Multi-cell Deployment for Experimental Research in Visible Light Communication-based Internet of Things

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ABSTRACT

Visible Light Communication (VLC) provides both illumination and communication thanks to the usage of Light-Emitting Diodes (LEDs). In order to support the research in the field, the study of possible infrastructures to enable constant illumination and reliable communication becomes a necessity to pair up the evolution of both fields. Leveraging the fact that LEDs are getting more densely deployed to provide uniform illumination, in this work we present the design of a multi-cell deployment that uses several LEDs as VLC Access Points (APs) for Internet of Things (IoT) applications. We characterize the light emitted by the selected LED and show how this deployment complies with the illumination standards, as well as providing a reliable communication network. We present our design choices for controlling and communicating to the network of VLC APs, and show the required functionalities that must be fulfilled such as power monitoring, power management, and communication management.

CCS CONCEPTS

• **Networks** → *Wireless local area networks.*

KEYWORDS

Visible Light Communication, LiFi, IoT, Multi-cell setup, Prototyping.

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1 INTRODUCTION

Since its most relevant improvements to produce white light efficiently, the usage of light-emitting diode (LED) for lighting purposes has experienced a considerable increase with a market that is expected to achieve a global revenue of USD 135.58 billion by 2028 [9]. Its superior power efficiency is still increasing, its lifetime is several times longer than that of its competitors and its provided color quality, discrete dimensions and weight are better in comparison to other options [17]. Besides, LED luminaries can be modulated at very high speed, which enables Visible Light Communication (VLC). This allows LED lighting to provide the dual functionality of illumination and data transmission, also reducing the carbon footprint of wireless communication technologies.

Providing communication capabilities to LEDs is not straightforward. Communication hardware is not installed in commodity LEDs yet, and multiple options have been proposed to connect LEDs with Internet, then providing a networked VLC system, called Light Fidelity (LiFi) [10]. While VLC researchers have typically focused on point-to-point communications, there has been limited work on addressing the networking issue in a multi-cell LiFi deployment. Dense networks are specially required since LEDs tend to be deployed more and more uniformly for user comfort. Such backhauling support to connect these LEDs operating as Access Points (AP) is needed, and there is currently a lack of knowledge in the scientific community about how to build such a testbed. To address this problem, we present an experimental testbed where multiple low-cost VLC APs are installed and controlled from a central station, then providing a uniform lighting across the room that reproduces the lighting of a workplace in a realistic way, while providing Internet of Things (IoT) wireless services.

There are few works that present a hardware deployment of multi-cell LiFi networks. Authors of [3] presented a dense deployment of VLC transmitters and they evaluated the power allocation and synchronization issues. Although they studied the energy consumption in the LEDs operating as APs, the overall network design is not detailed. Besides, constant illumination is not always considered in VLC systems [15]. Both works above centralise the VLC transmitter decision logic, which affects the system flexibility. Also, power networks are a relevant issue in LiFi, which must be studied to extend the reach of VLC over illumination deployments. Power line communication has been proposed to face this problem [11, 18], but a dense LiFi network based on this principle has not been established yet.

Against this background, this work presents the design and implementation of a LiFi backhauling network to control the illumination and data transmission of LEDs used as VLC APs. Our deployment easily uses commercial off-the-shelf (COTS) hardware components that we hope will facilitate the reproducibility of our setup. As a transmitter, OpenVLC 1.3 [8] is used, which is a low-cost open-source platform oriented to VLC research whose networking capabilities make it a suitable option for performing research in LiFi networks for IoT applications. As a central station, we use a laptop with a customized graphical user interface (GUI) and a COTS switch to connect with multiple APs.

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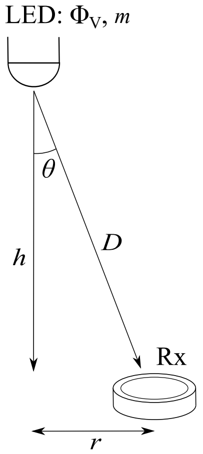


Figure 1: LED and receiver relative position diagram.

2 VLC EQUIPMENT CHARACTERIZATION

In this section we evaluate the lighting characteristics of the LED. The main objective is to achieve comfortable and sufficient illumination levels in the room. Thus, the bulb used as VLC AP is characterized so that we can perform a network analysis and create a multi-cell LiFi network that provides uniform illuminance according to lighting standards [13].

2.1 LED characterization

We must know the photometric specifications of the lighting source. OpenVLC 1.3, which is used as VLC transmitter for our setup, uses an LED model Cree XLamp XHP35A-00-0000-0D0HC40E7CT [1] and a collimating lens [2] on top of the LED in order to concentrate the light and to increase the effective transmission distance. This LED and its driver are managed by a BeagleBone Black (BBB) providing constant illumination even when no transmission is performed.

The radiation pattern of an LED follows a Lambertian emission model [16]

$$I = I_0 \cos^m(\theta), \tag{1}$$

where θ is the LED viewing angle, I_0 is the luminous intensity when $\theta = 0°$ and $m = -1/\log_2\left(\cos(\phi_{1/2})\right)$ is the Lambertian emission index of the source, being $\phi_{1/2}$ the half-power semiangle. Geometric variables can be seen in Fig. 1. The LED is assumed to be located on the ceiling and pointing downwards. On the receiver side, considering the free-space channel in VLC [14], the illuminance at one point is measured as

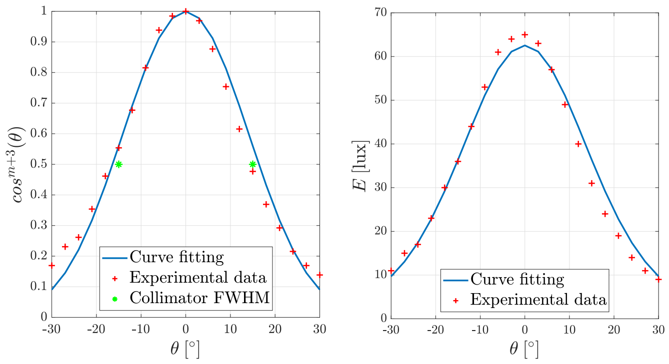
$$E = \Phi_V \frac{(m+1)h^{m+1}}{2\pi(r^2+h^2)^{\frac{(m+3)}{2}}} = \Phi_V \frac{(m+1)h^{m+1}}{2\pi D^{(m+3)}} \quad \text{[lux]}, \tag{2}$$

where Φ_V is the output luminous flux of the LED measured in lm, and h, r and D are the vertical, horizontal and Euclidean distance between the LED and the receiver, respectively. Note that the LED radiation pattern is fully characterized by knowing the parameters Φ_V and m. In the following we explain how we compute such values.

The ratio between the illuminance at any point n with Euclidean distance D_n and the illuminance under the LED ($\theta = 0°$, $h = D$) can be formulated as

$$\frac{E_n}{E_0} = \left(\frac{h}{D_n}\right)^{m+3} = \cos^{m+3}(\theta_n), \tag{3}$$

where θ_n is the irradiance angle from LED to the receiver located at position n. This relationship indicates the illuminance loss associated to the position of the receiver. Using (3), m can be calculated by measuring the LED illuminance from just two locations. However, for the sake of results accuracy, in this work we carry out several measurements along a radial direction to obtain the m parameter. Illuminance is measured with the LED located at a height of 1.5 m with respect to the receiver, in the range $\theta_n \in [-30°, 30°]$, with a resolution of 3°. Then m is fit by least-squares and we obtain a value of $m = 13.71$. Using this value, Φ_V can be calculated by fitting (2) to the experimental illuminance data, obtaining $\Phi_V = 60.12$ lm. Fitting functions are depicted in Fig. 2.



(a) Curve-fitting for Lambertian index.

(b) Curve-fitting for output luminous flux.

Figure 2: Photometric parameters of the LED used. Lambertian index m is the parameter to fit in (3), whereas the luminous flux Φ_V is in (2). Green star markers indicate the Full Width at Half Maximum (FWHM) of the collimator according to the datasheet. Note that it is very close to our experimental results.

These photometric characteristics may result insufficient to illuminate a regular indoor space. Then, OpenVLC is modified to overcome this issue. Its main advantage is the higher current driven to the same LED to produce a larger output luminous flux. OpenVLC 1.3 drives the LED with a current of 292 mA when transmitting bit '1', whereas 0 mA when transmitting bit '0'. The new design allows us to drive the LED with 678 mA when transmitting bit '1', then leading to a larger constant output luminous flux. This flux increase also means a larger achieved distance for communication. Using the same process represented in Fig. 2, the new values for Lambertian index and output luminous flux are $m = 13.91$ and $\Phi_V = 284.20$ lm, respectively. Note that m is almost the same as the radiation pattern has not been changed (we are using the same LED). These experimental results are subject to small errors due to parameters that are not easy to control, such as junction temperature or small misalignment between devices.

2.2 Illumination analysis

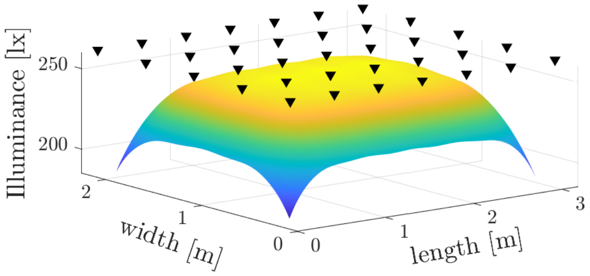
The characterization of the light source allows us to simulate the illuminance distribution in a room. Indoor illumination determines the visual capacities of a person and the spatial coverage of the VLC system. In [13], standard lighting requirements to perform visual tasks efficiently are presented, and we must provide a LiFi system that fulfills those requirements.

Two lighting parameters are typically measured to comply with illumination standards: average illuminance $\overline{E}$ and illuminance uniformity $U = \overline{E}/E_{\max}$, which must be larger than a certain value depending on the type of tasks to carry out in the room. These two are the ones that relate the most to the LED properties affecting VLC performance: emitted optical power and directionality. The distribution of LEDs across the room is quantitatively determined by the illumination requirements, since there is not an strict requirement in the number of LiFi cells.

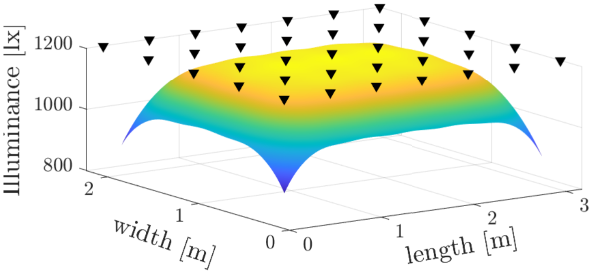
Using (2) and the position on the ceiling plane of each transmitter, the illuminance at position n within the room can be formulated as

$$E_n = \sum_{i=1}^{N} \Phi_V \frac{(m+1)h^{m+1}}{2\pi D_{n,i}^{(m+3)}}, \tag{4}$$

where $D_{n,i}$ is the Euclidean distance between i-th AP and position n. N stands for the total number of VLC APs. The dimensions of the considered room are $3.6 \times 2.4 \times 2.5$ m. This setup is required to comply with office illumination specifications: $\overline{E} > 500$ lux and $U > 0.7$ [13]. The proposed network uses 35 VLC transmitters disposed on the ceiling plane in a 7×5 grid. The height of the receiver is not explicitly established in the standard, although we consider a reasonable receiving plane of 1.2 m over the floor and parallel to it. This is the expected height for activities developed inside an office. Fig. 3 depicts the illuminance distribution across the room with transmission parameters presented in Section 2.1: $\{m = 13.71, \Phi_V = 60.12\,\text{lm}\}$ and $\{m = 13.91, \Phi_V = 284.20\,\text{lm}\}$ for typical OpenVLC 1.3 and a higher-power OpenVLC version, respectively. In the first setup, $\overline{E} = 237.2$ lux and $U = 0.78$ where the average illuminance does not comply with lighting standards. Increasing the number of transmitters is an inefficient way to overcome this problem, since cells would largely overlap, then increasing inter-cell interference. Moreover, the high uniformity achieved indicates that the low average illuminance issue can be solved with a more powerful transmitter. Indeed, working with the second setup (higher output luminous flux) achieves $\overline{E} = 1122.28$ lux and $U = 0.78$, which totally comply with lighting standards. This margin from the minimum required averaged illuminance translates into greater flexibility to modify the grid due to communications aims, in addition to apply this setup to larger scenarios such as industrial ones.



(a) OpenVLC 1.3.



(b) Higher-power OpenVLC version.

Figure 3: Illuminance distribution in the room on a plane 1.2 m height parallel to the floor (ceiling at 2.5 m over the floor) for a 7×5 transmitter grid (black) using OpenVLC 1.3 and a higher-power OpenVLC version. The higher-power OpenVLC version provides an illuminance which is in accordance with standard lighting conditions.

3 NETWORK DESIGN

To fulfill the communication and illumination functionalities described above, the LiFi network to be deployed must accomplish the following design criteria:

Power budget. The system must be able to provide enough power to all the VLC APs at the same time. The fixed power consumed by the cape is approximately 3 W in OpenVLC 1.3 and 7.5 W in the higher-power version. The BBB power consumption depends strongly on its running processes, but after reading BBB manual [5] and confirming it experimentally, the maximum consumption assigned to the BBB is 2 W. Considering a sufficient power margin, each VLC AP will require 10 W available at any time. Thus, for a target setup of 35 VLC APs, the system will require up to 350 W.

Single device power. Devices must be powered on/off individually and remotely, without a physical manipulation of any power source, cable or transmitter. This will allow us to save much energy, as only VLC transmitters involved at each specific experiment will be switched on.

Wired communication. The network must exploit the wired communication possibilities integrated with the BBB: Ethernet or USB. Both interfaces ensure a sufficient data rate. Wireless solutions are discarded since they incur in an extra power consumption in RF (oscillators, antennas, etc.), or in an strict alignment between transmitter and receiver in optical technologies, and do not allow powering and communicating simultaneously.

Centralized management. A single Linux machine must manage the power and communication with every device.

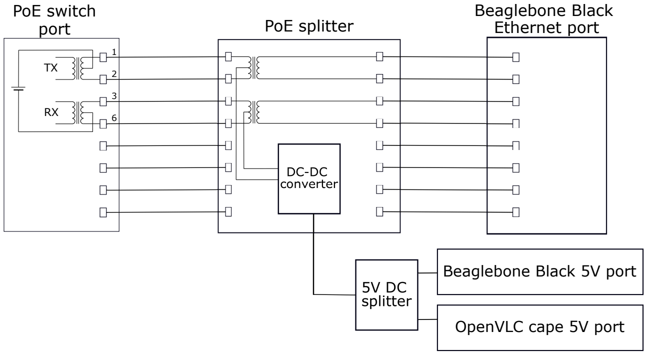


Figure 4: Representation of PoE connections in our setup. We are using devices compliant with alternative A pinout in standard IEEE 802.3af, where pins 1, 2, 3 and 6 are shared for both carrying power and data.

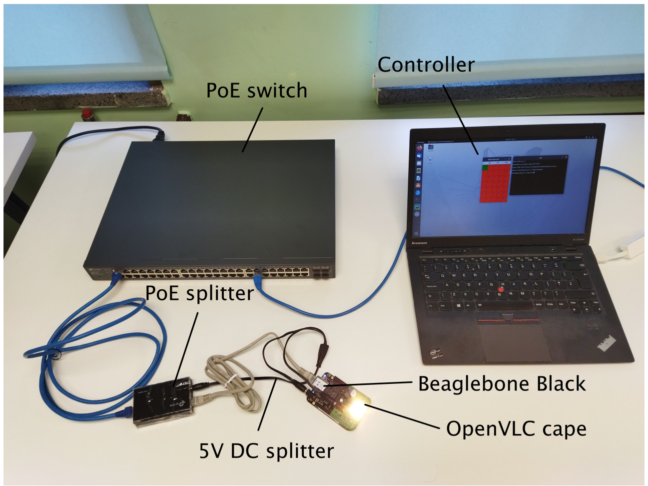


Figure 5: Real connections for a single VLC AP.

Both BBB and cape are powered using a 5 V DC connector. BBB can use the USB port for power and communication purposes, but since a 5 V power supply is necessary for the cape, it is worthy to reuse it for both devices using a power splitter. Regular power supplies are avoided, since they cannot be managed remotely. Also, power and communication signal through a single cable is desired to avoid the deployment of too many cables. There exist mainly two technologies that transport power and data simultaneously: Power over Ethernet (PoE) and Power Line Communication (PLC). Due to specific power requirements, the complexity of manipulating wiring infrastructure in power line, and the availability of PoE products in the market, we opted for a PoE solution in our setup.

PoE describes a system to transmit electrical power over twisted-pair Ethernet cable without interfering in data transmission. Figure 4 represents a diagram of connections in PoE, and how it is applied to our setup. Four pins are dedicated to carry power and data, whereas the other four pins can be dedicated only to sending data. Then, we take power from the PoE switch with the help of a PoE splitter and provide it to both the BBB and the OpenVLC cape, while guaranteeing a communication with the BBB. Figure 5 shows the real connections in a close setup for a single VLC AP. PoE is broadly used in networks where remote devices (access points, VoIP phones...) require an external power supply and network connection simultaneously. PoE systems compliant with IEEE 802.3af [12] guarantee a minimum power of 12.95 W for a device located at a distance of up to 100 m. According to the requirements aforementioned, this maximum power and distance are within our working operation characteristics. For the sake of completeness, some alternative implementations to deliver a power signal over an Ethernet cable were considered. It is possible to inject a 5 V power signal directly into the Ethernet cable (passive PoE). However, these solutions are not manageable and they also suffer from a voltage drop along the cable that our BBB and cape cannot afford, because they require precision in such power signal.

We use a PoE switch to provide both power and Ethernet connection. A PoE switch has the network capabilities of a regular switch in addition to providing PoE on its Ethernet ports up to a maximum power budget. PoE can be enabled individually on the desired port and its management can be performed remotely. Thus, the dual functionality of networking and powering is integrated on the same controller. To complete the state-of-the-art solutions, a midspan PoE injector was also considered, but then an additional regular switch is still required, which made us to discard this option and to simplify the setup.

As represented in Fig. 6, every PoE connection is split in two DC barrel 2.1 mm power outputs and the non-PoE Ethernet link using a PoE splitter. Power is supplied to BBB and OpenVLC using, each one, its own connector. The PoE splitter deals with possible voltage drops along the cable and ensures a 5 V output for each device.

4 IMPLEMENTATION

The network described above is deployed using the devices in Table 1. Note that, although we have used OpenVLC 1.3 as VLC AP, any other hardware with networking capabilities (Ethernet port and IP layer support) can be used in our setup. PoE devices such as DC splitters should be revised to install the ones that are compatible with new hardware. In our setup, static IP addresses are previously assigned to each transmitter depending on its position on the grid. PoE switches allow to monitor the power consumption on ports. This becomes useful in this setup, where each device connected can change substantially its consumption. It is important to notice that, by supplying a great amount of electrical power, the energy loss in form of heat is higher than in regular switches. Thus, these devices tend to require noisy fans to operate correctly. It must be considered in case the network is deployed in a quiet place, although it can be easily solved by installing the switch within an isolated enclosure.

When implementing the system, we found an unexpected problem: when powering off one VLC AP, it rebooted again due to the Powered Device (PD) detection process invoked by the PoE switch. When PoE capability of a port is enabled, the switch proceeds to apply a sequence of voltage signals to monitor the device located at the other side of the link. When it is completed, if the detected device is PoE compliant, appropriate power is provided through this port. Thus, the BBB can be totally powered off from the command line but, when done, the PD detection protocol triggers, power is

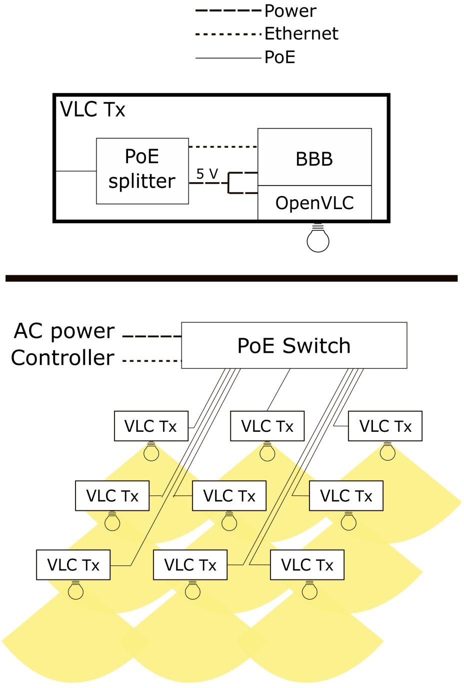


Figure 6: Example of network diagram with 9 VLC APs.

Table 1: Devices employed in the LiFi network.

Device	Model	EUR Price
PoE switch	TP-Link T1600G-52PS	400
PoE splitter	TP-Link TL-POE10R	14.63
5 V DC splitter	Tensility 10-02737	3.43
TX board	Beaglebone Black	59.95
LED driver	OpenVLC cape	24 + PCB production

provided again and BBB powers on. The interval while the BBB is still powered off is too short to interact with the PoE switch and disable PD detection. Instead, our solution was to not completely power off the BBB but drive it to a low-consumption state where all CPU functions are stopped. Processes such as memory writing do not take place in this state and, if power is cut off, all major damage to the board is avoided. Once this command is executed to drive BBB to a low-consumption state, the controller waits for the board to reach this state, double-checks it by trying a network connection, and then disables the PoE port.

We have developed an intuitive Python GUI to ease the access and monitor each cell activity. This one exploits the PoE switch command-line interface through Netmiko [4]: a module based on the SSHv2 implementation Paramiko [7] and dedicated to network equipment. From the GUI, the user can power on/off any VLC AP and start an SSH session with them, from where we can carry out all functionalities that OpenVLC allows to do. Figure 7 represents the implemented GUI. It shows the VLC AP grid, the state of each device, and different buttons to interact with every AP. Red colour

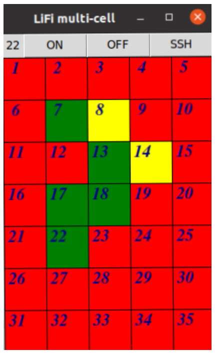


Figure 7: Customized GUI shown in Ubuntu 20.04.

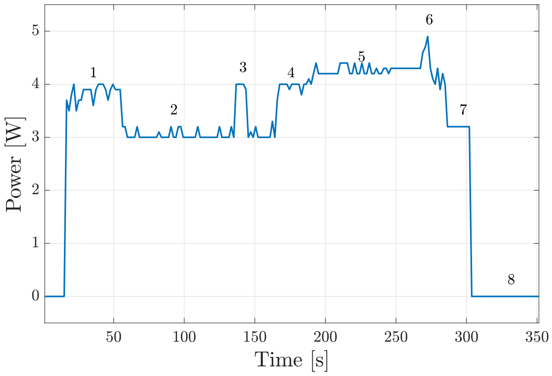


Figure 8: Power consumed by a single transmitter at different stages: 1) BBB boot; 2) Idle state; 3) OpenVLC configuration; 4) OpenVLC configured: LED on; 5) VLC Transmission; 6) Halt system; 7) System halted; 8) Power off.

means that that specific VLC AP is OFF, yellow colour means that the VLC AP is ON and green colour indicates that such VLC AP is ON and with an open SSH session.

5 RESULTS AND EVALUATION

In this section, we evaluate the performance of the full deployment. The density of VLC APs and their individual power management are two desired characteristics for a research-oriented LiFi network. While the performance of the device deployment in terms of illumination has been provided in Section 2.2, here we focus on VLC parameters for a specific AP.

Power consumption on each PoE port can be monitored from the switch. This power measurement includes the power consumed by the BBB, the OpenVLC cape and the power dissipated in the PoE splitter. Figure 8 shows the power consumption in different stages. Note that the power consumed increases when the AP is booting and the LED is on, whereas the consumption reduces when the system is halted. Little inaccuracies with respect to expected results come from PoE splitter energy consumption and imperfections in estimation made by the switch.

The maximum UDP throughput that OpenVLC 1.3 achieves is 400 kbps at a maximum distance of around 5 m [8] in a single link

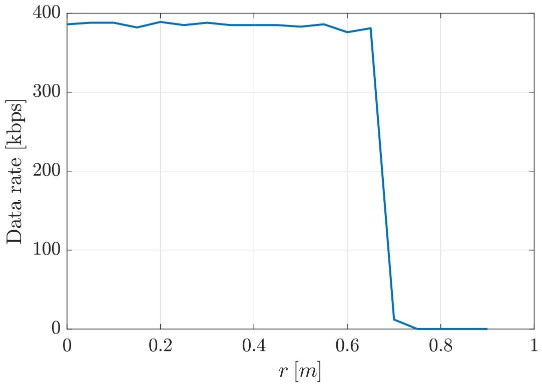


Figure 9: Data rate versus displacement from the LED optical axis in OpenVLC new version.

configuration. However, in the here presented work, we suggest the use of multiple cells. Thus, it is of upmost importance to know the cell radius and then enabling the study of multi-cell VLC deployments both experimentally and by simulations. The Lambertian index and output luminous flux of the LED, together with the geometric parameters of the scenario such as the height and the inter-AP distance, determine the LiFi performance within each cell. The diameter of the cells is evaluated over the VLC AP that complies with lighting standards as demonstrated in Section 2.2. To determine the UDP throughput over the cell, OpenVLC 1.3 is used as a receiver at 1.5 m from the LED and it is positioned perpendicular to the optical axis. Any other light source or reflection was avoided during the test, but it will be considered in the near future. As it can be seen in Fig. 9, the APs provide the maximum data rate achieved by OpenVLC 1.3 (≈400 kbps) in a radius cell of up to 0.65 m at a reasonable height of 1.5 m. Considering that the physical separation among APs in the suggested scenario is 0.5 m, each AP may cooperate with neighboring APs to serve users located in the whole neighboring cell area. Note that this redundancy in AP is an intrinsic characteristic of lighting systems, as a uniform and robust illumination is provided, i.e., each point in the room is typically illuminated by multiple fixtures. This enables the implementation of MIMO techniques, cooperative techniques to overcome line-of-sight blockage and precoding techniques, among others [6]. Finally, the total experimental delay from central station to user device is 2.68 ms. This work opens the door to a great amount of experimental work that will be studied in the future.

6 CONCLUSION

In this paper, we have presented our design of a LiFi multi-cell network that complies also with lighting standards. OpenVLC 1.3 and a higher-power OpenVLC version were tested to prove their performance as LiFi transmitters and luminaries. We presented the different design options and motivated the selection of PoE as the most suitable one to provide power and communication, simultaneously, to the VLC APs. We showed the implementation of a GUI to manage all APs remotely. Finally, we demonstrated that each AP guarantees communication at the whole VLC cell area, also covering full area of neighboring cells, which enables the possibility of exploring multiple cooperative transmission schemes in a practical way. This setup lays the foundation for further experiments in LiFi IoT scenarios.

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