Hence, no modifications are necessary at the optical receiver.

The operation in both the visible light and infrared spectra necessitates the development of novel modulation schemes that effectively integrate transmissions in both bands, while also considering dimming challenges specifically in the visible light band. This paper addresses these concerns and proposes solutions accordingly. *This work has been presented at Wireless On-Demand Network Systems and Services Conference (WONS), 2023 [3].*

Figure 4 illustrates an example of dimming techniques, utilizing OOK modulation. However, it is important to note that any other modulation scheme can be employed in this context. Analog dimming using OOK modulation (Figure 1a) offers advantages such as low computational complexity and straightforward implementation. However, it is important to note that directly adjusting the forward current through the LED in this approach can lead to a change in the emitted wavelength of the light, degrading the spectral efficiency [3]. Digital dimming utilizing OOK modulation (Figure 1b) exhibits limitations in terms of the achievable data rate [4]. To address these limitations, various dimming techniques have been proposed, combining both analog and digital dimming with existing modulation schemes, which is the case proposed in Figure 1c [5].

Nevertheless, many existing dimming proposals suffer from several drawbacks, including: (i) limited dimming precision; (ii) constrained dimming range; (iii) increased complexity when trying to guarantee a balance between communication performance and illumination; and (iv) poor communication performance under high dimming conditions. Moreover, most of current solutions can only be applied to specific scenarios (only to multi-carrier [6] or only to multi-LED systems [7]) and have not been experimentally tested.



(a) Analog dimming - OOK modulation.

(b) Digital dimming - OOK modulation.

(c) Combined analog/digital dimming - OOK modulation.

Figure 4: State-of-the-art OOK dimming techniques

Proposed Approach

The block diagram of our proposed LiFi transmitter and receiver, designed to operate simultaneously in both the visible light (VL) and infrared (IR) spectra, is presented in Figure 4. The diagram illustrates that by utilizing two input signals, namely an On-Off-Keying (OOK) signal and a Pulse Width Modulation (PWM) signal, and passing them through various logic gates, we derive the corresponding signals to be transmitted by the VL and IR LEDs.

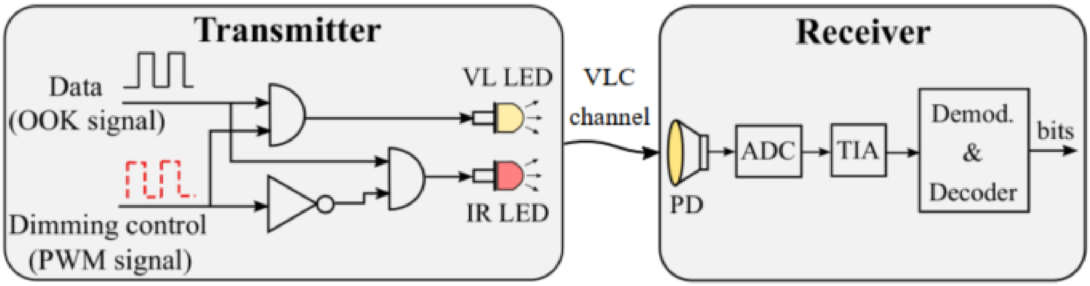


Figure 5: Block diagram of the proposed LiFi system

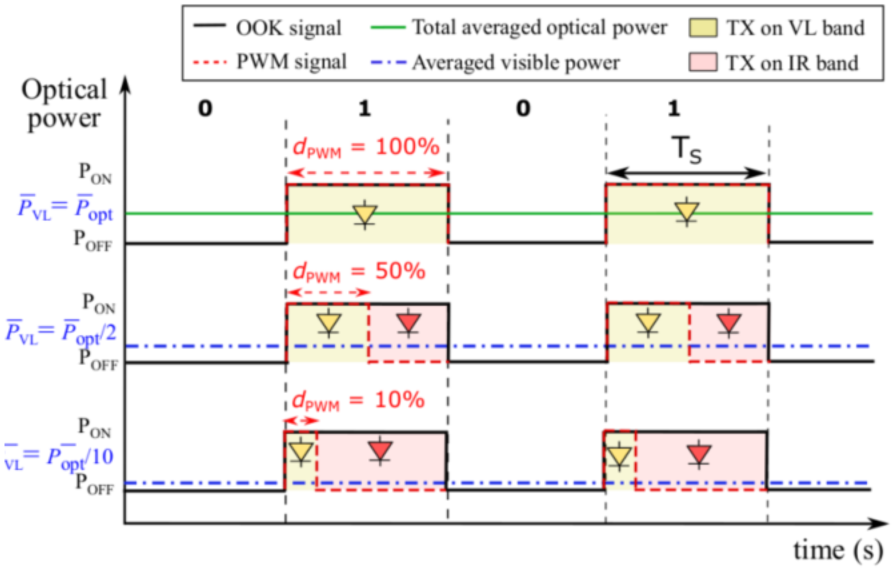


Figure 6: Proposed modulation scheme

Figure 5 illustrates various instances of the emitted signals from each LED, corresponding to different dimming levels. The figure demonstrates the integration of OOK and PWM modulations for communication and dimming functionalities, respectively. In particular, when transmitting the OOK symbol '1', the transmitter switches between the VL and IR bands based on a PWM signal. The duty cycle (dPWM) of the PWM signal determines the level of dimming that is achieved. As illustrated in Figure 5, when the PWM signal is set to 'ON', the transmitter functions in the VL (Visible Light) band, transmitting a VL signal primarily used for illumination. Conversely, when the PWM signal is set to 'OFF', the transmitter operates in the IR (Infrared) band, generating an IR signal that contributes to dimming. Consequently, the dimming level is inversely proportional to the duty cycle (dPWM) of the PWM signal, meaning that a higher dPWM results in a lower dimming level. In Figure 3, P_{VL} represents the average optical power emitted in the visible light (VL) spectrum for each dimming scenario, while P_{opt} denotes the total average optical power emitted across both VL and IR spectra. It is worth mentioning that the proposed technique can be expanded to incorporate other modulation schemes by employing alternating VL and IR LEDs. However, for the sake of simplicity, we focus on the use of OOK (On-Off Keying) modulation in this paper.

In LiFi networks utilizing the proposed transmitter, any photodiode (PD) capable of detecting signals in both the visible light (VL) and infrared (IR) bands can be utilized as a receiver. When considering the responsivity of photosensitive devices, we observe that PDs offer improved performance when operating within the infrared band (800 nm to 1,000 nm) range as shown in Figure 4.

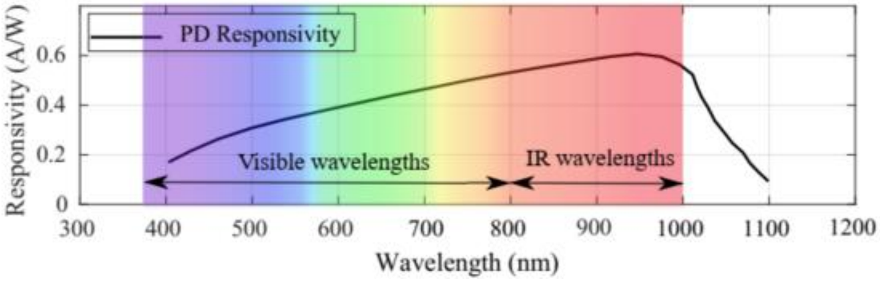


Figure 7:Responsivity of the 'VTP4085H' PD at the receiver

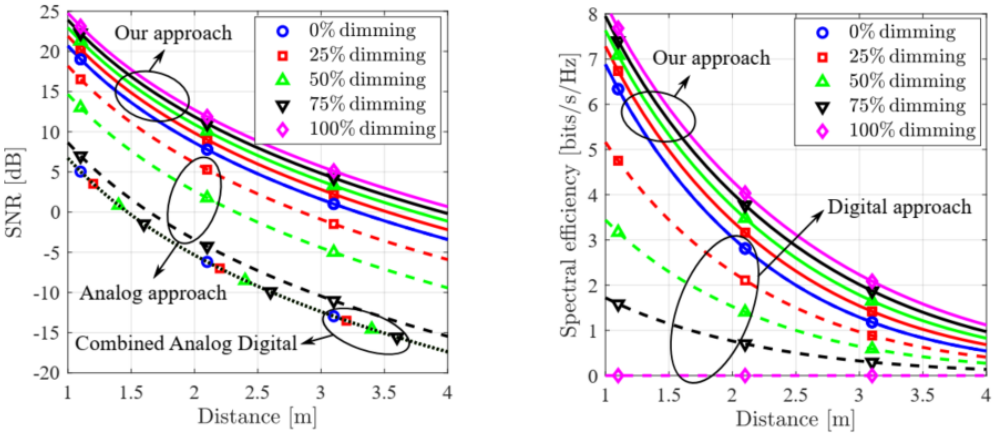
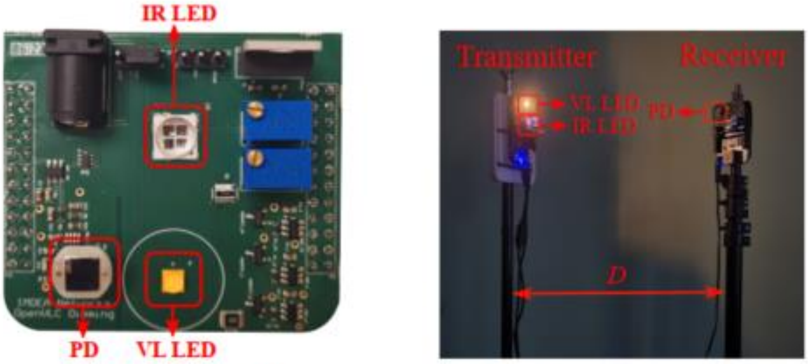


Figure 8:Performance comparison between our proposal and state-of-the-art OOK dimming technique:(a) SNR against distance for our proposal, analog dimming and combined analog/digital dimming and (b) Spectral efficiency against distance for our proposal and digital dimming



(a) Fabricated PCB.

(b) Setup for experiments.

Figure 9: Hardware and setup used for experiments

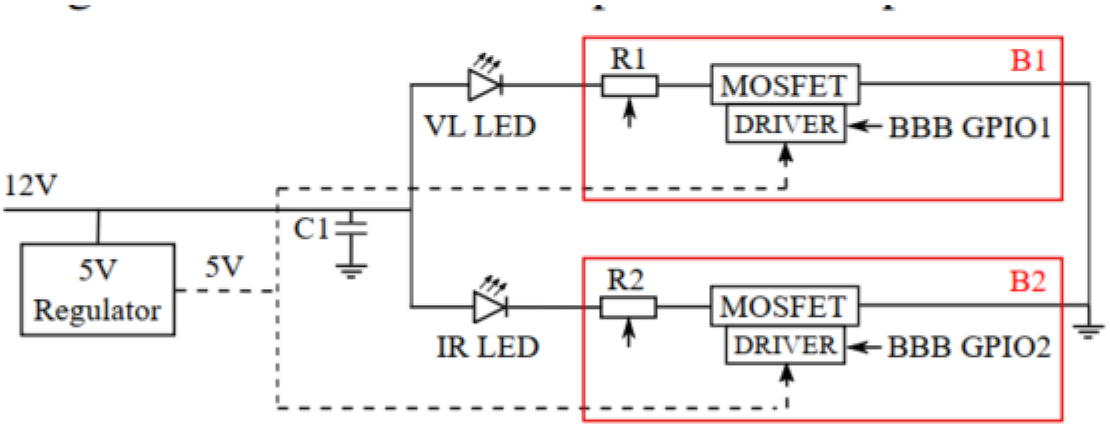


Figure 10: Schematics of the designed transmitter

Implementation

Figure 8 presents simulation results comparing our proposed solution with state-of-the-art alternatives, including analog, digital, and combined digital-analog approaches as depicted in Figure 1. The results presented in the study are obtained using established equations derived in [8], along with the following simulation parameters, an optical power when LED is ON of 1 W, sampling frequency of 10 MHz, absolute temperature of 300 K, receiver load 50 Ω, LED models XHP35B-00-0000-0D0HC40E7 and LZ4-00R708 for VL and IR LEDs, respectively, and PD VTP4085H. Figure 9 depicts our prototype and the experimental setup utilized in the study, providing a visual representation of the physical implementation, and the and the transmitter schematic is detailed in Figure 10.

The firmware designed for transmission is intended to run on the Programmable Real-time Unit 0 (PRU0) of the BeagleBone Black (BBB). It encompasses three primary functionalities, each serving specific purposes for the transmitter's operation, i) generating the modulating signal to the selected LED (OOK signal in Figure 5), ii) creating the PWM signal whose duty cycle (dPWM) determines when to switch between the VL and IR bands and thus the provided dimming level, and iii) switching between the VL and IR LED by enabling the proper General Purpose Input Output (GPIO) to control each LED (B1 or B2 in Figure 10).

Results

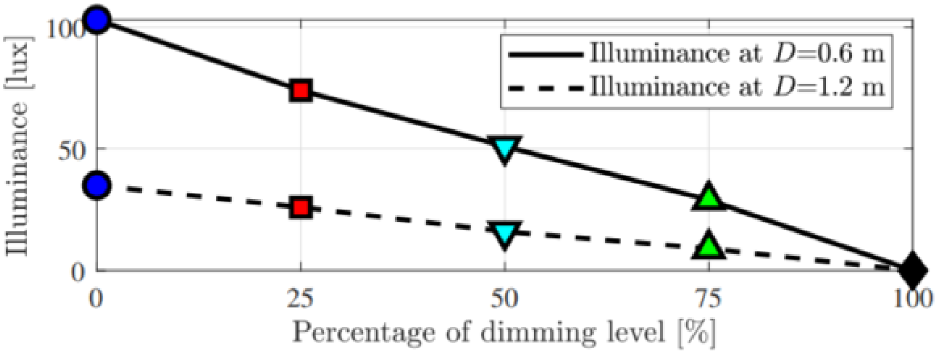
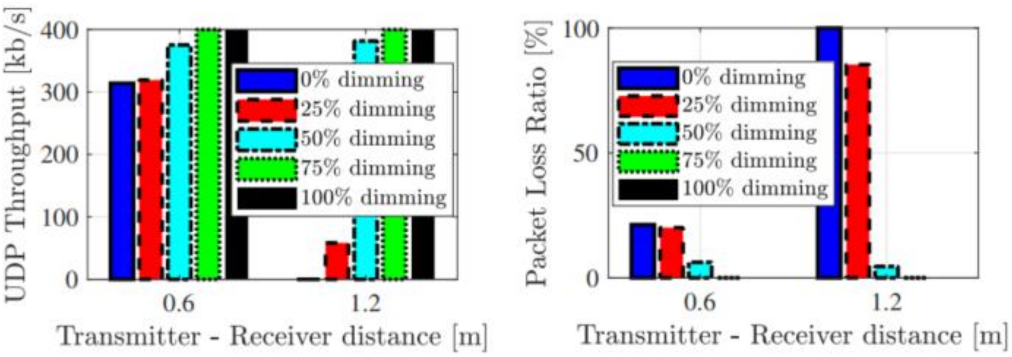


Figure 11: Illuminance for different dimming levels and distances

Our experimental results demonstrate that our solution is capable of delivering different illuminance values, as illustrated in Figure 11. To ensure a fair comparison, we adjust the potentiometers R1 and R2 in Figure 10 to achieve an equal amount of received power in both the VL and IR spectra. This adjustment ensures that the comparison between different illuminance values is based on an equalized power level in both spectra.



(a) UDP throughput results. (b) Packet loss ratio results.

Figure 12:Experimental results

Figure 12 illustrates the experimental results of UDP throughput and packet loss ratio for two different distances, D = 0.6 m and D = 1.2 m, at various dimming levels. The test is conducted using the iperf command to transmit data from our LiFi transmitter to a LiFi receiver. It is worth noting that, as expected, the UDP throughput increases with higher dimming levels compared to lower dimming levels. However, it is important to acknowledge that the illuminance is lower at higher dimming levels due to the fact that the VL LED is turned off for a longer duration compared to the IR LED.

At a distance of 1.2 m, the option of 100% dimming yields the highest UDP throughput of the OpenVLC platform, reaching 400 kb/s. Conversely, when only the VL LED is turned on, i.e., with 0% dimming, the UDP throughput drops to 0 kb/s. This comparison highlights the significant impact of dimming on the achievable throughput in LiFi communication systems. This is because photosensitive devices exhibit better performance when operating in the infrared band. It is worth noting that 100% dimming corresponds to the complete absence of visible light emission, and that the dimming level is selected by the user based on comfort and not on communication performance.

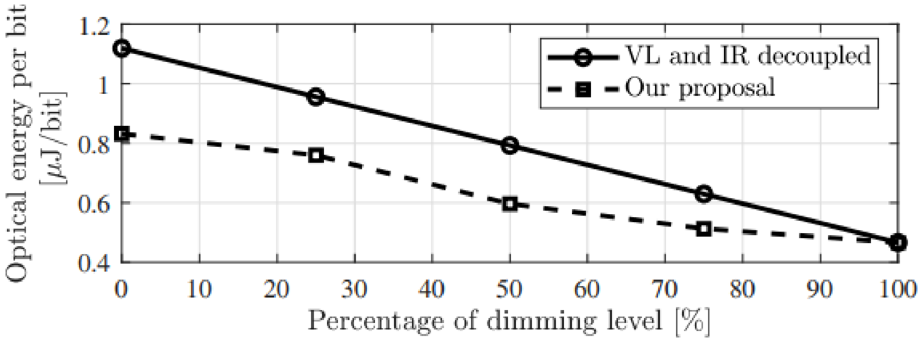


Figure 13:Optical energy per bit transmitted for each dimming level when the VL and IR LEDs are decoupled. Distance between transmitter and receiver is 0.6 m

Figure 13 illustrates the outcomes regarding the optical energy per bit between our proposal and if VL and IR are decoupled. It is important to observe that as the dimming level increases, the optical power per bit decreases due to the improved throughput. In the situation where both LEDs are decoupled, a maximum UDP throughput of 400 kb/s is achieved. However, the VL LED consumes additional power, resulting in higher optical energy per transmitted bit. This leads to consumption levels approximately 30% greater than those attained with our suggested system.

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