Rethinking LiFi for Carbon Neutral Sunlight-based Communication

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***Abstract*—Wireless communication has to be redesigned to achieve sustainable communication infrastructure providing net-zero carbon dioxide emission. This paper presents a novel Light Fidelity (LiFi) design that exploits the concept of tubular light guides that can be installed in new buildings. While these guides bring natural sunlight indoors, our proposed system LiFiTube modulates it with low-power liquid crystal (LC) shutters to provide wireless data services without using any power hungry electronic components. Preliminary results show that our proposed LiFiTube system can provide a self-sustainable communication technology and can guarantee demands of Internet of Things networks, while illuminating indoors. We also draw some future research directions.**

***Index Terms*—Carbon neutral, Light Tubes, Buildings, Internet of Things (IoT), LC shutter, LiFi, Sunlight Communication.**

I. Introduction

The deployment of ubiquitous communication networks is allowing people to have a better Internet wireless connection and it is enabling new digital services. However, it also involves substantial issues, such as an increase in the overall energy consumption of wireless connectivity. Rethinking about wireless communication infrastructure is a necessary step towards a sustainable society. In particular, carbon neutrality, which consists in net-zero carbon dioxide emissions, is targeted by the Intergovernmental Panel on Climate Change (IPCC), detailed in the Special Report on Global Warming to meet the 1.5°C goal by mid century [1]. The problem of sustainable communication infrastructure is also aligned with the seventeen United Nations (UN) Development Goals by 2030, which include, as part of Goal 9, "upgrade infrastructure and retrofit industries to make them sustainable" in particular "with greater adoption of clean and environmentally sound technologies" [2].

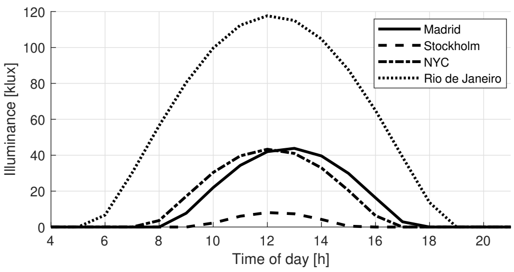
In our view, *we need to rethink about communication systems, designing the first generation of devices that pursue a carbon-neutral wireless communication. This proposal opens the door to a new generation of carbon-neutral communication technologies.* In this regard, electricity for lighting accounts for approximately 15 per cent of global power consumption [3], and Light Emitting Diodes (LEDs) replacing traditional light sources for indoor illuminations aim at significantly reducing this consumption. In the attempt to seek new ways for sustainable wireless communication, Light Fidelity (LiFi) has emerged in the last few years as a wireless communication technology that uses artificial light sources such as LEDs for communication, transmitting data by exploiting the optical channel. As such, a LiFi system itself can be designed with low-power consumption by conception. In its simplest form, a light turned on consists of a bit '1' of information, and a light turned off sends a bit '0'. LiFi can be modulated at a high speed such that the human eye cannot see any light variation.

In this paper, we fundamentally rethink about how communication is performed with lighting. Complementary to using LEDs as lighting source and LiFi transmitters during the night time, we envision to use sunlight for communication during the daytime, for both residential and industrial environments, then reducing drastically the energy consumption of the communication system. Sunlight power may depend on the earth location, climate conditions, day of the year, etc. Therefore, *although sunlight is powerful and ubiquitous, the usage of sunlight for communication is difficult to achieve given the remote position of its light source and the technical requirements in LiFi systems, such as impossibility to actively modulate it and its apparent limited availability in indoor spaces*. In fact, work in the state of the art has particularly focused on exploiting the sunlight coming from a window for indoor communication. But the problem has been shown to be very challenging, due to the large dimensions of windows, cost of the electronic solutions, and the importance that windows have in the user comfort [4]–[7].

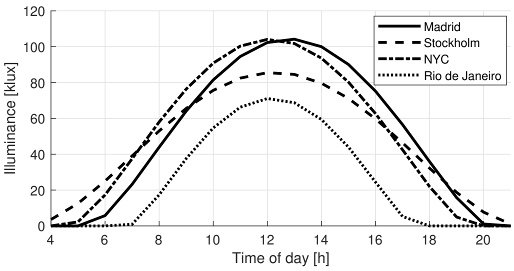
Against this background, in this paper we propose to *directly modulate incoming sunlight for communication*, by exploiting novel fabrication constructions to bring sunlight indoors beyond traditional methods such as windows, and by introducing novel modulating elements to provide indoor environments with wireless connectivity. To the best of authors' knowledge, this is the first time that the development of a system that is able to provide uniform LiFi coverage to indoor spaces suitable for IoT communication, exclusively using sunlight, is presented. We go beyond the state of the art by making the following contributions:

- We propose a system architecture that is able to deliver illumination and uniform downlink LiFi communication to an indoor space, using sunlight only.
- We present the achievable data rate and energy requirements of such a system.
- We evaluate how the implementation of this system can provide simultaneously sufficient communication and illumination.

The article is organized as follows. After some necessary



(a) January 1st



(b) July 1st

Fig. 1: Illuminance at different times, day of the year and locations (Coordinates - Madrid: 40.42°, -3.70°; Stockholm: 59.33°, 18.07°; NYC: 40.71°, -74.01°; Rio de Janeiro: -22.91°, -43.21°).

background in Section I, we analyze the state-of-the-art in Section II. In Section III we present our vision and proposed system, while in Section IV we analyze and discuss the results obtained through experiments and simulations, and Section V provides potential research directions. Finally, Section VI provides conclusions.

II. Related work

Current state-of-the-art work states that indoor sunlight cannot be modulated for communication and it has rather focused on altering its direction of propagation. Creating signal variations on the receiver side using reflective surfaces is a frequent approach in this sense. In LuxLink [4], authors redirected sunlight onto a photosensitive receiver to achieve a transmission distance of 65 m at 80 b/s using a diffuse reflective surface with an area of around 60 cm^2. Despite using a relatively small area, this prior work showed the large potential that environments with abundant light, achieving a 4.5 m range for indoor scenarios. ChromaLux revealed a novel approach in terms of sunlight modulation in the wavelength domain, reaching up to 50 m at 1 kb/s [5]. This system uses a metallic surface instead of a diffuse one, which suggests that exploiting a specular reflection for this purpose can be beneficial. Despite achieving the largest distances when using the natural ambient light, both systems required a small field-of-view on the receiver to reduce as much external noise as possible, leading to a very limited coverage if the transmitter is not aligned. An alternative way to transmit data using sunlight is described in [8] and [6], where ambient light is modulated and reflected by moving patterned surfaces, with the message encoded on this pattern.

All these approaches incur the same limitation; they cannot provide full coverage due to the strict need of alignment between elements. A complete model on a sunlight-based communication system without redirecting light is described in [7]. This prior work studied how different parameters such as the number of modulating elements, their disposition and distance with the receiver affect the communication in an indoor scenario. However, it assumed that the incoming light comes only through a window located in a wall, damaging the user comfort and involving large power consumption. Concentrating sunlight systems have been researched for several years [9], with significant progress achieved by applying optical fibre to the field [10], [11]. Their existence means a missed opportunity of implementing sunlight LiFi systems orders of magnitude less power-expensive than those based on artificial light.

III. Our Proposal: LiFiTube

In the last years, optical systems have been developed to deliver sunlight into indoor spaces requiring a minimum architectural intervention. Exploiting sunlight indoors incurs in straightforward energy savings in illumination with respect to using artificial light sources, as well as in terms of the benefits associated with natural (and controlled) sunlight exposure [12], [13].

Figure 1 represents the illuminance in lux received along the day in some world capitals under clear sky. As a reference, note that 500 lux is the minimum recommended indoor illuminance for user comfort. The results have been measured using the SPCTRL2 simulation model [14], assuming a horizontal plane, an averaged luminous efficacy of the direct solar radiation at the earth's surface of 105 lm/W [15], and we have considered measurements in two different days of the year to have a better understanding on how the year period may affect. Note that Rio de Janeiro illuminance gets the largest (smallest) illuminance in January (July), differing from the other capitals due to being in a different hemisphere.

Traditionally, the main way to achieve sunlight exposure indoors has been through an appropriate architectural design of the building, including a proper distribution of windows and skylights, and considering the space distribution and orientation. However, in the last decades, several optical systems have been developed to deliver light into indoor spaces that can be installed with a minimum architectural impact. The most promising one and currently commercialized is the tubular light guide (TLG) or light tube.

In light tubes, light is gathered by an optical dome especially designed to collect as much sunlight as possible, located on a roof or against an outer wall. A transparent luminary is installed indoors at the end of the tube where light is scattered into the room. Light tubes produce adequate and comfortable indoor illumination levels, and can be installed without disturbing neither the indoor nor the outdoor design. A single light tube substituting an artificial luminary can provide energy savings between 0.5 and 4.5 kWh every day [16]. Current light tubes hold a high light-guiding efficiency, and barely rely on sun orientation to provide large illuminance. These properties allow them to reproduce efficiently outdoors daylight conditions in indoor spaces, which is especially useful in latitudes with many and intense sunshine hours.

In this paper we leverage these sustainable architectural deployments, and design a novel LiFi system that modulates the sunlight passing through these tubes to convey data, a

TABLE I: Comparison of technologies.

	Prior works	LiFiTube
Access technology and devices	Dedicated infrastructure in RF (WiFi, mobile systems such as 3G, 4G, 5G, etc.) and LiFi (dedicated bulbs with special LiFi components).	Exploiting light tubes for new buildings, installed to leverage natural light. Only passive optical components and external LC shutter are required.
Energy consumption	Power hungry solutions with dedicated hardware.	Carbon-neutral solution that drives tubes for downlink communication solely with harvested sunlight.

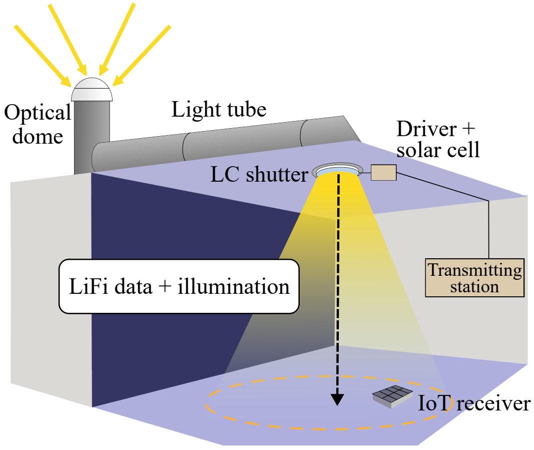
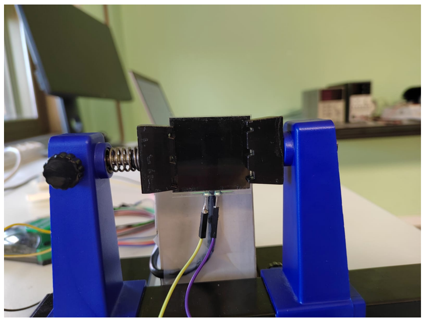


Fig. 2: Overview of the proposed LiFiTube system.

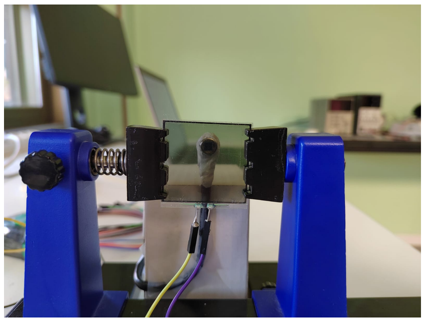
concept we call LiFiTube. The main concept of LiFiTube is represented in Fig. 2 and its performance is detailed in the following.

First, the sunlight is collected by an *optical dome*, then re-directed through the interior by means of reflections in the *light tube* with a reflection index close to 1 to minimize path losses. Light tubes offer a concentrated sunlight source above the room with zero energy consumption, and it additionally improves the visual user experience in comparison to artificial lighting sources. The uniform distribution of light inside the room provides not only a comfortable visual environment, but also increases the LiFi communication coverage.

Second, we introduce the usage of *Liquid Crystal (LC) shutters* to modulate light coming from the light tube. An LC shutter consists in a liquid crystal layer enclosed between two electrodes and two polarizing layers. Applying a voltage difference between these two electrodes produces an electric field through the LC layer, aligning their molecules. When aligned, light is blocked by polarizing films. Controlling this applied voltage, we can therefore change the incoming light at a sufficient speed to transmit data effectively over it, similarly to how LEDs are modulated in LiFi systems. In the most simple way, when we apply voltage across the LC shutter and it closes, it means a bit '0' transmission, whereas no voltage applied opens the LC shutter and transmits bit '1'. Figure 3 shows a visual appearance of the LC shutter in open and closed modes. In this way, LiFiTube provides an infrastructure for communication to every point in the room sufficiently illuminated. Differently, when there is no data transmission, the shutter is open so that the light passes through the interior. The main benefit of this approach is that *LC shutters for modulating sunlight have power consumption as low as a few microwatts per squared cm, while achieving the same illuminance with modulated artificial light suitable for LiFi (e.g. LEDs) consumes power in the order of a few watts* [17]–



(a) LC shutter in closed mode.



(b) LC shutter in open mode.

Fig. 3: Transparency of LC shutter in closed and open modes.

[19]. With the sunlight source at hand, we modulate the LC shutter at a very low-power budget toward a carbon neutral design. This allows to self-sustain the transmitter with a small *solar cell*. The sunlight impinging into the solar cell incurs the generation of electricity for communication solely from solar energy, considered by the Energy Information Administration (EIA) in US to be carbon neutral technology [20].

Third, a *driver* is needed by the LC shutter to manage the voltage between terminals with the aim of conveying data, while ensuring an operating voltage region within the limits accepted by the device. This driver has a small size, low-power consumption and it is interfaced with a *transmitting station*, which holds and sends the data to be emitted to a wireless light channel. The fact that we modulate incoming light does not dismiss its usage as illumination device. LC shutters can be driven at a sufficient speed so that the blinking cannot be perceived by the human eye. Indoor users will only perceive a constant illumination level, proportional to the outdoor sunlight.

Finally, on the *receiver* side, modulated sunlight has two simultaneous purposes. First, a light-sensitive device can receive and process this encoded data. Optical receivers can be designed at a very low cost, low consumption and small form factor. These properties make them a promising solution as receivers in Internet of Things (IoT) scenarios. Second, this sunlight can be exploited for energy harvesting in the

IoT devices leveraging current research on the topic [21], then contributing even more to attaining a fully sustainable network. These designs are able to separate DC signal for harvesting and AC for communication [22].

A summary of comparison with respect to traditional technologies is provided in Table I. Our approach involves concentrating the output from the light tube, modulating it with an LC shutter and scattering it into the room. To our knowledge, no optical setup with communication functionality has been applied to a natural light illumination structure with communication purposes, and it requires dedicated investigation.

A. Illumination

The implementation of LiFiTube in this TLG structure must not hinder its illumination purpose. The main inconvenient of this approach is that, even in open state, the LC shutter will block large part of the incoming light. Transmittance will be in the range of 40-50% due to the polarizing and absorption effect of the liquid crystal layer. However, the large amount of light available at the TLG input enables sufficient indoor illumination even with this attenuation. Also, the space taken by TLGs inside a building is such that it is not possible to include too many of them per ceiling area, so minimizing the blocked light power is key in the design.

The output of a TLG admits different kind of optical elements to customize the light radiation pattern. However, as the TLG ends with large flat radiant surface, it can be modelled as a Lambertian source [23], which is the radiation pattern of a standard LED and it is typically used to model the LiFi channel. In the expected scenario, where the output of the light tube is placed on the ceiling, the illuminance E for a given position inside the room can be formulated by:

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

where h and D are the vertical and the Euclidean distance between the light (in the ceiling) and the measuring point, respectively, Φ_{TLG} is the output luminous flux of the TLG and m is the Lambertian index which describes how directive is the light source.

With this equation, we can simulate the illuminance distribution produced by the TLG indoors. We consider a 30 cm diameter TLG with a length of 1 m, which is sufficient to overcome a ceiling or the cornice of a wall. Regarding the incoming sunlight, we consider the same area of the tube capturing light outdoor and the lighting conditions expected for the July 1st in Madrid at 13h, as shown in Fig.1b. Φ_{TLG} can be calculated as:

$$\Phi_{\mathrm{TLG}} = E_{\mathrm{sun}} \cdot A_{\mathrm{TLG}} \cdot \eta_{\mathrm{TLG}} \cdot \tau_{LC} \quad [\mathrm{lm}], \tag{2}$$

where E_{sun} = 104.88 klux is the illuminance received outdoors, A_{TLG} = 707 cm^2 is the area of the tube section, η_{TLG} = 0.67 is the efficiency of the TLG computed as the output over the input luminous flux, which is extracted from [24], and τ_{LC} = 0.45 is the transmittance of the LC shutter introduced by LiFiTube for joint sunlight illumination and communication. The Lambertian index m = 1.3 is estimated based on the experimental results shown in [24].

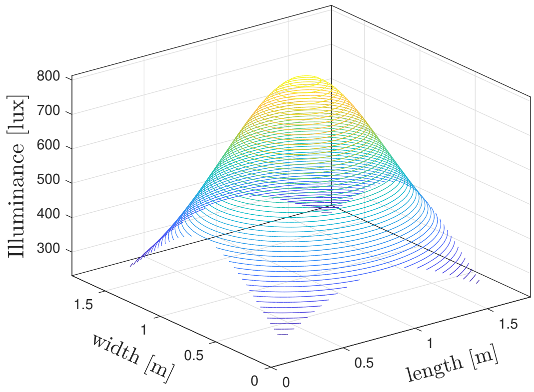


Fig. 4: Illuminance distribution in a 1.8×1.8 m room with a TLG place in the center. Indoor illumination is sufficient for the human eye, and its distribution can be more uniform and comfortable with additional fixtures on the tube's output.

Figure 4 shows the illuminance distribution in a room of 1.8×1.8 m, where the TLG is located in the center. Note that a larger area can be covered by installing multiple TLGs, as in a typical lighting infrastructure with multiple light sources. This arrangement achieves an average illuminance $\overline{E}$ = 508 lux, which complies with the recommended illumination for a regular office [25] ($>$ 500 lux). TLGs admit different kind of optical elements in case a different light distribution and LiFi coverage are required. Also, these results can be improved with an exterior dome or solar concentrator able to gather more light.

IV. Preliminary Results

This section presents some preliminary simulation and experimental results for the LiFiTube system in energy consumption and achieved data rate. Compared to traditional LiFi systems, we can expect few orders of magnitude less in power consumption for simultaneous illumination and communication, as there are not luminaries to power on. But the same applies to data rate given the maximum switching speed of LC shutters. This compromise between data rate and power consumption is sufficient for downlink communication with autonomous IoT devices in the room.

A. Energy consumption

The proposed scenario allows modulating ambient light for communication purposes. Therefore, the transmitted optical power does not rely on transmitted electrical power as when using LEDs, but it relies on the natural lighting conditions and the effect of the LC shutter. However, differently from the conventional LiFi where the LED is the most energy hungry element, in this novel design the LC shutter and driver demand a small amount of energy to perform the modulation. We focus here on the LC shutter power consumption, as it substitutes the dominant element (LED) in terms of energy consumption.

One of the most extended structures for LC shutters are twisted nematic crystals [26]. In this structure, power is consumed only when the crystal molecules are being aligned. On the other hand, there is no current flowing through it when they are on a steady regime. When locked in a state, the bias voltage source can even be removed from the terminals of the

TABLE II: Average current consumption in small sized LC shutters when modulated with a bipolar signal, for devices with different areas manufactured by LC-Tec Displays.

Area [mm^2]	**Current** [μ**A**]
25	21.8
8	6.1
2	1.6

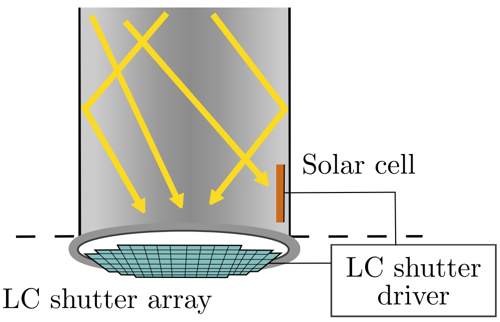


Fig. 5: Schematic of the self-sustainable implementation of LiFiTube. A solar cell harvests a fraction of the light inside the TLG, enough for powering both the LC shutter and driver.

device and it will keep its state. Since *state transitions set the power consumption*, increasing the modulating frequency will increase power consumption. However, the power consumed by the LC shutter is admissible given the low frequency at which they can be modulated. This modulating voltage can be (1) either a unipolar signal ($[0, V_{mod}]$), then introducing a DC component in the device that can damage the crystal structure permanently, decreasing contrast and shortening its lifetime, or (2) a bipolar signal ($[-V_{mod}, V_{mod}]$) modulating a carrier, i.e., modulating with a constant tone to open the LC shutter, and a zero-voltage signal to close the LC shutter. The latter guarantees the proper functioning of the device, at the expense of an increase in the power consumption due to having a larger amount of transitions.

Independently from the way the LC shutter is driven, another parameter that affects the power consumption is its area. *The current required to align or relax the crystal molecules increases almost linearly with the LC surface*, as it can be seen in Table II. We modulate the same model of LC shutter, manufactured by LC Tec Displays, with different sizes. Note that the current increases almost linearly with the area. This also motivates us to look at light concentrators like TLGs, rather than embedding LC shutters in windows as considered in prior work [7], where the area to cover is much larger. This fact is especially important for a design choice in our application: For covering the whole light tube area to provide a communication service indoors, is it better to use a single big LC shutter or an array of small LC shutters? Given the linearity in the power consumption with the size, we then propose to *use an array of shutters driven by a synchronization circuit to retain the higher data rate of the single LC shutter, while keeping the consumption low.* However, note that part of the radiant area is blocked by the non-active area of the array of shutters (i.e. edges of each small shutter), which could compromise the illumination and coverage provided.

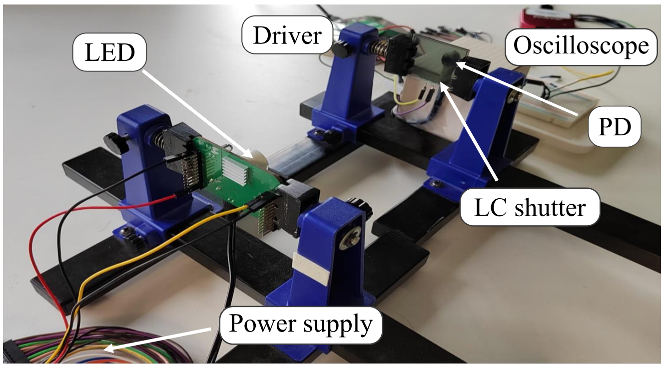
Considering this conceptual design, the output of a TLG with a diameter of 30 cm (707 cm^2) can be covered with an array of 25 mm^2 LC shutters with 2828 elements. With a modulation between ± 3.3 V, this design requires a power consumption of 102 mW (duty cycle 50%). This consumption is much lower than the consumption with a traditional LiFi bulb: using this tube under summer clear sky conditions in Madrid (Fig. 1b), LiFiTube could modulate up to a luminous power of 4934 lm [24]. Generating this amount of light suitable for modulation with a conventional off-the-shelf LED can consume up to 40 W [27], not even considering the power loss from the LED driver for transmitting LiFi data.

This makes our design two orders of magnitude more power efficient that using conventional LED lighting. This low-power consumption dedicated to LiFi transmission facilitates the design and implementation of a local autonomous driver powered by a small solar cell to self-sustain the communication. If located inside the TLG where illuminance is very high, a solar cell of around 6 cm^2 will suffice to power the driver [28], as shown in Fig. 5. Moreover, an optical system to concentrate, modulate and diffuse light into the room can be used to reduce the LC shutter required area, with the subsequent power reduction.

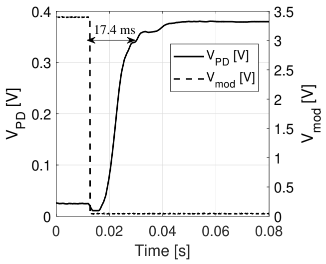
B. Communication data rate

The communication data rate relies on the speed of the LC shutter to switch between open and closed modes. LC shutters are not traditionally applied for communication, but for display applications. Though some datasheets provide the switching speed, they do not provide both the closing and opening times, which both are critical for communication purposes. We then have deployed an experimental setup shown in Fig. 6a to study the total data rate of some of these devices. We simulate the sunlight with a high-power LED and its power supply. We then introduce the LC shutter to modulate the light, and a photodiode (PD) located behind the LC shutter to receive the modulated light. The LC shutter is modulated by a driver, and the optical power received by the PD is monitored by an oscilloscope, after applying sufficient gain to the signal. Note that this setup is aimed for measuring the data rate of the system, relying on the switching speed between open an closed modes of the LC shutter.

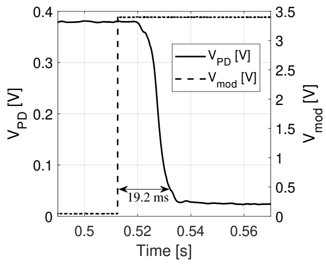
Figures 6b-6g depict the voltage received across the PD (V_{PD}) and the modulating signal, i.e, the voltage applied to the LC shutter (V_{mod}), for three different LC shutter models. Note that we have introduced a new model from Adafruit to have a larger LC shutter variability, as the smallest LC-Tec shutter with a size of 2 mm^2 is extremely difficult to manage for this study. In these figures we can see that there is always a delay between the modulating signal and the received voltage, which means that the LC shutter does not react instantaneously, but its molecules take some time to reconfigure when a voltage is applied between its electrodes. The time response has been measured from the time in which the modulating signal switches, to the time where the LC shutter achieves a 90% of its final state. For the Adafruit LC shutter (Fig. 6b and 6c), switching from the closed to the open state takes around 17.4 ms, whereas switching from the open to the closed state takes 19.2 ms, which leads to rates of 57.47 Hz and 52.08 Hz, respectively, being the latter the limiting one.



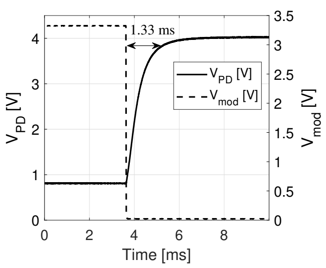
(a) Measurement setup.



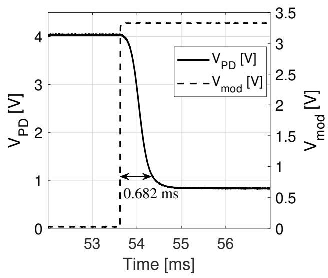
(b) Rise (open) time on the LC shutter of 1023 mm^2 (Adafruit)



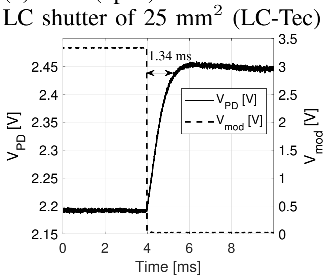
(c) Fall (close) time on the LC shutter of 1023 mm^2 (Adafruit)



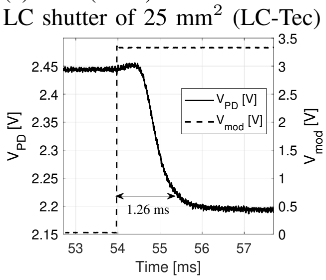
(d) Rise (open) time on the fast LC shutter of 25 mm^2 (LC-Tec)



(e) Fall (close) time on the fast LC shutter of 25 mm^2 (LC-Tec)



(f) Rise (open) time on the fast LC shutter of 8 mm^2 (LC-Tec)



(g) Fall (close) time on the fast LC shutter of 8 mm^2 (LC-Tec)

Fig. 6: Measurement setup and time response of several LC shutters. The material and manufacturing of the device have a severe impact on rise and fall times.

Closing and opening times are shorter if a more cutting-edge fast LC shutter such as X-FOS(G2) from LC-Tec [29] is used (Fig. 6d-6g): Closing (opening) time = 0.682 ms (1.33 ms) and rates = 1.47 kHz (0.75 kHz) for the 25 mm^2 version, while closing (opening) time = 1.26 ms (1.34 ms) and rates = 0.79 kHz (0.75 kHz) for the 8 mm^2 version. Data rates can be larger if M-ary modulation schemes with multiple bits per symbol are employed [30]. These data rates, though low with respect to current communication standards, are enough for most of the IoT applications, considering the benefit of a self-sustainable performance. Finally, note that the data rate values will not vary when a larger LC shutter must be built by using the proposed approach of configuring an array of LC shutters, as all of them can be easily controlled by synchronized drivers.

V. Research Directions

LiFiTube proposes an innovative architectural and technological solution to alleviate the environmental concerns to which current wireless communication systems contribute. It means a step forward to achieve green wireless communication systems. However, to make it real, we must work on the following aspects:

Energy-efficient IoT receivers: Energy autonomy is an aspect to optimize in IoT receivers. These are typically powered by batteries (Li-Ion, LiPo) adapted to their size and consumption. Their fabrication involves important greenhouse gas emissions, contributing to climate change [31]. Also disposing these batteries can be highly contaminating to soil or large water bodies, and indeed only 30% of population properly dispose them [32]. Carbon-neutral devices that do not have any batteries have been investigated in the recent past. Several of them operate using solar cells [33], [34]. However, many limitations are found due to the constrained amount of energy harvested by solar cells when employed in artificial lighting systems. A typical problem of using solar cells in LiFi systems is that they are optimized to operate with natural sunlight, while their harvesting efficiency reduces significantly with artificial light such as LEDs. In fact, the problem is that artificial light has a different optical spectrum and a lower power than sunlight.

Our proposed LiFiTube concept does not face this problem, as we provide LiFi data by modulating the optical wavelengths of sunlight in indoor environments. Given their low-power requirement, a solar cell as small as few squared centimeters is enough to charge up an IoT device with limited functionalities. However, more efforts must be invested in developing battery-free IoT devices to operate in this scenario, in favor of more environment-friendly energy storage devices that keep their energy in the electric field of capacitors.

Simultaneous Wireless Information and Power Transfer (SWIPT) techniques: Solar cells can not only be used as power harvesters, but they can also be energy-efficient data receivers [21]. Inspired by this related work, we must study different solar cells and find an optimal joint configuration to perform as both receiver and harvester. Time-, Power- and Spatial-Division Multiple Access (TDMA, PDMA, and SDMA) have been invoked in the literature for SWIPT in LiFi, but none of those solutions offer a reliable communication and power link: TDMA improves the signal in both power and communication modes, but at the expense of reducing the charging time and data rate; PDMA involves a trade-off between harvested energy and communication performance on the IoT receiver, without guaranteeing a joint-optimal performance in the published works; SDMA uses two solar cells, one for each purpose, then increasing the size of the device.

Uplink communication: LiFiTube offers a downlink energy-efficient wireless solution, but we must invest great efforts in low-power uplink communication systems. Prior works have used Radio Frequency (RF) backscatter as an uplink solution for this type of energy-constraint devices [21], but also visible light backscatter has been presented as an alternative [35]. However, their global performance is still far away from the market requirements.

Optics and physics of natural light elements as indoor light sources: LC shutters can achieve sufficient bandwidth for most of IoT applications [5]. However, if not connected synchronously in an array mode, the larger the LC shutter, the lower the bandwidth is. Besides, an LC shutter intrinsically reduces the light power by half, as it removes polarization in one plane. New LC shutter designs must be considered to relax these two limitations, i.e., rate and light power. We must also deeply study how daytime and climate conditions affect the performance of our proposal, and analyze the influence that tube characteristics make on illumination and communication, such as tube length, tube diameter, tube material (commercial aluminum and zinc alloys), concentrator and diffuser shapes at both extremes of the tube.

Network architecture: Conventional wireless communication systems (e.g., WiFi) are mature and very well adopted by the final user, but they are getting saturated and they will no longer satisfy the total demand of those wireless services. The research community put much effort in heterogeneous networks (HetNets) and how every multiple system can complement each other [36]. The here-proposed alternative will complement those traditional systems, rather than replacing them. Then, LiFiTube must be integrated in the global network architecture, establishing proper links and cooperative protocols with traditional communication systems.

VI. Conclusion

In this paper we proposed to modulate the light passing through light tubes for transmitting data. Light tubes and LiFi are two domains apparently independent, but brought here with the joint purpose of providing a beneficial self-sustainable communication network. We presented LiFiTube, a system capable of providing a wireless data service toward carbon-neutral communication for IoT applications. We demonstrated the transmission of IoT data rates while guaranteeing illumination requirements in an indoor environment. We believe that there are significant advantages in this novel green design, but much effort must be invested in its development, as well as overall architectural design in aspects such as IoT receivers, simultaneous wireless information and power transfer, uplink communication, optical materials and its integration with existing communication systems. Our vision is that, in order to achieve carbon neutral communication networks, novel architectural elements in buildings must be leveraged and they must be jointly designed with communication systems.

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