LuxLink: Creating a Wireless Link from Ambient Light

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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 light bulbs). These *uncontrollable* light sources provide an immense amount of ambient light that could be used for wireless communication, yet few studies are exploiting this opportunity. We provide a detailed analysis of a Hardware- and Physical-Layer to create safe and reliable wireless links relying solely on ambient light and simple photosensors. Motivated by recent studies, our platform builds upon liquid crystal displays (LCDs) to backscatter ambient light, but it provides a unique and novel feature: our platform utilizes *frequency signals* to modulate ambient light. Compared to the state-of-the-art, which rely on either *pulse- or color-based modulation*, our approach allows us to provide simultaneously: a simple and energy-efficient platform (no cameras), flicker-free communication (safe), and the ability to work reliably in spite of the interference and light fluctuations caused by uncontrollable light sources (reliable). We test our platform in indoor and outdoor environments, and show that an LCD surface of 6×8 cm can transmit 80 bps at ranges between 4 meters (indoors) and 60 meters (outdoors), consuming a fraction of the energy required by comparable systems using cameras.

CCS CONCEPTS

• **Networks** → *Physical links.*

KEYWORDS

Ambient Light, Passive Communication, Backscattering

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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), and that spectrum is getting crowded. To ameliorate this problem, the research community is investigating various approaches to add a second pillar: the visible light spectrum. By modulating artificial light sources at high speeds, visible light communication methods can transmit information without disturbing in any way the illumination observed by people.

Visible light communication (VLC) brings an indisputable benefit in terms of adding spectrum, but it has a distinctive property in terms of energy consumption. The energy cost of VLC can be divided into two main parts: the cost of *illumination* itself (a few Watts for a standard LED fixture) and the cost of *modulation* (20% or more of the cost of *illumination* [5], which adds a few hundred mW). Thus, energy wise, communication with light becomes significantly more competitive when data piggybacks on top of *existing* illumination. And that is precisely the advantage of *ambient* light: it is pervasive, with the added benefit of being significantly more intense than artificial lighting. The LED fixtures on ceilings are designed to provide a few hundred lux, but normal daylight conditions can provide tens of thousands of lux. The challenge with ambient light is that, contrary to traditional VLC, the communication system has no control over the light source to modulate information.

Vision & Applications. We want to exploit ambient light to create a new type of communication channel. Sunlight, or any type of light impinging over a surface, will be modulated via controlled absorption, and a simple low-power photosensor will be used to decode information (no cameras). These changes in light intensity will not be perceived by people, the transmitting surfaces will appear as tinted glass. This new channel could allow us to transform the surfaces in our cities into wireless transmitters. For example, facades could be covered with smart materials to allow building-to-building communication via their external surfaces, or as shown in Figure 1, the panels of a bus stop could be modified to modulate the impinging sunlight with information about events in a city and a pedestrian could use any wearable device with a photodiode to obtain the information.

Figure 1: A sample application.

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Communication via controlled reflections is an old idea. Armies in the 1800's used mirrors to communicate over long distances [10]. In the same century, the first wireless telephone was created by Alexander Graham Bell connecting a microphone to an oscillating mirror that changed the reflections of sunlight to modulate voice. Even though advancements in optics are not yet at par with RF technology, we can leverage existing smart materials to transform this old idea into a pervasive communication channel, enabling our cities to receive light and reflect back information.

Research Challenges. Communication with visible light can be divided into four quadrants depending on the type of transmission and reception used. The transmitter can be active or passive. *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). Our work focuses on the quadrant combining passive light sources and simple photosensors because that leads to the most energy-efficient communication system. Next, we describe the key concepts we build upon from the state-of-the-art and the novelty of our work.

Building Block 1: use of liquid crystal displays (LCD) to create backscatter VLC. In traditional VLC, bidirectional communication requires active light sources at both ends of the wireless link. Retro- [15] and Passive-VLC [24] propose bidirectional links using backscattering techniques. For the downlink, an LED lamp transmits information to a *tag* using traditional VLC (active communication). For the uplink, the tag uses an LCD shutter to block and reflect the light coming from the LED lamp to send data back (passive communication). Our work is strongly motivated by these two studies. Retro- and Passive-VLC use photodiodes as receivers, which leads to simple and energy efficient hardware. At first glance, one could argue that a minor tweak of these platforms could be used to form wireless links out of ambient light: instead of using a VLC lamp to provide illumination, we could put the tags under any light source, including sunlight, and the tag's reflections will transmit information. *The key limitation is that the modulation used by the tags causes flickering*. Those flickering effects are not an issue for the scenarios targeted by Retro- and Passive-VLC because they do not expose their tags to the field-of-view of users, but LuxLink aims at being pervasive in people's environments, and thus, flickering cannot be allowed. In our Physical Layer analysis, we show that techniques based on amplitude/pulse modulation (including those used in Retro- and Passive-VLC) lead to flickering effects. We propose the use of frequency based modulation (FSK) to provide flicker-free and reliable communication.

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 [25] and MobileVLC [21]. When there is no control over the light source, the modulation of light can be attained by changing its polarization [25] or modifying the external coverage of surfaces [21]. 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 (CSK), which is an elaborate scheme, and the receiver uses a camera (energy hungry). By using FSK modulation, we also achieve non-flickering but the signal can be decoded by a simple phototransistor. The advantage of phototransistors, compared to color sensors, is that they allow us to exploit fully the energy present in ambient light (as described in section 2). MobileVLC embeds barcodes on the surfaces of objects. As the objects move, the light reflected from their surfaces conveys the barcode information. MobileVLC uses only ambient light and the receiver is based on photodiodes (energy-efficient), but the links are unidirectional (from the object to the receiver) and the objects *must* move at constant speed to modulate information. Motivated by these studies, our system also exploits ambient light, but we do not require cameras or mobility to establish a link.

Contributions. LuxLink's key novelty is to provide an ambient light link that works with a simple photosensor without causing flicker. In particular, the main contributions of our platform are:

1) A detailed analysis of a Hardware and Physical Layer for ambient light communication [section 3]. Backscatter visible light systems use various types of LCD shutters with pulse-based modulation schemes. But there is no detailed analysis identifying what type of LCD or modulation scheme are best for communication. We benchmark the performance of different LCDs to design a Hardware Layer that minimizes the response time, energy consumption and the likelihood of causing flickering. At the Physical Layer, we show that pulse-based modulation cannot provide flicker-free communication with existing LCDs. Instead, our work shows that frequency-based modulation (FSK) can provide flicker-free communication using a simple photodiode as a receiver.

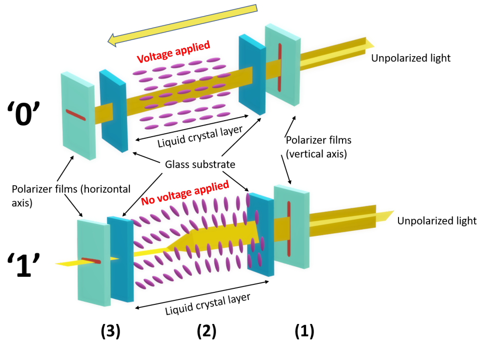
2) A reliable ambient light link that works indoors and outdoors [section 4]. Given that we have no control over the light source, our system needs to be designed to work outdoors, in sunny and cloudy days with sudden changes in light intensity, and indoors, considering the interference caused by artificial lighting. To overcome these problems, we carefully design an opto-electronic receiver that maximizes the signal-to-noise ratio and build on top of our frequency-based modulation techniques to avoid interference.

In section 5, we evaluate our platform in various scenarios and show that it is flicker-safe according to IEEE standards. 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). An LCD surface of 6×8 cm can transmit 80 bps consuming a fraction of the energy required for a system using an active light source or cameras.

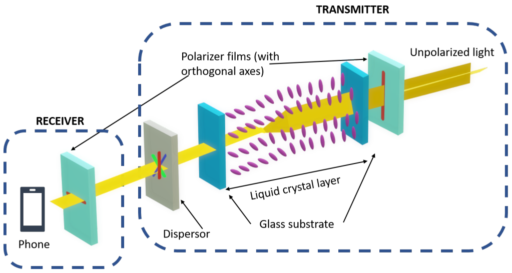
2 BACKGROUND

2.1 Challenges

Challenge 1: Non-flickering communication with simple photosensors. A must for any communication system based on visible light 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 [11]. To eliminate flickering, changes in light intensity must be faster than 200 Hz, and the *average* brightness must be constant throughout the transmission [17]. 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



(a) Intensity-based modulation



(b) Polarization-based modulation.

Figure 2: LCD operation

brightness [23]. LCDs, on the other hand, have low modulating frequencies (~kHz). In section 3, we show that at these low modulating frequencies, pulse-based methods such as those used in Retro- and Passive-VLC [15, 24] cause flicker because fluctuations in the data patterns can induce illumination changes below 200 Hz.

To avoid flickering with LCDs, Pixel proposes an ingenuous approach: to modulate light based on polarization instead of amplitude [25]. LCDs have three layers that electrically control the amount of light passing through, as shown in Figure 2a. The first layer (vertical polarizer) only allows light of a single polarization direction to pass through. The second layer (liquid crystal) maintains the polarization direction if voltage is applied, or rotates the polarization direction by 90° if no voltage is applied. The third layer (horizontal polarizer) 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 polarization layer from the transmitter and move it to the receiver, as shown in Figure 2b. The outcome at the transmitter 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. Polarization-based modulation, however, is not resilient to relative rotations between the transmitter and receiver along the field-of-view axis (the link quality degrades rapidly). To overcome this problem, Pixel adds dispersors to the transmitter, cameras to the receiver and use elaborate CSK encoding.

One could argue that replacing the energy-hungry camera with a single color sensor could make Pixel a competitive alternative for ambient light communication, but color-based modulation does not fully exploit the energy present in sunlight. As stated by the authors of Pixel [25], *"we have also performed similar evaluation experiments for fluorescent light and* ***solar light****, but we found little difference from LED"*. Those results are expected because, by definition, color sensing focuses on a narrow portion of the spectrum, filtering out most of the energy present in solar radiation, in particular, in the Infrared-red (IR) band. For LuxLink, there is a strong difference in performance between indoor scenarios, which are exposed to the narrow spectrum of LED lighting (LuxLink achieves a few meters range, like Pixel), and outdoors, which are exposed to the full spectrum of sunlight (several tens of meters range). Furthermore, LuxLink more than quadruples Pixel's data rate, even though it uses a much simpler sensor, a 'single-pixel' phototransistor instead of a multi-pixel camera. Leaving aside color-based modulation, however, brings back the flickering problem and exposes the channel to changes in light intensity and interference from LED lighting.

Overall, the SoA provides either *color-based communication with cameras* (flicker-free but energy-hungry and with limited exploitation of the energy present in ambient light), or *pulse-based communication with simple photodiodes* (energy efficient but flicker prone). We uncover a third alternative: *frequency-based communication with simple photodiodes* (flicker-free, energy efficient and with the ability to exploit the full spectrum of ambient light).

Challenge 2: Reliability in indoor and outdoor scenarios. An important limitation of using ambient light for communication is that we lack control over the intensity 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 its harmonics) but also related to the operation of smart lighting systems, which use pulse-width modulation for dimming. These oscillations are not a problem with active VLC, because the modulation frequencies of LEDs in VLC are several orders of magnitude higher. 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. Using mirrors or retro-reflectors to increase the range [15, 24] (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.

Losing control over the light source, 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 build on top of our FSK modulation scheme to filter out interference from external light sources.

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 and beam direction of the emitter. *(2) Transmitter.* One or multiple LCD panels modulated by a microcontroller to transmit information. *(3) Receiver.* A simple phototransistor with a lens, and a microprocessor to decode information.

The LuxLink system is depicted in Figure 3. Next, we provide a detailed analysis justifying (i) the selection of a particular type of LCD shutter and FSK modulation; and (ii) the methods used to overcome the interference present in ambient light.

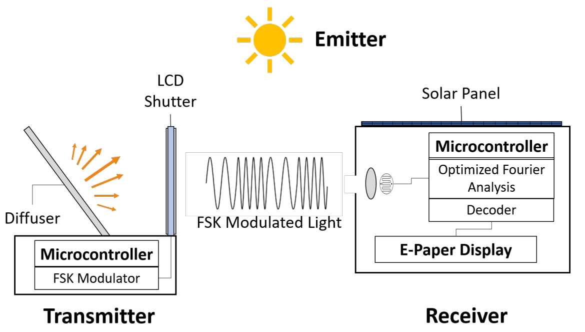


Figure 3: The LuxLink system.

3 ANALYZING THE HARDWARE AND PHYSICAL LAYERS

In this section, we present a detailed analysis of LCDs and modulation schemes to design robust Hardware and Physical Layers. All the evaluations in this section were performed indoors with an LED light to guarantee a fair assessment (same illumination level).

3.1 Hardware layer: selecting the right LCD

LCDs have been used for backscatter [15, 24] and ambient light [25] systems, but they were not designed for communication. The manufacturers do not provide the parameters required to determine the communication capabilities of their LCDs. We evaluate the performance of LCDs considering three important metrics: (1) Response time, which impacts the maximum data rate; (2) Energy consumption; and (3) Contrast, which impacts the range and SNR.

3.1.1 Response time. LuxLink uses commercial, off-the-shelf LCD shutters. For communication purposes, 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 4 shows the rise and fall times of a shutter. The modulation frequency of an LCD, at maximum contrast, is determined by the *response time*, which is 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. Table 1 shows the properties of four shutters driven at 3.3 and 5.0 V, and Figure 5 provides further details about the rise and fall times. This table and figure provide two important insights.

First, all shutters have modulation frequencies below or near 200 Hz. Thus, for safety, LCD-based modulation cannot be done utilizing the entire rise and fall times. Symbols need to use periods that are shorter than those times, which prevents the modulated signal from reaching a 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.

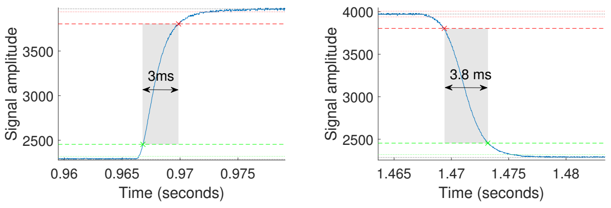


Figure 4: The rise and fall time of a 3D shutter at 5V

Shutter type	Area (cm^2)	Response time (ms)		Modulation Freq. (Hz)	
		3.3 V	5 V	3.3 V	5 V
Circular[2]	95	48.7	28.6	20	35
Rectangular [4]	37	57.4	12.2	17	82
Video [2]	15	8.1	4.3	123	233
3D [3]	14	8.2	6.8	122	147

Table 1: Properties of shutters for varying supply voltages.

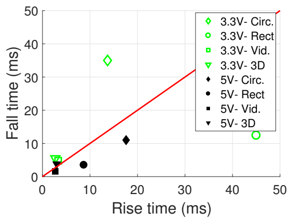


Figure 5: The rise and fall times of LCDs at 3.3/5 V

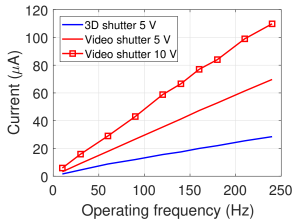


Figure 6: Current consumption of shutters

Second, the rise and fall times of shutters are different (Figure 5), which would cause asymmetric (distorted) square waves with pulse-based schemes. This phenomenon 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 rise time is 1.7× higher than the fall time. The 3D shutter has a rise time that is only 0.2× shorter than the fall time. The selection between the video and 3D shutters presents a trade-off between the modulating frequency and the asymmetric shape of the signal, 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 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 increasing the power consumption by approximately a factor of four, $I(\times 2) \times V(\times 2)$, as shown in Figure 6. Driving the shutter at such high voltage would make the design of our system more complex and less energy efficient. When both, the video and 3D shutters, operate with 5 V, the 3D shutter draws half the power. Another important point is cost. Both shutters have similar sizes, but 3D shutters cost one quarter of the price (6 vs. 25 USD).

Design Guideline 1: 3D shutters are the best option for the Hardware Layer. They 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.

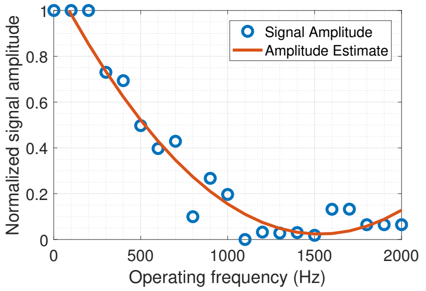


Figure 7: Signal amplitude of 3D shutter at 5V

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 the corresponding frequency is too low and causes flickering effects. Switching the shutter at higher frequencies is necessary, but reduces the signal amplitude, i.e. the difference between the high and low symbols in Figure 2a flattens. Thus, a key question for our design is: what is the relationship between the operating frequency and the resulting contrast for 3D shutters? Figure 7 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 because there is not enough time to fully switch between transparent and opaque states. Considering that the modulation frequency must be higher than 200 Hz (to avoid flickering), we are limited to partial transitions between 'intermediate transparent' states (low contrast). As we will describe later in this section, we will leverage these partial transitions to create a frequency-based modulation scheme.

3.2 Physical Layer: The limitations of pulse-based modulation

To be energy efficient, LuxLink utilizes a simple phototransistor at the receiver (section 4). Contrary to studies utilizing cameras [25], 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 pulse-based modulation schemes [15, 24]. In this section, we show that these 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 visible light communication is to use encoding schemes where each bit is represented by the same number of zeros and ones. In this way, a constant average light intensity can be guaranteed independently of the data pattern. Manchester encoding, used in Retro-VLC [15], is an example of this type of scheme, and a modulated signal is shown in Figure 8a. The problem is that the pulse widths are variable and shorter than the rise and fall times. As a consequence, the light intensity radiating from the LCD is a series of irregular light pulses causing strong flickering effects. PassiveVLC [24] uses Miller coding to increase the data rate, but Miller coding does not guarantee a constant average signal level, and consequently, has a higher chance of causing flickering.

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. The limitation of this scheme is that it does not ensure the same number of peaks per bit. For example, depending on the data pattern, eight bits could map to eight peaks or to five peaks as depicted in Figure 8b. Modified Miller causes less flickering than Manchester and Miller, but the variable presence of peaks still causes some flickering effects depending on the payload.

3.2.3 *Limitation 3: variable pulse position.*

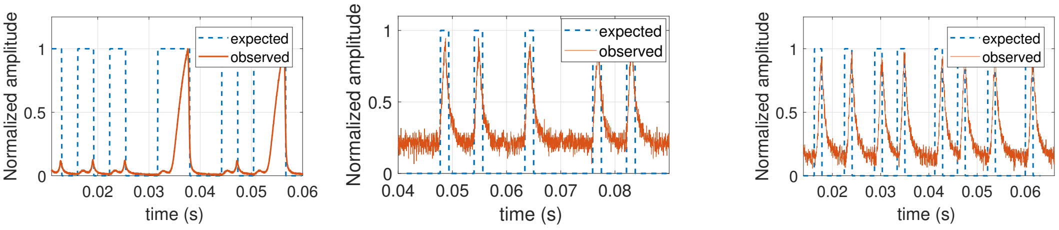
An encoding method that guarantees a constant pulse width and the presence of a single pulse per bit is Pulse Position Modulation (PPM). Within PPM, a scheme that minimizes the gap between pulses is to denote bit 0 as `0010` and bit 1 as `0100`. As shown in Figure 8c, the only irregularity in the signal is an occasional longer gap between pulses. These irregularities induce (data dependent) lower frequency components at reciprocals of the base frequency that might cause flickering effects. We tested the flickering effects of Manchester, Modified Miller and PPM with 10 people. The best performing method was PPM but still showed some flickering effects, as depicted in Figure 9.

Overall, we could not obtain a non-flickering link with any of the amplitude-based modulation methods.

3.3 Physical Layer: The advantage of frequency-based modulation

3.3.1 *Key insight.*

The fundamental limitation of the above described methods is that they have a *wide bandwidth*. Considering a carrier frequency f_m, the information is carried over the band $f_m \pm \Delta f$, and Δf depends on the data pattern. Thus, given the narrow communication bandwidth of LCDs –a few hundred Hz, as shown in Figure 7–, data patterns can easily push the lower end of the bandwidth ($f_m - \Delta f$) below 200 Hz, leading to flickering effects. As the shutters cannot cater to high speed switching, the best option to avoid flickering effects is to use a modulation scheme



(a) Manchester **(b) Modified Miller** **(c) PPM**

Figure 8: Effects of pulse modulation: (a) variable pulse width, (b) variable pulse presence, (c) variable pulse position

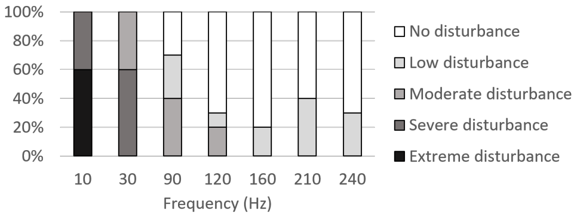


Figure 9: Flickering results with PPM modulation

that has a *narrower bandwidth* spectrum. Frequency shift keying (FSK) 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, eliminating in that manner flicker.

3.3.2 Generating an FSK signal. When driving a 3D shutter with an electrical square wave signal above the frequency stated in Table 1, the transparency of the shutter follows a near-sinusoidal pattern, as illustrated in Figure 10. The simplest FSK modulation only requires two different sine waves. However, generating FSK with LCDs is not straightforward, two important requirements must be met.

First, the LCD must maintain a constant average brightness. 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 10, at a higher frequency (640 Hz), the peaks get lower, which in turn, reduces the average brightness, leading to potential flickering effects. 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 11. The higher the duty cycle, the higher the brightness.

Second, there cannot be abrupt transitions between the two frequency signals. The shutter can only generate a continuous signal, consequently, 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_0, f_1 must be a multiple of R, i.e.

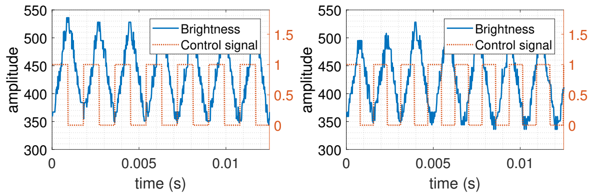
$$f_0 = n_0 \cdot R, f_1 = n_1 \cdot R \text{ with } n_0, n_1 \in \mathbb{N}. \quad (1)$$

As a baseline implementation, we choose $R = 80$ bps, $n_0 = 8, n_1 = 7$, such that $f_0 = 640$ Hz, $f_1 = 560$ 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`, as shown in Figure 10.

Design Guideline 2: Considering the narrow bandwidth of LCDs, FSK is a suitable Physical Layer scheme to avoid flickering when simple photosensors are used as receivers. The fundamental limitation of pulse-based methods, including those used in Retro- and Passive-VLC, is that they have a *wide bandwidth*.

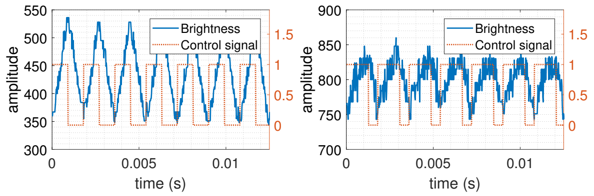
3.4 Transmitter design

We now describe the reflective properties of our transmitter and the electronic design.



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

Figure 10: A square wave control signal leads to a sinus-like pattern in brightness.



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

Figure 11: The duty cycle of the control signal has a direct influence on the average brightness

3.4.1 Diffuse reflections. The surface of our transmitter should reflect as much light as possible, but a high reflection coefficient is not the only parameter that matters. Depending on the material's smoothness, we can have different types of reflections, as shown in Figure 12. Mirrors and retro-reflectors provide long narrow beams (specular reflection), which increase the range and SNR of the signal, but put severe constraints on the location of the receiver. Retro- [15] and Passive-VLC [24] 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. 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 tilted at an angle of 45° to improve coverage, at the cost of reducing the signal strength (due to the diffuse material). In section 4 we describe the use of 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 two commercial LCD shutters (from 3D glasses), controlled by an STM32L031K6 microcontroller to send continuous FSK signals with constant brightness. 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 13. Embedded in this transmitter are sensors and an interface to connect a keyboard, so users can also send their own test messages. The transmitter has a dimension of 8.6 cm× 7.2 cm×12.1 cm.

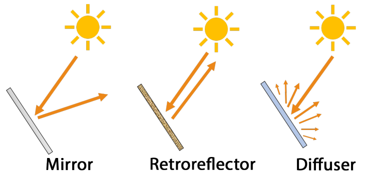


Figure 12: Effect of material on reflections.

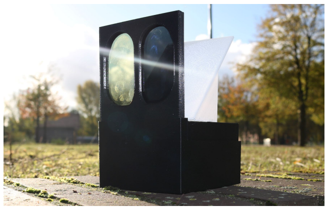


Figure 13: The LuxLink transmitter: light is reflected on the white surface and passes through the LCDs.

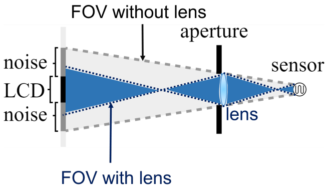


Figure 14: The sensor captures signal and noise

4 COPING WITH CHANNEL DYNAMICS

Our platform must be able to decode the transmitted signal with any source of ambient light. Loosing control over the light source raises up a unique problem: both, the signal and noise, come from the same source and the receiver should be able to discern them. As illustrated by the gray area in Figure 14, the receiver's field-of-view (FoV) will cover the LCD surface, which contains the signal, but it will also cover the surrounding area that contains noise. To reduce the impact of noise, we limit the receiver's FoV to ~1°. The specific challenges faced by our platform depend on the operating environment: indoors or outdoors.

4.1 Indoors: interference from LED lighting

Preferably, our system should be installed on a place where sunlight is available, but it is designed to work with any ambient light. If the system is placed indoors, interference is likely to occur because nearly all artificial lights have fluctuating brightness. 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. 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, on the other hand, are often toggled at 300, 400 or 500 Hz for dimming support[1]. These oscillation frequencies are near the selected FSK frequencies and can lead to the following phenomena:

1) Degradation of the link quality. The modulation intensity of the light source can be 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 connection.

2) Flicker due to interference. Mathematically, the modulation of LED light 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 $f_A = 500$ Hz (e.g. due to a dimmable LED) and the shutter oscillates at $f_S = 530$ Hz, the light intensity will also oscillate at the harmonics $f_S + f_A = 1030$ Hz and at $f_S - f_A = 30$ Hz. The latter low frequency oscillation can cause flicker.

To mitigate these phenomena, we recommend selecting 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 to the range $[f_1 - R, f_2 + R]$[7]. For example, our baseline implementation with R = 80 bps, $f_1 = 560$ Hz, $f_0 = 640$ Hz has an approximated bandwidth of $[440, 720]$ Hz. This is a proper choice when LuxLink is used nearby LED lights oscillating at 400 Hz (that might have a harmonic component at 800 Hz), but it would encounter interference if the light sources oscillate at 500 Hz.

4.2 Variable light intensity and low SNR

4.2.1 Variable light intensity. Ambient light can go from being intense outdoors (causing the receiver to saturate); to being weak indoors (causing link failures). Under daylight conditions, the illumination usually ranges from 1 klux (overcast day) to 10 klux (indirect light on a sunny day), up to 30 klux to 100 klux (with direct sunlight). Indoors, on the other hand, the illumination is much lower, often between 100 lux and 500 lux.

The photosensor, and its circuitry, must be chosen to maximize the sensitivity of the receiver (to decode signals indoors) and minimize the likelihood of saturation outdoors, while providing a bandwidth that is high enough to transmit the FSK signals (at least 800 Hz in our system). We use a TEPT4400 phototransistor, which is sensitive to the full spectrum of solar radiation (visible light + infrared). This response bandwidth was chosen explicitly to exploit all the energy contained in ambient light, indoors and outdoors, as opposed to using only the energy present in the much narrower bandwidth of color sensors. To generate a voltage from the incident light, we place the sensor in a transimpedance amplifier (around an OPA2325 op-amp). The resistor in this circuit is chosen empirically to be 9 $k\Omega$, giving a bandwidth of at least 1.1 kHz. If the system is used only indoors, one can increase the resistor value to make the receiver more sensitive, but the bandwidth would decrease [2].

Our platform is not only designed to cope with the drastic differences in illumination between indoor and outdoor scenarios, but is also well suited to mitigate smaller fluctuations, such as those caused by clouds. This is due to the fact that frequency modulation was inherently designed to overcome the pernicious effects of interference in amplitude modulation[3].

4.2.2 Low SNR. Independently of the scenario where LuxLink operates, indoors or outdoors, it is important to reduce the influence of noise and improve the signal-to-noise ratio. To achieve that goal, one could limit the field-of-view with an aperture to focus as much as possible on the LCD panel, as shown in Figure 14.

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. 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), as shown by the blue area in Figure 14. Lenses

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

[2] The selection of the resistor could be automated if an extra photodiode is used to monitor the available spectrum. Adding light fixtures from different manufacturers may increase interference, and thus, reduce the spectrum and data rate of the system.

[3] This is a well known fact in communication theory. The non-expert can note this benefit by comparing the superior quality of FM radios against their AM counterparts.

maximize the ratio between the LCD area and the noise area, which in effect, increases the SNR. We add a cheap lens (0.5 USD, as used in cardboard VR glasses) to our receiver. The lens has a diameter of 25 mm and a focal distance of 45mm. A 3D printed mount keeps the lens on this position and provides an aperture with a diameter of approximately 20 mm. To focus on a far distance (≈7 m), the lens should be placed between 45 mm and 50 mm in front of the sensor.

In LuxLink, the position of the lens is *fixed*, it is not calibrated for specific transmitter-receiver distances. In spite of not having an autofocus system, the platform works better with a lens for all the transmitter-receiver distances in our evaluation.

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 data.

4.3.1 Analog filtering. The signal is filtered with a narrow bandpass 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. The signal is amplified again and fed to a 12-bit MCP3201 ADC that samples at 10 kHz.

4.3.2 Digital decoding: Fourier analysis. A binary FSK signal can contain a wave on two different frequencies: f_1 and f_0. Common methods to perform such frequency analysis are to apply a Fourier transform or the Goertzel algorithm. The Goertzel approach 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 that is not a 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 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 Receiver design

We now describe the design of the receiver. 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 11.3×6.4×6.6 cm, as shown in Figure 15.

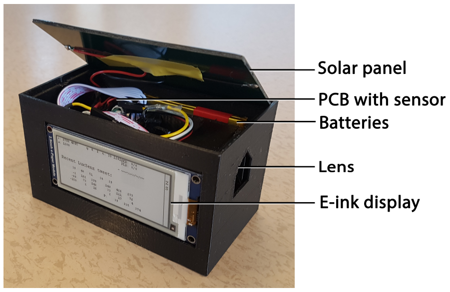

Figure 15: The LuxLink receiver: light coming from the right side is focused with a lens on a sensor

4.4.1 Reducing electrical noise. 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. *(1)* 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. *(2)* 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. *(3)* The 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.

4.4.2 Further implementation details. The transmitter has a 6×11 cm solar panel to operate continuously and two TP4056 battery charger modules to charge both LiPo batteries. The solar panel is rated at 6V with a maximum power of 1W. The MCU is an STM32L031K6 low-power MCU running on 32 MHz with an ARM Cortex-M0+ core. The MCU runs the decoding algorithm 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 ~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. In the idle state of the communication channel, the transmitter sends a SYN (`00010110`) pattern to synchronize with the receiver. The SYN pattern is transmitted *continuously* to avoid flickering effects. If we pause the SYN transmissions, the LCD would loose its tinted appearance and become fully opaque.

`00010110`	`00000010`	`01001000`	`01100101`	`01101100`	`01101100`	`01101111`	`00000011`	`00010111`	`00010110`
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

Battery voltage Component	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: Average power consumption

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. These values are a result of the measurements performed for each of these parameters for varied voltages. 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 (12 mW) and 12% by the e-ink display (6 mW). When driven at 3.8 V, the receiver consumes 20% less power than 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 consumption of the transmitter and receiver, the MCU consumes the biggest share (≈85%). *This implies that increasing the area of the transmitter, to increase the overall performance of the system, would not be costly in terms of energy expenditures.* 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. The IEEE provides guidelines for safe operating regions [11], shown in Figure 16. Based on the modulation frequency, the operation regions provide the maximum modulation depth[4] that systems can use to have *low* or *no* flickering risks. For example, to have *low* flickering risks at 200 Hz, the modulation depth must be less than 20%. The higher the modulation frequency, the bigger the allowed modulation depth.

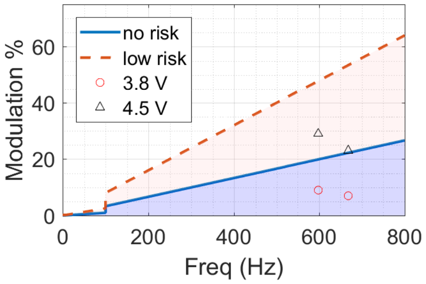

Figure 16: Modulation levels for no or low health risks

We measure the modulation depth (Mod%) of transmissions in our system and evaluate them against the operation regions in [11]. The guidelines recommend systems to work in the low-risk or 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. The results in this table are also plotted in Figure 16 to put the values in context. 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.

Freq. (Hz)	Supply voltage	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

5.3 Performance

We evaluated the system under different lighting conditions. Test messages are sent every three seconds. Each test message has 8 bytes of data (text) and 3 bytes of overhead (start and end keywords).

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 17 we show the performance of the system for different illumination levels. The plot

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

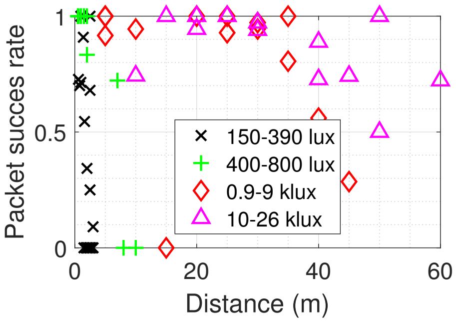
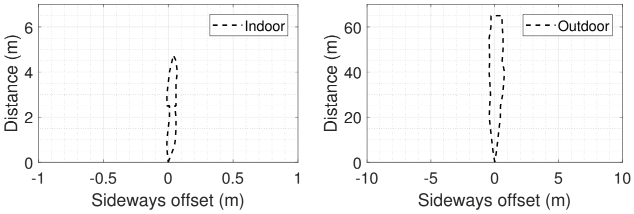


Figure 17: Range performance



(a) indoors (~600 lux)

(b) outdoors (~23 klux)

Figure 18: LuxLink coverage

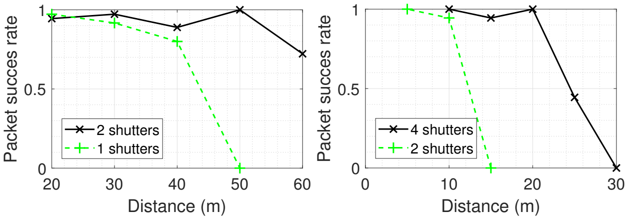
shows that for LuxLink to start being operational, we require limited lighting (≈200 lux). When the light level is below 400 lux the achieved range is less than 4 meters. EU regulations state that the lighting in office spaces should be 500 lux. Thus, in indoor scenarios with sufficient lighting LuxLink con provide ranges of several meters. Outdoors, the range can increase significantly (several tens of meters). However, due to the high variability of sunlight, the quality and range of links can change significantly. For example, for the 0.9-9 klux category (red rhomboids), some links can have perfect reliability at 35 m, while others may have zero at 15 m.

5.3.2 *Coverage.*

The coverage of the LuxLink platform, for indoor and outdoor environments, is shown in Figure 18. In these experiments, the orientations of the transmitter and receiver are fixed. We move the receiver to different positions in the x- and y-axis, but we do not rotate the transmitter or receiver to point to each other, we only change their relative location and identify the points where we get a reliable link. In an indoor environment with illumination around 600 lux, the maximum operating range is 4.75 m. In comparison, the outdoor environment has a range of 65 m (14× better than indoors). *It is important to highlight that this long range is obtained because we use photosensors that exploit the full spectrum of sun radiation, which is not possible to do with color based sensors, such as those used in Pixel [25]* (as described in section 2). The narrow coverage region means that if the 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).

5.3.3 *Transmitter area.*

The area of the transmitting surface influences the communication range of the system. A bigger 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). Similar tests were performed with 2 and 4 shutters during sunset (1000-1800 lux). In this case, Figure 19b shows that increasing the area by a factor of two, also leads to a significant increase in the range. From the above results, however, we cannot make conclusive statements such as stating that doubling the area of the transmitter, doubles the range. This is because during the experiments we had changes in sunlight, especially for the sunset experiments where there were high relative variations (between 1000 and 1800 lux).



(a) PSR on a sunny day

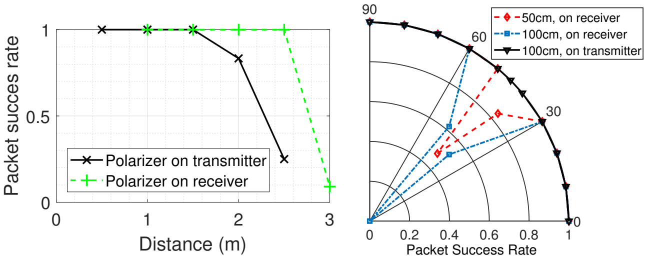
(b) PSR at sunset

Figure 19: Effect of varying transmitter area

5.3.4 *Placement of polarizer film.*

In section 2, we described the limitations of using color sensors. One may argue, however, that it is possible to use polarization-based modulation without the need of using color sensors and CSK encoding. The problem of such an approach is that the communication system cannot tolerate the relative rotations of the transmitter and receiver. To highlight this point, we remove one of the polarizer films from the transmitter and move it to the receiver, as in Pixel [25].

We evaluate the effect of this change indoors to have a controlled environment. Moving the polarizer film from the shutters to the receiver has not only the positive effect of removing flicker (because data is encoded with changes in polarization, not brightness), but we also noticed that the range was longer, as shown in Figure 20a. We hypothesize that this improvement is obtained because the polarizer at the receiver acts as a filter, blocking some noise sources of unpolarized light. This improvement, however, imposes an important constraint: the transmitter cannot rotate relative to its field-of-view axis, otherwise, there will be rotation angles where both polarization directions lead to the same light intensity, making it impossible to decode information. To showcase this point, we test both systems at two distances, 50 and 100 cm, which according to Figure 20a are ranges where both approaches have a solid 100% packet success rate (PSR). The results are presented in Figure 20b. We can observe that if the relative misalignment is 45°±15°, the PSR of the system with the polarizer at the receiver can decrease all the way to 0. This relative rotation problem was the reason Pixel proposed the use of a color-based platform (dispersors, CSK encoding and cameras) [25]. Our FSK modulation scheme allows us to obtain a flicker-free rotation-resilient system using a simple phototansistor.



(a) Placement **(b) Rotation**

Figure 20: Effect of polarizer film

5.4 Analysis of ambient light sufficiency

Given that LuxLink requires ambient light to operate, an important question is: what is the percentage of time that LuxLink can be powered and communicate with real sunlight conditions? To gain some insights into this question we use solar data for Elizabeth City in North Carolina, US [1]. In Figure 21, the grey background reflects the radiation data for all 365 days in 2012. The black curves (full and dotted) represent the average radiation for each season. We use three lines to estimate the performance of LuxLink. The cyan line is the amount of radiation required to power our receiver with the solar panel stated in section 4. The dotted blue line is the amount of radiation required for LuxLink to start being operational (short range communication), and the full blue line is the amount of radiation required to obtain long ranges. Given that the sun changes orientation during the day, these lines are not calculated assuming that light impinges at 90°(best case scenario), but rather assuming that light impinges at 45°.

Considering the 24 hours of a day, LuxLink can be powered for 43% of the time, it can be operational for 50% of the time (i.e. transmit information at a few meters range), and it can provide long ranges for 22% of the time. These percentages include cloud effects. If we consider only the daylight hours (since LuxLink cannot work at nights), the above stated percentages increase to 86%, 98% and 44% respectively. Note that the radiation required to be operational is lower than the radiation required to power the system. For the data in Elizabeth City, we observed that, during daylight, the longest period where there was enough radiation to be operational but not enough to be powered, was around five hours. That amount for energy could easily be stored in batteries. Therefore, for practical purposes the minimum radiation for LuxLink to work is the dotted blue line. Different latitudes and meteorological conditions will provide different outcomes, but a potential 98% operational time during daylight hours for a city is an encouraging result.

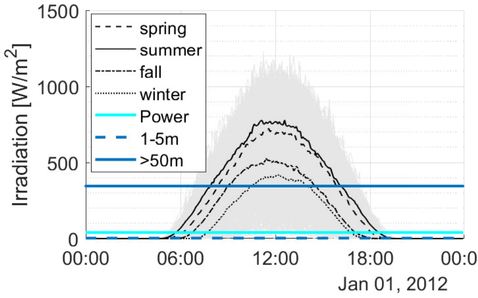
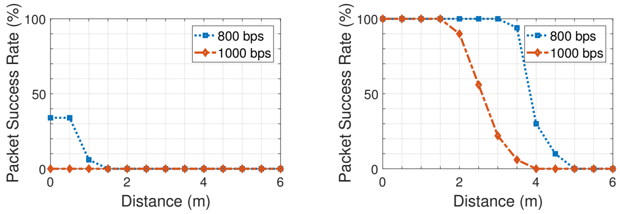


Figure 21: Solar radiation in Elizabeth City, NC, US.



(a) 500 lux **(b) 2000 lux**

Figure 22: Range performance of M-ary FSK

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. We are exploring two ways to increase LuxLink's data rate. First, we are increasing the channel bandwidth between f_0 and f_1. For example, if we use a pair of frequencies f_0=1 kHz and f_1=1.5 kHz, the data rate increases to 500 bits. Second, we are using M-ary FSK to send multiple bits per symbol. If, for our prior example, we add an extra pair of frequencies, f_3=2.0 kHz and f_4=2.5 kHz, to send two symbols per f_i, the data rate increases further to 1 kbps. Figure 22 shows preliminary results for 500 and 2000 lux. Outdoors, with stronger sun radiation, we expect the range to increase further. It is important to highlight, however, the trade-off between data rate and range. For 80 bps, we get a range of 4 m for 600 lux (Figure 18). With M-ary FSK we cannot get a reliable link at 500 lux even at close distances. This trade-off, between data rate and range, is a fundamental property of all wireless communication systems.

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 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. Photodiodes are the most popular option because they have a high bandwidth, which enables 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 [9], and Gbps links have also been demonstrated [20]. Cameras consume more power than photodiodes and are slower receivers (kbps at a few meters range), but given that they are pervasive in smartphones [8], they have been used to enable indoor localizatoin [16] achieving sub-meter accuracy [12]. A more recent area is screen-to-camera

Name	Light source	Data rate	Range	Power TX	Power RX	Location	Receiver
RetroVLC [15]	LED	0.5 kbps	2.4 m	~2.4 W*	234 μW	Indoor	Photodiode
PassiveVLC [24]	LED	1 kbps	2 m	~0.6 W*	525 μW	Indoor	Photodiode
PIXEL[25]	LED& Amb. light	14 bps	10 m	~1 mW*	>300 mW*	Indoor	Camera
POLI[6]	LED	568 bps	40 m	O(W)*	>300 mW*	Indoor	Camera
MobileVLC [21]	Ambient light	~30 bps*	1 m	0	~10 mW*	Outdoor	Phototransistor
LuxLink	Ambient light	80 bps	4.5 / 65 m	30 mW	36 mW	In/outdoor	Phototransistor

Table 5: Comparison of LuxLink with the most related systems in the state of the art.

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 [13, 26]. 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 a source of noise, but also the communication carrier.

Polarization-based systems. Polarization is used in various SoA studies. In LiCompass [22], 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 [19]. 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 systems. A major inspiration for our work comes from semi-passive communication systems with visible light. The use of LCD shutters to backscatter light is studied in Retro- [15] and Passive-VLC [24]. Their goal, however, is different. Since the tag *only* communicates back to the light source, there is no need to control flicker effects. As shown in section 3, the modulation schemes used in those studies, and pulse-based modulation in general, have fundamental limitations that create flicker with LCDs. Pixelated-VLC follows a similar research line [18], but uses multiple shutters and a special casing that can be controlled to use 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 bps at 2 m. This type of 'retro-reflecting' communication does not require analyzing flickering effects either, because there are no users in LoS. Compared to these systems, LuxLink does not require any control over a light source, works with any type of ambient light and is flicker-free.

Passive systems. Pixel [25] and MobileVLC [21] also provide important ideas that we build upon (even though Pixel aims at indoor localization, not communication). Like LuxLink, they do not need control over the light source (fully passive). Similar to Pixel, we do not cause flickering effects, but we have two important differences. First, we do not rely on cameras, which makes our system more energy efficient. The CMOS camera used in Pixel, on average, consumes around 300 mW of power [14], one order of magnitude more than our receiver. Second, by using a phototransistor, we do not constraint the link to use only the energy present in the color spectrum, we exploit the full spectrum of solar radiation thanks to our novel FSK modulation method. Another study that exploits polarization modulation is Poli [6], but it requires control over the LED light and uses a camera (not a fully passive system). Similar to MobileVLC [21], we use photodiodes, but MobileVLC requires objects to be mobile and at a constant speed.

Comparison. Table 5 shows the comparison between LuxLink and the SoA. Not all data was available in the cited papers. The information marked with (*) reflects our own estimations based on the described system. The values without (*) are the ones reported in the respective studies. For systems using LED lights as a source, we assume a customary 20% overhead considering the power required by the bulb [5]. Retro- and Passive-VLC, state the power of their LED bulbs (12 and 3 W, respectively), but Poli does not. We assume that Poli's transmitter power is in the order of a few W because it uses three LEDs. Overall, LuxLink advances the SoA by creating a wireless link that relies solely on ambient light, works indoors and outdoors (with the capability to attain long ranges), and uses the least combined energy at the transmitter (no need of LED bulbs) and receiver (no need of cameras). More importantly, LuxLink provides a novel FSK modulation for LCDs, which allows us to exploit fully solar radiation for ambient light communication without flickering.

8 CONCLUSIONS

Ambient light is pervasive, but hitherto, there has been little research exploiting it for wireless communication. We propose a novel platform to establish safe reliable wireless links with ambient light. Our work performs a detailed analysis of the Hardware and Physical Layers. This analysis allowed us to design a platform that does not require cameras or control over the light source. Utilizing small LCDs at the transmitter, a single phototransistor at the receiver, and a novel FSK method to encode information, we show that ambient light can be used to communicate information with a data rate of 80 bps at a range of several tens of meters (depending on the ambient light intensity). Cities around the globe receive vast amounts of sunlight, this work could help transforming their exposed surfaces into wireless transmitters with zero-energy cost.

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