Delft University of Technology
Master of Science Thesis in Embedded Systems

Passive VLC: Spatial Color Channel Modulation through Dispersion of Light

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Abstract

In the last decades our usage of the Radio Frequency (RF) spectrum has intensified a lot due to the increasing number of mobile devices. The spectrum is getting crowded and new communication alternatives might become necessary in the future. One such alternative is Visible Light Communication (VLC), which uses the visible light spectrum instead of RF. Passive VLC, in particular, combines this property with a low power usage, suited for battery powered devices. However, high data rates are lacking.

This thesis proposes a multi-channel passive VLC system, based on light dispersion principles, as a novel concept to try and enhance these data rates. Results of the system so far only show low data rates however, at a maximum of 4 bits per second. The low data rate in particular is caused by choice of transmitter and receiver, thereby limiting the bandwidth and the number of channels that can be created. Yet, the concept itself is still considered a valid and valuable approach, and higher data rates can be expected from future works.

In this thesis we will see exactly how we can go from light dispersion to creating a multi-channel passive VLC system. As we will see this requires an optical design, a transmitter and a receiver, all of which will be working together. Besides an evaluation of the performance it will give insight in challenges this concept faces and, also, what improvements might increase the system performance.

Preface

My interest for VLC started to grow after taking a course in it given by prof. Marco Zúñiga. Because the communication is happening on a medium that we can observe it is a very tangible and, for me, attractive concept. Especially passive VLC held my interest, due to the potential of it being a very energy efficient means of communication.

Glossary

VLC Visible Light Communication

RF Radio Frequency

LED Light Emitting Diode

LC Liquid Crystal

LCD Liquid Crystal Display

OOK On-Off Keying

DMD Digital Micromirror Device

PCB Printed Circuit Board

SPI Serial Peripheral Interface

RAM Random Access Memory

ROI Region of Interest

BER Bit Error Rate

ICI Inter Channel Interference

TFT Thin Film Transistor

FSK Frequency Shift Keying

Contents

Chapter 1

Introduction

Light forms an important part of the world around us and is very much omni-present in our everyday life. Therefore, it is not so strange that the idea to use light or other visible signals as a means of communication has been around for quite some time.

Ancient forms of visible communication include smoke signals or using fire-light as a beacon. Later, signalling lamps or mirrors have been used to convey messages. An interesting form of communication was developed in 1880 by Alexander Graham Bell, called the photophone [2]. This device modulated acoustic (speech) signals onto sunlight using a mirror that would vibrate under the influence of the aerial vibrations.

However, around the same time the photophone was invented, Maxwell made his prediction on the existence of Radio Waves [14]. Which in turn led to the development of RF communication. Since RF communication quickly surpassed VLC in terms of range and resilience against bad weather conditions, develop-ment of the latter was abandoned for some time.

Nowadays, RF communication has advanced very far. Yet our demands keep increasing as well, and more and more devices are being connected wirelessly. And even though the Radio Wave spectrum is used ever more efficiently and its boundaries are pushed into higher frequency regions, it is still growing more and more crowded, since the RF part of the Electro Magnetic wave spectrum is still limited in its bandwidth.

And this is where VLC can come into play. With a spectral bandwidth ap-proximately ten thousand times the size of the bandwidth of the RF spectrum, this technology has a promising prospect [11]. Not necessarily to replace RF, but at least to complement it.

VLC roughly comes in two flavours, these flavours being active and passive. In active VLC the light source itself is being controlled to transmit information. An important thing to note here is that the transmitting device has to power this light source, which can consume a significant amount of energy, especially for small, battery powered devices. Therefore, research is done into passive VLC as well. In passive VLC a modulation device is placed between a light source and a receiver. Since the transmitter does not have to power the source, but instead makes use of a source of light from the environment, less energy will be consumed by this device.

So passive VLC can be advantageous for low energy devices. Moreover, if we can use for example the sun as our source of light, not only the transmitter will become energy efficient, but instead the whole transmission. Therefore, passive VLC has its promises. Currently, however, it is also lagging far behind active VLC in terms of achievable data rate. Luckily researchers are attempting to make improvements to start closing this gap.

1.1 Problem Statement

This thesis will propose a novel passive VLC communication scheme to try and boost transmission data rates. In particular this will be done by creating a multi-channel transmitter as shown in figure 1.1. With a dispersive element, white light can be spread to reveal its colour/wavelength components. Then, afterwards, an array of modulators can modulate each of these components separately such that each wavelength component can form its own transmission channel. For the overall data rate the data rates of the separate channels are simply added together. Therefore, compared to a single-channel transmitter using the same modulator, the overall data rate is multiplied by the number of channels.

At the basis of this proposal lies the realisation that, while the visible light spectrum is actually larger than the RF spectrum, it has not been used efficiently so far. The reason for this is that we cannot use the same electronic components (oscillators, modulators and antennas) used in standard RF communication for VLC. However, the components that are used for VLC transmissions give in comparison very little control over the emitted wavelengths.

Adding the dispersive element to make available the spectrum of a light source should be able to help in gaining some control over the wavelengths in a VLC transmission. The idea is a promising one, however, this approach also comes with its own challenges as we will see throughout the rest of the thesis. In summary we will be answering the following question:

How can light dispersion be used in a passive VLC system to create a multi-channel communication link and boost overall data rates?

1.2 Limitations

As this thesis presents work based on a brand new concept within passive VLC, it was relatively unknown what challenges would be encountered upfront. In the end quite some challenges were encountered and this did have a negative influence of the achievable performance, both in terms of data rate and transmission distance of the communication the system. This is however not to say that this thesis will be of no value, as uncovering what these challenges are can be equally important in exploring a new concept.

One major challenge during this thesis proved to be the creation of the optical setup that makes available the spectrum for modulation. As it turned out, this was much more involved than anticipated. Especially since optics is not an area of expertise for me, a lot of time was spend on getting this part working.
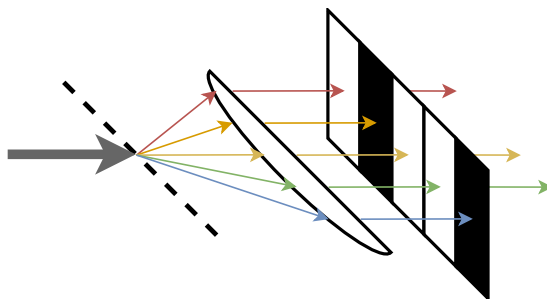
Figure 1.1: **Concept sketch of the envisioned transmitter. Light can be dispersed to make available its different wavelength components. These can then be modulated separately to form a multi-channel transmitter.**

Other performance limitations were introduced in some parts of both transmitter and receiver design and component choices. We will discover what these are in the rest of this report. All in all, throughout reading this report we will gain a better understanding of the proposed communication system. We will see where lie the challenges, what are the pitfalls to avoid or improvements to be made, and what are some more fundamental limitations that will prove harder to tackle.

1.3   Contributions

- Application of the concept of light dispersion to the field of passive VLC to gain more control over the visible light spectrum.

- Implementation of a passive VLC transmitter that can modulate different wavelength components separately to create a multi-channel communication link.

- Implementation of a passive VLC receiver able to distinguish between different wavelength based channels and decode data from them.

1.4   Outline

The rest of this report will be structured as follows. Before going into the details of the system itself, first some more background is provided in chapter 2. Here, the basics of a VLC system and its components will be discussed as well as some related work in the literature. After this, the system design will be detailed in the next three chapters. Chapter 3 will provide the optical design. Here, light dispersion is discussed and how to use it in a passive VLC system. Then, chapter 4 will discuss the transmitter design. To conclude the system design is chapter 5 about the receiver design. After concluding the design description, the system and its performance will be evaluated in chapter 6. Lastly, a conclusion and recommendations for future work are given in chapter 7.

Chapter 2

Background

Before going into the design details of a system that uses light dispersion in a passive VLC link, let us first take a look at some more basic concepts. After these basic concepts are introduced, the chapter will be concluded with an overview of scientific works related to this thesis.

2.1 Relevant Concepts

In this section, first of all an introduction will be given to how a passive VLC link is build up and what components are typically used in this. Secondly, we will touch on the basics of light dispersion, why this is an interesting phenomenon to use in VLC and, again, take a look at the components we might use for this.

2.1.1 Passive VLC: System Components

VLC in general requires three main components to function. These are: 1) A light source, 2) a modulator, and 3) a receiver. In active VLC, the modulator directly controls the light source, which is usually a Light Emitting Diode (LED). In passive VLC, on the other hand, the modulator consists of a controller connected to some separate device. This device will then either block incoming light rays, or allow them through to the receiver. Figure 2.1 shows the two setups for active and passive VLC. Now, we will further look into the passive VLC setup by looking into the different options available for the three components.

Light Source One of the merits of passive VLC is that, in the ideal case at least, we can make use of any existing light source. Lamps in an office might be used to set up a connection with a mobile device. Or, when outside we may even exploit the sunlight as a carrier to get really energy efficient. To test a new concept, however, it is often easiest to use a flashlight as a light source. Though this is not representative for all cases, its directional light beam makes it easier to run tests and estimate the potential of such new concepts.

Modulator For a modulator there are two main options, or at least two options that will scale to the multi-channel transmitter envisioned in this thesis. The options being Liquid Crystals (LCs) and mirrors.
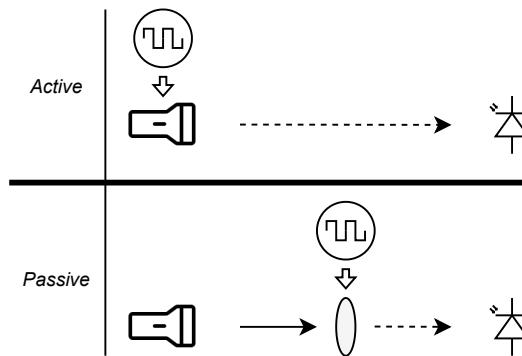
Figure 2.1: **Distinction between active (up) and passive (down) VLC illustrated. In active VLC the data is modulated on the carrier directly at the source, whereas in passive VLC a separate modulator is placed somewhere between a source of light and the receiver.**

LCs, first of all, can change their opacity by applying a voltage to it. An example of this is shown in figure 2.2. First the incoming light is polarised by the polariser. After this, a rotation in the polarisation direction is applied, where the angle depends on the applied voltage. The intensity of the output beam then depends on how well the polarisation angle of the light lines up with that of the analyser. Since we are now able to control the light intensity at the output, the LC can considered to be a light modulator.

The same concept is used in Liquid Crystal Display (LCD) screens. Where each pixel contains such an LC element as discussed above. By applying different voltages to different pixels, we can create a different light intensity for each pixel and an image can be displayed. However, since we can control these pixels separately, an LCD can also be applied as a multichannel transmitter, where each pixel or groups of pixels can be used as a separate channel.
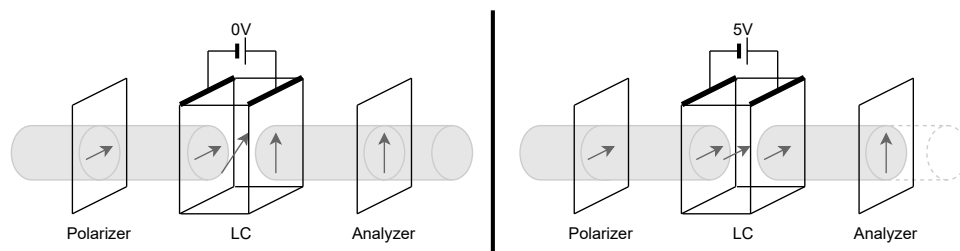
Figure 2.2: **Build up of an LC modulator. A light beam enters from the left. After polarisation, the light can only pass the analyser if its polarisation direction matches that of the analyser. This is controlled by applying a voltage to the LC. At 0 V the light exits on the right hand side. At 5 V the light is blocked by the analyser.**

On the other hand, we can also use a mirror. The concept behind this is quite simple. Using a mirror we can deflect a beam of light into different directions based on angle and position. Thus, we can rotate a mirror to have a beam of

light either head towards a receiver or away from it. This is illustrated in figure 2.3.

Again, the scale up to a multi-channel modulator comes from display technology. In certain projectors, elements called Digital Micromirror Devices (DMDs) are used. These devices consist of arrays of microscopic mirrors. By applying voltage to the separate mirrors their angles can be controlled independently. Same as for the LCD, we now have an array of separately controllable pixels that might just as well be used as a multi-channel modulation device [24].

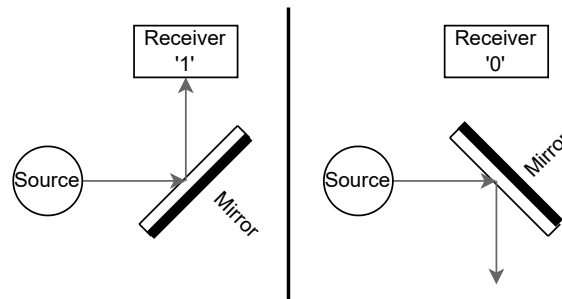Figure 2.3: **Example of a mirror based light modulator. By rotating the mirror we can aim the source beam either towards the receiver or away from it. Thus changing the light intensity observed by the receiver.**

Both modulators come with some advantages and disadvantages compared to the other. These will further be discussed in chapter 4.

Receiver   For the receiver a device is required that is able to measure light intensities. Furthermore, since multiple channels will be created in the wavelength/colour domain, it also should be able to distinguish between those. Three devices capable of this are: a colour sensor, a camera and a spectrometer.

Colour sensors consist of an array of photodiodes (usually three) to measure light intensity. When light hits a photodiode a current is generated, which is like the inverse operation of an LED. To distinguish between different wavelengths/colours, each of these photodiodes is covered by a different colour filter. Therefore, multiple colour channels can be received, making it a suitable receiver.
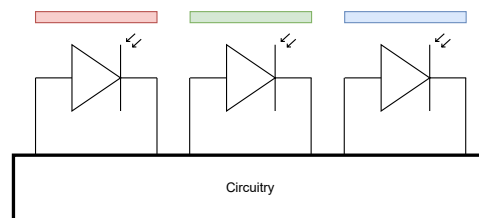

Figure 2.4: **Schematic representation of a colour sensor. Multiple photodiodes measure light intensity. All receive a different light colour because of the colour filter placed on top of them.**

A camera is basically an extension of the colour sensor. Each pixel of a digital

camera is really its own colour sensor. Therefore, also a camera might be used as a receiver.

Lastly, there is the option to use a spectrometer as a receiver. A spectrometer works differently in the sense that no colour filters are used, but the light is split into its spectrum. Then, by placing photodiodes in different parts of the spectrum, intensity changes for those parts can be measured separately. An image of a spectrometer can be found in figure 2.5.
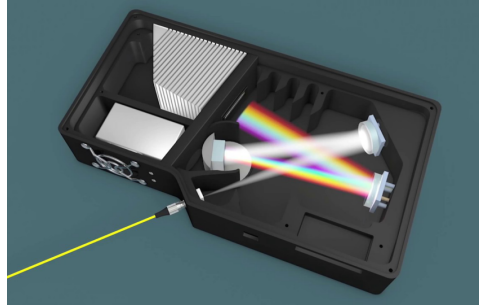

Figure 2.5: **A spectrometer and its interior design [6].**

Again, the more technical details and considerations for the chosen receiver can be found in the design chapters, specifically in chapter 5.

2.1.2 Dispersion of Light

This thesis is build around light dispersion and its integration into a passive VLC system. But why is this an interesting concept anyway? The one thing lacking in passive VLC is high data rates. Now, data rate depends on two things: the bandwidth per channel and the number of channels transmitting. In this thesis we will try and increase the latter, to increase overall data rates. And one resource we have for this is the available amount of spectrum.

Different parts of the visible light spectrum can be used to create separate communication channels. However, first we have to gain access to these spectral components. One way to do so is to disperse the light, which will spatially separate the spectrum. For light dispersion two different components can be used: the prism and the diffraction grating. Both are detailed below.

The Prism A dispersive prism is a triangular piece of transparent material. When a collimated light beam (a beam of parallel rays of light) hits the prism under the right angle, the light is bend and a spectrum emerges on the other side of the prism. This is shown in figure 2.6.

One important aspect of the material used is that it should have a refractive index different from its surrounding. It is because of this difference in refractive index that the light is bend under an angle following equation 2.1 [9]. Where δ is the deflection angle, n is the refractive index of the material and α is the angle of the prism (see figure 2.6).

$$\delta = 2\arcsin\left(n\sin\left(\frac{\alpha}{2}\right)\right) - \alpha \qquad (2.1)$$

Now, following Cauchy's equation, the refractive index of a material is wavelength dependent (equation 2.2) [3]. In this formula n is again the refractive index, λ is the wavelength and the other parameters are empirically determined coefficients. Because of this relation, all wavelengths components get deflected under a different angle. This results in a spectrum emerging on the other side of the prism.

$$n \approx A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} \tag{2.2}$$

The Diffraction Grating   A diffraction grating also disperses the light, though its working is based on a different principle. An image is shown in figure 2.6. A diffraction grating is a piece of material with regularly spaced grooves or slits. When shining light through multiple slits, an interference pattern forms on the other side.

The interference pattern of a grating shows slightly different locations of peaks and valleys for different wavelengths. Thus, different wavelengths get projected to different spatial locations and a spectrum emerges. The relation between incident and output angle, based on the wavelength s given in equation 2.3 [4]. Where θ_{inc} is the incidence angle of the incoming light, θ_{diff} is the diffraction angle of the light at the output, p is the order of diffraction, λ is the wavelength and α is the spacing between the slits of the grating.

$$(\sin \theta_{diff} - \sin \theta_{inc}) = p\frac{\lambda}{\alpha} \tag{2.3}$$

There are two major differences worth mentioning between the spectrum produced by a grating and a prism. The first is that where the prism produces a single occurence of a spectrum, the grating shows multiple spectra at different locations. Figure 2.6 only shows the two spectra of the first order, but higher order spectra will be present as well. The second is the relation between wavelength and deflection angle, which is linear for a diffraction grating, but non-linear for the prism. These technical details as well as some others shall be considered in choosing one of the two elements as a dispersor for the communication system developed in the thesis. For more details on this, please refer to chapter 3.

2.2   Related Work

With some background info we can now take a look at some research closely related to this thesis. A number of passive VLC systems will be discussed. This will lead up to what the current limitation is in this type of communications and will finally lead to the design idea for this thesis.

Passive VLC came first into life when it was realised that active VLC draws a lot of power since it has to power an LED. This is not a problem for light sources connected to the mains. And energy efficiency is not really a concern either, since the light source is not only a transmission device but also an actual light source. However, lots of devices are mobile and battery powered devices, for which the high power draw is a problem.

So, to counter this issue, passive VLC was conceptualised. Some concepts showed a semi-passive approach, where the downlink to the mobile device is
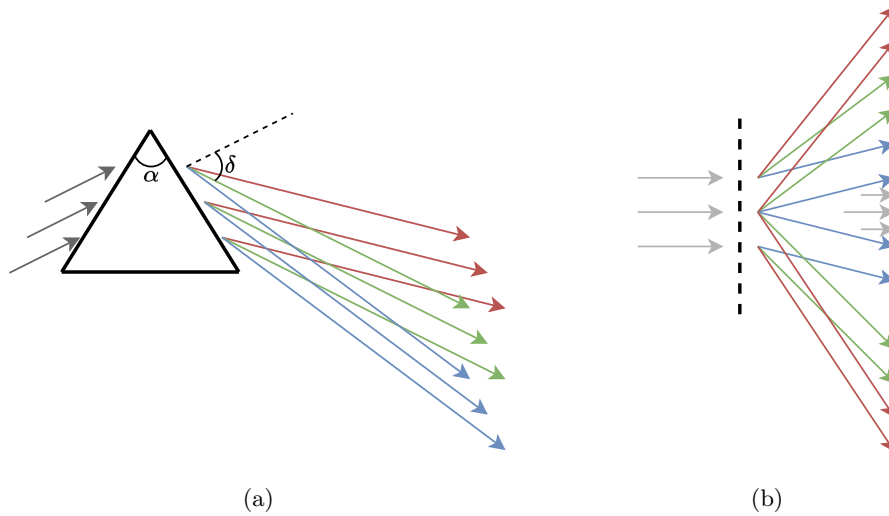
Figure 2.6: **Schematics of two distinctive dispersive elements. On the left (a) dispersion by a prism is illustrated. On the right (b) dispersion by a diffraction grating is illustrated.**

active, but the uplink back from the mobile device is made passive. Others show a fully passive approach, though only for a uni-directional communication link. Below we will take a t look at some of those concepts.

2.2.1 Backscatter Communication

Backscatter communication can be considered a first step towards passive communication. The downlink is still active, but the same light is reflected back to be used in the uplink as well [13]. By using a retro reflector, the light can be reflected back to a receiver placed next to the source. An LC placed over this retro-reflector is what modulates the light for the uplink. The concept is also depicted in figure 2.7.

Several improvements, in the modulation mostly, have been proposed and implemented [25, 22, 23]. This technique is now able to reach data rates of 8 kbps up to a range of 7.5 m. A note her eis that to reach these data rates a considerable amount of hardware has been deployed, with 64 LCs at the transmitter and two photodiodes at the receiver side.

2.2.2 Full Passive

From the backscatter techniques we take the step to fully passive, uni-directional communication systems. We will take a look at a couple of these systems. Afterwards, we can then compare them to one another.

PIXEL   PIXEL is a VLC system developed for a visible light positioning system [26]. It was designed with a lower data rate compared to active VLC, such that it could be decoded by mobile devices with a camera. The concept for the
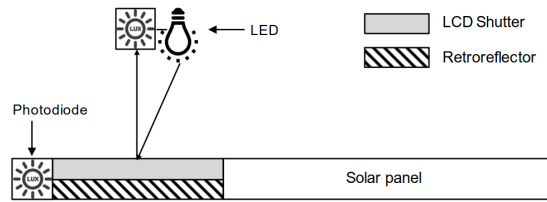
Figure 2.7: **Illustration of the concept of backscatter VLC. For the uplink light is reflected back to the source by a retro-reflector and modulated by an LC. [25]**

communication link is shown in figure 2.8. Its design is based on that of an LC. Only, here the analyser is moved to the receiver and a dispersor is added.

A disadvantage of the lower data rates envisioned by the authors would be that we as human can observe a flickering in the light. This is however countered by moving the analyser film to the receiver side. Between the LC material and the analyser, the light intensity is constant, so no flicker can be observed. the details for the dispersor will be omitted here, but in short it makes the system less susceptible to relative rotations between transmitter and receiver. All in all, the authors report an a achievable data rate of 14 bps and a range of 10 m.
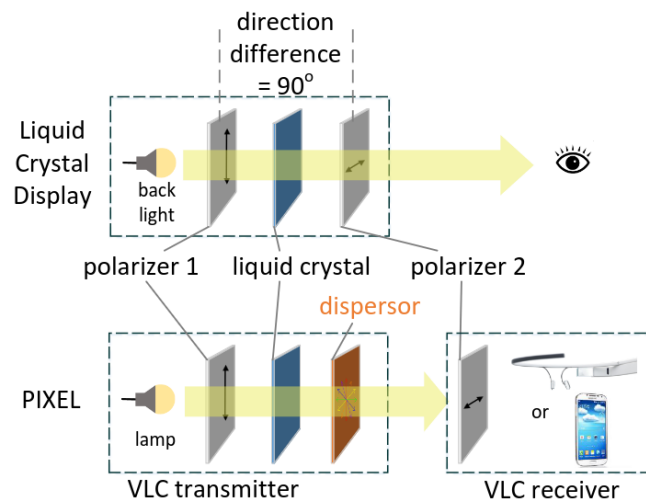

Figure 2.8: **Illustration of the concept behind PIXEL. The design is based on that of an LC. The analyser is, however, moved to the receiver and a dispersor is added. [26]**

LuxLink LuxLink is another passive VLC communication system [16]. The key design principles of LuxLink are to be able to use any form ambient light as a source and, again, to create a system that is flicker free.

The system design of LuxLink is shown in figure 2.9. In this design the diffuser plate is added to make sure that the system works from ambient light sources under different angles. The plate now forms a light background, no matter the orientation, and the LCs can modulate the light scattered off of it. Instead of modulating the amplitude of the light intensity, LuxLink employs Frequency Shift Keying (FSK) to change the frequency instead. Doing so makes sure that the system can be flicker free.

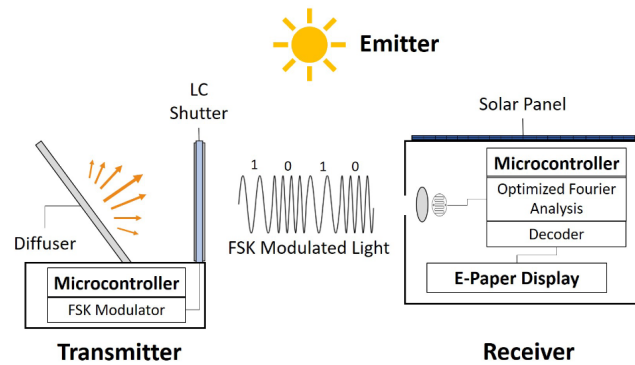For this system the authors report a data rate of 80 bps and a range of 65 m.

Figure 2.9: **Design of the LuxLink communication system. A diffuser scatterss light to an LC modulator. The light is modulated using FSK as a modulation scheme.** [16]

ChromaLux   Next up is ChromaLux [8]. A schematic of the system design is provided in figure 2.10. In ChromaLux it is again the case that LCs are used for modulation purposes. What distinguishes ChromaLux, however, is that instead of a single LC a stack of them is used. What was overlooked so-far is that the response of an LC is actually wavelength dependent due to birefringence properties [5]. By using a stack of them the thickness is increased to a point where this feature of LCs is highlighted.

Now, the receiver does not just measure a light intensity but a change in the colour content of the light. As these changes in colour space occur at faster frequencies than the switching of an LC between a completely translucent and opaque state, modulation at higher frequencies is achievable. Therefore, ChromaLux is able to reach data rates up to 2.4 kbps. The range mentioned is up to 3 m.

SpectraLux   Lastly we will take a look at SpectraLux [7]. SpectraLux partially applies the same concept as ChromaLux. Meaning that again a stack of LCs is used as a modulator to not just change the overall light intensity, but create a different spectrum at the output for different voltage levels applied.

The receiver of SpectraLux consists of a spectrometer. And, since different voltages produce different output spectra, such a spectrometer can distinguish between the different voltages being applied as though they are different sym-
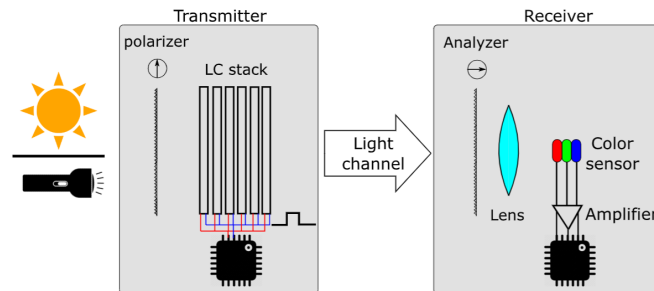
Figure 2.10: **Design of the ChromaLux communication system. A stack of LCs modulates the colour of the light, which is detected by a colour sensor.** [8]

bols. Being able to transmit not just a logic 1 or 0, but instead larger symbols, increases the data rate of the overall system.

In this way SpectraLux can output a data rate of 1.5 kbps. The communication range is 10 m.

2.2.3 Performance Comparison

Passive VLC forms a solution to reduce the power draw compared to active VLC systems. However, where active VLC is now capable of transmitting at data rates of multiple Gbps [12], data rates of passive systems are much more limited, as is also summarised in table 2.1.

Besides the actual performance numbers, this table shows two extra columns of information. The receiver type and use of colour spectrum columns are added to exemplify what influence some parameters might have on the performance. For example, PIXEL is the only system using a camera. It has the lowest data rate because a camera imposes a limitation in the achievable bandwidth. On the other hand, a camera is a pervasive sensor and readily available for many devices. The column displaying the usage of the colour spectrum shows us how data rates may be improved by making more effective use of the available visible light spectrum.

Though data rates have already improved over some years of research, it is my belief that there is a lot of potential left for further improvement. A very promising aspect, is to start making better use of the available spectrum, as was started in ChromaLux and SpectraLux. Therefore, in the rest of this thesis we will see how using more of the visible light spectrum could improve the data rate. Specifically by creating transmissions over separate wavelength based channels.

Before starting on the design, however, it will be good to note that, had this been a particularly easy task it would likely already have been implemented. Using the colour spectrum can only be done by getting into more advanced optical designs or more advanced understanding of optical properties of some components. Still, let us take a look what the designed communication system might provide us with.

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Table 2.1: **Comparison of the performance of the related research**

	Data Rate	**Range**	**Receiver**	**Uses colour spectrum**
PIXEL	14 bps	10 m	Camera	No (not for data rate)
LuxLink	80 bps	65 m	Photosensor	No
ChromaLux	2.4 kbps	3 m	Colour Sensor	Yes
SpectraLux	1.5 kbps	10 m	Spectrometer	Yes

Chapter 3

Optical System Design

The following three chapters will detail the design of the VLC setup. The design is split into three parts. First of all, is an optical part to make available the spectral components of a light source for modulation. Once the spectral components are made available, we then need a device to modulate data onto these separate components. Lastly, a receiver is required that should be able to decode the data in this multi-channel communication setup.

In this chapter we will start by taking a look at the optical design. The optical part is build around the transmitter. Its task is to reveal the wavelength components of a light source, as discussed earlier, but also to recombine these components back into a single light beam after modulation. We fill find out why and how this is done in three steps. First we will look at the theoretical, optimal design. Then some challenges will be introduced. And, finally, the resulting implementation will be shown.

3.1   Theoretical Design

In chapter 2 we learnt how light can be split up in its spectral components, either by using a prism or a diffraction grating. However, splitting the light is more involved than just placing one such element somewhere in a beam of light. Moreover, some extra complexity is added to make it perform well when combined with the transmitter. And, lastly, we still face the challenge of re-combining the spectrum. An important note is that a large part of the design is based on spectrometer design, as for example shown in [9].

To understand the full theoretical design, let us break it up in four stages. We will take a more detailed look at each stage and discuss its functionality in the complete theoretical design. But first the four stages are shown in figure 3.1.

Collimation   In the first stage we want to form a beam of collimated light. A light beam is said to be collimated if the rays are travelling parallel to each other, meaning that the beam is neither diverging nor converging. The light being collimated is a requirement for the prism or grating afterwards to cleanly break the light into its spectrum.
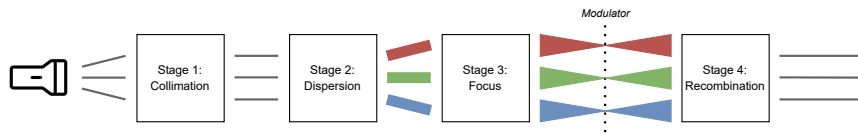
Figure 3.1: **Schematic overview of the stages of the optical setup**

To form a collimated light beam from a point source, a collimating lens can be used. To form a collimated beam from any source, we therefore first have to create a point source. The process is shown in figure 3.2. By shining the light through an aperture we create a point source with its origin at the aperture. Then a collimating lens can be placed. It should be placed at a distance from the aperture equal to the focal length of the lens. The lens will bend the diverging rays of the point source to become parallel. A big downside to this transformation is the use of the aperture. Because of this a lot of light intensity is lost, since only small part of the original light will pass through it. This seems, however, to be the cost that must be paid to create a beam of collimated light.
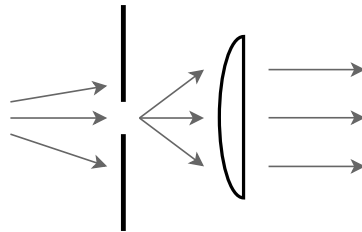

Figure 3.2: **An example of light collimation. Incoming light hits an aperture to create a point source. A lens is then used to form a collimated beam out of it.**

Dispersion   Stage two is where the actual breaking of the light takes place. With the light collimated, the theory presented in chapter 2 can be applied for both prism and diffraction grating. At the output of this stage, we can see the spectrum emerging. However, the beam is now diverging. Moreover, the separate colours are broad beams of parallel rays. A schematic of the breaking of the light and these two effects are shown in figure 3.3.

Focusing   To refocus the light and the spectrum, we add stage three. Another collimating lens is used here, as shown in figure 3.4. This lens actually performs two things simultaneously. First of all it stops the spectrum from diverging any further. Secondly, it focuses all rays of equal wavelength into a single point on the same plane. A modulator can now be placed in this plane, so that it can modulate the different wavelengths, by brightening or darkening these points in the space where the wavelengths are focused. By using this focusing element, a clearer image can be obtained, allowing to better separate the different wavelengths. Applied to the VLC transmitter being build, this results in better distinguishable channels.
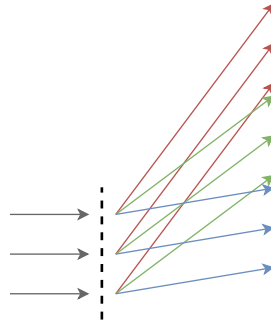
Figure 3.3: **Dispersion through a diffraction grating. Each wavelength is bend to a different angle. After some distance, the colours diverge far enough so they start to be non-overlapping. At that point we can see a spectrum emerging.**
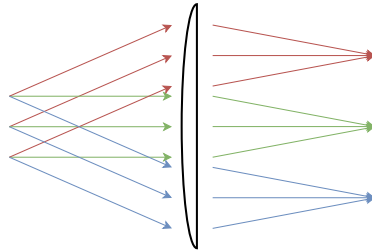
Figure 3.4: **Focusing lens after dispersion. Since the rays of a single wavelength are parallel to one another, they get focused to a single point.**

Recombination   The fourth and final stage recombines the spectrum back into a single ray of light. At the output of this stage, we want to recreate the collimated beam as created by stage 1. Since the used optical elements are actually reciprocal, this can be done by applying the inverse of stages 3 and 2. So, we use the exact same elements but now backwards to step by step go back to the collimated beam of light. There are two reasons why we want to go back to this type of beam. The first is that, because its a non-diverging beam, it should be possible to transmit over larger distances. The second is that in more advanced versions of this concept we likely want to use the source for the communication link as a normal light source as well. This means that we want approximately white light at the output.

3.2   Challenges

In the creation of the physical setup, some challenges had to be overcome. However, before discussing those let us take a look at the requirements of the optical design:

1. The creation of the spectrum should be such that it allows for the creation of distinguishable wavelength channels in a multi-channel VLC link.

2. The recombination of the spectrum should be such that beam divergence at the output is minimised to a point where a receiver at 5 cm distance is able to catch all wavelength components of a transmission.

It is important to note that these requirements are the very minimum of what must be achieved to be able to get the rest of the communication link working. The reason for choosing minimal requirements here comes from the fact that it was unclear upfront what performance was actually achievable. This is because of this work being a novel concept, but in part also because of a lack of expertise in optics design. Instead of going for high performance we will go for at least the minimal. Then, in the process we will see and evaluate how much is achievable, without going overboard on expenses, and what the expectations should be for future work on this.

Now let us take a look at why the optical design was challenging in the first place. The first challenge, actually, was finding a theoretical design that would be able to accomplish the desired functionalities of splitting and recombining the light. The resulting design has already been presented above. The other challenge is getting a high enough accuracy in the light transformations of each stage to fulfill both of the presented requirements. The accuracy depends on both the alignment of the optical components as well as on the accuracy of each individual component.

The combination of these challenges led to the development of an experiment rail. This rail helps in both enhancing accuracy in the alignment, as well as making it easier to replace components when testing different iterations of the theoretical design. The design of this rail is one of the things that will be shown in the implementation section below.

3.3   Implementation

Now, with the theory and the practical challenges in mind, we can finally take a look at the system as it has been implemented. A photo of the complete system can be found in figure 3.5. Below we will see, how this design came to be.

Component Selection   The component selection forms part of what determines the accuracy of the optical system. In general higher accuracy components are also the more expensive ones, as can be seen in table 3.1. Considering the exploratory nature of this work, it was opted to work with the cheaper, less accurate options, or in some cases what components were already available. Though less accurate these components are still at least able to satisfy the requirements as stated in the previous section.

With this first decision out of the way, there is only one more decision to make for the component selection. This is the choice between using a prism or a diffraction grating as a dispersive element in the final design. Both of these elements are expected to satisfy the requirements of above section. In the end the diffraction grating has been selected for the design for two reasons. First of all, the alignment of a diffraction grating is less critical than that of a prism. Especially an offset in the incidence angle of the incoming light beam can have a large effect on the output spectrum. Secondly, a diffraction grating creates a wider spectrum. This influences the number of pixels of the LCD that are lit by
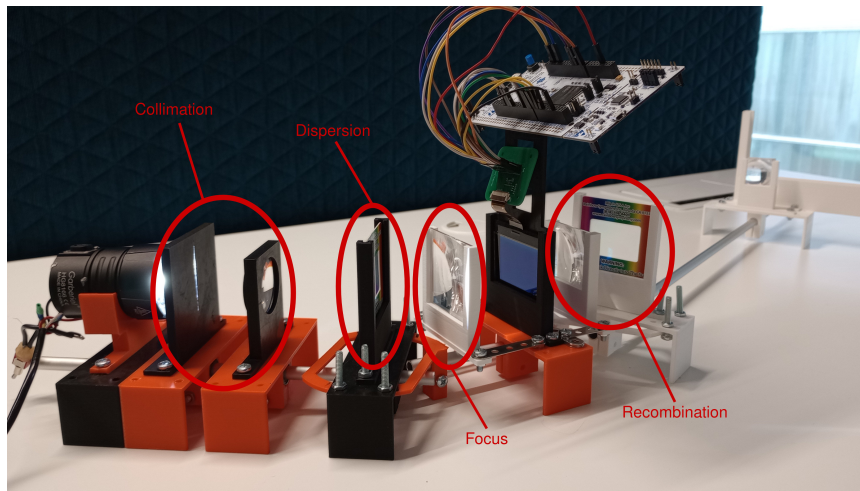
Figure 3.5: **Full test setup design**

the spectrum and thus the number of channels we can create. For this specific grating, 36 pixel columns are illuminated by the light and, therefore, we can expect to create 36 channels in the transmitter at most.

Component Mounting For the component mounting two things should be considered. The first of which is the accuracy in the alignment to satisfy the requirements. The other is the ease with which different optical elements and setups can be tested, without having to spend a lot of time on realignment of the test setup.

In order to do this a rail system has been created. 3d-printed railcarts can slide along a metal rod as shown in figure 3.6. In this particular figure, a lens is mounted on top of the cart, but it can also hold mounts for all the other components. Using this system, we can place different components and easily alter the distance between them. At the same time they can only move along one axis (following the red arrows), thus minimising misalignments in other directions.

One small complication is the fact that at the dispersive elements an angle is introduced in the setup, as can also be seen in figure 3.5. To account for this an extra element was 3d-printed as shown in figure 3.7. This element can hold a second piece of rail under an angle compared to the first piece. The piece can

Table 3.1: **Comparison of the prices of high end optical components (as sold from Thorlabs [21]) compared to components bought off Amazon. All prices are an approximate starting price in euros. The total is computed from an order of 4 lenses, 2 prisms and 2 diffraction gratings.**

	Lenses	Prisms	Diffraction Grating	Total
Amazon	5	5	1	32
Thorlabs	20	80	80	400

19

be rotated as indicated to adjust the angle θ.
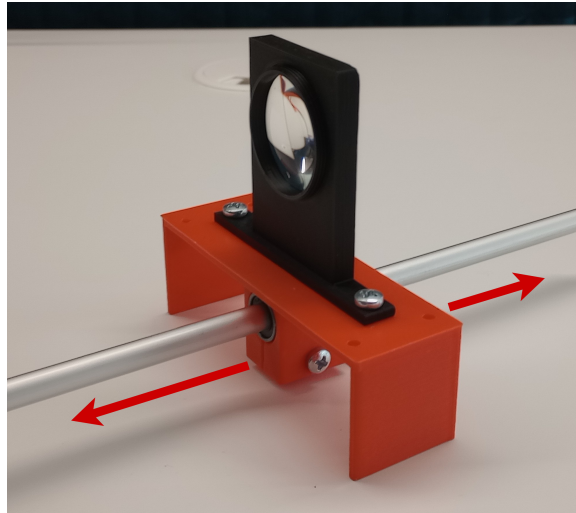
Figure 3.6: **Photo of a railcart (orange) and mount of a specific component (black). These carts are designed to slide over a metal rod such that their movement is constrained to the axis indicated by the red arrows. All component mounts can be mounted to the same railcart.**
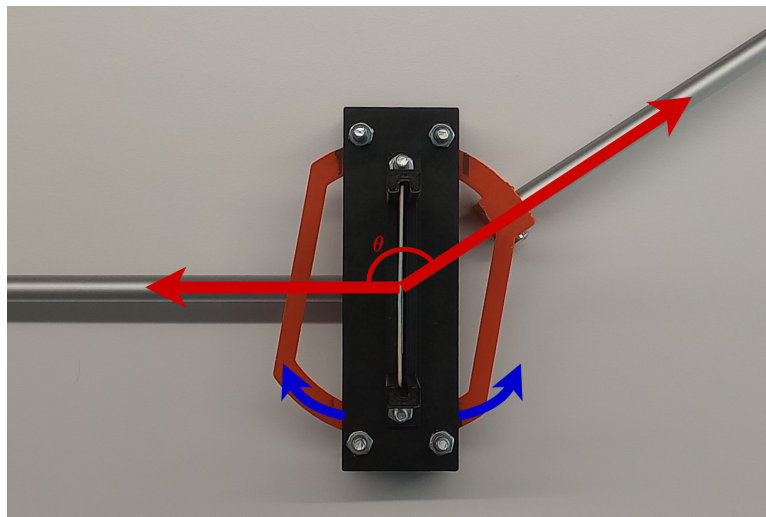
Figure 3.7: **Photo of a rotation ring (orange) placed under a railcart (black). The rotation ring can create an angular offset between two pieces of rail (θ). The rotation ring can be rotated relative to the railcart along the blue arrows, such that θ can be adjusted.**

Chapter 4

Transmitter Design

In this second design chapter, the transmitter of the communication link will be presented. First we will look at the hardware components and choices. After this the software designed to drive the transmitter will be presented as well.

4.1 Transmitter Hardware

To transmit some data we need something to modulate the spectrum created in Chapter 3. We also need a micrcontroller to drive the modulator. And, lastly, the two must be interconnected. An image of this construction is shown in figure 4.1.
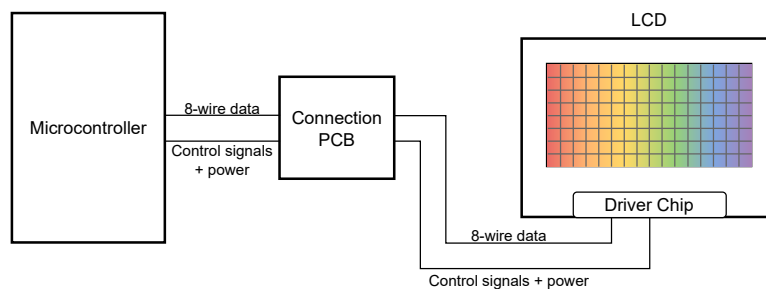

Figure 4.1: **Macro view of the LCD based transmitter.**

Modulator The main requirement for the modulator is that we need to be able to create multiple channels alongside one another. In Chapter 2 we have seen that both LCDs and DMDs are capable of this. A short summary of some other important traits is given in Table 4.1.

Table 4.1: **Summary of some traits of the LCD and DMD modulators.**

	Response Time	**Price**	**Driving Complexity**
LCD	milliseconds	10-100 euro	low
DMD	microseconds	60+ euro	high

Considering again the exploratory nature of the work, the LCD was chosen as the best option. The most important aspect is to be able to create multiple channels. Therfore, although the data rate is seriously lower for an LCD, due to its response time, price and ease of implementation were considered of higher importance.

The specific LCD that has been used is the `MIDAS MCCOG128064B12W-BNMLW` [15]. The specifications considered in this choice are the construction of the driver chip and the type of LCD. Both are important since we want to be able to deconstruct the LCD such that only the transparent layers remain and the spectrum can actually pass through the modulator. Ofcourse the response time is also very important, however, all available LCDs reported the same response time of around 250 ms.

The possible different layers of an LCD are shown in figure 4.2. In the end we want to deal with as little blocking layers as possible to ease deconstruction. Now, the driver chip option determines whether or not the PCB layer is present. The Chip on Glass option was chosen here as this means the driver chip is mounted onto the glass LC layer and the LCD will come without a PCB layer.

For the type of LCD a transmissive LCD screen was chosen. Other options would be reflective or transflective. In terms of light blocking layers, the transmissive LCD would only have a backlight, which from previous experience I was pretty sure I could remove cleanly. The other two types add a reflective film at the back of the LCD instead of or together with the backlight.

A note to add here is that these requirements left a blue LCD screen as the best option. This means that in its opaque state the LCD will turn blue instead of black. This, in turn, results in the inability to block the blue part of the spectrum. How this will affect the overall system is further discussed in the system evaluation in chapter 6.
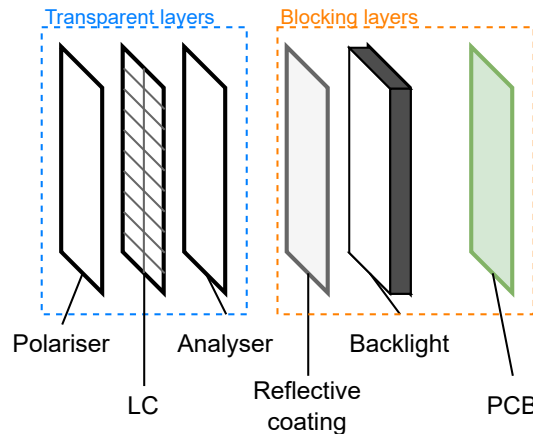

Figure 4.2: **Layers of an LCD. The blocking layers present in an LCD vary per LCD type. Therefore, LCDs may come with or without reflective coating and/or PCB.**

Microcontroller   The microcontroller should be able to communicate to the driver chip (Sitronix ST7565P) of the LCD. A readily available microcontroller

board was the `Nucleo-F446ZE` [20]. In terms of communicating with the LCD driver chip, it supports both Serial Peripheral Interface (SPI) and parallel interfaces advertised in the datasheet of the LCD. In terms of processing power the required software demands very little, and the Nucleo board is more than capable of delivering this.

Interconnection The connector cable leaving the LCD driver chip is a flat cable, so a conversion to a more compatible type of connection is required. Also, some additional capacitors are required for proper working of the chip's DC/DC converter and voltage regulator.

These two functionalities have been combined on a single interconnection Printed Circuit Board (PCB). The layout of this PCB is shown in figure 4.3. The LCD can be connected with a flat cable connector. For the connection towards the microprocessor a pin header is added. This allows for the use of jumper cables or a custom connector.

(a) (b)
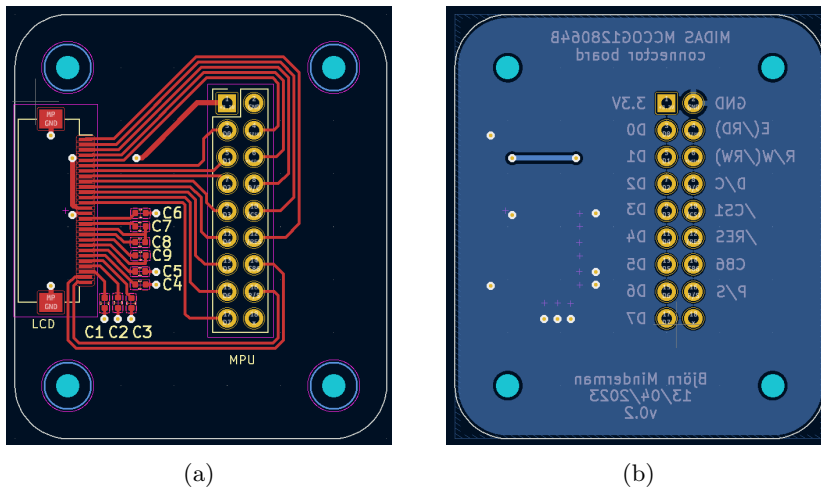
Figure 4.3: **Layout of the PCB forming the interconnection between the LCD driver chip and the microprocessor. (a) shows the front, and (b) the back side.**

The capacitors are chosen and placed according to the datasheets of the LCD itself, as well as that of the driver chip [15, 19]. The schematics of this circuitry are shown in figure 4.4.

4.2 Transmitter Software

The transmitter software is what will allow us to modulate a data sequence upon the light spectrum using the chosen LCD. Therefore, this piece of code must be able to transform a string of input data to the proper commands being send to the LCD to activate the right pixels. This transformation is done in a couple of steps, as shown in figure 4.5. Below we will go through them in a bottom up approach, starting from the communication protocol and ending up at the main file.

Figure 4.4: **Schematics of the supporting circuits for the voltage regulator (a) and the DC/DC converter (b) for the ST7565P LCD driver chip.**

First, however, it is important to get a basic insight in how the data is mapped to the LCD. This is shown in figure 4.6. An input string first gets divided in symbols. In the example we use a four channel transmitter, so eac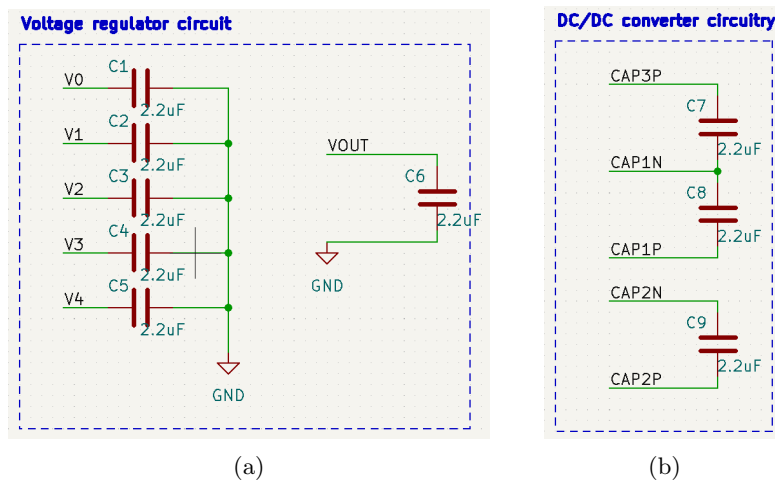h symbol should consist of four bits as well. The symbol is then mapped to an array to fill one page of the screen. Each bit maps to the pixels corresponding to the respective channels. All other pixels are set to 0. Writing this array to the LCD happens per column, so one column of the array is sent at a time to map to one column of the current page on the LCD. After a page has been filled column by column, we move on to the next page where we write the same data array column per column. This repeats until the screen is filled with the proper data.

For the actual screen there are 128 columns and 8 pages (64 rows). As can be seen from figure4.6, a channel is made up of a set of consecutive columns. How to best divide the columns over the different channels is a topic that will further be investigated in chapter 6. For now, let us take a look what are the steps taken in the software to perform the mapping of the data and write that to the LCD.

Communication Protocol For the communication with the LCD driver the parallel protocol was chosen over SPI. The reason for this being that while implementation complexity is roughly the same, the parallel protocol supports higher data rates.

The protocol works such that the LCD is seen as an extension of the Random Access Memory (RAM) of the microprocessor. Meaning that if we want to send a byte over the bus lines, we can do so by writing this to a specific memory address. Two addresses are specified, one for writing an 8-bit command to the driver chip, the other for writing data for the LCD to display.

Basis Command Set This layer contains the most basic communication functions. It has a function to write a sequence of data bytes to the LCD
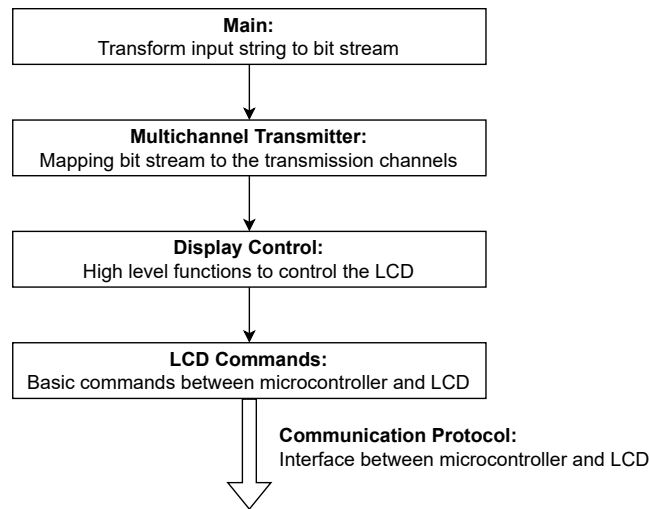
Figure 4.5: **Layers of the transmitter software. The arrows indicate the data flow through the layers, from the main to the actual communication link between microcontroller and LCD.**
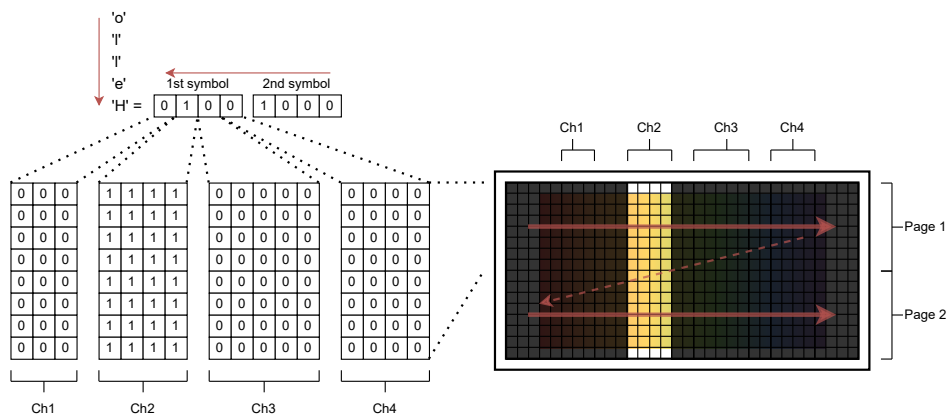
Figure 4.6: **An example of mapping data to the pixels of the LCD. The characters of an input string get converted to a bit sequence divided in symbols. Per symbol a mapping is made from the bit sequence to fill the channels on the LCD. Then the data is written to the LCD one page at a time.**

and a function to issue 8-bit control commands. All available commands are listed in the software for ease of use. The core of both functions is to simply write a byte to a specific memory address. In the end these commands are processed by the microcontroller to generate the right signals for the communication link. An example of a communication sequence on this most basic layer is given in figure 4.7.

When it comes to writing data for the pixels to display, usually one first has to set the page address and column address to which you would want to write.

Setting these pixel addresses is part of the available command set. An exception is when writing to consecutive columns on a single page. Namely, after writing data to a page/column combination, the column address is updated afterwards to increment by 1. This makes writing an entire page in a single run more efficient, which is handy to take into account when writing the rest of the code.

Display Functions   In this layer the basic commands of the layer below are grouped to more advanced functions. For example, a reset function will issue a hardware reset of the LCD and afterwards reinitialize all settings to their desired values.

The most important function here, however, is the `writeToDisplay` function. This function combines the commands to set the page and column addresses and sending the data to the selected pixels. Besides a single byte, this function also allows to write a byte array to consecutive columns on a single page.

Multichannel Transmitter   The transmitter layer forms the bridge between the LCD operating functions and using the LCD as a light modulating device. Here is where the channels are specified, both the number of channels and what pixel ranges they cover. Furthermore, it houses the functions that allow the transmission of data over these channels.

First of all, the data should be converted from a bit string to a byte sequence. This is done because a single bit in the data stream does not just control a single pixel, but instead all the pixels that belong to a single channel. Therefore, first the data is expanded into a byte sequence that can fill an entire page on the screen. Then this same byte sequence is communicated to the display for each page, thus filling the entire screen with the right modulation pattern.

The modulation itself is kept simple. Using On-Off Keying (OOK), a 1 in the bit stream translates to the pixels of a channel turned transparent, while a 0 translates to an opaque channel.

Main File   In the main file one can specify the message to be transmitted in string format. The bits that make up the string are shifted into an array. This array has the size of the number of channels of the transmitter. After a new batch of bits is shifted in, the transmission is initiated, and the data is processed through the other layers to be send to the LCD.
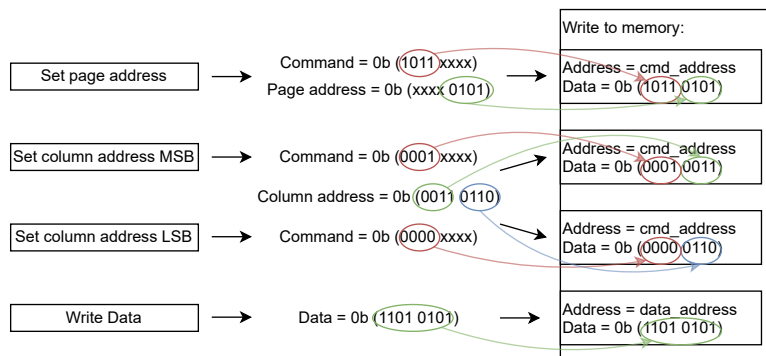
Figure 4.7: **Example of a command sequence to drive the LCD. In this example the pixel addresses are chosen by setting a page and column address. After doing so data can be written to the selected pixels. Note that in the last step we write to a different memory address.**

Chapter 5

Receiver Design

To conclude the design is a chapter about the receiver. As for the transmitter this includes a piece of hardware and software. The hardware will be detecting the light, the different colours and changes in intensity. It is then up to the software to make sense of the received signals and process them to decode back to the message that was transmitted in the first place.

5.1   Receiver Hardware

The detector requires a piece of hardware that should be capable of two things mainly. First of all, it should be able to detect light intensities and changes in them. Secondly, it must be able to distinguish between wavelength components to be able to distinguish between the channels.

We will be reviewing the same receiver options as presented in chapter 2. Some more technical details will be introduced and, based on those, one of the three options will be selected for the final design.

To recap, the three options presented before are: a colour sensor, a camera and a spectrometer. To make a decision between them, their important technical details are presented in table 5.1. For a quick validation of the designed system, it was decided to use a camera as a receiver as this option requires no driver software to be written. As we can see from the table this will mean lower sampling rates and less channels. The sampling rate of the receiver specifically is however not a limiting factor in this system as we will see in chapter 6. The low number of channels is unfortunate, but at least we can still validate the creation of a multi-channel VLC system. The specific camera used is that of a Motorola Moto G31 smartphone, which can sample at 30 Hz.

Table 5.1: **Technical specifications for the possible receiver options.**

	Sampling rate (Hz)	**Number of channels**	**Driver software required**
Colour sensor [1]	20	3-11	Yes
Camera	30-120	3	No
Spectrometer [10]	13 k	288	Yes

5.2 Receiver Software

Now that the camera has been chosen as a receiver, let us take a look at the software to process the video captures of a transmission. The decoding of the videos requires two components working together. These components are some image processing functions and a state machine for the decoding. Both are detailed below.

Image Processing   All image processing functions are combined in a single class. An image can be loaded into an object created from this class, so all functions have easy access to the current image being processed. A list of the relevant functions and a short description can be found in table 5.2.

Table 5.2: **A list of the written image processing functions along with a function description.**

Function Name	Description
roiDetection	Determine the area where the transmitted light beam is incident on the image. This is done by setting a threshold for the light intensity. All pixels with a grayscale intensity above the threshold are considered part of the ROI. Based on this a mask is created to single out the ROI in later images.
setMinMaxValues	This function aids in finding a threshold for decoding a sample value as a 1 or a 0. It keeps track of a maximum and minimum value encountered across the samples. When a new value is either higher than the current maximum or lower than the minimum, the respective variable is updated.
getThreshold	Function to set a threshold to determine if a data sample is considered a 0 or 1. The threshold for each channe; is chosen as the average value of the currently stored maximum and minimum value of that channel (see setMinMaxValues).
readValue	This function determines a value per colour channel of the camera, used for further processing afterwards. The value is determined as the average value for all non-zero pixels. Since a ROI mask is already applied when loading an image into the object, the average colour values of the pixels within the ROI are obtained.

Decoder   The actual decoder comes in the form of a state machine that makes use of the image processing functions. A schematic overview of the state machine can be found in figure 5.1. Frame by frame the video is being processed by this state machine to try and retrieve the transmitted data. To keep the amount of data processing manageable, the camera is set to a low resolution at 640 by 480 pixels.

Let us now see how the decoding works, following the state machine and the example data provided in figure 5.2. The decoding process starts by finding the pixels of the camera that are actually influenced by the light from the

transmission. Using the `roiDetection` function, this region is determined at start up. After creation of a mask for the ROI, this same mask is applied to every new image being loaded. For each masked image the values per channel can then be computed using the `readValue` function.

With the masking applied, two parameters need to be determined. To avoid making the system unnecessarily complex, it is assumed that the symbol period is already known at the start of the decoding. The symbol period in the example is 1 second, or 30 frames. Then, the only other parameter to be determined is the threshold per channel. To this end the `setMinMaxValues` function is run for a couple of periods to find some extreme values. In figure 5.2 these values are indicated by the cross markers. The `getThreshold` function then uses these values to set a threshold per channel as the average of the minimum and the maximum, as is indicated by the dashed grey line.

To know at what frame numbers to sample, threshold crossings are used as synchronisation points. The detection of such crossings is shown as an orange vertical line. In the detect threshold state we wait for the first detection of a crossing in either channel. After a crossing has been detected the data sampling can start.

Data is being sampled at the blue lines. Above the threshold a logic 1 is sampled, below it a 0. The basic principle here is to sample at every symbol period, which means sampling every 30 frames. However, when new threshold crossings are detected these are used to re-synchronise the sampling. The latter will counter a possible drift in sampling times due to uneven frame rates of the camera.

The data sampling continues throughout the detect preamble state until a preamble is detected in the decoded data. Then we move on to the last state where the data bits of the actual message are decoded. This state terminates when a newline byte is decoded, signalling the end of a message. Finally, the process loops back to the detect preamble state to wait for the start of a new message.
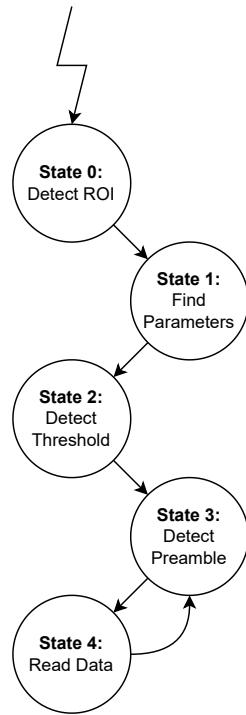
Figure 5.1: **State machine of the receiver code.**

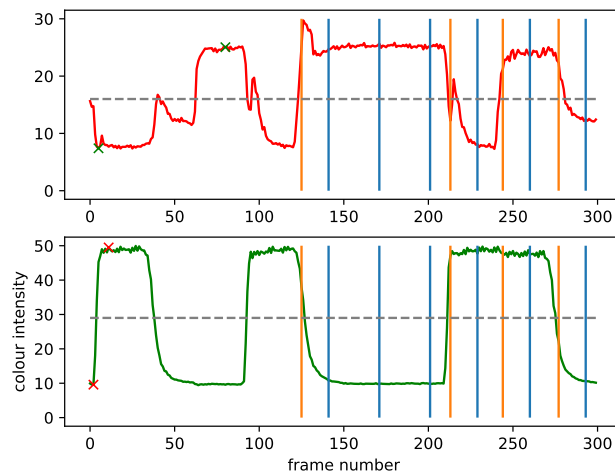

Figure 5.2: **Example plot of data decoding for two channels. At the start of a decoding the minimum and maximum values are tracked (indicated by the crosses). Taking the average of the minimum and maximum sets a threshold (dashed grey line). Then we wait for a threshold crossing in either of the channels (orange lines). Finally the blue lines show at what frame numbers the data is sampled.**

Chapter 6

Evaluation

With the design complete, it is time to evaluate that design. For this evaluation we are mostly interested in the number of channels we have been able to create and what data rate has been achieved. We will also take a look at some of the design choices made earlier and their influence on the performance of the complete system.

6.1 Theoretical Performance

Before heading over to the results, let us first quickly recap the theoretical system performance. The main reason for introducing a passive VLC system with multiple colour channels is to enhance the data rate. The data rate is determined by two factors: the bandwidth of transmitter and receiver and the number of channels (equation 6.1).

$$R = B \cdot \text{nr\_channels} \tag{6.1}$$

The limiting bandwidth is that of the transmitter at 2.63 symbols per second. To get to this bandwidth an additional factor was taken into account besides the LC response time of 250 ms. This other factor is the amount of time it takes to write data to not one, but all pixels of the LCD, and this is mentioned to take 130 ms as well [19]. The new bandwidth is then computed as $1/(0.250 + 0.130) = 2.63$ Hz. For the number of channels the camera as a receiver is the limiting factor, supporting only three channels. Therefore, at most we can expect a data rate of 12 bits per second. A summary of these parameters is also shown in table 6.1.

Table 6.1: **Transmitter and receiver bandwidth and number of channels. These factors together will determine the maximum achievable data rate. The limiting factors for both bandwidth and number of channels are displayed in red.**

	Bandwidth	Number of channels
Transmitter LCD	2.63 Hz	128
Receiver Camera	15 Hz	3

Another important aspect of the performance of any wireless communication link is the maximum transmission distance. In theory, the range is only limited by the light being dispersed through the air. This would mean tens to hundreds of meters should be achievable. This is, however, under the assumption that at the output of the transmitter the light forms a perfectly collimated beam. In practice we will see that this is not achievable and some dispersion takes place after wavelength recombination at the output of the transmitter.

With the theory in mind, the following section will show how the implemented system holds up to the predicted performance.

6.2   System Evaluation

The system evaluation will take into consideration all of the aspects mentioned in the theoretical performance as well. We will take a look at the maximum number of channels that can be created in practice, then the transmission/reception bandwidth will be investigated and, lastly, the transmission distance will be evaluated.

Number of Channels For the maximum number of channels, the receiver seems to be the limiting factor, since a camera only knows three colour channels. For the implemented system, however, the number of channels had to be reduced to two channels even. The reason for this is illustrated in figure 6.1.
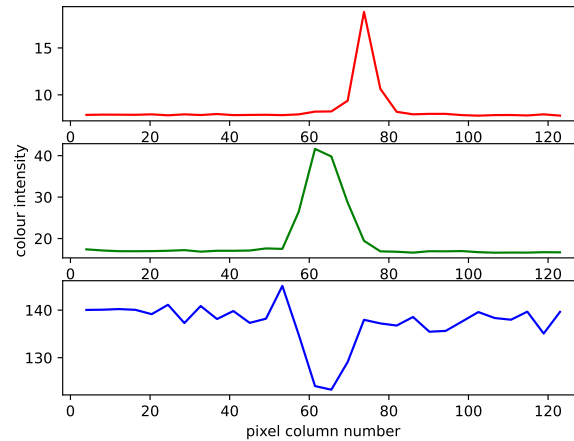
Figure 6.1: **Receiver response to consecutively switching on and off the pixel columns of the LCD transmitter. The three plots each represent one of the three colour channels of a camera, from top to bottom: red, green and blue.**

In this figure, the red and the green channels show a response as can be expected. When columns of the LCD in their wavelength regions are turned on, an increase in the measured intensity value is detected. The same can however not be said for the blue channel. What would be expected is another

peak, further to the left compared to the green channel. We see a very small peak around pixel column 50, however, not enough to create decodable signals. Furthermore, a much larger dip is observed when the columns in the green region of the spectrum are turned on.

The small peak for the blue channel can be contributed to the choice of a blue LCD screen. When a pixel is turned on it is transparent and colourless, while in its off state it basically turns into a blue colour filter. Therefore, in its off state it blocks all wavelengths but the blue part of the spectrum. Since blue light is allowed through no matter the state of a pixel, the transmitter is unable to very effectively influence this part of the spectrum. The dip in the blue channel is another story. A problem here is that because the blue and green receiver channels respond to largely the same part of the spectrum, there will be a lot of interference between the channels. A possible source of this behaviour might be the calculation of the receiver channel values done by the camera software. It could be that if more green is detected, the blue value is adjusted downwards. More research is required, however, to find the exact reason.

Two techniques were attempted to still be able to reduce Inter Channel Interference (ICI) and recover the blue channel. First, the channels can be spaced some distance apart to reduce their effect on one another. Secondly, if the channels are distinct enough, the overlap might be removed through some matrix calculations.

First of all, the channel separation was attempted by leaving some part of the spectrum in between the channels blocked at any time. An illustration of this method is shown in figure 6.2. As can be seen from this figure, there generally is an overlap in the wavelength response of the different receiver channels. On the right it is shown that when the channels are separated a bit, the overlapping parts can be (partially) removed from the channels. Though this technique decreased the ICI for the red and green channel, and was kept in the design for this reason, the blue channel was still irrecoverable.
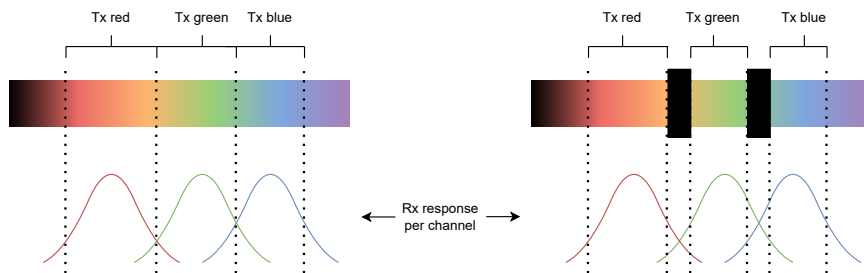
Figure 6.2: **Illustration of how channel responses of the receiver may overlap for certain parts of the spectrum. Leaving the overlapping parts out of the transmission channels as shown on the right side, will reduce the interference between the channels.**

As a second attempt there are the matrix calculations, to try and recover the transmission values per channel. The matrix calculations are based on a model presented in equation 6.2. This equation tells us how to compute the receiver values per channel ($\mathbf{r}$) from the transmitter values ($\mathbf{t}$), the influence of each

transmitter channel on each receiver channel (A) and ambient light values per channel ($\mathbf{c}$). Also, an example of what the equations would look like for three channels is given in equation 6.3

$$\mathbf{r} = A\mathbf{t} + \mathbf{c} \tag{6.2}$$

$$\begin{bmatrix} r_0 \\ r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} A_{00} & A_{01} & A_{02} \\ A_{10} & A_{11} & A_{12} \\ A_{20} & A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} t_0 \\ t_1 \\ t_2 \end{bmatrix} + \begin{bmatrix} c_0 \\ c_1 \\ c_2 \end{bmatrix} \tag{6.3}$$

Now, in the ideal case A would be a diagonal matrix, as this would mean every receiver channel is only influenced by the corresponding transmitter channel. In other words, every element in A not in the diagonal represents an interference term between two channels.

Of course, before calculations can be done using this equation, first the parameters must be estimated. This can be done by transmitting a sequence of known symbols. For the first symbol all transmitter channels are set to zero to estimate $\mathbf{c}$. Afterwards, the channels are turned on one at a time to estimate one column of A at a time. How this works for three channels is shown in equations 6.4 - 6.7.

$$\text{For } \mathbf{t} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \Rightarrow \begin{bmatrix} r_0 \\ r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} c_0 \\ c_1 \\ c_2 \end{bmatrix} \tag{6.4}$$

$$\text{For } \mathbf{t} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \Rightarrow \begin{bmatrix} r_0 \\ r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} A_{00} \\ A_{10} \\ A_{20} \end{bmatrix} + \begin{bmatrix} c_0 \\ c_1 \\ c_2 \end{bmatrix} \Rightarrow \begin{bmatrix} A_{00} \\ A_{10} \\ A_{20} \end{bmatrix} = \begin{bmatrix} r_0 \\ r_1 \\ r_2 \end{bmatrix} - \begin{bmatrix} c_0 \\ c_1 \\ c_2 \end{bmatrix} \tag{6.5}$$

$$\text{For } \mathbf{t} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \Rightarrow \begin{bmatrix} r_0 \\ r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} A_{01} \\ A_{11} \\ A_{21} \end{bmatrix} + \begin{bmatrix} c_0 \\ c_1 \\ c_2 \end{bmatrix} \Rightarrow \begin{bmatrix} A_{01} \\ A_{11} \\ A_{21} \end{bmatrix} = \begin{bmatrix} r_0 \\ r_1 \\ r_2 \end{bmatrix} - \begin{bmatrix} c_0 \\ c_1 \\ c_2 \end{bmatrix} \tag{6.6}$$

$$\text{For } \mathbf{t} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \Rightarrow \begin{bmatrix} r_0 \\ r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} A_{02} \\ A_{12} \\ A_{22} \end{bmatrix} + \begin{bmatrix} c_0 \\ c_1 \\ c_2 \end{bmatrix} \Rightarrow \begin{bmatrix} A_{02} \\ A_{12} \\ A_{22} \end{bmatrix} = \begin{bmatrix} r_0 \\ r_1 \\ r_2 \end{bmatrix} - \begin{bmatrix} c_0 \\ c_1 \\ c_2 \end{bmatrix} \tag{6.7}$$

Once the parameters are known, the equation can then be inverted to go from receiver values back to transmission symbols. This is shown in equation 6.8.

$$\mathbf{t} = A_{inv}(\mathbf{r} - \mathbf{c}) \tag{6.8}$$

A comparison of a capture with and without correction through matrix calculations is shown in figure 6.3. Here it can be seen that the red and green channel after conversion are very similar to the actual data being transmitted. For the blue channel, on the other hand, this is unfortunately not the case. Instead it resembles much more the inverse of the green square wave with extra noise added. In conclusion, we can only use the red and green channel.

Bandwidth For the bandwidth the theoretical limiting factor would be the bandwidth of the LCD, resulting in transmissions of maximum 2.63 symbols per second. And as we have seen a transition should, therefore, take around 380 ms. In the actual received data the fall time was concluded to be the bottleneck.
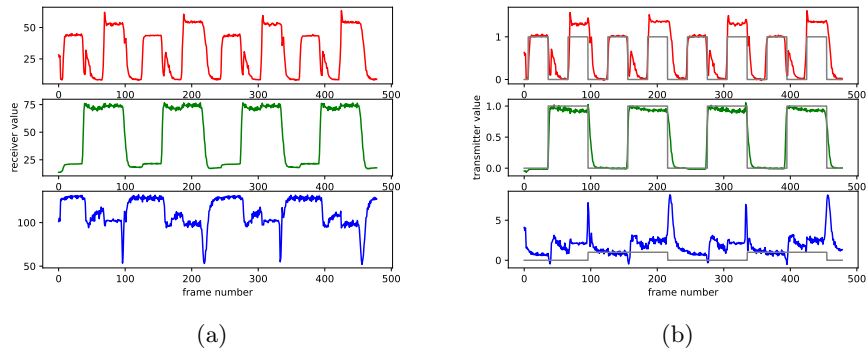
Figure 6.3: **Two plots of the same capture. (a) shows the received data, without matrix calculations. (b) shows the computed transmitted values after matrix calculations, as well as the actually transmitted square wave in grey.**

For both channels it was observed that the fall time takes around 10 frames on average. At 30 fps, this would equal 333 ms. This is actually a little bit faster than expected. The reason for this is that the spectrum mainly hits the top half of the screen. Therefore, the bottom few pages of the LCD, which are updated last, do not contribute to a channel transition. This is what makes the transitions end slightly earlier.

Transmission Distance   In the ideal case, the transmitted ray of light would form a perfectly collimated beam. In practice, however, this was not achieved, and the beam is diverging into its spectrum once more. To still be able to capture all the wavelengths in the transmission, a lens has been placed in front of the camera, to roughly focus all colours back to the same point as shown in figure 6.4.

The lens used here has a surface of 30 x 30 mm. This means that the lens is only able to capture the full spectrum if its divergence is limited to a width of 30 mm. Since this limit is reached at 40 cm from the transmitter output, the transmission distance is limited to 40 cm as well.
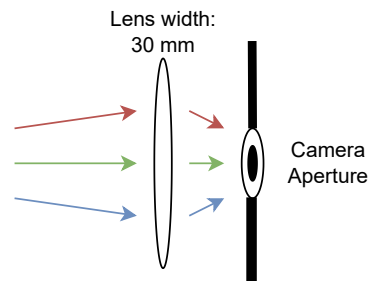

Figure 6.4: **In front of the receiver camera a lens is placed to refocus the diverging spectrum towards the camera aperture.**

6.3 Performance Evaluation

To get an idea of the performance of the VLC system, some transmissions have been captured and decoded. The structure of the message that was sent can be found in figure 6.5.

Preamble (1 byte)	Data (13 bytes)	Newline (1 byte)
0x16	"Hello, World!"	0x0A

Figure 6.5: **Graphic of the transmitted message, along with its preamble and newline character.**

The evaluation has been done for two different symbol periods and three different distances. For each setting, three captures have been taken, each containing three times the `Hello, World!` message. The results are presented in tables 6.2 and 6.3.

Table 6.2: **Performance evaluation of the communication link for total data rates of** 2 **and** 4 **bits per second, at a transmission distance of** 3.5 **cm.**

Symbol Period	1000 ms	500 ms
Preamble Found	100 %	78 %
BER	0 %	2.20 %

Table 6.3: **Performance evaluation of the communication link at distances** 3.5, 20 **and** 40 **cm, for a symbol period of** 1000 **ms.**

Distance	3.5 cm	20 cm	40 cm
Preamble Found	100 %	100 %	78 %
BER	0 %	0 %	0 %

In these tables the preamble found rows show what percentage of the messages was actually detected by the decoder. The Bit Error Rate (BER), on the other hand, shows how many of the total number of bits of a message were decoded to a wrong value. For the BER only the messages for which the preamble was detected are counted.

What we can see in these tables is that for the base case all messages could be decoded without error. Also, at a slightly larger distance of 20 cm, all messages were decodable. This means that the system works properly up to a data rate of 2 bits per second, and up to a distance of 20 cm. However, issues start to occur for larger distances (of 40 cm) or when the data rate is increased to 4 bits per second.

What is interesting to note as well, is that sometimes relatively few preambles are found, while BERs are not so high. What was observed is that while the decoder is locked on properly to a data stream, it can decode long sequences without error. However, as soon as an error occurs it can get locked in decoding wrong values as well. Therefore, when one preambles is decoded wrong and remains undetected, the next one is likely to be the same. Since these missed

packets are not counted against the BER, the BER will remain relatively low.

Now let us consider what happens when the data rate is increased. By increasing the data rate to 4 bits per second, the decoder is having a harder time to find the right moment to sample. This is due to the fact that the transitions start taking up a significant amount of the symbol period, thereby decreasing the amount of time a valid sample can be obtained. Therefore, sometimes wrong values are being sampled resulting in bit errors or packet losses. Going to even higher data rates, renders the messages completely undecodable.

For the longer distance of 40 cm, it was observed that the amplitude of the received signal is rather low, likely causing the errors in the decoding. The reason for the low amplitudes compared to the short distance transmission is the divergence of the light spectrum. This can be explained using figure 6.6.

Over short distances, the total ROI in the captured recording is relatively small. Over longer distances, however, the ROI is much larger. In case of the latter, the same amount of energy is split over more pixels, resulting in lower average colour values per pixel. A consideration could be to either get a brighter source or to use something other than the average colour value per pixel as indicator for a channel value to compensate for the spread.
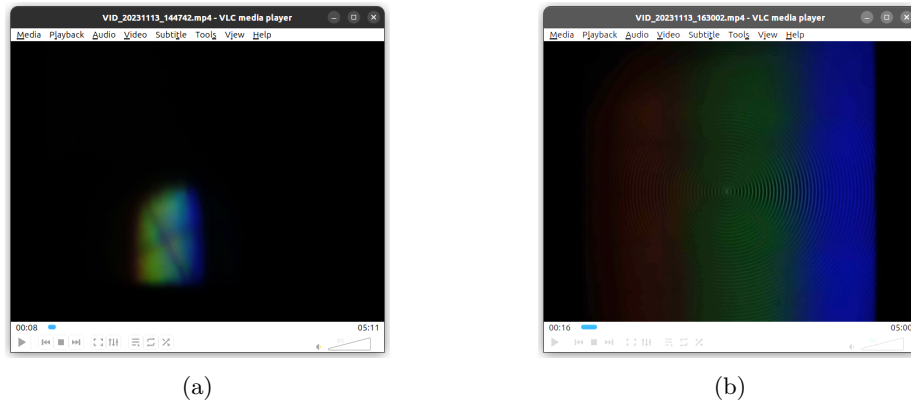

| (a) | (b) |

Figure 6.6: **Screenshots of two different captures of a transmission. (a) shows a transmission over a short distance, where the spectrum is contained to a small region. (b) shows a transmission over a longer distance, where the spectrum is spread over an entire frame.**

6.4   Discussion

In the evaluation it was proven that the system is capable of passive VLC over two channels. The resulting total data rate is 2 bits per second for a transmission range of up to 20 cm.

Especially the data rate of this system can be considered rather low. However, from the evaluation some steps can be suggested that should help to improve this low data rate in future works.

The most important takeaway is to consider another transmitter receiver pair. For the transmitter, a Thin Film Transistor (TFT) LCD could be considered

[18]. These were unfortunately overlooked in the LCD choice for this thesis, but they support higher bandwidths than traditional LCDs in the order of tens to hundred Hertz. Also, a coloured LCD should be avoided, since it introduces interference in some of the channels. For the receiver a spectrometer should be considered. Not only does it offer more channels than a camera, but it can also sample at faster rates.

Another advantage of getting a spectrometer would be that much more detailed information about the entire transmission and optical setup can be obtained, since it is a much more fine grained measurement tool.

These two improvements alone, should result in much higher data rates already. From there on it would be interesting to see how much channels can be created without causing too high levels of ICI. And eventually gradual improvements to the optical system and the receiver code can be implemented to really get the most out of the system.

Chapter 7

Conclusions

In this thesis we have been taking a look at a new passive VLC concept. It was discussed how data rate is currently a limiting factor of passive VLC. In this thesis specifically, it has been investigated whether this might be improved by creating a wavelength based multi-channel communication system based on dispersion of light. This led to the following question being asked:

How can light dispersion be used in a passive VLC system to create a multi-channel communication link and boost overall data rates?

This question has been answered by creating such a multi-channel communication system and evaluating its performance. The design was divided in three steps:

1. An optical part, used for dispersion of light.

2. A modulation device, used for transmitting data.

3. A receiver, used for detecting and decoding a transmission.

The main performance metric for the combined system was the data rate, calculated as the bandwidth of the system multiplied by the number of channels. From the experiments we can report a stable system at a data rate of 2 bps, some decoding errors at a rate of 4 bps and undecodable data at higher rates. Compared to other passive VLC systems these are low data rates. The reason for this is twofold. The first is that only 2 channels are available in the final design, due to the combination of the chosen transmitter and receiver. Secondly, the bandwidth of the transmitter is very limited at 2.63 Hz.

Another metric that has been assessed is the transmission distance. Here the limitation lies within the optical system. Due to beam divergence at the output of the optical system, the current transmission range is limited to 40 cm.

Though the performance is low, it should be considered that this thesis presents a new concept for passive VLC transmissions. A lot of insights have been gained, in the challenges this concept presents, but also how to make improvements on the current system. Most importantly, it is still believed that the presented concept can provide data rate enhancements compared to the current

standard, by creating a multitude of transmission channels. Below suggestions are given for directions future work might take.

7.1 Future Work

With only the very basics of this multi-channel passive VLC system explored, there is a lot of room for further research and further improvement. Below we will take a look at some possibilities that would have the biggest positive impact on performance, or might present another interesting take on the system.

- **Transmitter**: The transmitter, together with the receiver is responsible for the low data rates. Other options here would be TFT LCDs or DMDs. Both would provide higher bandwidths (tens of Hz at least) and thus higher data rates.

- **Receiver**: As a receiver it is suggested to have a look at spectrometers. This is expected to scale the number of communication channels up to 10 to 100+ channels. Combining a new transmitter with a new receiver is thus expected to improve the current data rate at least by a factor of 100.

- **Measurements on optical system performance:** Getting a spectrometer in the system also allows for more detailed measurements on how well the optical system performs. For example, one could start to measure how many wavelength components are actually distinguishable or, what wavelengths are actually present at the different stages of the optical system and how they are influenced throughout these stages.

- **Add diversity to measurement conditions:** All measurements so far have been done in the same room under the same lighting conditions. It would be interesting to see how the system might react to different conditions and make it robust against changes in these conditions.

- **Laser pulse shaping research [17]:** Laser pulse shaping is a technique to shape a laser pulse by altering its wavelength components. To do so, it applies very much the same principle of dispersion and recombination as was used for the communication system of this thesis. It would be interesting to see what can be learned from this technique that could be applied to passive VLC as well.

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