2024 23rd ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)

Sol-Fi: Enabling Joint Illumination and Communication in Enclosed Areas with Sunlight

Miguel A. Chávez Tapia*
Delft University of Technology
Delft, The Netherlands
m.a.chaveztapia@tudelft.nl

Talia Xu
Delft University of Technology
Delft, The Netherlands
m.xu-2@tudelft.nl

Marco Zúñiga Zamalloa
Delft University of Technology
Delft, The Netherlands
m.a.zunigazamalloa@tudelft.nl

ABSTRACT

Consider an enclosed area, such as a room without windows. During the *day*, artificial light can provide illumination and communication thanks to advances in Visible Light Communication (VLC). Artificial lighting, however, has some drawbacks compared to using daylight in enclosed spaces. First, using sunlight consumes less power. Second, the use of natural light improves the health and comfort of the occupants. *We propose a system, dubbed Sol-Fi, to provide joint illumination and communication in enclosed spaces using sunlight.* Sol-Fi relies on two main components: commercial sunlight collectors and a novel transmitter to modulate ambient light. The sunlight collectors utilize optical fibers to guide natural light from open to enclosed spaces, and our transmitter modulates the incoming light providing two novel features. First, to analyze the pros and cons of the optical devices used in the literature for ambient light communication, Sol-Fi examines the properties of Liquid Crystals (LCs) and Digital Micro Mirror Devices (DMDs). Second, to investigate the trade-off between single- and multi-band communication, Sol-Fi proposes an optical design that can modulate the entire spectrum or divide it into different (individually modulated) bands. Our evaluation shows that, depending on the number of bands (single or dual) and the type of modulator (LC or DMD), Sol-Fi provides a data rate between 0.8 to 80 kbps, a range between 0.5 to 5 m, and a field-of-view between 30° to 60°.

1 INTRODUCTION

The aim of our work is to create a new type of light bulb, one that provides joint illumination and communication with sunlight. This new light bulb builds upon two main concepts: visible light communication and sunlight collectors.

Visible Light Communication. The increasing demand for wireless connectivity is pushing the limits of radio technology and its crowded bandwidth. As an alternative, a research area called *visible light communication* (VLC) has been proposed to use the free and available bandwidth of the light spectrum. The most popular application of VLC is LiFi, a technology that can transform light bulbs into wireless transmitters through the modulation of light intensity [21]. These systems use fast-switching LEDs to render illumination and wireless communication.

Sunlight collectors. Natural illumination is fundamental for humans and several studies report that the type of light affects our physiological [23] and mental well-being. Regarding the latter, rooms without windows lack natural light and visual stimuli [43], with consequences such as increased risks of depressive disorders [10] and reduced performance in workers [11] and students [22]. To quantify this situation, a wide study considering 3600 employees from eight countries, mainly in Europe, found that 42% of workers have no natural light [11]. The benefits of sunlight have motivated innovative *daylighting systems* that bring natural light to enclosed areas. These systems are classified as *passive* and *active*. Passive systems, known as sun tunnels, place a concave lens on a roof and use tubes to guide sunlight indoors. This approach is simple and not so expensive but does not provide much sunlight. *Active systems* have the opposite trade-off, they use a set of lenses to track the sun and optical fibers to guide natural light. Active systems, known as *sunlight collectors*, are more costly, but provide massive amounts of light at further distances [16], enabling the creation of 'natural' light bulbs. In this way, people enjoy the full benefits of natural illumination, even in the absence of windows.

Motivation. Inspired by the area of VLC and its application on *LiFi*, we focus on the following research question: *if a sunlight collector is already installed to bring natural light indoors, can we embed data inside sunlight to create a natural light bulb that provides illumination and communication?*

Such a communication system could provide three advantages: (i) a free, safe, and healthy spectrum, (ii) reduced power consumption, and (iii) reduced economic costs. Regarding the spectral benefits, the broad spectrum of daylight ensures a good quality of color rendering for the human eye and positively affects our body and mind in terms of physical, physiological, and psychological aspects [3, 38, 40]. To emulate a light source with a spectrum similar to sunlight, more than one type of LED is required. Regarding power consumption, daylight systems offer the advantage of avoiding the *double energy conversion* required by solar panels to power LEDs [36]. For example, converting sunlight to energy using solar cells provides at best a 40% lumen-to-watt conversion [7], and converting energy to light with LEDs provides a 10-30% watt-to-lumen conversion. Finally, regarding cost, research in the area of daylight systems suggests that redirecting sunlight is about 25 times more cost-effective than using solar panels to power LEDs [17]. Moreover, the energy that is not converted to light is usually dissipated as heat, which increases the cooling costs of buildings [27, 40].

Challenges. Modulating ambient light is a complex process studied in the area of Passive-VLC. Contrary to artificial light (LEDs), which are diodes modulated *directly at high speeds*, natural light bulbs are purely optical and require external modulators. This fundamental difference raises two challenges to design Sol-Fi.

Challenge 1: Limited optical modulators. Passive-VLC does not have modulators purposely designed for wireless communication, researchers are re-purposing optical devices originally designed for image projection. Currently, the state-of-the-art (SoA) relies on two types of modulators: liquid crystals (LCs) and digital-micro-mirror devices (DMDs). LCs are easy to modulate but have a slow

*Corresponding author

979-8-3503-6201-5/24/$31.00 ©2024 IEEE
DOI 10.1109/IPSN61024.2024.00010

bandwidth, and DMDs have the opposite trade-off. The design of transceivers with these optical devices is complex and no work has analyzed thoroughly their trade-offs.

Challenge 2: Single-band modulation. A salient feature of visible light is its broad spectrum. Active-VLC (e.g. LiFi) exploits this broader spectrum to attain high-data-rate links. However, most Passive-VLC transmitters modulate the *entire* visible light spectrum as a single band without exploiting multiple narrower bands to increase the data rate [8, 18, 31, 37, 45–48]. Multi-band modulation with sunlight is an open challenge in Passive-VLC and it is important to tackle it, otherwise, a key spectral advantage of natural light will remain unexploited.

Contributions. To provide natural light and communication, Sol-Fi makes the following contributions.

Contribution 1: Device analysis [section 2]. We propose a system that integrates novel Passive-VLC methods with sunlight collectors. Our design removes the need of reflective surfaces to guide natural light and analyzes the pros and cons of the two modulators used in the SoA (LCs and DMDs).

Contribution 2: Optical design [section 3]. We combine optical and embedded systems to build a natural light bulb that modulates information. The design considers both modulators (LCs and DMDs) and utilizes Frequency Shift Keying (FSK) to compare their performance *under the same setup*.

Contribution 3: Multi-band modulation [section 4]. Contrary to other passive platforms, we propose the first method to modulate two independent bands. Our approach follows a careful optical design to divide the wide spectrum of sunlight into two narrower bands in order to increase the data rate. We implement a basic multi-band prototype and test it in two scenarios: a controlled environment using constant light, and under the changing conditions of natural sunlight.

Our evaluation shows that depending on the number of bands and the type of modulator used (LC or DMD), Sol-Fi can modulate the healthy spectrum of sunlight attaining links with a data rate between 0.8 kbps and 80 kbps, a range between 0.5 m to 5 m, and a FoV between 30° to 60°.

2 ANALYZING PASSIVE MODULATORS

The main idea of Sol-Fi is to combine commercial sunlight collectors with a novel framework for passive modulation, as shown in Figure 1a. If sunlight collectors are already present in a building, our framework shows that data could be added to the system. In this section, we introduce the sunlight collector used in our work and analyze the different types of modulators available in the SoA.

2.1 Sunlight collectors

Sunlight collectors are a subclass of a broader type of solution, called *active daylight systems* [26]. These systems use a mechanism to track the sun's position in order to gather and concentrate the largest amount of sunlight. Among the various daylight systems in the market, the sunlight collector has three main features that make it suitable for our prototype implementation: mobility (it can be carried to different places), flexibility (light is guided by optical fibers, which can be bent), and a small output area, which eases the modulation process. Two types of collectors are provided by Parans [1] and Himawari [25], both designed to be placed over roofs. Our implementation uses the latter (Figure 1b) because it is lighter and easier to move. The main shortcoming of the sunlight collector is its price (around €5000) due to its optical components and the complexity of the sun-tracking mechanism. This particular system provides optical fibers for two natural light bulbs.

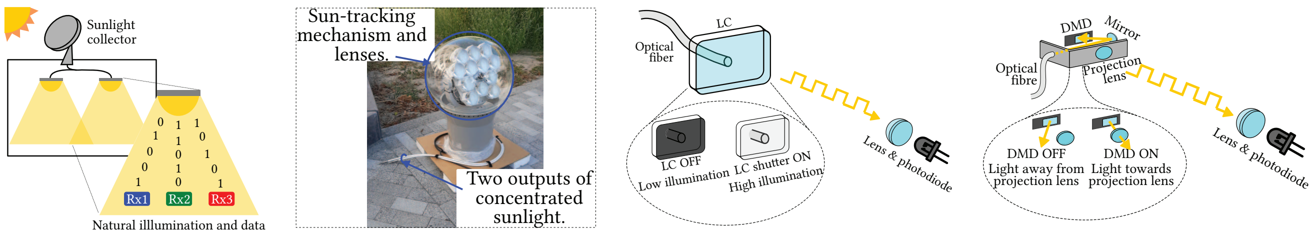
Although research studies suggest that daylight systems can save more than 60 % of energy consumption [40], it is important to empirically measure the sunlight collector's power consumption. Figure 2 shows the power consumption of the collector we use during one hour. At the startup, which occurs once a day, the power goes up to ~8 W and after that, it oscillates between 1 W to 2 W to track the sun. The realignment occurs every two seconds, which are the peak values around 2 W, and then reduces to around 1 W. For this amount of power, the collector provides an average luminous flux of 4500 lumens. This large amount of flux is attained because sunlight's illumination ranges from a few klux at sunrise and sunset to more than 100 klux at midday. To obtain the same amount of lumen, LEDs would require a power between 35-40 W.

Regarding communication, *natural and artificial light systems can complement each other using hybrid systems*. For example, natural light systems are better suited for environments that are predominantly occupied during the day, such as classrooms, libraries, and laboratories that have limited or no access to windows. However, similar to *hybrid* daylighting systems [40], which combine artificial and natural light bulbs, our approach can leverage active-VLC (LiFi with standard LEDs), during the night or periods of low sunlight intensity. In our Discussion section (section 7), we concisely review hybrid systems.

2.2 Modulator requirements

There are two aspects that make the modulation of natural light challenging. *First*, while optical fiber systems offer a wide range of components for fast switching, attaining data rates of Pbps [34], they are designed for light that is polarized, monochromatic (around 1550 nm) and coherent. Sunlight is unpolarized, broadband and non-coherent, thus, preventing the use of these fast-switching optical devices. *Second*, the inherent limitations of LCs and DMDs. Due to the lack of modulators for ambient light, all the advancement in Passive-VLC relies on devices originally designed for displays (LCs) and projectors (DMDs). These devices pose various trade-offs that need to be analyzed. Before describing the unique features of LCs and DMDs, let us introduce six requirements that an *ideal modulator* for Sol-Fi should have.

- (R1): **Low attenuation.** The modulator should not decrease the luminous flux delivered by the sunlight collector. The efficiency should be close to one.
- (R2): **Large area.** The larger the area, the more flux that can be modulated. An ideal modulator should have an area compared to an artificial light fixture (several cm^2).
- (R3): **Fast switching.** Passive modulators have an intrinsic (slow) mechanical component. The faster the mechanical switching, the faster the link.
- (R4): **No flickering.** Contrary to radio waves, light waves can be seen by people. Thus, all communication systems based on light must be flicker-free.



(a) General concept

(b) Collector

(c) Sol-Fi with LC

(d) Sol-Fi with DMD

Figure 1: Sol-Fi concept and components. With LCs (c), the light is either blocked or let pass through. With DMDs (d), the light is either directed towards the intended direction or towards a different one.

(R5): **Low power.** Passive modulators are low power, but the lower the power consumption, the more cells that can be used to increase the transmitter's area (R2).

(R6): **Low cost.** Similar to the low power case (R5), the lower the cost, the more devices that can be used to increase the transmitter's area.

Requirements R1 and R2 improve the range and coverage of the link. Requirement R3 increases the data rate and requirement R4 is needed to pass the IEEE standard for safe VLC transmissions. Requirements R5 and R6 facilitate the design of bigger transmitters, improving in that manner R2.

2.3 Passive modulators

To modulate ambient light, all Passive-VLC systems in the literature use either LCs [44, 47, 48] or DMDs [29, 46]. The operating principles of both devices are shown in Figure 1, and the relation between their features and the requirements for our ideal modulator is summarized in Table 1.

LC shutters are transmissive surfaces that either block or let light pass through, based on a driving voltage. Except for a couple of studies, Passive-VLC has relied almost exclusively on this modulator. Considering Sol-Fi's requirements, the main advantages are their large surface area (R2, several cm^2), low power consumption (R5, sub-milliwatt), and low cost (R6, a few dollars per cell). There are, however, a few shortcomings. First, the attenuation is high due to the use of polarizers (R1), which cut 50% of the luminance. Second, the switching speed is slow (R3), reaching only a few hundred Hz. These low switching speeds lead to single-cell data rates that attain at most 1 kbps [44, 47]. Third, the slow speed leads to a higher probability of observing flickering (R4).

DMDs are reflective surfaces consisting of micro-mirrors that switch between two angles. By default, DMDs have a slow refresh rate (60 Hz), but a recent study proposed a new controller that can modulate low-end DMDs at hundreds of kHz [46]. The advantages of DMDs are *(i)* their low attenuation, since they reflect more than 97% of light (R1); *(ii)* their high switching frequency (R3), which is over 30 times faster compared to LC shutters; and *(iii)* the reduced risk of flickering due to the high switching frequency (R4). However, DMDs have several disadvantages too. The most important is its reduced area (R2), which is two orders of magnitude smaller than LCs, reaching only a few mm^2. Other disadvantages are the higher power consumption (R5, tens of milliwatts) and cost (R6, a few tens of dollars per DMD).

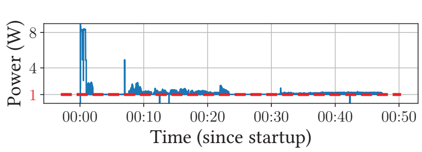


Figure 2: Sunlight collector's power consumption.

2.4 Trade-off analysis

As shown in Table 1, no modulator satisfies all requirements. R4 (no-flicker) is satisfied by both devices because we use FSK to modulate signals, as described later. Thus, the trade-off analysis has to focus between requirements R1 (attenuation) and R3 (data rate), which favor DMDs; and requirements R2 (area), R5 (power) and R6 (cost), which favor LCs.

DMDs have the advantage of providing a switching speed that is 30 times higher than LCs' (R3), but comparing R1 (attenuation) versus R2/5/6 (area, power, and cost) requires more analysis. The (de)modulation of FSK signals in passive systems consumes tens of mW [8]. Hence, the benefit of the sub-mW operation of LCs is not in reducing the system's *overall* power consumption, but in enabling a bigger transmitter's area with negligible extra power. Similarly, the benefit of the LCs' low cost is its ability to increase the transmitter's area rather than on reducing the total cost of the platform. All in all, we have a trade-off between low attenuation (R1) and bigger areas (R2/5/6). To analyze this trade-off, we quantify the optical performance of a single LC cell versus a single DMD cell. Considering an illuminance $\mathcal{I}$ (in lux), and denoting A and a as the areas of an LC and DMD, respectively, the luminance provided by the LC is $\mathcal{L}_L = \mathcal{I}A/2$ (divided by 2 due to the polarizers), and the one provided by the DMD is $\mathcal{L}_D = \mathcal{I}a$. However, considering that the area of the DMD is two orders of magnitude smaller, the luminance provided by the LC is, approximately, fifty times higher than the one provided by the DMD ($\mathcal{L}_L/\mathcal{L}_D \approx 50$). To match the LC's luminance, an optical system would need to concentrate more luminous flux on the DMD.

<u>*Contribution 1:*</u> Our analysis of LCs and DMDs clarifies their fundamental trade-offs. Overall, we are left with one modulator (LC) that can provide 50 times more luminous flux, enabling a longer range and wider coverage; and another modulator (DMD) that can provide 30 times faster switching speed, enabling higher data rates. *Due to this disparate trade-off, we cannot select only one modulator, and thus, Sol-Fi considers different optical designs to evaluate both modulators.*

	R1	R2	R3	R4	R5	R6
LC	~50%	cm^2	100's bps	can flicker	sub mW	few $
DMD	~100%	mm^2	10's kbps	no flicker	10's mW	10's $

Table 1: Comparison between LCs and DMDs

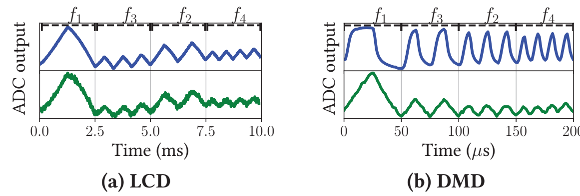


Figure 3: Measured MFSK symbols. The blue and green signals are measured at 20 cm **and** 160 cm**, respectively.**

3 SINGLE-BAND LINK

To evaluate the illumination and communication capabilities of Sol-Fi, we consider three metrics: FoV, range and data rate. These metrics are evaluated on two optical designs, one for LCs and the other for DMDs. This section first describes the transmitters and receiver, and then, presents their evaluation.

3.1 LC modulator

The simplest implementation of Sol-Fi is to place the optical fiber coming out of the sunlight collector behind an LC shutter, as shown in Figure 1c. Compared to other sunlight links based on LCs, the advantage of using the sunlight collector is that the optical fibers provide a wider field of view with the same direction throughout the day. The SoA relies on reflective surfaces to direct sunlight toward the LC. Those reflective surfaces are not realigned through the day, and when they are aligned with the sun, usually radiate parallel rays that form FoVs close to 0°. Below, we present the nominal (theoretical) values of our design and later we evaluate them in a real setup.

- **Switching speed.** The modulator's switching speed is defined as the sum of the rise and fall times. We use an LC shutter with a switching speed of 160 Hz.
- **FoV.** LCs do not change the direction of light passing through. Hence, the FoV is determined by the aperture of the optical fiber, which in our case has an FoV of ±30°.
- **Loss.** Since LC shutters utilize polarizers, the optical power is reduced by half. In theory, this attenuation reduces the range by a factor of $\sqrt{2}$.

Hardware implementation. We build a 3D holder to place the fiber behind the LC and the LC is controlled by an Arduino-Due. This implementation is shown in Figure 9a.

3.2 DMD modulator

Contrary to LCs, which are not designed for a specific light pattern (diffused or directional), DMDs are designed to receive directional light (parallel rays). When used for Passive-VLC, DMDs have the advantage of low attenuation (R1), but the fact that the area is small (R2) and the impinging rays are parallel, leads to a reflected beam with an almost 0° FoV.

To broaden the FoV of our DMD-transmitter, we build upon the principles used in (mini)projectors. Modern projection technology uses LEDs, filters, mirrors, lenses and DMDs. These components perform two tasks. First, they guide the light emitted by the LEDs into the DMD. Second, they cast the image reflected by the DMD into the intended projection area. For Sol-Fi, we disassemble a commercial mini-projector and modify it in two main ways. First, we remove the original controller and DMD, which are designed for video rendition, and connect a controller and DMD designed for Passive-VLC. The contribution of Sol-Fi is not on the DMD controller, we use methods that have been already reported in the SoA [46]. Second, we remove the LED lights and filters, and modify the casing to place our optical fiber as the light source. With these modifications, shown in Figure 1d, our DMD-transmitter is able to (i) receive sunlight, instead of LED light, and (ii) project a wide FoV, similar to a lamp, instead of a narrow beam. Considering these factors, the features of this design are:

- **Switching Speed.** DMDs modified for Passive-VLC operate at switching speeds of hundreds of kHz, several orders of magnitude higher than LCs.
- **FoV.** Since we follow the mini-projector guidelines, the FoV should be similar to the one stated in the datasheet of the original mini-projector, which is ±32.8° [24].
- **Loss.** The DMD reflects most of the light, but the system faces losses because the coupling between the optical fiber and the DMD is suboptimal compared to the coupling between the original LED and DMD. Next, we describe the measures taken to minimize optical losses.

Hardware implementation. To reduce the losses, it is important to use a projector where the diameter of the original LED is similar to the optical fiber's diameter. For this reason, we select the DLPM2000EVM mini-projector from Texas Instruments and an Eska® 3mm-diameter plastic optical fiber (POF). A 3D support is built to place the fiber close to the internal mirror and DMD of our custom projector. For the controller and DMD, we use an FPGA to modulate the DLP2000 DMD. This DMD has two tilt angles, 12° and −12°, and a rotation axis of 45°.

3.3 Receiver

Photodiodes (PDs) and cameras are widely used as receivers in Active- and Passive-VLC. Our receiver uses a PD due to its fast response and low power consumption compared to a camera. The receiver is the same for both modulators and places a TEPT4400 phototransistor on a board that includes a single-stage amplifier with variable gain. Following the customary principle of adding a lens to increase the received light intensity, our design uses a 9.5 mm plano-convex (PCX) lens with an anti-reflective coating on top of the PD. This increases the range of the system without compromising the lightweight property (and mobility) of the receiver.

3.4 Modulation

The contribution of our work is *not* on the modulation approach. We follow the guidelines presented in prior studies for LCs and DMDs. FSK is chosen because it prevents flickering in slow LC modulators (R4). Our Mary-FSK (MFSK) approach is the same for both transmitters (LCs and DMDs). The only difference is the base frequencies chosen for each.

Considering the switching speeds of each modulator and the bandwidth of the receiver, we use four base frequencies for the LC[1] (M=4, 2 bits per symbol): 400 Hz, 800 Hz, 1.2 kHz, 1.6 kHz; and higher frequencies for the DMD: 20 kHz, 40 kHz, 60 kHz, 80 kHz, as shown in Figure 3. These schemes lead to a data rate of 800 bps for the LC and 40 kbps for the DMD. Both data rates fall between the ranges reported for other single-cell transmitters: 0.1 to 1.0 kbps for LCs [8, 47, 48], and 4 to 80 kbps for DMDs [29, 46]. The transmissions use the following sequence: `IDLE`, `STX` (Start Transmission), `DATA PACKET`, `ETX` (End Transmission), and `ETB` (End of Transmission Block). And with both modulators, the transmitters send the message `"Hello world!"` continuously. The receiver sends the data to a laptop, where an FFT is used to decode the data.

3.5 Evaluation

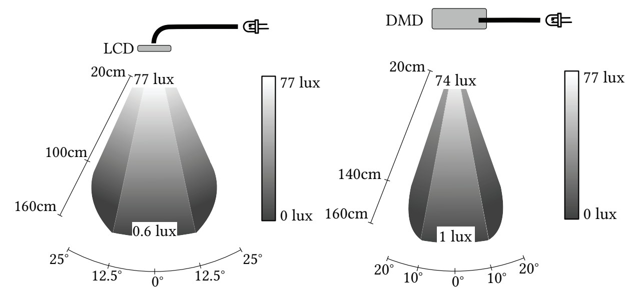
The evaluation has two components, illumination (optical loss and FoV) and communication (BER). Given that sunlight is variable, *we use an artificial light source to have a controlled setup for this section and the next one. In section 5, we evaluate the system with sunlight.* To mimic the optical input provided by sunlight collectors, we connect one end of an optical fiber to a flashlight, and the other end to our transmitters.

To resemble an enclosed space, the evaluations of this section and the next one are done in a dark room. For each transmitter, we measure the illuminance (lx) and bit-error-rate (BER) every 20 cm along two lines. One line goes through the middle of the FoV (bisector) and the other through one of the edges of the FoV (due to symmetry, the other edge has the same result). The results for illumination are presented in Figure 4 and for communication in Figure 5.

3.5.1 Optical losses. Given that we are not interested only in illumination, but also in communication, we borrow the concept of *close-in measurements* from wireless communication to analyze optical losses. We set a luxmeter at a distance of 20 cm from the output of the optical fiber and evaluate two setups, one connecting the fiber to the LCD-transmitter and the other connecting it to the DMD-transmitter. With these measurements, we find a loss of 66 % for the LCD-transmitter (higher than the expected theoretical loss of 50 %); and a loss of 70 % for the DMD-transmitter. This evaluation shows that –in spite of the lower attenuation of the DMD (R1, 97% reflectivity)– both transmitters lead to similar losses. *The losses of the LC, however, are fundamental due to the use of polarizers, while the DMD losses can be reduced significantly with a better optical coupling between the fiber and the DMD (to reach the 97 % efficiency), as discussed later.*

3.5.2 Field-of-view. Figure 4 shows that the FoV of the LC design is similar to the aperture of the optical fiber, 30° versus 25°, which is expected since the LC is agnostic to the radiation pattern. But the FoV of the DMD-transmitter is narrower, 30° versus 20°. This is likely due to the suboptimal coupling of the optical fiber with the mirrors, lens, and DMD.

[1]Note that with FSK, we can modulate the carrier at higher frequencies than the switching speed (160 Hz) because we do not need square waves, triangular waves are sufficient.



(a) LCD (b) DMD

Figure 4: Controlled illumination for single-band.

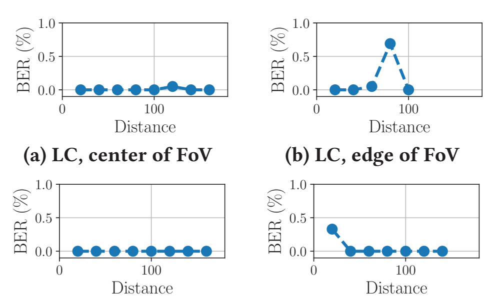
3.5.3 Communication. To assess the reliability of the link, we measure the BER along the bisector and one of the edges of the FoV. As Figure 5 shows, both transmitters provide perfect links along the bisector up to 160 cm. But along the edges, the link becomes unreliable after 100 cm for the LC-transmitter and after 140 cm for the DMD-transmitter. Having shorter edge links is not unusual because many radiation patterns are stronger along the bisector and weaker at the edges (called Lambertian patterns). The reason for the longer range along the edge of the DMD-transmitter is the optical design. Projector optics aim at casting light in a more homogeneous manner across all angles.

It is important to note that the highly reliable links in this section are obtained even for low light conditions (below 80 lx). These lux values are clearly too low to provide adequate illumination, but these are controlled tests done with artificial light to benchmark both modulators under the same conditions. With sunlight, which is stronger, we will see that the illumination increases significantly.

Contribution 2: Our results show that it is possible to connect optical fibers with passive modulators, which will enable using the output of sunlight collectors. Furthermore, as we will discuss in the related work section, our optical designs overcome the most important limitation in current Passive-VLC studies in the SoA: the fact that the FoV of SoA platforms is close to 0° when working with natural light.

4 DUAL-BAND LINK

The prior section uses a single-band link, that is, the entire spectrum is modulated at once. To increase the data rate, it would be valuable to divide the spectrum into multiple channels. A well-known



(a) LC, center of FoV (b) LC, edge of FoV (c) DMD, center of FoV (d) DMD, edge of FoV

Figure 5: BER for controlled single-band setups.

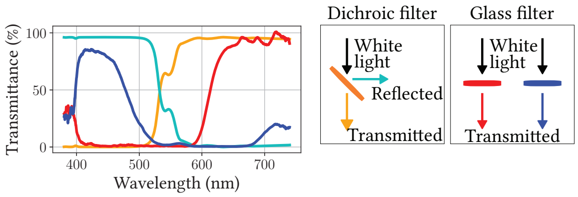


Figure 6: Spectral response of dichroic filters used at the transmitter (turquoise and orange) and glass filters used at the receiver (blue and red).

method for exploiting the spectrum in communications systems is to divide the available bandwidth into narrower bands. These OFDM approaches are widely used in Active-VLC. Passive-VLC, on the other hand, has no control over the light source, and hence, the challenge is greater. *To the best of our knowledge, there is no passive communication platform that attempts wavelength division with natural light.*

To tackle this challenge, we apply the general principle of wavelength division multiplexing (WDM). Applying this principle to Passive-VLC, however, requires considering some important differences. First, in optical fiber systems, WDM is an efficient technique because either the laser light is already divided in narrow bands or *in-fiber* filters allow band division within the fiber, thus reducing loss. Sol-Fi, on the other hand, requires an efficient filtering approach to divide natural light into narrower bands. Second, the light transmitted in optical fiber systems is not exposed to users. This means that the fibers' output can emit any spectrum. Sol-Fi, on the other hand, needs to guarantee that the (re)combined bands produce a white spectrum that is suitable for illumination.

4.1 Sunlight (de)multiplexing

Our prototype divides the spectrum into two bands. With facilities able to build purpose-designed filters for communication (and not only for human vision) the approach can be generalized to obtain more bands.

4.1.1 Multiplexer. The goal of the multiplexer is to divide the spectrum into *complementary* bands, whose (re)combination delivers white light suitable for illumination. Among the various types of off-the-shelf filters, the *Dichroic filter* has a response that satisfies this need. Figure 6 depicts the response of a dichroic filter that splits the spectrum into two complementary bands: one band is transmitted (orange) and the other band is reflected (turquoise).

An important property of dichroic filters is that by changing the light's angle of incidence (AoI), we can fine-tune the cut-off wavelength. Our implementation uses a red color dichroic filter from Thorlabs[2]. We select this filter because at an AoI of 45° the cut-off wavelength is 550 nm, close to the middle of the light spectrum. These dichroic filters are used for both modulators, LCs and DMDs. Given that the sunlight spectrum changes during the day, such as in sunsets with more red components, the system would require a tunable filter to split the spectrum into balanced bands.

[2]https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=986

4.1.2 Demultiplexer. The receiver for the dual-band designs requires two photodiodes, each having an optical filter in front. However, contrary to dichroic filters, whose response depends on the angle of incidence, the receivers need to be angle-independent so users can be located at any position within the transmitters' FoV.

A suitable filter for the receiver's requirements is the glass-colored filter, which is angle-independent, but the trade-off is that it has a narrower spectral response, which leads to some energy loss. One filter should be close to the blue band, and the other close to the red band, leaving the green band free to avoid cross-talk. We implement our receivers with commodity glass filters, with a response depicted in Figure 6. Similar to the case of dichroic filters, tunable filters would be required for different sunlight conditions, to match the filters in the multiplexer.

4.2 Transmitters and receiver

Given that both dual-band designs (LC and DMD) use the same filters, we first analyze their common characteristics regarding speed, FoV, and loss; and then, we provide the differences regarding the implementation.

- **Data rate**. Since we use two channels, the speed is double of the single-band design, leading to 1.6 kbps for the Dual-LC transmitter and 80 kbps for the Dual-DMD transmitter.
- **FoV**. In the dual-band design, the transmitter radiates two beams, each with a different color, as shown in Figure 7. With a proper optical design, the coverage of both beams would overlap precisely, recombining into white light and leading to the same FoV as for the single-band design. In our prototype, however, the coverage does not overlap precisely because of the big size of the dichroic filters (25.4 mm diameter), leading to three regions: a white cone in the middle, where both bands overlap and generate white light, and orange and turquoise stripes at the sides of the cone. Due to this effect, the FoV of the overlapping white cone is narrower than the FoV of the single band.
- **Loss**. A general principle of multi-band designs is to trade off a higher data rate for a shorter range. Since the energy of the entire spectrum is divided into sub-bands, the signals travel shorter distances. This trade-off applies to all wireless systems.

4.2.1 LC transmitter. The Dual-LC transmitter is depicted at the top of Figure 7a. Recalling that the sunlight collector has two optical outputs, our emulated setup has two flashlights each connected to one fiber. The fibers' outputs are orthogonal to each other and launched towards two dichroic filters oriented at an angle of 45°. This design allows rendering one spectrum with the *transmission* of the dichroic filter (orange) and the other with the *reflection* (turquoise). The output of each dichroic filter is modulated independently by an LC shutter but given that both optical outputs point in the same direction, they recombine into white light.

4.2.2 DMD Transmitter. The Dual-DMD transmitter is depicted at the top of Figure 7c. Given that the size of the dichroic filter is bigger than the optical enclosure of the mini-projector, instead of placing the filter before the modulator (as with the LCs), we place the filters after the DMD modulates the signal. The hardware setup duplicates the single-band design, we use two optical enclosures (mini-projectors) each with a DMD that is independently modulated.

4.2.3 Receiver. The receiver is the same for both designs and it duplicates the setup of the single-band receiver: two phototransistor boards, each with a glass filter in front.

4.3 Spectral analysis

To gain a deep understanding of Sol-Fi, we need to analyze the transformations of the spectrum at various points throughout the illumination process, as shown in Figure 7.

Step 1: Light source. The spectrum of the light source, point 1 in Figure 7, helps determine the width of the bands to balance the division of luminous flux. In our dual-band design, we use 550 nm as the spectral boundary. Note that for the sunlight spectrum (Figure 10), the spectral boundary should be slightly above the 600 nm mark. But given that the spectrum of the sun changes throughout the day, cooler (bluer) in the morning and warmer (more yellow) in the afternoon, we leave the boundary at 550 nm, at the risk of having one band stronger than the other.

Step 2: Modulator. The modulator should, in principle, cause only attenuation but no spectral distortion. The DMD does not cause any distortion, since there are no spectral changes between points 1 to 2 in Figure 7d; but the LC causes some distortions, which can be particularly noticed at points 3 and 5 in Figure 7b. This occurs because the LC is not really a shutter that blocks light, but rather a device that transforms the color of the incoming light via internal polarization changes [48]. Thus, the LC transforms the incoming spectrum into a different tone of white, but these tones are still perceived as white color by the human eye.

Step 3: Dichroic Filter. It is important to consider if *all* rays reach the filter in parallel, else each ray –arriving at a different angle– will be mapped to a different spectrum. Given that the FoV of the optical fiber (30°) is bigger than the FoV of the mini-projector (20°), the rays coming out of the fiber reach the dichroic's surface with a wider range of angles. Due to this reason, the bands of the DMD-transmitter (points 3 to 4 in Figure 7d) have less overlap (cross-talk) than the LC-transmitter bands (points 2 to 3 in Figure 7b).

Step 4: Recombined white light. The light coming from the dichroic filters will recombine. Some of the original spectra will be lost, but the remaining spectrum should still fall within the range associated with white light for the human eye. For the LC (point 6 in Figure 7b), the illumination attains a warmer tone (because some of the blue energy is lost), while for the DMD (point 5 in Figure 7d), the illumination does not change much compared to the original source.

Step 5: Glass filter. The glass filters have a narrower response than the dichroic filters, which helps to limit cross-talk. It is important to note that the spectra of the LC bands are a bit noisier than those of the DMD bands. This noisier behavior explains why LC links perform slightly worse than DMD links in the controlled scenarios (Figures 5 and 8), in particular for the blue channel (Figure 8).

Overall, our spectral analysis shows that the DMD is a better modulator because it sharply divides the communication bands, adds less noise, and provides illumination that is close to the original source. However, in our sunlight evaluation, we will see that the bigger area of the LC (R2) provides an important advantage due to the amount of luminous flux it modulates.

4.4 Evaluation

Similar to subsection 3.5, we assess the illumination and communication of the dual-band systems inside a dark room. The bands send different data: one sends `"Hello world!"` and the other `"Bye, aliens!"`, at the same rate. Thus, we have two channels with a joint data rate of 1.6 kbps and 80 kbps, for the LC and DMD setups, respectively.

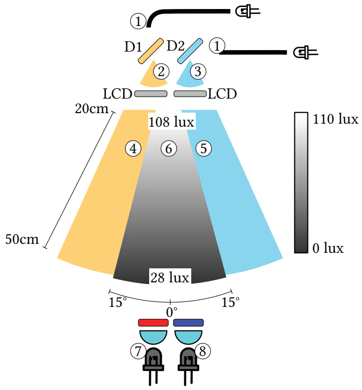
4.4.1 Optical losses. Following the same 'close-in measurements' method as for the single band, we place the luxmeter at a distance of 20 cm from the optical fiber's output, and in between, we measure the responses of the dichroic filter. Our design obtains an almost perfect division of the spectrum, 53.6 % of the energy goes to the orange band and 51.6 % to the turquoise band (the sum is greater than 100 % due to the overlap in the middle). The efficient division of the bands, however, is not maintained in the communication channel due to the mismatch between the filters at the transmitter and receiver. Based on the spectral responses in Figure 6, we estimate a loss of 52 % for the turquoise/blue channel and a loss of 24 % for the orange/red channel, but it is important to consider that the final loss depends on the spectrum of the light source, which is variable for sunlight.

4.4.2 Field of view. Contrary to the single-band case, the FoV has three regions: orange stripe, white cone and turquoise strip. Given that the overlap of the two bands is not precise, the FoV of the white cone is reduced to ±15°, with the LC setup showing wider stripes at the edges because it has a wider FoV than the DMD setup. *This non-overlapping issue is not a fundamental problem, a more elaborated optical design could obtain a precise overlap delivering the same FoV as the single-band case*: ±25° for LCs and ±20° for DMDs.

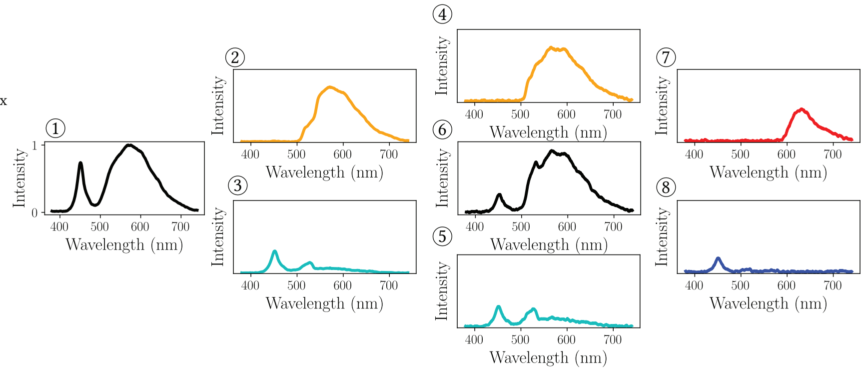
It is important to note that, compared to the single-band case, the dichroic filters change the illumination intensity. In the single-band case, both designs provide an intensity close to 75 lx at 20 cm, but in the dual-band case, the LCs provide 110 lx (Figure 7a) while the DMDs provide 51 lx (Figure 7c). In theory, the illuminance for both setups should be similar but they are not due to the different angles of incidence arriving at the dichroic surface, as explained in Step 3 in subsection 4.3. In the LC case, the wide aperture of the optical fibers causes heterogeneous angles of incidence, which lead to a spectral leakage that increases the overlap between the two bands. In the DMD case, the angle of incidence is more homogeneous due to the optical design of the projector, but this good filtering performance removes some energy around the 550 nm band compared to the single-band case.

4.4.3 Communication. Since the symmetry along the bisector is lost due to the different color bands, we measure the BER in three lines: the bisector and two lines at ±15° edges. For this evaluation, the receiver is placed at different ranges, in steps of 10 cm. The results are presented in Figure 8.

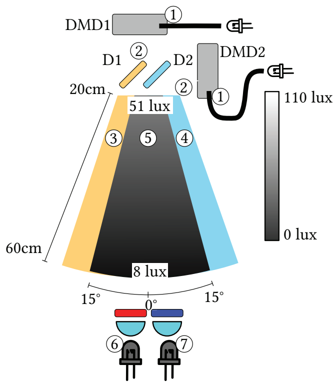
Overall, the LC setup does not have a good performance with the controlled scenario. The bisector and edge lines have locations where the BER is above 1 %, with the left edge having BERs that are above 20 %. This occurs due to uneven illumination and spectrum. But with sunlight, we will observe that the overlap gets better at longer ranges, providing reliable links with both bands. The



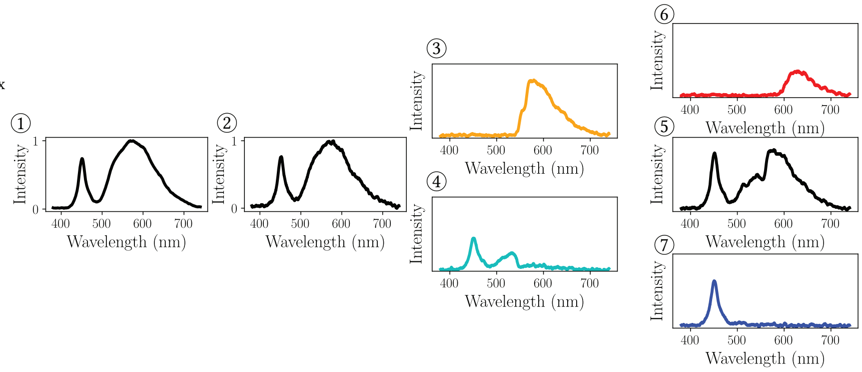
(a) Illumination for Dual-LC.



(b) Spectral analysis for Dual-LCD modulator.

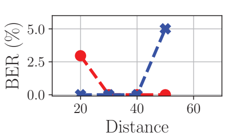


(c) Illumination for Dual-DMD.

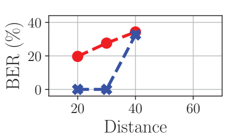


(d) Spectral analysis for Dual-DMD modulator.

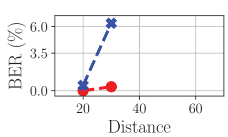
Figure 7: Illumination and spectral analysis for the dual-band setups.



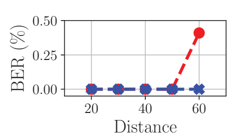
(a) LCD bisector.



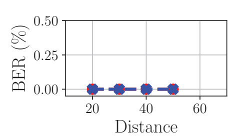
(b) LCD left edge.



(c) LCD right edge.



(d) DMD bisector.



(e) DMD edge.

Figure 8: BER for dual-band setups in a controlled environment. The color represents each channel.

DMD setup has a stronger performance, with a BER <1 % for all the positions and directions, due to the better filtering process and more even illumination and spectrum (compared to the LC setup). Thus, for the DMD setup, we only assess one edge.

Contribution 3: Until now all Passive-VLC studies have modulated ambient light as a single band. Our work is the first to provide a basic multi-band communication with sunlight. Overall, the DMD continues to appear as a device with better properties, leading to more reliable links.

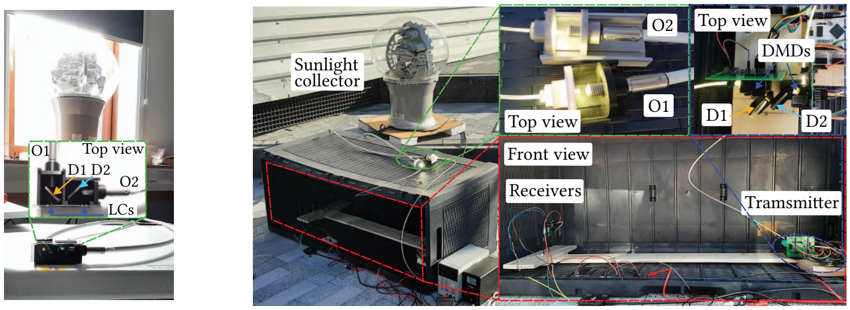
5 SUNLIGHT EVALUATION

Sunlight is inherently variable. During our experiments, it ranged from a few thousand lx to values above 100 klx, depending on how clear or cloudy the day is. The luminance gathered by the Himawari collector is delivered through two optical bundles (6 fibers per bundle) with an angular aperture of 58°. The sunlight spectrum can include strong IR (infrared), which radiates heat. Sunlight collectors can mitigate excessive heat with IR filters and cooling systems [39]. However, to reduce the design complexity, our implementation places the transmitters at a distance of 2 cm from the fiber's output. This distance allows heat to dissipate, at the cost of reducing the captured light.

Before proceeding, it is important to put ranges and illuminance in context. A communication range of 1.6 m from a ceiling is valid for user spaces[3], and desk lamps have a range that is half of that or less. Regarding illuminance conditions[4], a cozy (low-light) living room receives around 60 lx and a working desk around 360 lx. Table 2 summarizes the results of all setups regarding illumination, range, FoV and data rate.

[3]Construction standards suggest a ceiling height of 2.75 m (where light bulbs hang), and working desks (sitting or standing) are placed between 0.8-1.2 m

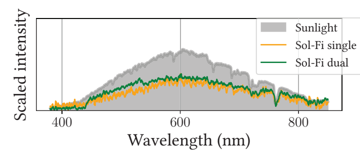
[4]Luminance (in Lumen, lm) and Illuminance (in Lux, lx) are different metrics: 1 Lumen = 1 Lux × 1m^2



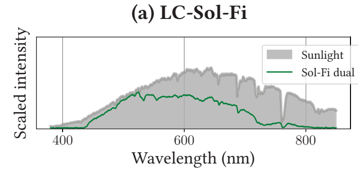
(a) LC setup.

(b) DMD setup.

Figure 9: Setups for both modulators using the sunlight collector. D: dichroic filter, O: output of collector.



(a) LC-Sol-Fi



(b) DMD-Sol-Fi

Figure 10: Measured spectra.

5.1 Sol-Fi with LCs: exploiting large areas

This experiment is performed in a *dark room:* the sunlight collector is located next to a window, while the other blinds are closed, c.f. Figure 9a. Note that this setup introduces undesirable noise because the room is not completely dark, but we will see that in spite of these non-ideal conditions, the system provides reliable links.

5.1.1 Single channel. For the single-channel setup, the two collector outputs are placed behind one LC shutter. The intensity of sunlight is so high that, in spite of the 66 % attenuation of the LCs, the illuminance at a 1 m distance is above 1000 lx (more than enough for any human task), and at a 5 m distance around 100 lx (sufficient for a living room or hallway). Due to this high intensity, the links are perfect at all locations and the spectrum still captures all the bands required for a healthy and comfortable natural illumination, as depicted in Figure 10a. To test the setup under more stringent conditions, we remove the lens from the receiver, which reduces the SNR. The results of this configuration are presented in Table 2 for the maximum range of our lab (5 m). Even in this case, the BER remains below 1 % for an FoV of ± 25°.

5.1.2 Dual channel. For the dual setup, the collector outputs (O1 and O2) are first aimed at their corresponding dichroic filters (D1 and D2), and the bands are modulated independently by the LCs, as shown in the top view box of Figure 9a. For the daylight conditions present during the experiment, the illumination at a communication range of 3 m ranges from 100 lx to 200 lx over the FoV. Table 2 presents the results, where we can see that except for the red channel at +30°, all the other links attain a BER below 1 %. Furthermore, the recombined spectrum is similar to the original (single-band) sunlight, providing all the health benefits (Figure 10a) plus an almost perfect color illumination at the bisector (Figure 11b).

5.2 Sol-Fi with DMDs: leveraging speed

A major advantage of the big LC area is that it can capture all the luminance radiated by the collector's output. Each output has six optical fibers put together into a sealed enclosure with a 1.2 cm diameter. Given that the LC's area has several cm^2, all the luminance radiated by the bundle passes through the LC. For our purposes, an *ideal DMD design would insert the fibers coming from the collector directly into the DMD*, but this is not possible because we cannot disassemble the fibers coming out of the sunlight collector without damaging them.

To overcome this issue, we place our 3 mm fiber at a distance of 2 cm from the bundle[5], as shown in one of the top views of Figure 9b (O1 & O2). The losses of this coupling can be overcome with a professional design. However, despite this loss, we will see that sunlight is so strong, that the DMD setup provides an illuminance similar to a desk lamp. Compared to the LC setup, the DMD design is more complex and delicate. For this reason, we build a *portable dark enclosure*, using a black box as shown in Figure 9b. In these experiments, due to the physical constraints of the black box, we only measure the bisector.

5.2.1 Single channel. Different from the LC, the DMD area does not allow pointing both collector's outputs into a single DMD. Thus, the setup takes only one of the collector's outputs and launches the light into the fiber connected to the DMD. Note that using a single output implies that in this case, we have half the luminous flux received in the LC case with a single-band. To place the receiver inside the box, we use a wood plank where the receiver is placed every 10 cm from a range of 0.7 m up to 1.5 m. The BER was zero for all the locations and the illuminance ranges from approximately 600 lx to 100 lx, providing sufficient light for a working space. Table 2 shows the results for the longest range.

5.2.2 Dual channel. For the dual channel, each collector bundle is coupled to the input fiber of the respective DMDs and then launched toward the dichroic filters. Considering that the signal strength of this setup is lower (because we use two bands instead of one), we test distances from 40 cm to 80 cm, in steps of 10 cm. The BER of both channels is 0.0 % at all points, and the illuminance ranges from around 100 lx at 40 cm to 30 lx at 80 cm. The latter is presented in Table 2. Regarding the recombined spectrum, most of the sunlight visible spectrum is present, with a reduced IR spectrum (Figure 10b) due to the heat dissipation of our optical coupling. Despite this loss, the color temperature is not affected significantly, as presented in Figure 11c. Losing some of the IR spectra simply makes the light cooler (less energy in the yellow and orange bands).

Important trade-off between single and bual bands. Table 2 shows that the dual band designs double the data rate but reduce the range. This is a standard trade-off in wireless systems because single channels maintain all the energy in one band, while multi-channel systems divide that energy.

[5]The distance of 2 cm is based on the fiber properties: glass fibers (bundle) can tolerate heat, but we use plastic fibers that are easy to handle but do not resist heat.

	Single band			Dual band							
Modulator	LC		DMD	LC						DMD	
Data rate	800 bps		40 kbps	2×800 bps						2×40 kbps	
Range	Up to 5 m		Up to 1.5 m	Up to 3 m						Up to 0.8 m	
Angle in the FoV	0°	25°	0°	+30°		0°		-30°		0°	
Illumination†	100 lx	80 lx	100 lx	100 lx to 200 lx						30 lx	
Channel	White	White	White	Red	Blue	Red	Blue	Red	Blue	Red	Blue
BER†	0.02 %	0.24 %	0.0 %	0.02 %	1.65 %	0.0 %	0.06 %	0.0 %	0.0 %	0.04 %	0.0 %

Table 2: Results for all setups using sunlight. 100 lx **is comparable to the light in a hallway. †: At the max. range.**

5.3 Variable sunlight conditions

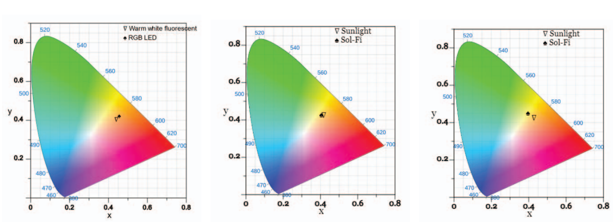
All previous results are obtained during clear days. A thorough evaluation requires cloudy periods with reduced sunlight intensity and diffused radiation. To anonymously describe our meteorological conditions, we provide as a reference New York City, which has a similar latitude to our location. At that latitude, sunlight ranges from a few thousand klx at sunrise and sunset up to values beyond 150 klx at noon. This radiation pattern holds for most of the year with some variance due to the different seasons [13].

We test Sol-Fi with clear (direct sunlight) and cloudy skies (diffused sunlight) using the single-channel DMD setup at two distances, 40 cm and 85 cm. Figure 12 shows the results, where the link oscillates between operational (green) and failure (red) depending on the cloudiness level. We noticed that the link's performance decreased during cloudy periods with diffused light intensities around 30 klux or lower.

Another effect of sunlight fluctuation is the variation of the unmodulated light intensity at the receiver. For the setup using LCs and sunlight, there was unmodulated light (noise) coming from the window and reaching the receiver but the system kept working. Moreover, there are two possible solutions to filter unmodulated/ambient light. First, the light can be filtered during the demodulation process as DC bias. Second, the receivers can restrict their FoV to partially block ambient light and increase the SNR [2].

6 RELATED WORK

Passive-VLC with LCs. In the SoA, Passive-VLC systems have widely adopted LCs as optical transmitters. These systems can be divided into two categories: when the light source and receiver are *co-located* (*reflective* systems), or in *different locations* (*transmissive* systems). In the first category, the LCs require *artificial lights* and retro-reflectors to modulate light back in the direction of the light source [31, 44, 45, 47]. In the second one, the LCs are used alone as a modulator, while another part of the system redirects light towards the receiver [8, 18, 19]. The version of Sol-Fi using LCs is similar to the latter group, but it has two main differences compared to all the reflective and transmissive systems cited above.



(a) Artificial light (b) LCD dual (c) DMD dual

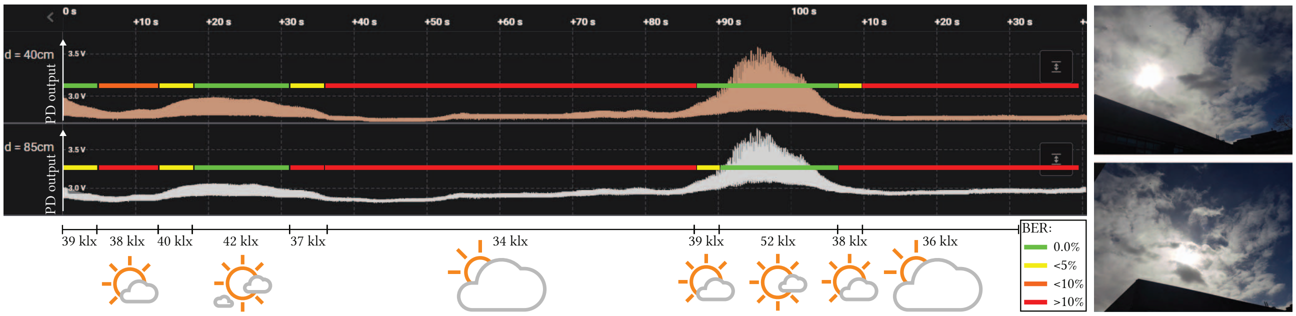
Figure 11: Color quality of Sol-Fi for the dual band

The *first difference* is only operational. All the above systems have narrow beams (limited FoV), either due to the inherent behavior of retro-reflectors or the small parallel beams radiated in transmissive systems. Thanks to the default properties of sunlight collectors, Sol-Fi's FoV is wide and constant throughout the day. The *second difference* is more fundamental. No study has provided WDM with sunlight. The majority of studies do not modify the spectrum in any way [8, 31, 44, 45, 47], and only two studies modify the spectrum but do *not* create independent channels [18, 19]. ChromaLux isolates a *single color channel* to obtain a faster-switching response of the LC [18], and SpectraLux 'distorts' the entire LC spectrum to transmit different colors [19], encoding multiple bits per color. Neither of these studies creates independent parallel channels inside the spectrum.

DMDs & (Passive)VLC. Even though commercial DMDs are developed primarily for video projection, they have also been used in applications such as spatial modulation, microscopy, and data center interconnection [15, 20]. Some studies have also explored the use of DMDs in VLC, specifically for localization [9, 28, 29]. In those systems, a dedicated light source (LED or laser) is required, and in addition, a limited range and data rate are demonstrated due to the slow switching times of the off-the-shelf controllers. Another study developed a custom controller and demonstrated that DMDs can be used for Passive-VLC, attaining data rates up to 80 kbps [46], with a *narrow beam*. Our system attains half this data rate (40 kbps) for the single-band case due to the optical losses at the interface with the sunlight collector, which limits the signal strength. Reducing these optical losses for the DMD-Sol-Fi setup would improve the data rate. However, aside from adding a dual-band feature, our system also largely improves the FoV compared to the SoA.

Sunlight communications. A few recent studies have also identified the benefits of using sunlight for indoor wireless communication. These are valuable designs, but *they do not provide real implementations, mainly simulations.*

In [5, 6], a *smart window* is embedded with a special dual-cell crystal shutter (DLS). The connectivity in this setup relies on the relative position of the window and the sun, while Sol-Fi's reliance on sunlight collectors provides a stable direction (link) throughout the day. Additionally, the number of DLS goes up to 70 for a single channel. In Sol-Fi, the number of LCs goes up to the number of channels. Another study, LiFiTube [41] explores the use of a tubular light guide (TLG), which could be seen as pipes that guide sunlight, but their efficiency is lower compared to the sunlight collector,



(a) Signal strength and BER (green/orange/red bars) of two PDs during cloudy conditions

(b) Cloud conditions

Figure 12: Sol-Fi's performance under variable sunlight conditions (30-40 klx with clouds).

which tracks the sun. Additionally, the TLG's output size is large, which requires LiFiTube to use 28 LCs for modulating a single

The fact that the above studies do not provide real implementations highlights the difficulty of combining complex optical systems with Passive-VLC. Sol-Fi's basic prototypes are the first to implement a natural light bulb that also provides communication by using not only LCs and implementing a single channel like the studies above but also using DMDs and dual-channel capabilities.

Multi-band systems with Active-VLC. The use of multiple bands is also explored in Active-VLC (LiFi). While the higher speed achieved by Active-VLC is orders of magnitude larger than the speed achieved by Passive-VLC, including Sol-Fi (tens of kbps vs. hundreds of Gbps), this is mainly due to the fact that Active-VLC systems can modulate LEDs at high speeds, but not because they use numerous channels. In one study [30], the system uses an RGB LED to provide illumination up to 3 m while providing 50 Gbps per channel, achieving a total of 300 Gbps with six channels: three color channels (red, green and blue) multiplied by two polarization directions. Other theoretical studies propose using more channels: up to 12 channels for short distances [12], and up to 20 channels for room illumination [35], but they rely on simulations. These studies show that achieving multiple channels with different spectra (more than three) is not simple even with artificial light (LEDs). Sol-Fi is a first attempt to get multi-band transmissions with natural light.

7 DISCUSSION

Sol-Fi is the first attempt to provide a natural light bulb with communication capabilities, but the power consumption and optical losses are still high, and its performance depends on environmental conditions. To describe the first two drawbacks, Table 3 shows the power required to provide an indoor area with illumination and connectivity using various methods.

Setup	Light		Wireless		Speed
	Lum. Flux	Power	Control	Modulator	
WiFi	~800 lm	~8 W	~6 W [33]		Mbps
LiFi[42]	~800 lm	~8 W	~1.4 W		Mbps
Collector	4.5 klm	< 2 W	-	-	-
LC-Sol-Fi	1-2 klm	<2 W	30 mW	µW	<1.6 kbps
			2 mW★	µW★	
DMD-Sol-Fi	10-130 lm	<2 W	1.3 W	193 mW	<80 kbps
			2 mW★	45 mW★	

Table 3: Sol-Fi and other wireless technologies, assuming an enclosed area. ★ The estimated low-power setup.

Hybrid systems. As stated in section 2, Sol-Fi is a diurnal technology that would require interacting with other wireless systems. Considering a room that requires illumination and communication, Table 3 shows that WiFi and *LiFi [42] can provide Mbps, but the costs of illumination and wireless connectivity would be above 10 W (8 W for illumination plus 1.4-6 W for wireless connectivity).* The sunlight collector can provide more illumination using less power, but there are 3 key challenges. The first two are to increase the data rate and reduce the optical losses (as discussed later in this section). The last one is to integrate this passive VLC with an active VLC system so the illumination and data rate can be kept constant during the day and night. If these issues are tackled, future wireless systems could provide the best combination of energy efficiency and robustness by designing a hybrid system that exploits natural light during the day (like Sol-Fi), artificial light during the night (mostly LiFi, since the cost of adding communication on top of illumination is not high), and radio systems to provide coverage in areas and times where light is not robust.

Optical losses & light quality. Table 3 shows that an 8 W LED provides a room with 800 lm (recall that lumen is not the same lux). In our experiments, the sunlight collector gave almost 6x more luminance (4.5 klm) consuming 4x less power (<2 W). However, even though DMDs have high reflectivity (97%), the luminance of our DMD-transmitter reduces to 10-130 lm. There are three main reasons for this loss. The first two are the optical couplings between the collectors' outputs and our fibers, and between our fibers and the DMD. These losses can be overcome by designing a custom collector with fibers that can be plugged directly into the DMD with the appropriate lenses. The third loss is due to the dichroic filters, which are also responsible for light division and further free-space recombination. An optical design that captures the transmitted and reflected components could overcome the losses. Moreover, a more elaborated solution is the use use of *in-fiber* filters in combination with optical fiber circulators. This system would keep the light-division system inside the fiber, thus reducing losses and resulting in two fibers with complementary spectra. After independent modulation, a fiber coupler recombines both bands into one fiber, with a better color distribution. This implementation would require combining cutting-edge *industrial* methods from sunlight collectors, optical fibers and projector technologies.

Power consumption. One advantage of Passive-VLC is its low power consumption compared to WiFi or LiFi, which require several watts. However, our DMD transmitter still uses too much power, more than 1 W, due to the precise timing required to modulate the *video controller*. We generate those signals with the Artix-7 FPGA board, which is not optimized for low power but for fast prototyping. Looking at the datasheet of the Apollo4 Plus (Ambiq) [4], working at 1.9 V and 40 MHz, we estimate that a DMD-transmitter could consume around 200 mW (controller+DMD), but this alternative requires a careful PCB design and interrupt handling. A further potential reduction is to design a custom DMD without the video projection overhead. We use the DMD as a single pixel modulating at max 80 kHz (all micromirrors move synchronously), we do not need to modulate each pixel at 40 MHz. The DMD data sheet indicates that bypassing the video control could reduce the power consumption to 45 mW. Such a design could only be done by a DMD manufacturer, but we estimate that a simpler slower controller with a 'single-pixel' DMD would consume around 50 mW.

Line of sight (LoS). Non LoS (NLoS) VLC is based on light reflections. In those cases, factors such as the SNR, the number of reflections and the surface reflectivity affect the link quality [14, 32]. Sol-Fi was not tested under NLoS, but the performance would reduce (similar to what would happen to any other VLC system).

8 CONCLUSIONS

This work proposes a novel framework to design the first natural light fixtures that provide all the health benefits of sunlight plus wireless communication. Our framework proposes a thorough analysis of different modulators, providing a wide FoV channel with multi-band capabilities. Our results show that even with sub-optimal off-the-shelf components, sunlight could provide illumination and communication through a new generation of low-power passive transmitters.

ACKNOWLEDGMENTS

This work has been funded by the Dutch Research Council (NWO) with a TOP-Grant with project number 612.001.854, and by the European Union's H2020 program under the Marie Skłodowska Curie grant agreement ENLIGHTEM No. 814215.

REFERENCES

[1] Parans Solar Lightning AB. 2022. Parans Solar Lightning System.
[2] Iman Abdalla et al. 2019. Dynamic FOV visible light communications receiver for dense optical networks. *IET Communications* (2019).
[3] Sergio Altomonte. 2008. Daylight for energy savings and psycho-physiological well-being in sustainable built environments. *J Sustain Dev* (2008).
[4] Ambiq. 2022. Apollo Plus SoC Datasheet.
[5] Sahar Ammar et al. 2022. Design and Analysis of LCD-Based Modulator for Passive Sunlight Communications. *IEEE Photonics J* (2022).
[6] Sahar Ammar et al. 2023. Sun-Fi: Architecting Glass for Sunlight Data Transmission. *IEEE Commun Mag* (2023).
[7] Lucio Claudio Andreani et al. 2019. Silicon solar cells: toward the efficiency limits. *Advances in Physics: X* (2019).
[8] Rens Bloom et al. 2019. LuxLink: Creating a Wireless Link from Ambient Light. In *ACM SenSys*.
[9] Charles J. Carver et al. 2022. Sunflower: Locating Underwater Robots from the Air. In *ACM MobiSys*.
[10] Ying-Chih Cheng et al. 2020. The effect of vitamin D supplement on negative emotions: A systematic review and meta-analysis. *Depress Anxiety* (2020).
[11] Cary Cooper. 2014. Human spaces report: Biophilic design in the workplace. *Interface* (2014).
[12] Lu Cui et al. 2016. Analysis of the Multichannel WDM-VLC Communication System. *J Lightwave Technol* (2016).
[13] Srikant Devaraj and Pankaj C. Patel. 2017. Taxicab tipping and sunlight. *PLOS ONE* (2017).
[14] Vipul Dixit and Atul Kumar. 2020. Performance analysis of non-line of sight visible light communication systems. *Opt Commun* (2020).
[15] Dana Dudley et al. 2003. Emerging digital micromirror device (DMD) applications. In *MOEMS Display and Imaging Systems*. SPIE.
[16] Mahmoud El-saggan et al. 2023. A Review of the Evolution of Daylighting Applications and Systems Over Time for Green Buildings. *IJAES* (2023).
[17] L. M. Fraas et al. 1983. Concentrated and piped sunlight for indoor illumination. *Optica Appl. Opt.* (1983).
[18] Seyed Keyarash Ghiasi et al. 2021. A Principled Design for Passive Light Communication. In *ACM MobiCom*.
[19] Seyed Keyarash Ghiasi et al. 2023. SpectraLux: Towards Exploiting the Full Spectrum with Passive VLC. In *ACM IPSN*.
[20] Monia Ghobadi et al. 2016. ProjecToR: Agile Reconfigurable Data Center Interconnect. In *ACM SIGCOMM*.
[21] Harald Haas. 2011. Wireless data from every light bulb | TED Talk.
[22] Lisa Heschong et al. 2002. Daylighting Impacts on Human Performance in School. *Journal of IES* (2002).
[23] Michael F Holick. 2004. Sunlight and vitamin D for bone health and prevention of autoimmune diseases, cancers, and cardiovascular disease. *Am J Clin Nutr* (2004).
[24] Texas Instruments Incorporated. 2021. TI DLP® Module 2000 EVM User's Guide.
[25] Himawari Solar Lighting System Laforet Engineeing Co. JP. 2022. Lightning solution.
[26] Jun-Tae Kim et al. 2016. *ZEMCH: Toward the Delivery of Zero Energy Mass Custom Homes*. Springer International Publishing, Chapter Active Systems.
[27] Jeong Tai Kim and Gon Kim. 2010. Overview and new developments in optical daylighting systems for building a healthy indoor environment. *Building and Environment* (2010).
[28] Motoi Kodama and Shinichiro Haruyama. 2016. Visible Light Communication Using Two Different Polarized DMD Projectors for Seamless Location Services. In *ACM ICNCC*.
[29] Motoi Kodama and Shinichiro Haruyama. 2019. Pulse Width Modulated Visible Light Communication using Digital Micro-mirror Device Projector for Voice Information Guidance System. In *IEEE CCWC*.
[30] Chung-Yi Li et al. 2020. White-lighting and WDM-VLC system using transmission gratings and an engineered diffuser. *Optica Opt. Lett.* (2020).
[31] Jiangtao Li et al. 2015. Retro-VLC: Enabling Battery-Free Duplex Visible Light Communication for Mobile and IoT Applications. In *ACM HotMobile*.
[32] Fayzatul Ashmera Binti Merdan et al. 2022. Non-line of sight visible light communications: A technical and application based survey. *Optik* (2022).
[33] Mario Poljak. 2021. How much electricity (power) does a wi-fi router use?
[34] Georg Rademacher et al. 2020. 10.66 Peta-Bit/s Transmission over a 38-Core-Three-Mode Fiber. *Optica OFC*.
[35] M.T. Rahman and Rajendran Parthiban. 2020. Modeling and analysis of multi-channel gigabit class CWDM-VLC system. *Opt Commun* (2020).
[36] Carmine Sapia. 2013. Daylighting in buildings: Developments of sunlight addressing by optical fiber. *Solar Energy* (2013).
[37] Sihua Shao et al. 2017. Pixelated VLC-Backscattering for Self-Charging Indoor IoT Devices. *IEEE Photonics Technol Lett* (2017).
[38] Frank Sharp et al. 2014. The use and environmental impact of daylighting. *J Clean Prod* (2014).
[39] Jifeng Song et al. 2021. Application of highly concentrated sunlight transmission and daylighting indoor via plastic optical fibers with comprehensive cooling approaches. *Renew Energy* (2021).
[40] Jifeng Song et al. 2023. Analysis and Comparison of Daylighting Technologies: Light Pipe, Optical Fiber, and Heliostat. *Sustainability* (2023).
[41] Javier Talavante et al. 2023. Rethinking LiFi for Carbon Neutral Sunlight-based Communication. In *IEEE MedComNet*.
[42] Lucas Teixeira et al. 2019. Review of LED drivers for Visible Light Communication. In *IEEE IECON*, Vol. 1.
[43] Jennifer A. Veitch and Anca D. Galasiu. 2012. *The Physiological and Psychological Effects of Windows, Daylight, and View at Home: Review and Research Agenda*. Technical Report. National Research Council of Canada.
[44] Purui Wang et al. 2020. Renovating Road Signs for Infrastructure-to-Vehicle Networking: A Visible Light Backscatter Communication and Networking Approach. In *ACM MobiCom*.
[45] Yue Wu et al. 2020. Turboboosting Visible Light Backscatter Communication. In *ACM SIGCOMM*.
[46] Talia Xu et al. 2022. Exploiting Digital Micro-Mirror Devices for Ambient Light Communication. In *USENIX NSDI*.
[47] Xieyang Xu et al. 2017. PassiveVLC: Enabling Practical Visible Light Backscatter Communication for Battery-Free IoT Applications. In *ACM MobiCom*.
[48] Zhice Yang et al. 2015. Wearables Can Afford: Light-Weight Indoor Positioning with Visible Light. In *ACM MobiSys*.