LuxLink: Creating a reliable wireless link out of ambient light

ABSTRACT

Transmitting information with visible light requires *controlling* the intensity of the light source. Many light sources in our environments, however, cannot be controlled (not only the sun but also plenty of artificial light bulbs). Thus, existing approaches are not exploiting the potential of ambient light for wireless communication. We propose a novel platform, named LuxLink, that creates reliable wireless links relying solely on ambient light. Our platform builds upon liquid crystal displays (LCDs) to modulate the intensity of ambient light and provides two unique features compared to the state-of-the-art. First, sustainability. Ambient light is our only source for energy and communication. The transmitter uses LCDs to send information (μW consumption), and the receiver uses a single low-power phototransistor (mW consumption). Second, safety and reliability. We show that a careful design of frequency-based modulation eliminates simultaneously flickering effects (safety) and interference from artificial lighting (reliability). We test our platform in indoor and outdoor environments, and show that an LCD surface of 6 cm×8 cm can transmit 80 bps at ranges between 4 meters (indoors) and 60 meters (outdoors). The power consumption of both the transmitter and the receiver is 65 mW. Compared to similar systems using cameras, LuxLink can transmit more information, at longer distances and with less energy.

KEYWORDS

Visible light, Passive communication, Liquid crystal shutter

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1 INTRODUCTION

For decades, wireless communication in our societies has relied on a single pillar, the radio-frequency spectrum (WiFi, Cellular, BLE, to name a few). To ameliorate this problem, the research community is investigating various approaches to add a second pillar to our wireless communication infrastructure: the visible light spectrum. By modulating artificial light sources at high speeds, such as any LED bulb, information can be transmitted without disturbing in any way the illumination observed by users.

These are notable advances but have two important shortcomings. First, all these approaches assume that the light source can be controlled. Most of the light in our environments, however, comes from sources that cannot be controlled, such as the sun and LED bulbs that are not enabled for Visible Light Communication (VLC). Second, the power required to modulate LED bulbs increase their energy consumption by 20% or more [1], and some devices use cameras as receivers, which are power hungry. Thus, visible light communication does not piggyback information on top of existing lighting for free, it can consume a non-trivial amount of energy to modulate and decode information.

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1.1 Vision & Applications

We want to create a new sustainable communication channel that relies solely on ambient light. Sunlight, or any type of light impinging over a surface, will be modulated via controlled absorption, and a low-power photosensor will be used to decode information (no cameras). These changes in light intensity will not be perceived by users, the transmitting surfaces will appear as tinted glass. This new channel could allow us to transform the surfaces in our cities and buildings into wireless transmitters. For example, as shown in Figure 1, a pedestrian could use any wearable device that has a photodiode to get information about activities in the city while waiting in the bus stop.

Figure 1: Smart surfaces for ambient light communication

Communication via controlled reflections is an old idea. European armies in the 1800's used mirrors (heliographs) to communicate at long distances [5]. In the same century, the first wireless telephone was created by Alexander Graham Bell connecting a mouthpiece (microphone) to an oscillating mirror that changed the reflections of sunlight to modulate voice.Advancements in optics and smart materials could be leveraged to transform this old idea into a pervasive and sustainable communication channel, enabling our cities and buildings to receive light and reflect back information.

1.2 Research Challenges

Communication based on visible light can be divided into four quadrants depending on the type of transmission and reception used. The transmitter can be based on active or passive light sources. *Active* refers to light sources that can be controlled, and *passive* refers to light sources that cannot be controlled. The receiver can be based on cameras or simple photosensors (photodiodes or phototransistors). The most sustainable solution is to combine passive light sources and simple photosensors. Next we describe the key concepts we build upon from the state-of-the-art (SoA) and the novelty of our work.

Building Block 1: use of liquid crystal displays (LCD) to create semi-passive VLC links. In traditional Visible Light Communication, bidirectional links require active light sources at both ends of the communication. RetroVLC [9] and PassiveVLC [16] explore backscattering with visible light to create a semi-passive link. For the downlink, an LED lamp transmits information to a *tag* (receiver) using traditional VLC. For the uplink, the tag replies back using an LCD shutter to block and reflect the impinging light. RetroVLC and PassiveVLC use photodiodes for the receiver, which are energy efficient, but they require an active light source. Furthermore, given that they use retro-reflectors, the tag is constrained to communicate *only* with the lamp providing illumination. We build on top of the idea of using LCDs to modulate light, but explore a more general and unrestrained problem: a system that requires no control over light sources and with the ability to create point-to-point links irrespective of the location of the light source.

Building Block 2: use of sunlight for wireless communication with cameras or mobile objects. The main inspiration for our work comes from two studies that exploit sunlight to modulate information, Pixel [17] and MobileVLC [13][1]. When there is no control over the light source, the modulation of light can be attained by changing the polarization of light [17] or modifying the external coverage of surfaces [13]. Pixel uses LCDs and dispersors to modulate artificial and natural light. The modulation relies on changes in polarization, which do not cause flickering effects, but the encoding utilizes Color Shift Keying (an elaborated scheme), and the receiver requires a camera. MobileVLC embeds barcodes on the surfaces of mobile objects. As the objects move, the light reflected from their surfaces conveys the barcode information. MobileVLC is energy-efficient because it uses only ambient light and the receiver is based on phototransistors, but the links are only unidirectional (from the object to the receiver) and the objects *must* move at constant speed to modulate information. Motivated by these studies, our system exploits ambient light, but we do not require cameras or mobility to establish link.

1.3 Contributions

The key novelty of work is to provide the first point-to-point ambient light link that works with a simple photosensor. In particular, the unique features of our LuxLink platform are:

1) Sustainability and safety [section 3]. In low-power IoT systems based on visible light, it is a de-facto guideline to use amplitude based modulation schemes. We benchmark the performance of different types of LCDs based on their energy consumption and response times, and show that with ambient light, amplitude based modulation cannot provide safety (non-flickering effects) and sustainability (use of simple photosensors). We show that frequency based modulation can provide both.

2) Reliability [section 4]. Given that we have no control over the light source, our system needs to be designed to work outdoors, in sunny and cloudy days; and indoors, considering the interference caused by artificial lighting. To overcome these problems, we carefully design an opto-electronic receiver that maximizes the signal-to-noise ratio and employs frequency based modulation techniques to avoid interference.

We evaluate our platform in indoor and outdoor scenarios in section 5. To make our platform standalone and amenable to users, we enhance our transmitter with sensors and a keyboard to facilitate the input of data, and we add an e-ink display at the receiver to present the received data. Our results show that LuxLink works indoors (4 m range) and outdoors (10-60 m range) consuming a fraction of the energy required for a system using cameras.

2 BACKGROUND

2.1 Challenges

Communication with visible light usually entails modulating the illumination intensity. A must for any such system is to be flicker-free. Apart from being visually disturbing, prolonged exposure to flickering can result in dizziness, headaches, and in extreme cases, cause epileptic seizures [6]. To eliminate flickering, changes in light intensity must switch faster than 200 Hz, and the system must ensure a constant *average* brightness throughout the transmission [10]. With active light sources, flickering can be eliminated in various ways because LEDs have fast switching speeds (~MHz), which provides ample room to modulate data with constant average brightness [15]. LCDs, on the other hand, have low modulating frequencies (~KHz). In section 3, we show that these low modulation frequencies can induce illumination changes below 200 Hz due to fluctuations in the data patterns, signal amplitude and duty cycle.

An ingenuous approach to avoid flickering with LCDs is to alter their operation to modulate light based on polarization instead of amplitude [17]. LCDs have three layers that electrically control the amount of light passing through it, as shown in Figure 2. The first layer (vertical polarizer film) only allows light of a single polarization direction to pass through. The second layer (liquid crystal) maintains the polarization direction if voltage is applied. The third layer (horizontal polarizer film) either blocks light from passing through (if voltage is applied) or allows the polarized light to pass through (if no voltage is applied). Polarization based methods remove the third layer [17]. The outcome is always polarized light but in different directions. The light intensity is the same, and since people cannot notice changes in polarization, this system is flicker free. This approach, however, requires adding dispersors to the transmitter, cameras to the receiver and using elaborated Color Shift Keying encoding.

Challenge 1: Sustainability and flickering. To be energy efficient, ambient light communication should use simple photosensors, but simple photosensors can only distinguish changes in amplitude, which cause flickering. The SoA provides either color-based flicker-free communication with cameras, or amplitude-based flicker-prone communication with photosensors. We uncover a third alternative: frequency-based flicker-free communication with photosensors.

Another important limitation of using ambient light is that we lack control over the intensity, oscillations and beam direction of the light source. This limitation can lead to unreliable links. *Indoors*, artificial lighting oscillates at various frequencies, not only related to the power grid (50/60 Hz and their harmonics) but also related to

[1] The authors do not provide a name for their system. This is a name provided by us.

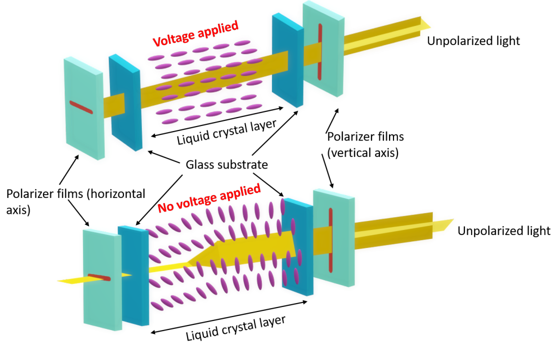


Figure 2: Working of an LCD shutter.

the operation of smart lighting systems which use duty-cycle techniques for dimming. These oscillations are not a problem if active light sources are used for communication, because the modulation frequencies of LEDs are several orders of magnitude higher than the interference created by artificial lights. With LCDs, however, the frequency of interference has the same order of magnitude as the transmitted data, greatly distorting the signal. *Outdoors*, sunlight changes its intensity and direction throughout the day. Cloudy days or regions with less sunlight would reduce the range of the link, and using mirrors or retro-reflectors to increase the range [9, 16] (by focusing the reflected energy on a single point) are not a good option because they provide poor coverage, the receiver can only be located on the angle of reflection.

Challenge 2: Reliability in indoor and outdoor scenarios. Losing control over the output power, beam direction and oscillation frequencies of light sources, means that it is not possible to provide a link with a guaranteed range and data rate. To ameliorate these effects, we use diffuse surfaces, lenses and low-power frequency-based filtering.

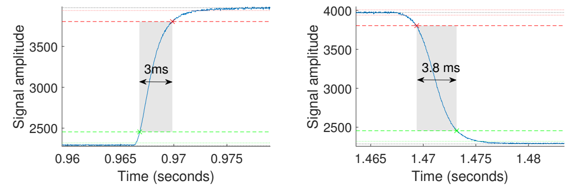
2.2 Basic system components

Our system has three basic components.

(1) *Emitter.* Any source of light, artificial or natural. We do not make any assumptions about the location, intensity or beam direction of the emitter.
(2) *Transmitter.* One or multiple LCD panels modulated by a microprocessor to transmit information. The transmitter has embedded sensors and a connection for a keyboard.
(3) *Receiver.* A simple phototransistor, together with a lens and a microprocessor to decode information. The receiver also has a low-power e-ink display to present the information.

3 TRANSMITTER

Wireless communication with ambient light has only been superficially studied []. In this section, we present the first detailed analysis of LCDs and modulation schemes to design robust Hardware and Physical Layers.



(a) Rise time **(b) Fall time**

Figure 3: The rise and fall time of a 3D shutter at 5V

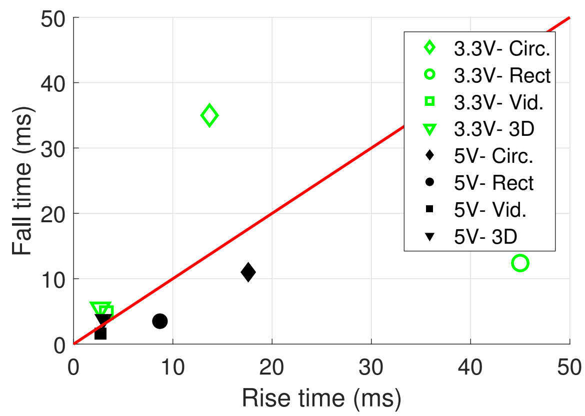


Figure 4: The rise and fall time of the shutters driven at 3.3 V and 5 V

3.1 Hardware Layer: Selecting the right LCD

As described in subsection 2.1, LCDs control electrically the amount of light that pass through their surface, but they have not been designed or analyzed for communication. We evaluate the performance of LCDs considering three important metrics for wireless communication: (1) Response time, which impacts the maximum data rate; (2) Energy consumption; and (3) Contrast, which impacts the range and signal-to-noise ratio (SNR).

3.1.1 Response time. LuxLink uses commercial, off-the-shelf LCD shutters. The most important properties of LCDs are their fall and rise times, i.e. the times taken to go from the transparent to opaque state (voltage *on*), and viceversa (voltage *off*). Figure 3 shows the rising and falling times of a 3D shutter. The maximum modulation frequency of an LCD is determined by the inverse of the sum of the rise and fall times. Furthermore, as we show later in this section, to avoid flickering effects, the rise and fall times should be as similar as possible.

We evaluate four different types of shutters[2]. Table 1 shows the area of the shutters, as well as their response times and maximum modulation frequencies when driven at 3.3 and 5.0 V. Figure 4 provides more details about the rise and falle times. This table and figure provide two important insights.

[2]**Marco: what are the key fundamental differences in the shutters? Are some shutters better for some applications?**

Shutter type	Area (cm^2)	Response time (ms)		Frequency (Hz)	
		3.3 V	5 V	3.3 V	5 V
Circular	95	48.7	28.6	20	35
Rectangular	37	57.4	12.2	17	82
Video	15	8.1	4.3	123	233
3D	14	8.2	6.8	122	147

Table 1: Response times and corresponding operating frequencies of the LCD shutters for varying supply voltages Add column for area, update response time (should be sum), update max modulation frequency and Should the numbers be rounded off?

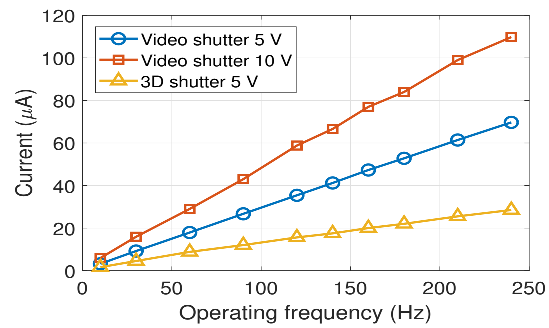


Figure 5: Current consumption by the video and 3D shutters

First, all shutters have maximum modulation frequencies below or near 200 Hz. Thus, LCD-based modulation cannot be done utilizing the entire rise and fall times. Symbols need to use periods that are shorter than the rise and fall times, which prevents the modulated signal from reaching an steady state plateau. Table 1 shows that the rectangular and circular shutters have very low modulation frequencies, and thus, we discard them as options for LuxLink[3].

Second, the rise and fall times of shutters are different (Figure 4). This occurs because the fall time is voltage dependent, but the rise time is material dependent. The liquid crystal molecules have an inherent torque and alignment. The higher the applied voltage (fall time), the faster the torque is overpowered. Once the applied voltage stops (rise time), the restoring torque twists the liquid crystal molecules back into their default state. Thus, the rise time, being material dependent, needs to be modified at the design stage to switch faster. The video shutter has a higher modulating frequency, but the ratio of its fall and rise time is 1.7, higher than the corresponding ratio for the 3D shutter, which is 0.8.[4]explain why it is bad to have large differences between rise and fall time, if there is a reason. The selection between the video and 3D shutters presents trade-offs, to further distinguish their performance, we analyze their energy consumption.

3.1.2 Energy consumption. The maximum supply voltage of LCDs is usually 5 V except for the video shutter which is suggested to be 10 V+. The summed response time of the video shutter at 10 V is 2.93 ms (333 Hz) (rise time 2.7 ms, fall time 0.23 ms), which is better than the values presented in Table 1. This improvement, however, comes at the cost of increased current consumption as shown in Figure 5. [5] Driving the shutter at such high voltage is not a feasible choice for a sustainable system, where we restrict the voltage to 5 V. [6] When both, the video and 3D shutter, are drawn with 5 V, the 3D shutter draws half the power of the video shutter.

[3]Note that a smaller circular shutter (≈ 6× smaller), may provide rise and fall times comparable to the video and 3D shutters, but we cannot modify the size (it is determined by the manufacturers).

[4]**Rens: talking about a ratio sounds confusing. "the fall time is 1.7 higher than the rise time" is easier to read.**

[5]**Rens: 100 microamps is not a lot. For the real difference, we must probably multiply(is that true?) with the voltage (to get consumed power). Then, beyond 250 Hz the difference might be interesting**

[6]**Rens: why do we restrict it to 5V?**

Besides power, another important point is cost. 3D and video shutters have similar sizes, but 3D shutters cost one quarter of the price (6 vs. 25 USD).

Design Guideline 1: For ambient light communication, 3D shutters are the best option. 3D shutters have a lower modulation frequency compared to video shutters (30% less) but they have more similar rise and fall times (50% more similar), consume half the power and cost 75% less for the same modulating area. These shutters have been used before for backscatter communication with light [9].

3.1.3 Contrast. The higher the contrast between the transparent and opaque states of the shutter, the higher the signal-to-noise ratio and the longer the range. The maximum contrast is achieved when the full rise and fall times presented in subsubsection 3.1.1 are utilized, but this frequency[7] is too low and may cause flickering effects. Switching the shutter at higher frequencies is necessary, but reduces the contrast. Thus, a key question for our design is: what is the maximum operating frequency for 3D shutters? Figure 6 shows our results. For frequencies up to 200 Hz, the shutter is able to perform full state transitions and reach the maximum contrast. At higher frequencies, the contrast decreases with increasing frequency, because there is not enough time to fully switch between transparent (white) and opaque (black) states. In both active and passive VLC, it is well known that for flicker-free communication the modulation frequency must be at least higher than 200 Hz. In effect this means that we are limited to partial transitions, that are between 'light gray' and 'dark gray' states (low contrast). We therefore need adequate signal control mechanisms at the receiver, to prevent our signal from being distorted.

3.2 Physical Layer: The limitations of amplitude-based modulation

To be energy efficient, LuxLink utilizes a simple phototransistor at the receiver (section 4). Contrary to studies utilizing cameras [], Phototransistors cannot detect changes in colors, they can only detect changes in light intensity. Due to this reason, platforms building on top of simple photosensors have been relying on amplitude-based modulation schemes []. In this section, we show that these

[7]**Rens: what frequency value?**

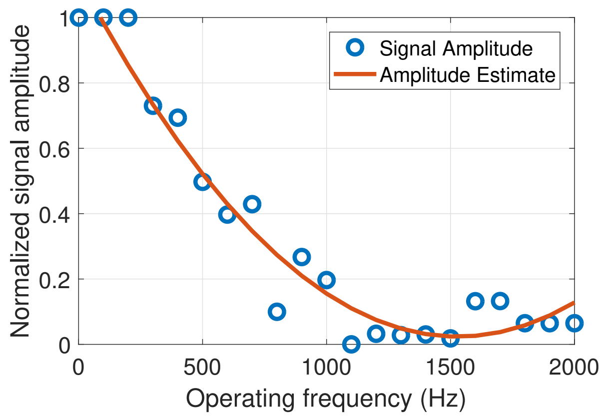
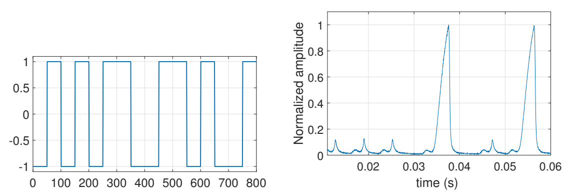
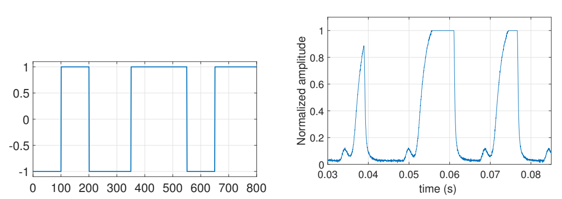


Figure 6: Signal amplitude of the 3D shutter at 5V for varying operating frequencies



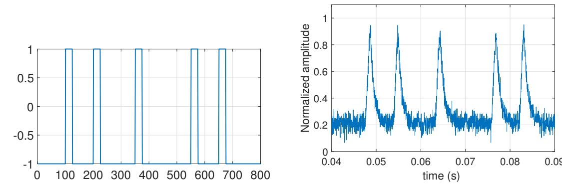
(a) Expected signal **(b) Observed signal**

Figure 7: Manchester coding



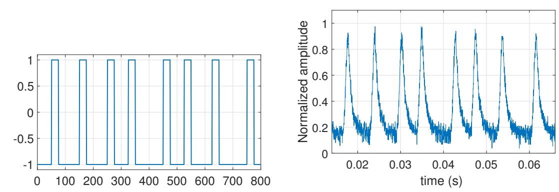
(a) Expected signal **(b) Observed signal**

Figure 8: Miller coding



(a) Expected signal **(b) Observed signal**

Figure 9: Modified Miller coding



(a) Expected signal **(b) Observed signal**

Figure 10: Pulse Position Modulation (PPM)

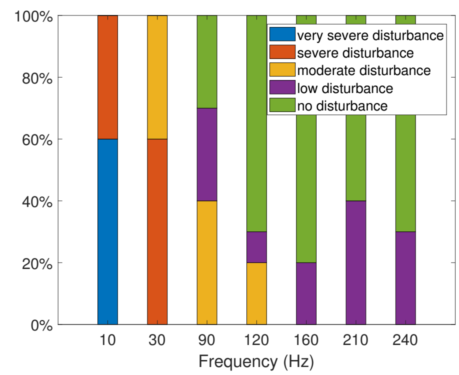


Figure 11: Flickering results with PPM modulation

traditional methods cannot be used for ambient light communication because they lead to flickering.

3.2.1 Limitation 1: variable pulse width. A common strategy to avoid flickering in systems based on visible light communication is to use encoding schemes where each bit is represented by the same number of zeros (*off* state) and ones (*on* state). In this way, a constant average light intensity can be guaranteed independently of the data pattern. Manchester encoding used in Retro-VLC [9] and Miller coding used in Passive-VLC [] are examples of this type of scheme. The behaviour of these encoding methods is show in Figure 7 and Figure 8. The problem is that these encoding schemes have different pulse widths, which lead to widely different light intensities, causing strong flickering effects. This phenomena occurs because LCD shutters have to be operated with pulse widths that are shorter than the rise and fall times to obtain modulation frequencies above 200 Hz. Since the pulse width is rarely long enough to reach the steady state plateau, the light intensity radiating from the LCD is usually a series of irregular light pulses with varying light intensities.

3.2.2 Limitation 2: variable pulse presence. Drastic changes in light intensity can be avoided by using encoding schemes that use narrow pulses with the same width. An example of such scheme is Modified Miller coding, shown in Figure 9. The limitation of this scheme is that it is data dependent, it does not ensure the same number of peaks per bits. For example, depending on the data pattern, eight bits could map to eight peaks or to five peaks as depicted in Figure 9. Modified Miller coding causes less flickering than Manchester and Miller, but the irregular presence of peaks still causes some flickering effects depending on the payload.

3.2.3 Limitation 3: lower frequency components. An encoding scheme that guarantees a constant pulse width and the presence of a single pulse for every bit is Pulse Position Modulation (PPM). Within PPM, an scheme that minimizes the gap between pulses is to denote bit 0 as a sequence `0010` and bit 1 as a sequence `0100`. The effect of applying this scheme is shown in Figure 10. The only irregularity in the signal is the occasional gap difference between pulses. These irregularities induce (data dependent) lower frequency components at reciprocals of the base frequency that might cause flickering effects.

We tested all encoding schemes [8] with 10 people, and event though PPM had the best non-flickering performance, there were still some minor flickering effects, as depicted in Figure 11. A simple solution to reduce flicker effects is usually to increase the modulation frequency, but with LCD shutters that has a negative effect on the signal strength and reliability of the communication link. Overall, we could not obtain a reliable and non-flickering link with any of the amplitude-based modulation methods.

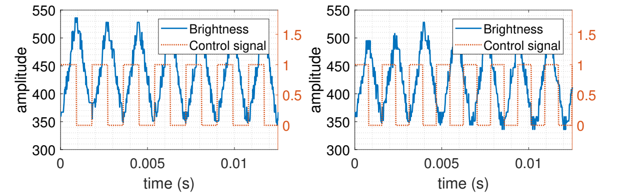
3.3 Physical Layer: Frequency based modulation

All the above described pulse modulation methods have a wide bandwidth, and data patterns can give raise to low frequency components that lead to flicker. As the shutters cannot cater to high speed switching, we resort to a modulation scheme that has a narrower bandwidth spectrum. Frequency shift keying (FSK) usually has a narrow bandwidth, especially when the frequencies are chosen to not differ much (e.g. 560 Hz and 640 Hz). In this section we show that we can generate an FSK signal with LCD shutters at frequencies above 300 Hz, which are not feasible with pulse-based modulation schemes. Thus, we propose FSK as a solution to enable a flicker free modulation using LCD shutters[9].

3.3.1 Generating an FSK signal. When driving a 3D glass shutter with an electrical square wave signal above x Hz, we are in effect driving the shutter faster than it can respond for full transitions. The transparency of the shutter (the generated brightness signal) follows a near-sinusoidal pattern at the same frequency as illustrated in Figure 12. To get a simple FSK signal, (sine) waves at two different frequencies must be generated. However, with a higher drive frequency, the contrast of the signal gets lower and the average transparency of the shutter might change, compare for example the amplitudes in Figure 12. To avoid flickering, the average brightness/transparency must be equal for both frequencies. We can adjust the average brightness by increasing or decreasing the duty cycle of the control signal for a single frequency, cf Figure 13. The higher the duty cycle, the higher the brightness.

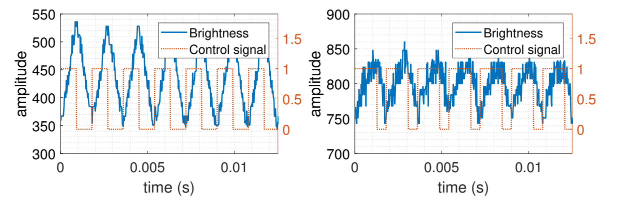
The shutter can only generate a continuous signal, thus the transition between the two FSK frequencies may only happen after an integer number of oscillation periods. For a constant bit rate R, this means that the FSK transmission frequencies f_1, f_2[10] must be a multiple of R, i.e.

$$f_1 = n_1 \cdot R, f_2 = n_2 \cdot R \text{ with } n_1, n_2 \in \mathbb{N}. \tag{1}$$



(a) 560 Hz (bit 1) **(b) 640 Hz (bit `0`)**

Figure 12: A square wave control signal leads to a sinus-like pattern in brightness. The brightness can change with the frequency.



(a) 50% duty cycle **(b) 70% duty cycle**

Figure 13: The duty cycle of the control signal has a direct influence on the average brightness

As a baseline implementation, we chose $R = 80$ bps, $n_1 = 7, n_2 = 8$, such that $f_1 = 560$ Hz, $f_2 = 640$ Hz. We then use 7 periods of 560 Hz to transmit a bit 1 and 8 periods of 640 Hz to transmit a bit `0`, cf Figure 12. [11]

3.3.2 Interference from light sources. In the ideal case, our system is installed on a place where (direct) sunlight is available, but it is designed to work with any ambient light. When the system is placed indoor near artificial lights, these light sources can interfere with the LuxLink signal. Incandescence light bulbs and fluorescent lights usually oscillate at one or two times the frequency of the power grid (50/100 Hz or 60/120 Hz) and might contain some higher order harmonics. find source. These frequencies are much lower than the frequencies we selected (above 500 Hz), thus these lights probably will not interfere a lot. Commercial LED lights are often being toggled at 300, 400 or 500 Hz for dimming support.[12] find source. When the LED light operates at a frequency near the selected FSK frequencies, interference can lead to the following phenomena:

- **Degrading of the link quality** The modulation of the light source is sometimes a lot stronger than the passively modulated FSK signal. The receiver might not be able to filter away the flicker from the light completely, leading to bit errors or loss of the connection.
- **Flicker caused by interference** The shutters modulate ambient light by changing their transparency. Mathematically, this can be seen as a multiplication of the ambient light $L(t)$ and the transparency of the shutter $T(t)$. When the ambient light oscillates at $f_A = 500Hz$ (e.g.

[8] **Rens: what is *all*?**

[9] **Marco: I am missing the nice bandwidth figure you drew for Chaitra and I. that fig was awesome!**

[10] **Marco: before we used f_0, let's make sure the notation is the same.**

[11] **Rens: The formulas have been deleted, while those showed how we must choose the frequencies. I re-added those**

[12] We observed these frequencies by measuring different office lighting systems.

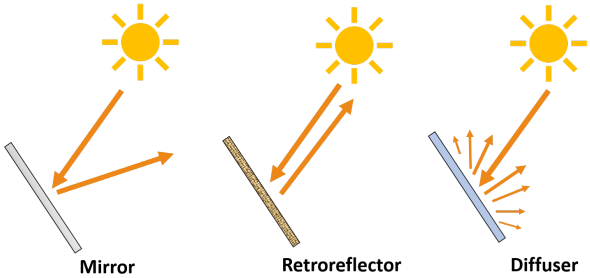


Figure 14: Effect of material on the reflection property.

due to a dimmable LED light) and the shutter oscillates at $f_S = 530Hz$, the light intensity will also oscillate at the harmonics $f_S + f_A = 1030Hz$ and at $f_S - f_A = 30Hz$. The latter low frequency oscillation can cause visible flicker.

To mitigate these phenomena, we recommend to select the signal properties such that the bandwidth spectrum of the FSK has no overlap with any frequency of nearby light sources. The bandwidth of an FSK signal can be approximated with Carson's rule citation needed to the range $[f_1 - R, f_2 + R]$. For example, our baseline implementation with R = 80 bps, f_1 = 560 Hz, f_2 = 640 Hz has an approximated bandwidth of [440, 720] Hz. This is a proper choice when used nearby LED lights oscillating at 400 Hz (that might have an harmonic component at 800 Hz), but it would have interference when the light sources oscillates at 500 Hz.

Design Guideline 2: Considering the low modulation frequency of LCDs, FSK is the scheme that best balance the needs of reducing flickering and providing reliability. The signal frequencies should be chosen considering the spectrum of the oscillating nearby light sources.

3.4 Transmitter design

In this section we describe the reflective properties of our platform and the electronic design.

3.4.1 Diffuse reflections. The signal strength in our system depends on the amount of light that is reflected from the transmitter towards the receiver. The surface of the transmitter should therefore have a high reflection coefficient. The reflection coefficient, however, is not the only parameter that matters for the design of our tags. Depending on the material' smoothness, there are two types of reflections: specular and diffuse. Specular reflection occurs on smooth mirror-like surfaces that reflect light on a *single* direction, while reflections on rough surfaces are diffuse, that is, light is reflected to all directions. For example, metallic plates and white paper have high reflective coefficients, but the former is a specular material and the latter is diffuse reflective.

Mirrors and retro-reflectors provide long narrow beams (specular reflection). These materials increase the range and SNR of the signal, but put sever constraints on the location of the receiver. Figure 14 depicts the effect of using mirrors, retro-reflectors or diffused reflectors with ambient light. Retro-VLC and Passive-VLC utilize retroreflectors because the receiver is colocated with the light source. We, on the other hand, want to create a link between any two points without having any control over the light source. Mirrors would require mechanical control to point towards the receiver, which would increase the complexity of our system; and retroreflectors are not useful because they always reflect light towards the source. Our transmitter uses a white diffuse panel to improve coverage, at the cost of reducing the signal strength. In section 4 we use an optical lens and a careful PCB design to ameliorate this problem and amplify the signal.

3.4.2 Electronic design. The LuxLink transmitter comprises of 2 LCD shutters (from 3D glasses), controlled by an STM32L031K6 microcontroller. To ensure enough power delivery to the shutters, a basic op-amp (OPA2325) is used between the microcontroller output pins and the shutters.

The setup is enclosed in a 3D printed case as shown in Figure 15 with the internal hardware as shown in fig ?. [13][14]

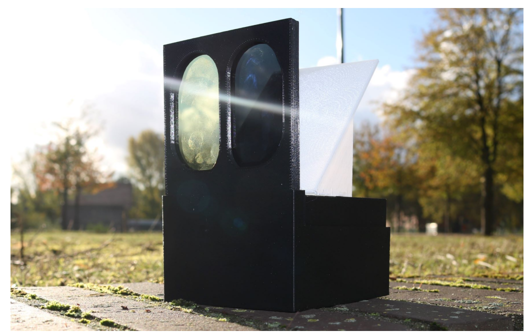


Figure 15: The LuxLink transmitter: light is reflected on the white surface, then propagates through the shutters

4 RECEIVER

4.1 Design challenges

The receiver must be able to decode the transmitted signal with any source of ambient light. But loosing control over the light source raises up two unique problems. First, varying light intensity, which can cause the receiver to saturate (when there is too much sunlight) or to have no link (when there is little ambient light). The receiver should have a wide operational range. Second, the same source provides the signal and the noise. As illustrated in Figure 16, the receiver's field-of-view (FoV) will cover the LCD surface, which contains the signal, but it will also cover the surrounding area which contains noise. Both elements, the signal and noise, come from the same source, and the receiver should discern them. We identify three main challenges in decoding the signal, all concerning the signal-to-noise ratio. These challenges depend on the location where the system is used, we divide these cases between indoor and outdoor scenarios.

- **Outdoor noise.** Under daylight conditions, the illumination usually ranges from 1000 lux (overcast day) to 10klux (indirect light on a sunny day) or up to 30klux to 100klux

[13] **Marco: show an image of the board as well**
[14] **Rens: Sure? It is just a LuxLink receiver with less things soldered...**

(with direct sunlight). On a sunny day, the noise in Figure 16 largely consist of a constant (high) amount of light. The sensor circuit must be designed such that it doesn't saturate because of the high brightness on a sunny day.

- **Indoor noise.** When the system is used indoors, most of the light originates from indoor light sources. Nearly all artificial lights have fluctuating brightness, for an incandescent or fluorescent light the brightness oscillates once or twice around the power grid frequency (50/100 Hz in Europe). LED Lights are often switched on higher frequencies (e.g 400 Hz) to make these light sources dimmable. The noise in Figure 16 will originate from these artificial lights, and will thus have a strong component at the oscillation frequency of the light. The receiver must be able to filter out these oscillating noise sources.
- **Indoor signal intensity.** In indoor environments, the illumination is often between 100 lux and 500 lux. The much lower illumination level (compared to more than 1000 lux outdoors) linearly reduces the strength of the modulated signal. The sensor circuit must have high sensitivity, such that a signal transmitted indoors can be captured and decoded as well.

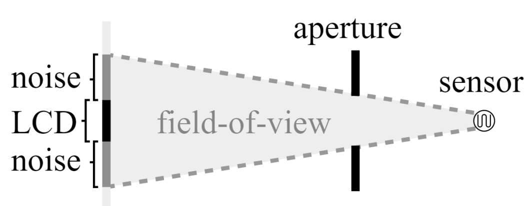


Figure 16: Despite the limited field-of-view, the sensor will not only capture the LCD signal, but also some noise.

4.2 Sensor and lens

To reduce the influence of noise sources and improve the signal-to-noise ratio, one can limit the field-of-view with an aperture to focus as much as possible on the LCD panel, as shown in Figure 16 . The problem is that reducing the FoV with an aperture always reduces the light that reaches the sensor. This is equivalent to decreasing the sensitivity of the system, while we stated that the sensor circuit must have high sensitivity. Therefore, controlling the FoV with only an aperture is not the best solution.

Lenses are known to focus light from far distances onto a sensor (e.g. in cameras). Focusing on a far distance equals limiting the field-of-view. By focusing the system with lenses, the sensitivity of the system is not reduced, because the aperture can be larger to get the same field-of-view. Thus, a lens helps reducing the amount of captured noise by limiting the field-of-view, while the signal sensitivity is maintained. We add a cheap lens (0.5 USD, as used in cardboard VR glasses) to focus light from the transmitter on the sensor in the receiver. These lenses have a diameter of 25 mm and a focal distance of 45mm. To focus on a far distance (≈7 m), the lens should be placed between 45mm and 50mm in front of the sensor. In LuxLink, the position of the lens is fixed, it is not calibrated for specific transmitter-receiver distances.

The photosensor must be chosen to maximize the sensitivity of the receiver, while providing a bandwidth that is high enough to follow the FSK encoded signal (at least 800 Hz in our system). We chose to use a TEPT4400 phototransistor, which is sensitive to the full spectrum of visible light. To generate a voltage from the incident light, we place the sensor in a transimpedance amplifier (around an OPA2325 op-amp). The resistor value in this circuit is chosen empirically to be $9k\Omega$, giving a bandwidth of at least $1.1kHz$. A higher value leads to saturation when used on a sunny day and decreases the bandwidth of the circuit. Lower resistor values will decrease the sensitivity of the receiver and have a negative influence on the signal-to-noise ratio.

4.3 Decoding algorithm

The decoding method consist of two parts. First, an analog filter isolates the FSK signal and removes noise. Second, the signal is processed digitally to decode the received signal.

4.3.1 Analog filtering. The signal is filtered with a narrow band-pass filter to isolate the FSK signal and remove noise. The center frequency of the bandpass filter is designed to be between the selected frequencies of the FSK signal, such that both frequencies are amplified. For different frequencies of the FSK signal, the filter must be tuned by changing resistors. The signal is amplified again and fed to a 12-bit MCP3201 ADC that is controlled to sample at 10 kHz.

4.3.2 Digital decoding: Fourier analysis. An (binary) FSK signal can contain a wave on two different frequencies: f_1 for a bit 1 or f_0 for a bit `0`. Common methods to perform such frequency analysis are to apply a Fourier transform or to apply the Goertzel algorithm. The Goertzel is known to be only marginally stable and sensitive to numerical errors. A Fourier transform is often disregarded because of its limited frequency resolution when using a small number of samples, but we can show that it is no drawback for our system.

In LuxLink, due to the properties of the shutters, the frequencies of the FSK signal are always a multiple of the baudrate (subsection 3.2), e.g. $f_1 = 560Hz, f_0 = 640Hz$ for the 80 baud/s of our system. The frequency granularity of a Fourier transform is equal to the inverse of the of the window length. If we use a window length equal to the duration of 1 bit ($\frac{1}{80}s$), the Fourier transform will be able to analyze the presence of all multiples of the bitrate, including the frequencies f_1 and f_0 used in the LuxLink system.

With a sample rate of 10 kHz, the duration of a single bit at 80 baud is equal to 125 samples. In our baseline implementation, we therefore apply a Fourier transform with a window length of 125 samples. To save computation time, we did not implement a full Fourier transform, but only compute the outcomes for f_0 and f_1. This optimization enabled the implementation of our decoding algorithm on an STM32L031 low-power microcontroller. The outcome is evaluated 400 times per second (5 times the baud rate) to be able to synchronize to the bit transmissions and correct for small frequency offsets and time drifts. When changing the bitrate and frequencies of the system, we adjust the window length of the Fourier transform accordingly.

4.4 Hardware implementation

In this section we describe the design of the LuxLink receiver, the different building blocks are illustrated in Figure 17. First, the light is captured with a lens and a photosensor to generate an electric current. Second, the current is amplified and filtered to isolate the FSK signal. Third, the signal is digitalized and processed on a microcontroller. A screen can be connected to show information about the signal, or messages that will be received. All parts are put together in a 3D printed casing of 113x64x66mm.

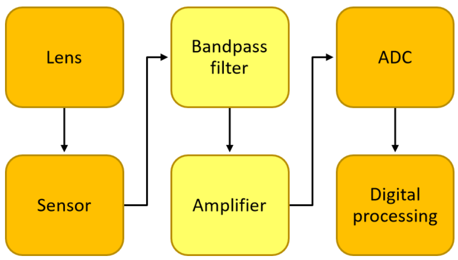


Figure 17: Block scheme of the receiver

4.4.1 *Reducing electrical noise.* [15]

We have designed the receiver's electronics with the goal of reducing noise sources as much as possible, to maximize the performance of the system. In our implementation we took into account the following recommendations, which are often used in circuit design. These details might be important for reproducing our work:

- The analog section is powered with a single (4.2V LiPo) battery, to have no voltage ripple on the analog power supply. A battery was required in our system, because the amplification circuit seemed to be sensitive even to small ($< 1mV$) voltage ripples. A TLE2425 precision virtual ground chip is used to generate an additional 2.5V reference voltage for the amplification circuit.
- The digital circuit is powered with a different (4.2V LiPo) battery (with a linear regulator to generate 3.3V), such that digital parts do not cause noise on the analog power line. This was a requirement in our system to get an acceptable performance.
- We use a 4-layer PCB, to provide ground and power planes.
- Analog and digital circuit parts are spatially separated on the PCB. Digital and analog ground are unconnected on the PCB, but connected externally to minimize noise coupling between the power planes.
- Shielding is added around the PCB, (leaving gaps for the sensor and wires) and connected to both the digital ground and analog ground.

4.4.2 Further implementation details. The transmitter is equipped with a 6x11cm solar panel and two TP4056 battery charger modules, to charge both LiPo batteries from solar power. The solar panel is rated at 6V with a maximum power of 1W. The goal of the solar panel is to have a receiver that doesn't need any power input to operate continuously, 24 hours a day.

The digital signal from the ADC is fed to the microcontroller on the digital section of the PCB. The MCU is an STM32L031K6 low-power MCU running on 32 MHz with an ARM Cortex-M0+ core. The MCU runs the decoding algorithm that is described in subsection 4.3. A small (2.9 inch) e-ink screen is connected to the digital circuit on the PCB and the MCU. On this screen the receiver can display received messages, validation results and debug information in real-time (but with a low refresh rate of approximately 1 Hz).

4.5 Data link layer

We implement a data link layer to transmit basic text/data messages, that is based on ASCII code. Data is grouped in bytes consisting of 8 bits, with the most significant bit first. In the idle state of the communication channel, the transmitter continuously sends a SYN (Synchronous Idle, `00010110`). The repetitive SYN pattern enables the receiver to synchronize itself with the transmitted signal.

A data frame is preceded by STX (Start of Text, `00000010`) and followed by ETX (End of Text, `00000011`) and ETB (End of Transmission Block, `00010111`). The overhead for a single text message is therefore 3 bytes. An example of the data link layer is shown in Table 2. The default maximum frame length in our implementation on the microcontrollers is set to 128 bytes, but may be altered.

5 EVALUATION

5.1 Power consumption

The power consumption of the system is a combination of the transmitter and receiver, and is measured for 80 bps as shown in Table 3. At the transmitter, the energy consumption can be divided into the power drawn by the shutters and the MCU. For a voltage of 4.5 V, the shutters consume only 2% of the total power (0.5 mW), while the rest is drawn by the MCU (≈29 mW). At the receiver, 30% of the total power is drawn by the analog circuit and 12% by the e-ink display (6 mW). When driven at 3.8 V, the receiver consumes 20% less power than that at 4.5 V (without the screen). Thus, in our evaluation, the receiver is designed to work at 3.8 V. The use of the transmitter at different voltages presents trade-offs. A high voltage (4.5 V) provides lower response times (Table 1) and better contrast, but increases the chances of flickering effects (analyzed in the next subsection). A lower voltage provides the opposite trade-off. In either case, considering the aggregated power conumption of the transmitter and receiver, the MCU consumes the biggest share (≈85%). A detailed comparison of our platform with the SoA, including energy consumption, is presented in section 7.

5.2 Validation with IEEE health risk guidelines

Any system using light for communication must assess the health risks associated with flickering effects (subsection 2.1). The IEEE provides guidelines for safe operating regions [6]. Based on the modulation frequency, the operation regions provide the maximum modulation depth[16] that systems can use to have a *low* or *no* flickering risks. For example, to have *no* flickering risks at 200 Hz, the

[15] **Marco: Some of the information in this subsubsection and the next can be removed if need space. It may be seen as too detailed, specially if we are going to release the design docs.**

[16] The modulation depth is the difference between the `high` and `low` symbols, divided by the average brightness

00010110	00010110	00000010	01001000	01100101	01101100	01101100	01101111	00000011	00010111	00010110
SYN	SYN	STX	H	e	l	l	o	ETX	ETB	SYN

Table 2: An example of the data link layer, showing transmission of a text message saying Hello

Component \ Battery voltage	3.8 V	4.5 V
Transmitter shutters	0.3 mW	0.4 mW
Transmitter MCU	23.5 mW	29.4 mW
Transmitter (total)	23.8 mW	29.8 mW
Receiver analog part	9.65 mW	11.75 mW
Receiver MCU	26.6 mW	33.3 mW
Receiver MCU + screen	32.7 mW	39.5 mW
Receiver (total)	36.1 mW	45 mW
Receiver + screen (total)	41.9 mW	51.2 mW

Table 3: Measured average power consumption of the LuxLink system with a transmission speed of 80 baud

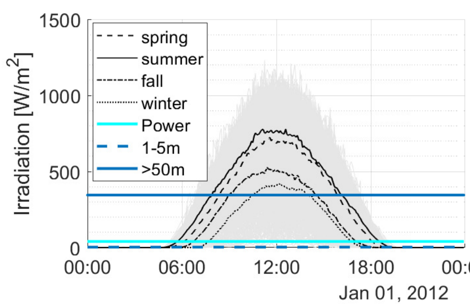


Figure 18: Average solar radiation in city, US, compared with required irradiation for LuxLink

modulation depth must be less than 15%. The higher the modulation frequency, the bigger the allowed modulation depth.

We measure the modulation depth (Mod%) of transmissions in our system and evaluate them against the operation regions in [6]. The guidelines recommend systems to work in the low-risk of no-risk operating regions. Table 4 shows the evaluation of health risks for different (battery) voltages supplied to the transmitter, and two different frequency settings. With a supply voltage of 3.8 V, our system poses no health risks. A higher supply voltage, 4.5 V, increases the modulation depth by a factor of three (stronger SNR), and the risk is classified as low for both frequency settings. Thus, the transmitter is safe to use at 4.5 V, and that is the voltage we use in our evaluation. We validated this technical analysis by showing the platform to several tens of people, set to 560/640 Hz with 4.5V. No flickering effects were reported.

5.3 Performance

We evaluated the system under different lighting conditions. Ten different test messages are sent alternately (approximately 3 seconds between test messages) where, each test message has 8 bytes of data (text) and 3 bytes of overhead (start and end keywords).

Freq. (Hz)	Supply voltage	Measured Mod%	Max. Mod% for low risk	Max. Mod% for no risk	Risk
560 / 640	3.8 V	9%	45%	19%	no risk
560 / 640	4.5 V	29%	45%	19%	low risk
625 / 714	3.8 V	7%	50%	21%	no risk
625 / 714	4.5 V	23%	50%	21%	low risk

Table 4: Evaluation of health (flickering) risks associated with LuxLink based on the IEEE guidelines [6]

5.3.1 Ambient light intensity. We evaluate the system under lighting conditions ranging from 150 lux (a rather dark room) to 10+ klux (outdoors with good daylight). In our indoor scenarios, the light intensity was always below 800 lux. In Figure 19 we show the performance of the system for different illumination levels. The graph shows that for LuxLink to start being operational, we require limited lighting (≈200 lux). When the light level is below 400 lux the achieved range is less than 4 meters. EU regulations state that the lighting in office spaces should be 500 lux. Thus, in indoor scenarios with sufficient lighting LuxLink con provide ranges of several meters. Outdoors, the range can increase significantly (several tens of meters), depending on the sun radiation. To provide an idea of the amount of sun radiation we are exposed to, our city has a latitude comparable to the southern part of Canada. [17]

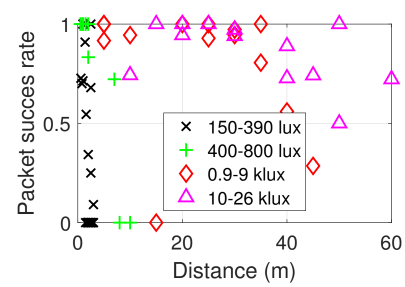


Figure 19: Range performance of LuxLink under varying lighting conditions

5.3.2 Coverage. The coverage of the LuxLink platform, for indoor and outdoor environments, is shown in Figure 20 [18]. In these experiments, the orientations of the transmitter and receiver are fixed. That is, we do not rotate the transmitter or receiver, we only change their relative location. In an indoor environment with illumination around 600 lux, the maximum operating range is 4.75 m and the width of the coverage is X. In comparison, the outdoor environment has a range of 65 m (14X better than indoors) and a wider coverage area (X cm). The narrow coverage region means that if the

[17] **Rens: This sentence can be removed. We already provide absolute numbers stating 10-26 klux.**
[18] **Marco: add figure for indoor**

receiver moves, the receiver's orientation must be adapted to point to the transmitter. A larger transmitter area or a wider FoV at the receiver would increase the coverage, at the cost of increasing the energy consumption or reducing the range, respectively. Note that increasing the area of the transmitter is not a bad option because adding LCD shutters consume very little power compared to the MCU (Table 3).

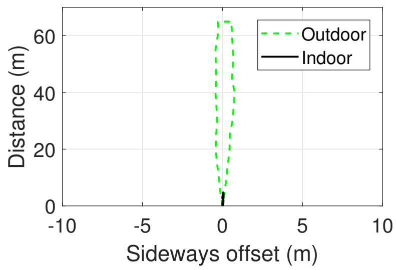
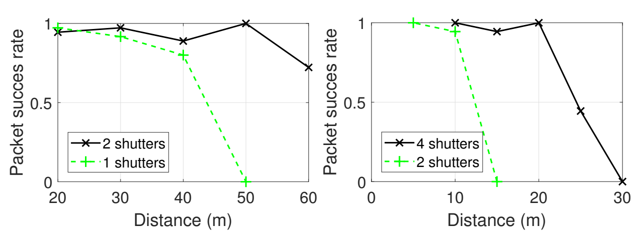


Figure 20: Coverage plot for LuxLink indoors (±600 lux) and outdoors on a sunny day (±23 klux)

5.3.3 Transmitter area. The area of the transmitting surface influences the communication range of the system, where a larger area implies a longer range. The packet success rate (PSR) is computed at the receiver when 1, 2 or 4 shutters are used. The size of a single shutter is 14 cm^2 (Table 1). On a sunny day (23k-26k lux), a single shutter has a PSR around 75% at 40m. With two shutters a similar PSR is obtained for a distance of 60 m (1.5 times longer range).



(a) PSR on a sunny day **(b) PSR at sunset**

Figure 21: PSR in outdoor environments with varying transmitter area

Similar tests were performed with 2 and 4 shutters during sunset (1000-1800 lux). In this case, Figure 21b shows that increasing the area by a factor of two, the range again is increased. Please note that from the results presented in Figure 21b, we cannot conclude that two times more shutters leads to two times higher range, due to high variations in the light intensity (1000-1800).

5.3.4 Placement of polarizer film. Similar to the implementation of [17], one of the polarizer films can be removed from the shutters at the transmitter. This polarizer film must then be attached to the receiver instead. Moving the polarizer film from the shutters to the receiver has two positive effects:

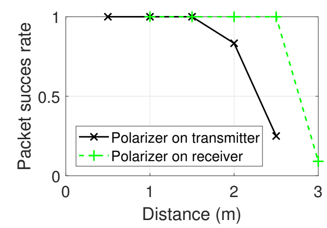


Figure 22: Moving the polarizer film from the transmitter to the receiver improves the system performance

- Data is not encoded in the brightness of light but in the polarization of light. This reduces visible flicker effects mentioned in subsection 2.1.
- By placing the polarizer film at the receiver, any unpolarized light is blocked partially. This partially blocked light includes noise sources in our system, thus noise will be filtered in a better manner, improving the performance of our system.

We evaluated the effect of moving the polarizer film in an indoor environment. As shown in Figure 22, the communication range of our system is indeed improved. This improvement, however, comes at the cost of an important constraint: the transmitter and receiver should not rotate relative to their alignment axis, otherwise, there will be rotation angles where both polarization directions lead to the same light intensity, making it impossible to decode information. Pixel overcomes this rotation problem by adding a dispersor [17], but it requires a camera to decode information.

6 DISCUSSION

Below we discuss some of the key limitations of our platform and propose potential ways to overcome them.

Data Rate. The data rate of the system is low and highly dependent on the response time (switching speeds) of the shutters. One way to improve the capacity of our channel is to use MIMO techniques. Multiple shutters can be fused to form a single transmitting surface where the data is split between the shutters. Each shutter would be driven at different frequencies f_0 and f_1. [19] These frequencies could be designed to be orthogonal, similar to OFDM approaches. A deep analysis would be required to identify how many parallel streams can be obtained, and the extra computation costs this approach would entail. Such a system would work well for outdoor scenarios, because there are no interfering frequencies. In indoor scenarios, it may be more challenging to identify orthogonal frequencies without much interference.

Mobility. LuxLink is a LOS based communication system. Our current prototype has been designed with a narrow FoV to attain the maximum possible range with a small transmitting surface. Under this setting, mobile objects would require to align the transmitter and receiver, especially at larger distances. There are two ways to ameliorate this problem, but both present trade-offs. A receiver with a wider FoV could facilitate the alignment problem at the cost of increasing the noise and reducing the range; and a bigger

[19] **Rens: A single FSK signal already consists of two different frequencies**

Name	Light source	Data rate	Range	Power	Indoor / Outdoor	Modulation	Receiver
RetroVLC [9]	LED	0.5 kbps (uplink)	2.4 m	234 μW (only uplink)	Indoor	Manchester	Photodiode
PassiveVLC [16]	LED	1 kbps (uplink)	2 m	525 μW (only uplink)	Indoor	Miller	Photodiode
PIXEL[17]	LED and Ambient light	14 bps	10 m	NA (300+ mW)	Indoor	Binary color shift keying	Camera
POLI[2]	LED	568 bps	40 m	NA (300+ mW)	Indoor	Polarization intensity	Camera
MobileVLC [13]	Ambient light	NA (~100 bps)	4 m	NA (~30 mW)	Outdoor	Barcode encoding [requires mobility]	Phototransistor
LuxLink	Ambient light	80 bps	4.5 m (indoor) 65 m (outdoor)	65.9 mW	Both	FSK	Phototransistor

Table 5: Comparison of LuxLink with state of the art VLC systems

transmitter surface, especially a concave one, would provide a better coverage at the cost of a (slight) increase in power consumption.

7 RELATED WORK

Active systems. Traditional VLC systems rely on artificial light sources. The receiver in these systems can be made of simple photosensors or cameras. Photosensors, such as photodiodes, are the most popular option because they have a high bandwidth, which enable high data rate links. For example, a bi-directional link using OFDM can achieve a data rate of 500 Mbps at 5 m and 100 Mbps at 20 m [4]. Cameras consume more power than photodiodes and are slower receivers (the links provide a few hundred kbps at a few meters range), but given that they are pervasive in smartphones [3], they have been used to enable sub-meter localization [7]. A more recent area is screen-to-camera communication. Instead of using a single LED bulb to transmit information, researchers modulate the various LEDs in a screen while they show videos or images. The modulation does not affect the user experience, but cameras can decode information at several hundred kbps []. In comparison to LuxLink, the data rates of active systems are higher and the links are more reliable, but these advantages require control over the light source and consume more energy. We tackle a different problem. For active systems, ambient light is a source of noise. For LuxLink, ambient light is source of noise, but also the communication carrier. By exploiting directly the natural light in our environments, we can create zero-energy links.

Polarization-based systems. An important component of our work is motivated by the use of polarized light in the SoA. In LiCompass [14], the polarization property of light is harnessed to measure the orientation of the receiver. LEDs have multiple polarizer films that range between 0°to 360°, and a camera with a polarizer measures the orientation having the transmitter as a reference. The accuracy of the system is very high, providing orientation information with just a few degrees error. Polarized light is also used to implement indoor inertial tracking in [12]. A polarizer with a birefringent film (transparent tape) is placed at the light source which generates color patterns. These patterns are captured by the color sensor covered with a polarizer film which is then processed to track the object. The 2D and 3D tracking errors are 4.2 cm and 10 cm respectively. These systems improve applications related to tracking, but do not focus on communication.

Semi-passive and passive systems. As stated in subsection 1.2, the main inspiration for our work comes from semi-passive and passive communication systems with visible light. The use of LCD shutters to backscatter light is studied in Retro-VLC [9] and Passive-VLC [16]. The goal, however, is quite different. A controlled light source is used as a central hub to send data to tags (active communication), and tags use retro-reflectors to send data *only* to the light source (passive communication). Pixelated-VLC follows the same research line [11], but uses multiple shutters and a special casing that can be controlled to use PAM (Pulse amplitude Modulation). Based on the area exposed by the casing, the signal level varies, enabling multiple bits to be encoded. With 3 shutters, they achieve a data rate of 600 bp/s at 2 m distance. This type of 'retro-reflecting' communication does not require analyzing flickering effects because there are no users in line-of-sight. LuxLink does not require any control over any light source, works indoors and outdoors, and is flicker-free.

Pixel [17] and MobileVLC [13] are the most related studies. Like LuxLink, they do not need control over the light source (fully passive). Similar to Pixel, we do not cause flickering effects, but we do not rely on cameras, which makes the system more sustainable. The CMOS camera used in Pixel, on average, consumes around 300 mW of power [8], one order of magnitude more than our receiver. Similar to MobileVLC, we use photodiodes, but MobileVLC requires objects to be mobile and at a constant speed. Another study that exploits polarization-based modulation is Poli [2], but it requires control over the LED light and uses camera.

Table 5 shows the comparison between LuxLink and the SoA. Overall, LuxLink advances the SoA by creating a wireless link that relies solely on ambient light, works indoors and outdoors and uses the least combined energy at the transmitter and receiver. In particular, compared to the Pixel system, based on cameras, LuxLink can transmit more data, at longer distances and with less energy.

8 CONCLUSIONS

Ambient light is pervasive in our environments, but hitherto, there has been little research exploiting it for wireless communication.

We propose a novel platform to establish reliable wireless links with ambient light. Our platform does not require cameras or control over any light source. Utilizing small LCD shutters (the size of a matchbox) and a single phototransistor, we show that ambient light can be used to communicate information with a data rate of 80 bps and a range of several tens of meters (depending on the surrounding light intensity). Cities around the globe receive vast amounts of sunlight. We hope that this work help transforming their exposed surfaces into wireless transmitters with zero-energy cost.

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