Delft University of Technology
Master of Science Thesis in Embedded Systems

Passive Visible Light Communication

Utilizing the Unstable Region Of Liquid Crystals

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Embedded Networked Systems

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Abstract

As more and more devices have become wireless, the traditional Radio Frequency (RF) spectrum has become densely populated. To relieve this pressure, communication using light, visible light communication (VLC), has been proposed by many researchers. However, not all light sources can be modulated to transmit information. Therefore, the use of materials that can change their state between translucent and opaque has often been investigated in order to modulate light. ChromaLux is a recent system that uses such a material. It uses Liquid Crystal shutters to transmit information. However, instead of a single crystal, a stack of crystals is used, which exposes an extra transient region. This transient region shows several peaks that allow faster communication, but makes the system unstable. This thesis addresses several issues that ChromaLux experiences, in order to improve the performance.

The system is changed from open-loop to closed-loop, creating a stable system that reaches higher speeds. However, in order to achieve this, part of the crystals is blocked, causing a lower Signal-to-Noise Ratio (SNR). For shorter distances up to 1m, we are able to increase the data rate by 140 %, while at longer distances of up to 3m we achieve an increase of up to 92 %. A second improvement which increases the SNR of the system, is the smart use of differential amplification. This allows communication at even greater distances of at least 5 meters.

Preface

For many years, the Internet of Things (IoT) has drawn my attention. As battery powered devices require a low power solution for communication, passive light communication could become a major player in the field. This thesis explores a new method of passive light communication, and is made as a completion of my master in Embedded Systems.

I would like to thank several people that helped me to accomplish this thesis. My supervisors Koen Langendoen and Keyarash Ghiasi were always willing to help and have had valuable input. Furthermore, I would like to thank my parents and girlfriend for their continuous support and constructive comments on this thesis.

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Chapter 1

Introduction

Wireless communication has been around for centuries. As early as the 3rd century B.C., light has been used to transmit information. The ancient Greeks developed a method with torches to communicate between two places. By using ten different torches at one location, every Greek letter could be represented, at a distance of up to 100 km [22]. Another famous example is the use of signal lamps in the navy. They were engineered by the British Royal Navy in the 19th century, and were used to transmit codes by blocking or passing light from a lantern [11].

Nowadays, wireless communication mostly uses the traditional Radio Frequency (RF) spectrum (e.g. Bluetooth, Wi-Fi, GSM). As more and more devices are connected using this spectrum, it becomes crowded. A potential candidate to relieve this overload is yet again the use of light to transmit information. This is called visible light communication (VLC). The potential of VLC becomes evident when comparing the RF spectrum to the visible light spectrum. While the RF spectrum covers the frequency range of 30 Hz up to 300 GHz, the visible light spectrum covers 400 THz up to 750 THz [23]. Because this spectrum is over a thousand times larger, the bandwidth is also a thousand times larger, paving the road towards high speed communication. It should have great potential to contribute to solving the problem of the ever-increasing demand for communication. In addition, the use of the VLC spectrum is not licensed, meaning that it is free to use as opposed to the RF spectrum.

There are other benefits to VLC as well. Since light does not traverse through walls, the communication can be more secure, as a person that would want to intercept communication has to be in the same room, as well as in the path of the light. Another factor in favor of the use of visible light is the rising use of Light Emitting Diodes (LEDs), which can be instantly turned on or off. Using this property, the on and off states can be modulated to send *'0'*s and *'1'*s, which is called *active* VLC. Overall, VLC can piggyback on the rising use of LEDs.

Because of these benefits, the potential applications for VLC are extensive [18]. For example, Li-Fi [14], the analogous counterpart of Wi-Fi, uses light to create a high-speed communication system that could be used in locations that are sensitive to RF signals, such as aircraft and hospitals. Another application, that requires low latency communication, could be a vehicle safety system, in which vehicles can interact with for example traffic lights and other vehicles in order to avoid collisions [7]. A third application to identify the room or corridor the person is located, by using a visible light ID system [19]. Obviously, many other applications could be thought of, and have been seen as well.

While this active form of VLC looks very promising, and is already used in the wild, there are downsides as well. The most obvious one is the fact that a light should be constantly on in order to send information. In an office environment, in which lights are on at all times, this is not an issue. However, in a room that has a lot of windows, it is a waste of energy to keep the lights on at sunny times. In addition, the intensity of these LEDs is low, which causes the range of active VLC systems to be short. Finally, since LEDs are non-linear devices [37], it is not a simple task to modulate information using them, especially when more advanced modulation schemes are used.

Another approach of VLC, which solves the majority of these issues, is the use of *passive* VLC. As opposed to active VLC, passive VLC makes use of ambient light such as sunlight, or other readily available sources of light, to transmit information, which can be much more energy efficient. In addition, some ambient light sources produce light containing the complete visible light spectrum as well as in much higher intensities, which therefore has great potential [10]. However, it is more difficult to use ambient light sources, as they cannot be turned on or off. New methods of modulation have to be created for passive VLC, as well as new materials to make this sort of communication possible. Examples of such materials are Liquid Crystals, micro mirrors and Fluorescent Light Communication. This provides a possibility to use VLC in low-power devices, such as Internet of Things (IoT) devices.

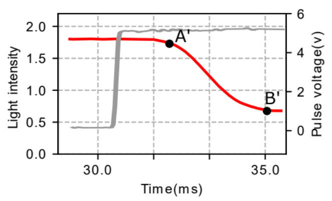
1.1 Passive VLC

There are several studies that make use of passive VLC, and in particular the usage of Liquid Crystals to modulate ambient light. Liquid Crystals are materials that can switch between opaque and translucent states by applying a voltage. However, these crystals behave similar to capacitors, making them slow in changing states. The most basic systems reach data rates of several bits per seconds [6, 20, 26], while more advanced systems reach speeds of several thousand bits per second [31, 33, 35] at different ranges.

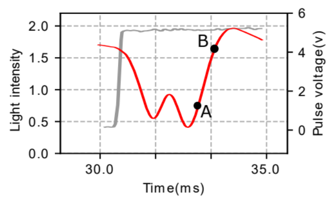
It is difficult to compare the state-of-the-art in (passive) VLC as authors typically present the results of their systems in situations at which they excel. Moreover, they barely make mention of the all-important trade-off that has to be made: data rate or communication at long distances. Reaching high data rates at low distances probably means that communication at long distances cannot be achieved. Another observation is that the systems that reach high speeds, usually do this by combining multiple channels in parallel.

Another important factor for communication quality which is often overlooked in these systems, is the Bit Error Rate (BER). This BER can be an efficient way to compare performance of systems. A high data rate means nothing if this is accompanied by a high BER. Finally, passive VLC systems generally make use of a 'binary view'; the crystals can be opaque or translucent, and any intermediate states are ignored.

These issues need further investigation. One study that takes the first steps to solve these issues is ChromaLux [13]. ChromaLux reveals a new transient state when multiple crystals are stacked on top of each other, creating a non-monotonic transition region, which allows high contrast[1] symbols as well as low transition times. Figure 1.1a shows the response of one Liquid Crystal, while Figure 1.1b shows the response for a stack of Liquid Crystals, exposing a transient state. For a stack of six crystals, multiple peaks and valleys can be seen in the same amount of time. Usually, a trade-off has to be made between high contrast of symbols and high bandwidth. However, ChromaLux is able to create a high contrast symbol, while also keeping the transition times low (like symbol A and B), resulting in a high range of communication and a high bandwidth.



(a) **Monotonic transition of a single liquid crystal. Usually a trade-off is made between high contrast (vertical axis) and high bandwidth (horizontal axis). For example, A' and B' can have a high contrast but a slow transition time.**



(b) **Transient state when using a stack of liquid crystals as uncovered by ChromaLux. By using this transient state, symbols like A and B can have a high contrast, as well as a low transition time.**

Figure 1.1: **Monotonic transition region and the transient region uncovered by ChromaLux. The red line represents the transition of one or more Liquid Crystals following from a $0-5V$ swing in input voltage represented by the grey line.**

ChromaLux takes advantage of the transient region by using a novel modulation scheme to send bits. To send a *'0'*, the system is kept at symbol B, by applying a static voltage. To send a *'1'* the system creates an B-A-B transition, in order to have a V shaped signal. This signal is received by a color sensor, with a lens in front of it, to direct the light. This creates the possibility to achieve speeds of up to 1 kbps at distances of up to 50 meters, while the state of the art either reach similar or higher speeds at much lower range, such as 1 meter.

1.2 Problem Statement

ChromaLux is not perfect. Although its approach is new and exciting, there is more potential. Because the crystals operate in an unstable region, drift occurs during transmission of symbols, which causes difficulties when demodulating the signal on the receiver side. Therefore, higher speeds are impossible, and as a result the BER is high. This BER is manageable for speeds up to 1 kbps,

[1] As the contrast is closely related to the Signal-to-Noise Ratio (SNR) (noise mostly remains at similar levels), we use contrast and SNR interchangeably throughout the rest of this thesis.

keeping it under 1 %, but as soon as the speed increases, the BER quickly increases to levels well above 1 %.

Another issue is that ChromaLux is not adaptive to the amount of incoming ambient light. To start the system, the system has to be meticulously tuned with an oscilloscope. When the system is transported to a different place, or when the light changes, the process of tuning has to be done again. These issues will be solved in this thesis.

The main problem statement of this thesis will therefore be as follows:

> *How can we improve ChromaLux so that the data rate increases, the system becomes adaptive to changes in light intensity, and the bit error rate decreases.*

To solve this problem, the problem statement is separated into two parts:

1. *Solve the drifting of the transmitter and make the system adaptive to light changes.* As the ChromaLux system is open loop, the system has the tendency to drift, causing difficulties in demodulation, as well as breaking the link. To make it somewhat stable, it requires meticulous tuning. Finally, because of the tuning that is required, the system has to be set up using an oscilloscope, which makes it difficult to operate. These problems require a form of feedback to stabilize the Liquid Crystals and, effectively, make it closed loop. This allows the system to reach higher speeds, as well as make it adaptive to light, more reliable and stable.

2. *Increase the signal-to-noise ratio of the system to reach higher data rates.* Because of Shannon's theorem [30], the capacity of the link can be increased by increasing the signal-to-noise ratio. This can be done by using differential amplification, which raises the signal level at the receiver.

1.3 Methodology

The system is created by building upon the existing ChromaLux work. Our improvements are not only theoretical in nature, but also practical, as a test system is also built. To test the performance of the system, quantitative data is collected by transmitting messages at different ranges at different data rates. These messages are specifically designed to incorporate different transitions, transitions for which issues arose for ChromaLux. This includes consecutive series of *'0'*s, consecutive series of *'1'*s as well as patterns of *'01'*s.

The transmitted data is then measured using a receiver consisting of one (basic version) or multiple (advanced version) photodiodes, after which the signal is demodulated. The demodulated signal is then compared to the transmitted signal in order to calculate the fraction of erroneous bits, the Bit Error Rate (BER). This is done at similar ranges to the measurements of ChromaLux to create a fair comparison. The results are then compared to those of ChromaLux, as well as to the results of other state-of-the-art systems, in terms of range, data rate and BER.

The contributions that are made by this thesis are as follows:

1. Several quality-of-life improvements are made to the ChromaLux system, which enables real-time communication with the computer, and enables us to use a photodiode instead of color sensors to receive data. This simplifies the system and reduces cost. (Chapter 3)

2. By applying a feedback mechanism, the data rate of the system doubles from 1 kbps to 2 kbps, and the bit error rate is lowered, while maintaining the range of ChromaLux. In addition, this causes the system to be more easy to reconfigure and be adaptive to changes in light intensity. (Chapter 4)

3. By making use of differential amplification in conjunction with effective use of polarization, the range of ChromaLux will be extended. (Chapter 5)

1.4 Structure of the thesis

This thesis is structured as follows: in Chapter 2, relevant information that is needed to understand the rest of the thesis is discussed, after which relevant state-of-the-art work is explained. In Chapter 3, the method of ChromaLux is described in more detail, after which the system itself is explained. The next chapter, Chapter 4, describes the feedback mechanism that we use to increase the data rate, as well as to stabilize the system. In Chapter 5 we solve issues that are created by the feedback mechanism. Finally, in Chapter 6, a conclusion, as well as future work is presented.

Chapter 2

Background & Related Work

To understand the following chapter, first VLC in general is explained. VLC is the data-exchange between a transmitter and receiver, by using visible light that has a wavelength between 375 nm and 780 nm. As a transmitter, a light source that can be turned on or off is used, such as a fluorescent lamp or LED. This light source can then be modulated to transmit data. The created signal is usually received by a photodiode, after which it can be demodulated.

This chapter is constructed as follows. It starts with describing the difference between passive and active VLC in Section 2.1. Section 2.2 continues by describing polarization of light and why it is so important for VLC. The next section, Section 2.3 describes the way that liquid crystals work and how they are deployed in the field of passive VLC, followed by a measure to compare VLC systems in Section 2.4. Finally, in Section 2.5, related work in the field of VLC is described, after which we end with a discussion about the positive and negative aspects of the different systems.

2.1 Active and Passive VLC

There are two basic forms of VLC, active and passive VLC. One of the simplest ways of achieving visible light communication is to use an LED to transmit data, which is called *active* VLC. This approach can be seen in the upper half of Figure 2.1. The light source itself is modulated to send information over a light channel. As data consists of zeros and ones, a simple solution is to use On-off keying; a *'1'* can be represented by turning the light source on, and a *'0'* can be represented by turning the light source off. This was a topic of research in the past, and has already been implemented by large companies such as Signify [27].

An LED is able to switch between the on and off states at very high frequencies, up to billions of times per second. This creates the possibility of wireless communication at much higher speeds than Wi-Fi. However, the state-of-the-art approach can reach speeds of up to 250 Mbps, while Wi-Fi can reach speeds of up to 1201 Mbps under ideal circumstances [32]. In practice, Wi-Fi speeds are relying heavily on free space in the EM spectrum, which is mostly not available. Therefore, VLC is already an improvement compared to Wi-Fi. Another factor in favour of VLC is the fact that the spectrum that is used is license free. Finally, because light does not traverse through walls, communication can be more secure, as a person that would want to intercept information has to be in the path of the light.

The main drawback of active VLC is the energy consumption. A light source uses lots of energy, up to 10 Watts for an LED, or even over 100 Watts for a fluorescent lamp. This is more than needed by wireless communication using Wi-Fi, which is normally about 5 Watts. The energy consumption will be less of an issue in office environments, where lights are usually always on, but will be an issue in locations where there is no need for artificial lighting throughout the whole day. Another drawback is the low intensity of LEDs. This causes a short effective transmission range.

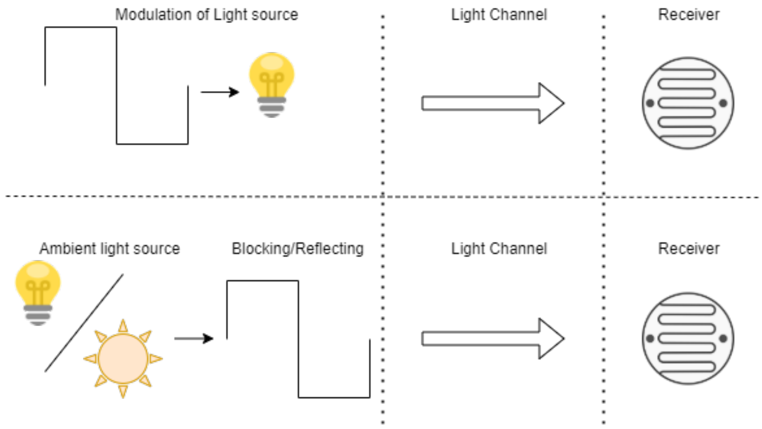


Figure 2.1: **Active VLC (top) and passive VLC (bottom).**

Passive VLC alleviates the energy consumption drawback by making use of ambient light that is already available, whether it is light from the sun, or indoor lighting. The lower half of Figure 2.1 shows a simple schematic of the passive VLC process. Ambient light is modulated by either blocking or reflecting the incoming light, after which it is received on the other side of the light channel. Another benefit of making use of ambient light is that it can provide a higher level of illumination in comparison with normal light sources. Where an LED usually provides between 750 and 900 lumens [29], the sun can provide a factor 100 more, over 100,000 lumens on a sunny day [3]. The main drawback of passive systems is that they do not have any control over the ambient light.

Active and passive VLC can make use of the same receiver. This receiver can be a photodiode, a color sensor, or a camera. A photodiode transforms light into a current, which can then be converted into a voltage using a transimpedance amplifier [5]. This method is a cheap and low-power method for a receiver. In addition, it can achieve a very high speed of over 100 GHz (e.g. [16]). A color sensor, which can measure one or more color channels, has the same benefits as a photodiode, because a color sensor is mostly created by adding a color filter to a photodiode. However, a lot of color sensors are systems on a chip, which measure the red, green and blue colors, and then send the measurements away through protocols like I2C, causing slow measurement times. Therefore, these forms of color sensors are not suitable for high speed communication. A second downside of color sensors is that they are usually more expensive than photodiodes.

For other circumstances, such as localization using VLC, a camera is preferred to be used as a receiver, because it can read several bits at once. The main downside is that a camera is slow, especially when compared to photodiodes. In addition, this method also uses more power and is more expensive.

There are several studies that make use of passive VLC such as [6, 13, 20, 26, 31, 33, 35]. These systems all make use of a material that can block or allow light to pass, Liquid Crystals, in combination with polarization of light.

2.2 Polarization of light

Similar to radio waves, light is an electromagnetic wave. A light wave oscillates perpendicular to its propagation direction [24]. This direction is called the polarization direction. Normal light consists of lots of different waves, all with their own polarization directions. When light consists of waves propagating in any random direction, it is called unpolarized light. Light that only oscillates in one direction is called polarized light.

It is possible to polarize unpolarized light. This is done by adding a polarizing filter, or polarizer. This polarizer will let through only one direction of light. Figure 2.2 shows the process. Starting from the left, a light source creates light waves that propagate in any direction. After entering a vertical polarizing filter, light with only one direction is left, vertical polarized light.

Polarization of light is often used in conjunction with Liquid Crystals for passive VLC.

2.3 Liquid Crystals

Liquid Crystals possess the ability to change the polarization direction of light that travels through them. Because of this property, they are often used in conjunction with polarizing filters for passive VLC. Figure 2.3 shows the basic operation of a Liquid Crystal (LC) [9]. First, incoming light is polarized by a polarizing film, letting only one polarization direction through. Then, depending on the voltage applied on the crystal, the polarization direction of the light is either rotated 90° when no voltage is applied, or kept the same when a voltage is applied. On the output of the crystal, a second polarizer is added, called the analyzer. This analyzer allows the passing or blocking of light depending on the polarization direction. This way, light can either be blocked or passed.

As these Liquid Crystals in conjunction with polarizing filters possess the property to block or pass light, simple modulation schemes can be created. For example, blocking the light could be a *'0'*, while passing of the light could be a *'1'*. There are multiple studies that use On-off keying, such as [6, 13, 20, 26, 31, 33, 35].

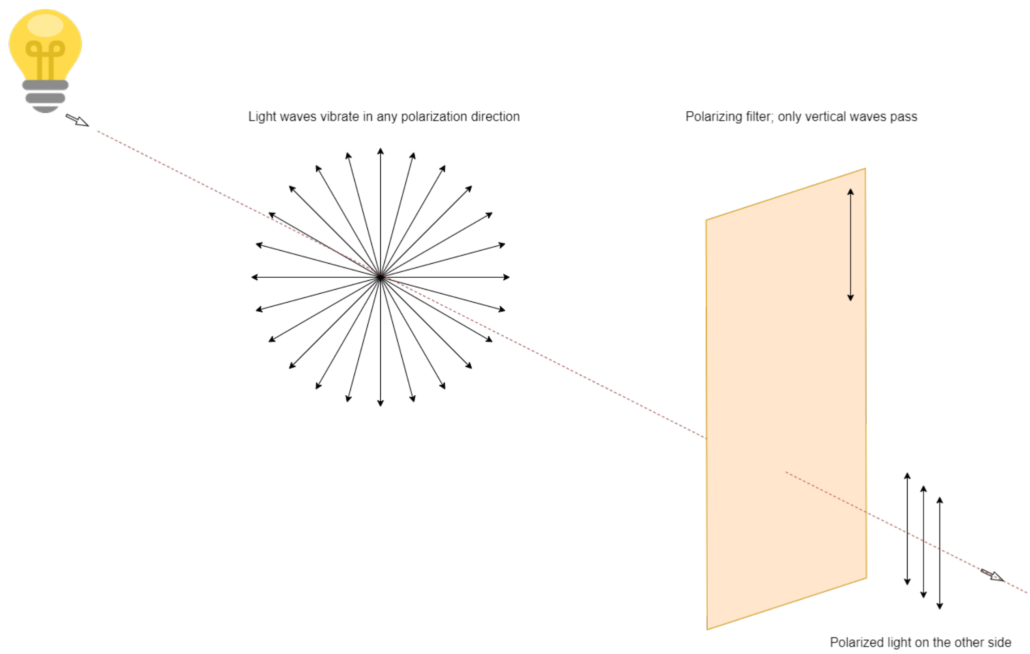


Figure 2.2: **Light is created by a light source. The light waves that are incurred propagate in all polarization directions. A polarizing filter is added to only let one polarization direction of the light waves through, creating polarized light.**

2.4 Bit Error Rate

The BER is a convenient metric to compare performance of different communication systems to each other. It is a measure to rate signal quality by measuring the number of errors (erroneous bits) in a set number of bits sent (total bits sent). It can be calculated using Equation 2.1.

$$BER = \frac{Erroneousbits}{Totalbitssent} \tag{2.1}$$

It is nice to have a high data rate when communicating, but when this is paired with a high BER, the quality of the signal may be worse than when a low data rate would be achieved, combined with a low BER. The BER is closely related to the Signal-to-Noise Ratio (SNR). The higher the SNR, the lower the BER and the other way around.

However, when looking into previous studies that are done in the field of passive VLC, the BER is usually not reported. About half of the investigated studies only report packet success rate. While this could also be a proper measure to test performance, it does not take into account that there exist error correcting codes that could still save the packet as long as the BER is low enough.

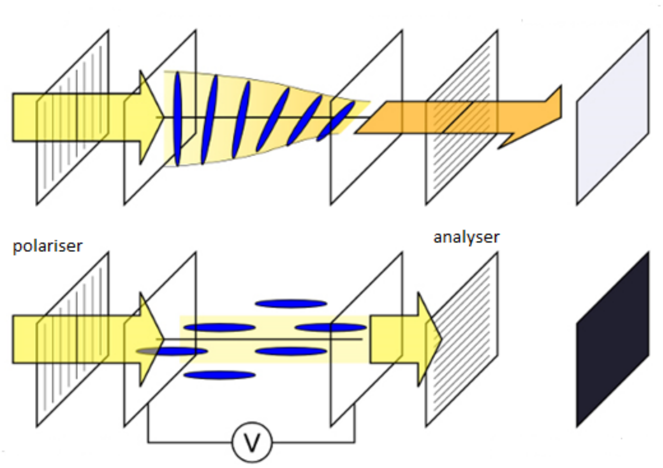


Figure 2.3: **Inner workings of an LC. Incoming light is polarized by a polarizer. Depending on the voltage, the polarization direction of the light is either rotated 90° or kept the same. A second polarizer, the analyzer will allow only one polarization direction of light through, so no light will be present at the output when a voltage is applied (bottom), and light is present when no voltage is applied (top).**

2.5 Related work

There have been plenty of studies that make use of passive VLC and in particular of passive VLC using Liquid Crystals. This section describes a number of these systems and discusses their strengths and weaknesses, so that we can learn from them. In addition, their performance is compared, by identifying measures that are important for characterizing wireless communication.

- Data rate: The number of bits that the system can send per second is important for a fair comparison between different systems.
- Range: The distance at which the system can reach the aforementioned data rate. As discussed before, usually a trade-off has to be made between range and data rate.
- BER: As discussed in Section 2.4, the BER is an important measure when combined with data rate.
- Number of crystals: The number of crystals that are used to transmit information are important, as it is a measure of how efficient the data transmission is. When 50 crystals are used, and they do not achieve a data rate or range that is 50 times higher, the use of more crystals is not efficient.
- Modulation scheme: There might be a relation between the used modulation scheme and the data rate/range of the system.

These measures are collected for the different systems, and put together in Table 2.1.

Retro-VLC [20]

Retro-VLC attempts to solve bidirectional communication between a low-power device and an active device. The active device is able to communicate with the low-power device using active VLC, in which the active device modulates an LED and the low-power device demodulates this signal using a photodiode. Normally, the low-power device would not be able to send back information, due to the high power demand for active VLC. To solve this, Retro-VLC makes use of an LC shutter in combination with a retro-reflector. A photodiode will be able to receive information, while the shutter is responsible for sending information back, through reflection. Figure 2.4 shows how the system works.

The modulation scheme that is used is On-off keying in combination with a Manchester encoding scheme. Manchester encoding [17] works by dividing a bit into two similar intervals. To send a *'1'*, in the first half of the symbol, the voltage is high, and the second half of the symbol the voltage is low. To send a *'0'*, this is the opposite; a low voltage is followed by a high voltage. This method makes sure that each bit has a transition in the middle so that it is easy to synchronize between receiver and sender.

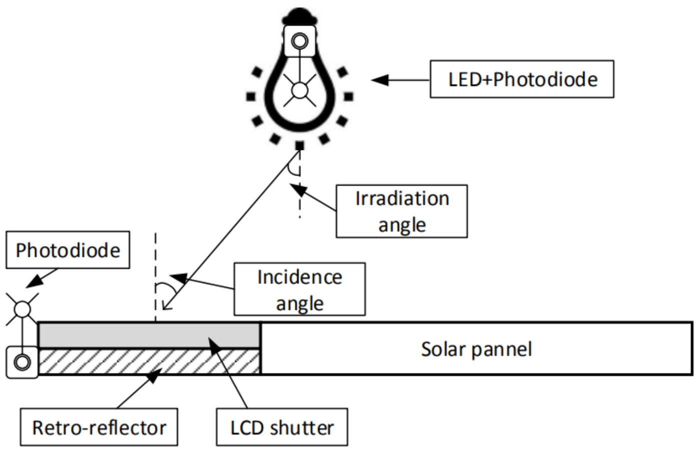


Figure 2.4: **The principles of the Retro-VLC system and pixelated VLC backscatter. To receive information, the system uses a simple photodiode. To send information back, the system will use an LCD shutter (liquid crystal) in combination with a reflective surface, to reflect incoming light. The original sender can then use a photodiode as well to demodulate the signal.** [20]

As only the uplink of the system is real passive VLC, only this performance will be taken into account. The authors measured the performance of the system by continuously sending a 500 bps signal with a packet size of 32 bits, while the range was changed. The packet loss rate, how many packets are lost compared to the amount that are sent, was then reported. The system achieved a data rate of 500 bps at up to 2.4 meters. However, when we look at Figure 2.5, this would mean a packet loss rate of 90 %. This does not seem feasible. In our opinion, the maximum range that can be achieved using this system, is around 1.5 meters, as more packet loss would render the system impossible to use for real-world applications.

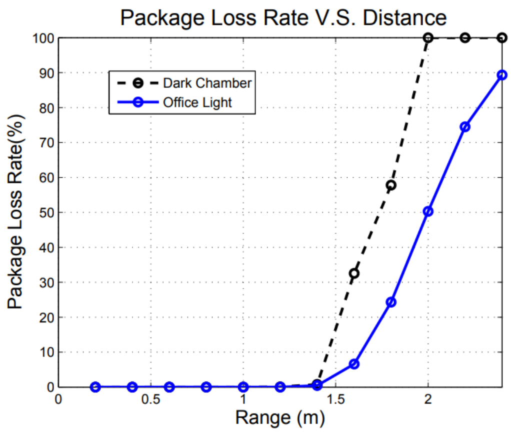


Figure 2.5: **packet Loss Rate vs distance as reported in the Retro-VLC paper. The performance in a dark room is worse than in a well lit room because the solar panel does not receive enough energy to power the system when there is no ambient light around.** [20]

Pixelated VLC backscatter [26]

Pixelated VLC backscatter works similarly as Retro-VLC. It uses a retro-reflector in combination with an LC to reflect or block incoming light. Therefore, this approach is useful for low-power devices. Communication to this device is created using active VLC, while the same light is used in order to reflect the light back. Figure 2.4 shows the main principle of pixelated VLC backscatter.

The difference with Retro-VLC is the fact that by using multiple shutters, different signal levels can be created, as seen in Figure 2.6. This creates the possibility to use other modulation schemes such as Pulse-amplitude-modulation, PAM [15]. PAM uses different signal level pulses in order to modulate information.

Another difference is that Pixelated VLC backscatter uses a set BER and measures the range that can be reached using different forms of modulation, while Retro-VLC uses the packet loss rate to measure performance. This leads to slightly higher speeds at slightly higher range (600 bps at 2 meters using 8-PAM), or lower speeds at higher range (200 bps at over 5 meters using On-Off Keying).

Passive-VLC [35]

Passive-VLC is also an improvement of Retro-VLC. It therefore has the same system setup as in Figure 2.4. The main improvement is found in the software

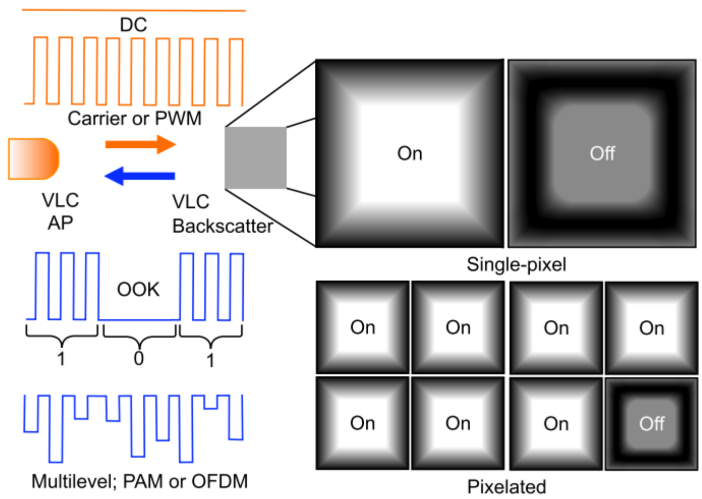


Figure 2.6: **The idea behind Pixelated VLC Backscatter. By using multiple crystals (called pixels here) a multilevel signal can be created, and more advanced modulation schemes can be used.** [26]

(de)modulation. Where Retro-VLC makes use of Manchester encoding, Passive-VLC uses Miller encoding. Figure 2.7 shows the difference between these two encoding methods.

Miller encoding represents a binary *'1'* as a high-to-low or a low-to-high transition in the middle of the bit window. A binary *'0'* does not cause a change in the signal level, unless it is followed by another *'0'*. In this case, a transition to the other signal level is made at the end of the period of the first *'0'*. As opposed to Manchester encoding, Miller encoding uses fewer transitions and uses larger pulse widths, requiring less bandwidth to transmit data, which could result in a higher data rate.

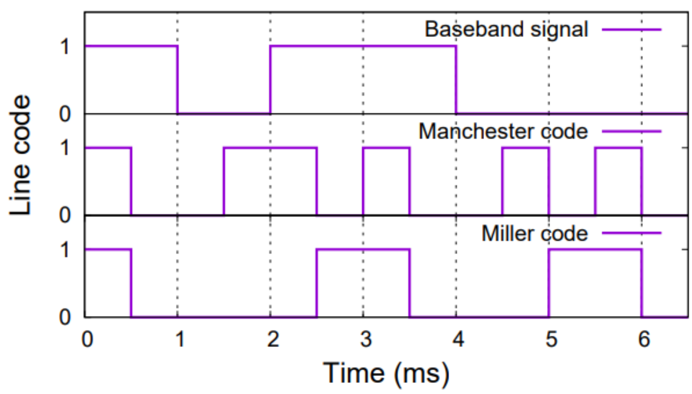


Figure 2.7: **Manchester encoding used in Retro-VLC vs Miller encoding used in Passive-VLC.** [35]

Passive-VLC uses a packet length of 32 bits. The performance is measured using the packet loss rate. As discussed before, in our opinion it would be better to measure the BER instead. The Passive-VLC system reached speeds of up to 1 kbps at a distance of 1 meter, while keeping a low packet loss rate of around 0 %. This is a doubling of the data rate at a similar distance compared to Retro-VLC.

LuxLink [6]

LuxLink uses an LC in order to send a signal using Frequency-shift keying, in which different frequency sine waves are used to differentiate between symbols. In addition, it uses a diffuser panel to redirect sunlight through a crystal. On the receiver side, a phototransistor is used to demodulate the signal, using a Fourier transform. Figure 2.8 shows the system in more detail. The performance of LuxLink is measured using the packet success rate, the inverse of the packet loss rate. LuxLink has reached speeds of 80 bps at a range of 65 meters, using sunlight, keeping the packet success rate over 75 %. However, to compare the performance to the other systems, the range reduces to 50 meters as in that case the packet success rate is nearly 100 %. In addition, this paper focuses on investigating flickering effects caused by the liquid crystals. It checks the flickering speeds with the IEEE health risk guidelines, to ensure safe operation.

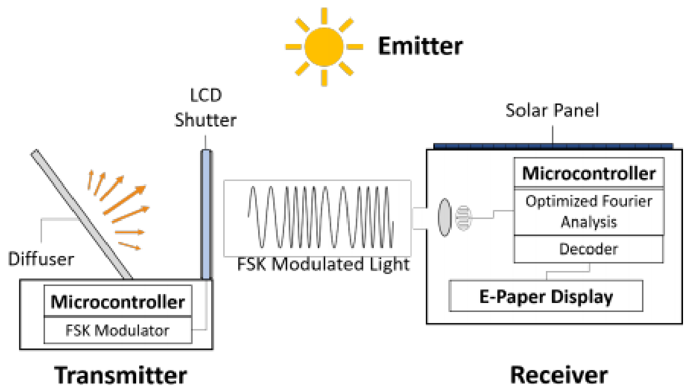


Figure 2.8: **The working principle of the LuxLink platform. Light is diffused through LCD shutters, which are modulated using FSK modulation. The receiver receives this signal and can demodulate it. [6]**

RetroTurbo [33]

RetroTurbo uses LCs as an optical modulator, just as LuxLink and the other systems already discussed. However, where LuxLink uses one crystal, Retro-Turbo uses LC panels to create multiple adaptable crystals. On the receiver side, two photodiodes are places with different polarizers at 45 degrees from each other. This makes the two channels form an orthogonal base with each other, causing them to be independent. The exact calculations can be found in [33]. To be able to use all crystals, a new modulation scheme is presented, Delayed Superimposition Modulation (DSM). As the name suggests, delayed signals are superimposed on each other in order to create more symbols. Figure 2.9 shows the idea behind the modulation scheme, with 3 crystals, although the same holds for more. Because LCs have an asymmetric response, the fast edges of the transitions are used to modulate the signal, while still giving plenty of time for the slow edges. This creates a pattern that can be demodulated to, in the case of 3-DSM, 8 different symbols.

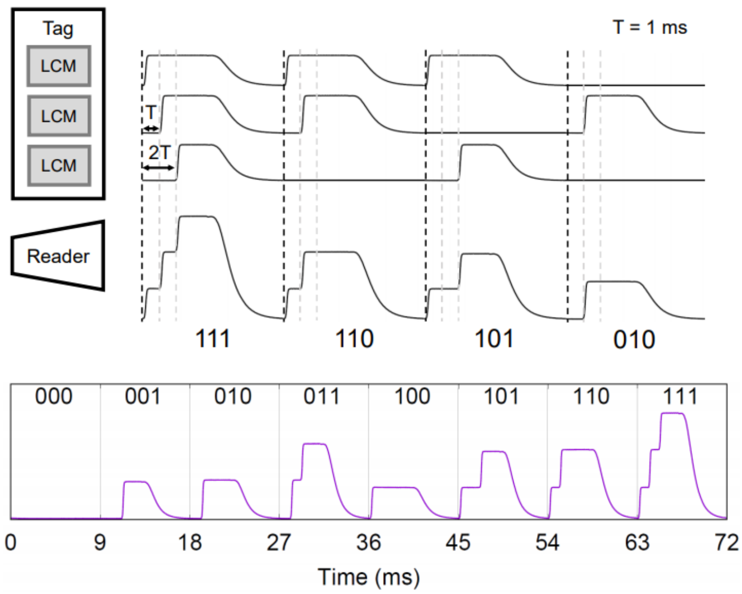


Figure 2.9: **The Delayed Superimposition Modulation scheme that is used in RetroTurbo [33]. As an example, three LCs are used to create 8 different symbols. More LCs can be used to create even more symbols.**

In addition, different polarization directions are used. This creates a polarization base QAM (PQAM) modulation scheme, a variant on PAM. By dividing the LCs in two groups, and changing the polarization of each group, even more symbols can be sent. Figure 2.10 shows this modulation scheme. This is where the second photodiode with its different polarization direction comes into play.

By using four LCD screens, equipped with either 0 °or 45 °polarizers, two I-LCMs and two Q-LCMs are formed. Each of these LCD's consists of four sets of four different groups of pixels. This creates 16 different levels per group of pixels. In combination with the other LCD screens, a 256-QAM modulation scheme is created. To measure the performance of the system, the BER is calculated for a set speed of 4 kbps and 8 kbps at different ranges. This system has reached a speed of 8 kbps at a distance of 7.5 meters or a speed of 4 kbps at a distance of 10.5 meters, while keeping the BER below 1 %.

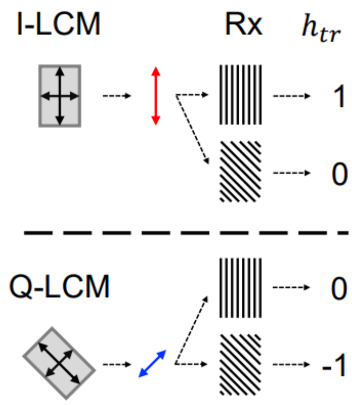


Figure 2.10: **4-PQAM as used in RetroTurbo [33]. By rotating the polarization of one send group, different signals can be received at the receiver side. As an example, this figure shows the symbol *'10'*.**

RetroI2V [31]

RetroI2V is a system that attempts to use LCs to create smart road signs that can convey information to vehicles traversing the sign. In combination with the reflective coating that is already present on the traffic signs, extra information can be sent, such as traffic information, road conditions, etc. The downlink of the system is created inside vehicles itself. It modulates the headlights of the car in order to send information to the road signs. To send back data to the vehicle, the light from the headlights is reflected, and modulated using liquid crystals with On-Off keying. An array of 6×6 crystals is used to create a larger surface, and to emulate the size of a real road sign. Different sizes and forms of road signs can be emulated by disabling part of the array. The performance of the system is measured, including the BER. The system has reached speeds of up to 1 kbps at a range of 80 meters, while keeping the BER below 1 %.

ChromaLux [13]

Finally, ChromaLux, which was already mentioned in Section 1.1, uses a similar setup as LuxLink. However, instead of a single LCD shutter, a stack of six is used, and instead of frequency shift keying, a novel modulation scheme is used. This allows ChromaLux to reach higher speeds. The system has reached speeds of up to 1 kbps at a distance of 50 meters, while using ambient light and keeping the BER under 1 %.

2.6 Discussion

To start our discussion, we begin by examining the previous systems, and discuss what we could learn from their experiences. In order to do so, the results for the state-of-the art systems are summarized in Table 2.1. In addition, we check what existing RF communication techniques could be used for VLC to see if there are missed opportunities.

Table 2.1: **Comparison between different passive light communication systems**

	Data rate	**Range**	**BER**	**Number of Crystals**	**Modulation Scheme**
Retro-VLC	500 bps	1.5 m	✗	1	OOK
Pixelated VLC backscatter	600 / 200 bps	2 m/ 5 m+	0.1 %	3	OOK/PAM
Passive-VLC	1 kbps	1 m	✗	1	OOK
LuxLink	80 bps	50 m	✗	2	FSK
RetroTurbo	4 / 8 kbps	10.5 m / 7.5 m	1 %	64	QAM
RetroI2V	1 kbps	80 m	1 %	36	OOK
ChromaLux	1 kbps	50 m	1 %	6	Custom

We start by evaluating the VLC systems themselves, using Table 2.1, and try to uncover trends in their results. The first thing that stands out is that the higher data rate systems, such as Passive-VLC, RetroTurbo, RetroI2V and ChromaLux, have limited range, with RetroI2V and ChromaLux as exceptions.

Another observation is the fact that usually, the higher the number of crystals, the higher the data rate. Almost all systems that use multiple crystals, do this by creating multiple parallel communication channels, which improves the data rate. Exceptions are RetroI2V, which uses multiple crystals to create a larger surface in order to increase the contrast, ChromaLux, which uses a stack of crystals to create a new transient region, and Pixelated VLC backscatter and RetroTurbo, which use multiple crystals to create different amplitude levels in their signal.

To see whether the use of multiple crystals is effective, we also plot the range vs. the data rate divided by the number of crystals. This way, we can see the number of bits that each crystal can transmit, and their range. Figure 2.11 shows the results. Notice that almost all systems make real trade-offs between range and data rate per crystal. Either the data rate per crystal is high with a low range, or the data rate per crystal is low with a higher range. In addition, a line is plotted as well, which shows an estimation of the trend, based on the fact that light intensity decreases quadratically with distance. Every system on the right and above the red line is better than the average system, and is capable of utilizing the crystals in a more efficient way than the other systems. The only system that really stands out in this figure, is ChromaLux. This shows that ChromaLux has already proven its potential.

The final takeaway from comparing all systems is that there is no consensus on how to measure performance. Some systems mention the BER, while other systems use the packet loss rate. Therefore, it is difficult to compare the systems. In addition, the systems that make use of the BER do not all use the same maximum BER for their results.

When looking at existing RF techniques, the most important attribute to achieve higher data rates is the use of different modulation techniques. When looking at Table 2.1, we can see that for VLC multiple different techniques are already implemented. When looking at the data rates and the range, there is no real trend to be found. However, when looking at Pixelated VLC backscatter, which switches between x-PAM and OOK, the used modulation scheme can be a way to switch between higher data rates and range. This suggests that there is a missed opportunity in their approach, because the authors could have implemented a form of automatic rate control, which switches between the

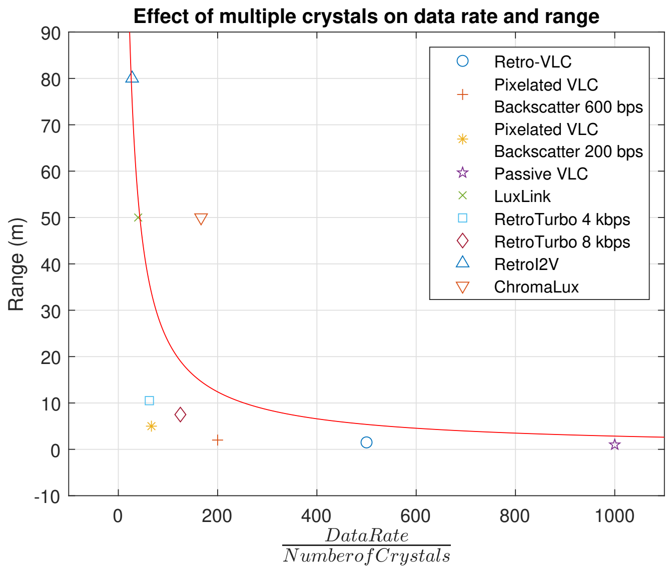


Figure 2.11: **Effect of multiple crystals on data rate and range. Plotted is the range vs. the number of bits that each crystal can transmit ($\frac{DataRate}{NumberofCrystals}$). The red line represents the trend that most systems follow: long range and low speed, or high speed and short range. The system to the right and above the red line has found a better trade-off than usual (ChromaLux).**

different modulation schemes to achieve the highest data rates are the given distance.

This brings us to the next point that could be learned from RF systems. In RF systems, there is usually a form of feedback to establish a connection or establish a common data rate. This could be a proper addition to the field of VLC. This thesis will use a feedback loop to improve the data rate of ChromaLux, and will make use of this knowledge from RF systems.

Another widely used technique in RF systems, is the use of differential coding. By using two opposite signals, the output signal can have a double amplitude as well as less noise. This technique will also be implemented in this thesis in order to improve the ChromaLux system.

Chapter 3

Improving Passive Light Communication

This chapter describes the basic idea behind the new system. It starts by describing issues that ChromaLux encountered in Section 3.1. It then continues with an explanation of liquid crystals, their response and their birefringent property in Section 3.2. The next section, Section 3.3.2 starts by describing a method to determine the optimal number of crystals, using the measurements from Section 3.2, and continues with the modulation and demodulation schemes of the new system. Finally, in Section 3.4, the transmitter and receiver are described. Furthermore, the first improvements to the ChromaLux system are discussed: the usage of a photodiode and the usage of real time communication with the pc.

3.1 ChromaLux issues

As mentioned in Section 1.2, ChromaLux has several issues that prevent it from achieving higher data rates. The main issue is the fact that it is open-loop controlled, which means it relies on a stable system. However, since the LCs operate in an unstable region, the system itself is not stable, which causes the signal to drift. This is especially true for sequences with lots of consecutive similar symbols. For a set of consecutive *'0'*s this will cause an upward slope, and for a set of consecutive *'1'*s this will cause a downward trend for the \/ signals, or the other way around, as can be seen in Figure 3.1.

Another issue is the fact that there is no real-time communication possible with a computer; the system saves the data on the controller itself, and sends it to the computer in one go, which takes a lot of time. This makes real-time communication impossible.

Finally, when the system is started up, it has to be meticulously tuned to fit the circumstances. This will include the middle voltage, the duration of the pulses, etc. The only possibility to do this, is by using an oscilloscope to set up the system. This is very impractical and can only be done by experts.

3.1.1 Stabilizing the system

The main issue with ChromaLux is the fact that it is unstable, and will therefore give rise to drift in the signal. Because of this drift, there is no possibility to achieve any speeds higher than 1 kbps, without an increasing bit error rate. This drift is mainly caused by lack of control over the timing.

As an example, look at Figure 3.1. In this figure, a set of *'1'*s are transmitted, followed by a *'0'*. This is right after the reset phase, in which the crystals are made ready for transmission. Because of this reset phase, the first part of the *'1'*s cause a downward trend. However, at the end of the transmission, an upward trend can be observed. This makes the signal unstable.

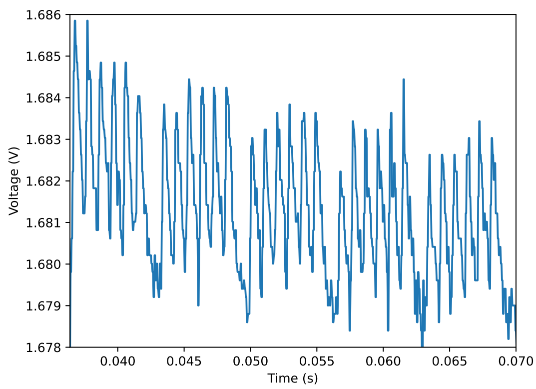


Figure 3.1: **Drift that occurs when consecutive *'1'*s are transmitted followed by a *'0'*.**

To solve this issue, a feedback controller will be added, which uses a second photo diode to give feedback to the system. This method will be discussed in Chapter 4.

3.1.2 Improving the contrast

To stabilize the system, a sensor is placed in front of the stack of LCs. Because this blocks the LCs partly, the SNR of the system is lowered. This lower SNR results in less range. To increase the SNR again, differences in polarization direction will be used at the receiver in combination with differential amplification methods. An added benefit is that differential amplification will reduce the noise created by the analog-digital controller. This method will be described in Chapter 5.

3.2 Response of liquid crystals

As discussed before, the system makes use of a transient state that is created by using a stack of LCs. The following sections explain why this transient state occurs.

3.2.1 Birefringence in Liquid Crystals

The underlying physicical property of Liquid Crystals is called birefringence [21]. This refers to the breaking of an incident light beam into two rays, the ordinary and extraordinary ray, both with their own polarization direction perpendicular to each other. The extraordinary wave will be slowed down more than the ordinary wave, causing a phase difference at the output of the material. This can be seen in Figure 3.2. The blue wave represents the ordinary ray, which is not slowed down by the material. The green wave represents the extraordinary wave, which travels slower through the material. On the right side of the crystal, the output, a phase difference between the two waves can be observed. This property can also be expressed in a formula, using the refractive indexes of both the ordinary (n_o) and the extraordinary (n_e) ray, where a refractive index is a measure for a material that describes how fast light travels through a material. The birefringent value, Δn, is then defined as the difference between the refractive indexes of the ordinary and extraordinary ray, Equation 3.1.

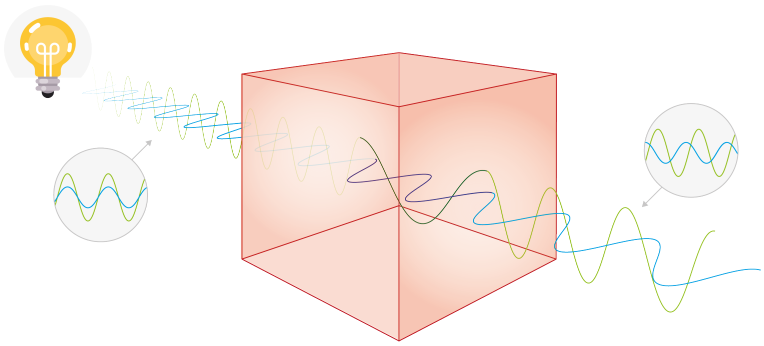


Figure 3.2: **The property of birefringence. Upon entering a birefringent material, the light is split into two polarization directions. The blue wave is called the ordinary ray, while the green wave is called the extraordinary wave. The extraordinary wave is slowed down more than the ordinary wave. Upon exiting the material, both waves will travel with the same speed again, but with a phase difference.**

$$\Delta n = |n_e - n_o| \tag{3.1}$$

The above holds for a single-color light beam that enters the crystal. However, when multiple different colors enter the crystal, for example white light, the colors will have a difference in phase at the output. Figure 3.3 shows this phenomenon.

The colors at the output are not visible to the naked eye. These out-of-phase colors will appear as white light. However, these colors can be measured using color sensors in combination with polarizers.

These colors are not just random colors, they are actually known. The Michel-Lévy chart shows all colors that can be observed, see Figure 3.4. This chart captures the different output colors based on the value of birefringence as well as the thickness of the crystal. The oblique lines represent the birefringence value Δn. The y-axis shows the thickness of the crystal and the vertical lines represent

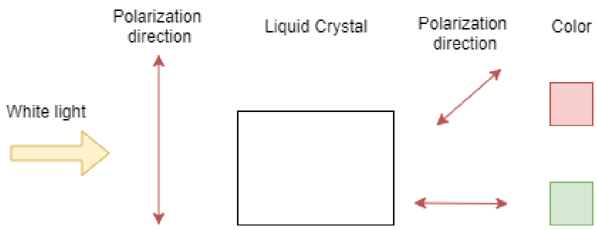


Figure 3.3: **White light (all colors) with a single polarization direction enters a liquid crystal. On the other side of the crystal, each color will end up with a difference in phase.**

the corresponding output color. Normally, a crystal has one birefringence value per wavelength, as well as one thickness value. The intersection between the oblique line and the horizontal thickness line will then be the output color that can be observed. However, an LC has a differing birefringence value as voltage is applied. Therefore, an LC has a color response that can be seen by drawing a horizontal line at the thickness of the crystal, between two different oblique lines. Notice that the thicker the crystal is, the more a difference in birefringence value changes the color response. Also, the higher the difference in birefringence is between the two states of an LC, the more colors can be observed.

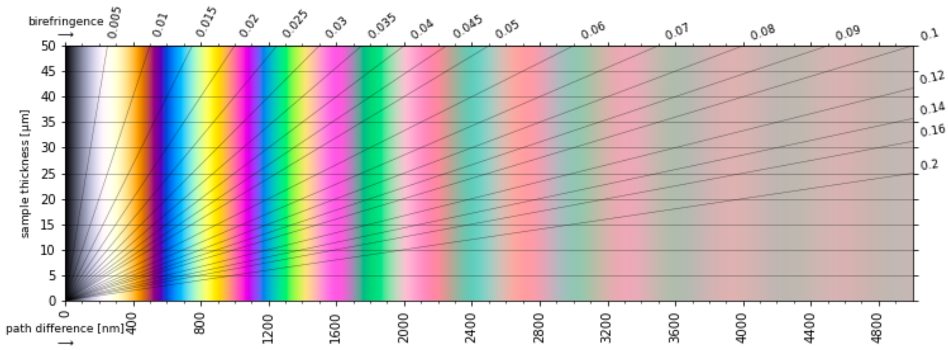


Figure 3.4: **The Michel-Lévy chart [2]. The oblique lines show the birefringence value (Δn). The y-axis shows the thickness of the crystal, and the vertical lines show the corresponding output color.**

When plotting the birefringence versus the sample thickness, Figure 3.5 is created, which is called the Raith-Sørensen chart. This way, the different colors that can be observed during transitions of Liquid Crystals are made more clear. When following a horizontal line in this plot, the colors for a crystal of that thickness can be observed.

Usually Liquid Crystals are created with a thickness and birefringence value to cover only the very first part of the chart, black and white. However, for the ChromaLux system, it is important to have more transitions than only from black to white. This is accomplished by stacking Liquid Crystals, to create a thicker crystal. This thicker crystal can have more transitions in the Raith-Sørensen chart.

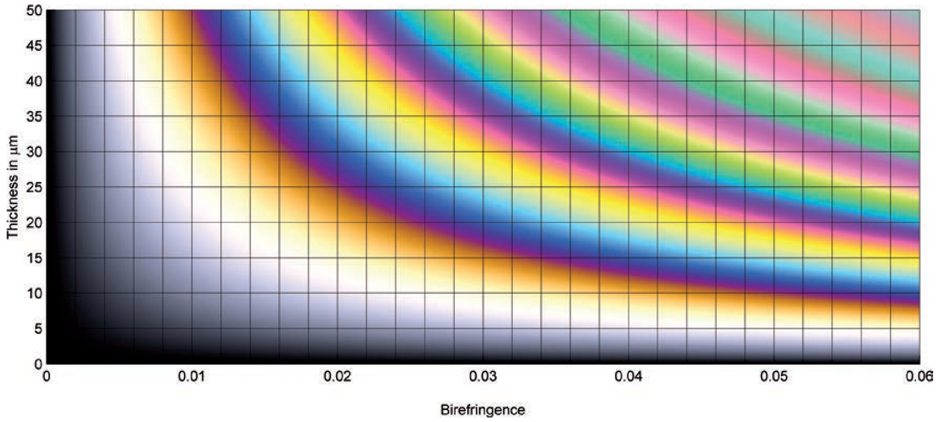


Figure 3.5: **Raith-Sørensen chart [28], with the birefringence value plotted against the sample thickness. When a horizontal line is followed, the different colors for a crystal of a certain thickness can be found.**

3.2.2 Theoretical response of Liquid Crystals

Now, to have a more theoretical approach of how Liquid Crystals behave, we use the same equations that were used to create the Michel-Lévy chart. These equations assume that a (stack of) liquid crystals is sandwiched between two polarizers, with polarization directions perpendicular to each other, and show the fraction of light I with wavelength λ that is passed [36]:

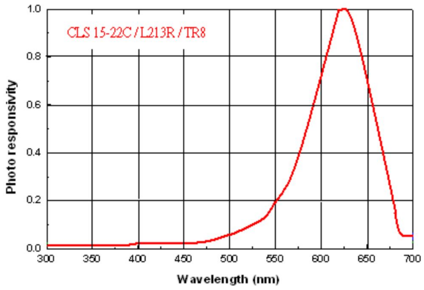
$$I = sin^2(\frac{180 \cdot \Gamma}{\lambda}) \quad (3.2)$$

$$\Gamma = \Delta n \cdot d \quad (3.3)$$

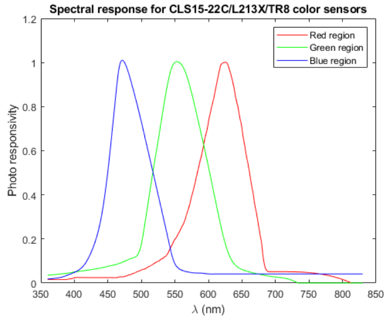
Using these equations, we can plot the theoretical color response of a Liquid Crystal. By summing over all frequencies in the visible light spectrum, 360 nm to 830 nm, the color that comes out of the analyzer can be calculated. However, as all color sensors have a different spectral response (the way they react to different colors of light), we still have to convert the calculated values into color values that correspond with our used color sensors. When we look in the datasheet for the CLS15-22C/L213R/TR8 color sensor [12], we find the spectral response for the red, green and blue variants of the sensor, such as in Figure 3.6a.

As there are no numerical values in the datasheet, we use Matlab to curve fit the three spectral responses, in order to be able to create the spectral response for visible light from 360 nm to 830 nm. The spectral response can be seen in Figure 3.6b. It can also be seen that, when comparing Figure 3.6a to Figure 3.6b, they are very similar, as was the goal in the first place.

To convert this spectral response into the theoretical response of a liquid crystal cell, we use a similar approach as in [28], but instead of using the CIE1931 [4] color space, we use the spectral response of our sensors. We call the resulting color channels X, Y and Z. The Equation that is used to convert the transmission to the theoretical response is stated in Equation 3.4.



(a) **Spectral response of the used color sensor. [12]**



(b) **Spectral response of the used color sensors using Matlab**

Figure 3.6: **Spectral response of the CLS15-22C/L231X/TR8 color sensors, compared to the curve fitted variant using Matlab.**

$$L_{XYZ} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \vec{r}_\lambda \\ \vec{g}_\lambda \\ \vec{b}_\lambda \end{bmatrix} I_\lambda \tag{3.4}$$

The result is the theoretical response for our liquid crystals/ color sensor combination in Figure 3.7.

This response gives us important insights into the behavior of liquid crystals, and is what causes colors of the Michel-Lévy to appear at the output of the liquid crystals. To further explain this, the responses for a stack of 1 up to 6 crystals are plotted in Figure 3.8. These plots are created by applying $0-5V$ in steps of $0.1V$ on the crystals, while light shines through them. The output is then captured using our red, green and blue color sensors.

When we look at Figure 3.8a, only a single transition can be noticed. This transition equates to a first order transition on the rising edge of Figure 3.7. This transition can also be translated to the black to white region in Figure 3.5. This makes sense, because when the original usage scenario is taken into account, usage in active 3D-glasses, these crystals are used to have only two states: opaque or translucent.

The same can be noticed for more crystals in Figures 3.8b to 3.8f. The more crystals are added, the more orders of the response in Figure 3.7 will be traversed with a zero to five volt transition. When we look more closely, the measured responses are not completely the same as the theoretical response. A reason is that the light that is used is not perfect white light, while the theoretical response is based on light that is composed of the same intensity of all light colors. Another factor is that the theoretical response from Figure 3.7 is not perfect, especially because we had to curve fit the spectral responses.

The next step is to measure the color spectrum for a different number of crystals. This is done by applying $0-5V$ in steps of $0.1V$, while light shines through the stack. A photo is then taken of each resulting color. The result can be found in Figure 3.9.

All the results from this section will later be used to determine the optimal number of crystals that could be used for modulation of symbols in Section 3.3.1.

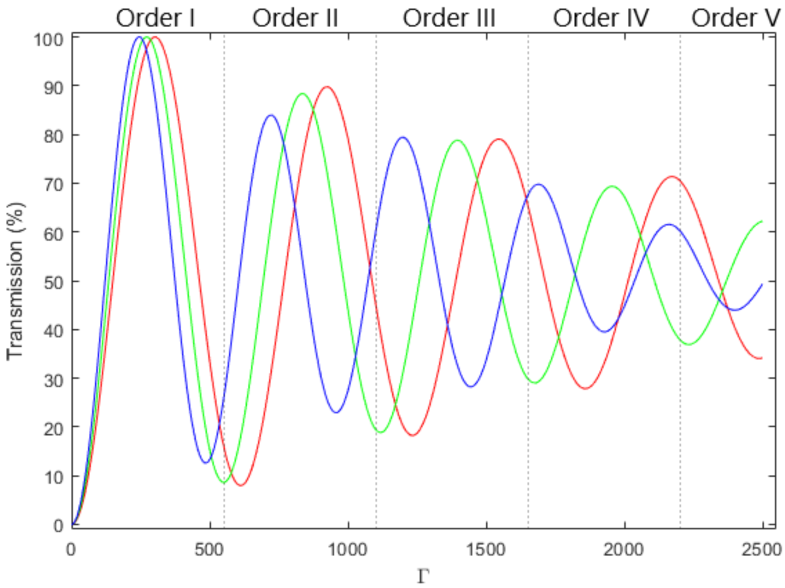


Figure 3.7: **Theoretical response for the CLS15-22C/L231X/TR8 color sensors. The red line represents red light, the blue line represents blue light and the green light represents green light, all as seen by the color sensor. By definition, every 550 nm is called an order.**

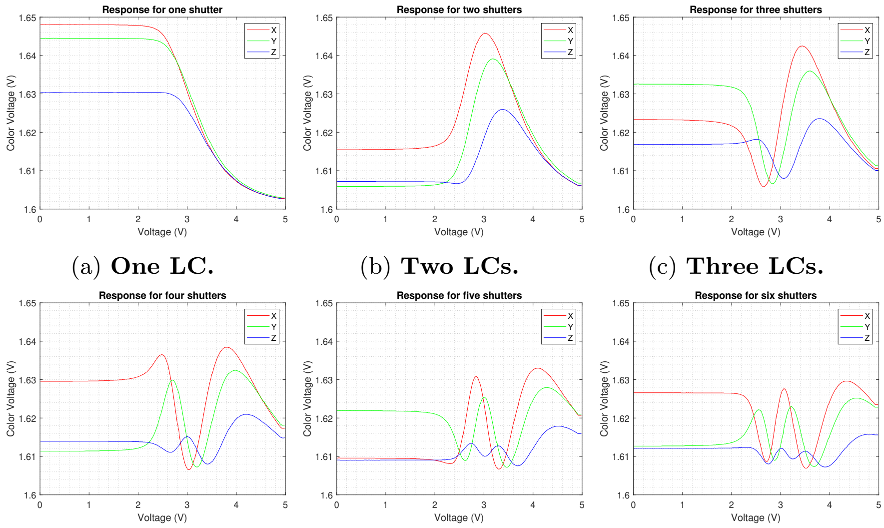
3.3 Communication

To make communication possible, the transient state of the liquid crystals is used. A high SNR can be achieved without waiting for the full transition to occur. Therefore, the number of crystals that has to be used to have the highest SNR has to be determined. At the same time, as each crystal is not perfectly translucent, not too many crystals should be used to keep the intensity of light travelling through them high. This section describes a way to determine the number of crystals, and describes how a symbol should be modulated and demodulated.

3.3.1 Number of crystals

It is important to note that there are two methods to increase the modulation spectrum of an LC. The thickness could be increased, or the range of birefringent values could be increased. These options would both give a broader range of color transitions in the Raith-Sørensen chart of Figure 3.5. However, both the thickness and the birefringent values are fixed during the manufacturing process, and therefore can not be changed. To still be able to have a broader range of transitions, we stack multiple crystals to create one crystal with a greater thickness.

To determine the optimal number of crystals in this stack, we use the theoretical response as well as the measurements we did in Section 3.2.2. We have identified a number of guidelines that we want to take into account. We believe



(a) **One LC.** (b) **Two LCs.** (c) **Three LCs.**

(d) **Four LCs.** (e) **Five LCs.** (f) **Six LCs.**

Figure 3.8: **Response for a stack of 1 to six LCs. A** 0 V **to** 5 V **signal is applied in steps of** 0.1 V**, after which the output is measured using our CLS15-22C/L213X/TR8 [12] color sensors.**

that these are the most important ones in order to create a system that has fast transitions, as well as a high SNR.

1. It is important to have as many transitions as possible in the Raith-Sørensen chart of Figure 3.5. Having more transitions automatically means that a single transition will be faster. This will benefit the maximum achievable data rate of the system.

2. We want to capture the first peak in the theoretical response of a liquid crystal in Figure 3.7. This peak is the highest, and therefore will give the highest SNR. The first rising edge is impossible to use, because as soon as multiple crystals are stacked, this region can not be used anymore. The next best thing is to use the first peak.

3. We do not want to use too many crystals. Each added crystal will affect the amount of light that gets passed. The more crystals in a stack, the more the light will be blocked, even in their translucent state.

The next step is to determine the optimal number of crystals for each of the parameters stated above.

To have as many transitions in the Raith-Sørensen chart, the thickness has to be maximal. So to satisfy (1), we choose to have as many crystals as possible, as long as it also satisfies (2) and (3). To know the maximum number of crystals to capture the first peak of the theoretical response, we compare the Michel-Lévy chart of Figure 3.4 to the theoretical response of a liquid crystal in Figure 3.7. As can be seen in Figure 3.7, the highest peak occurs at around 250 nm. This corresponds to the white region in Figure 3.4. This means that, in order to include this first peak, we want to include the white region in the color

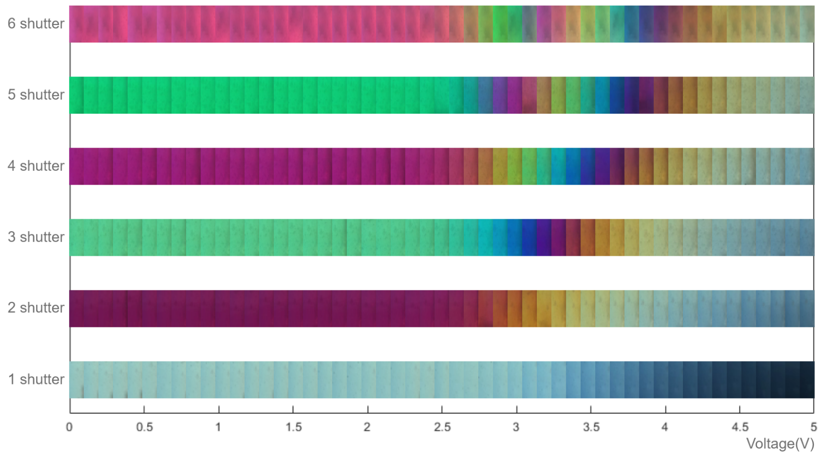


Figure 3.9: **Color measurements on one to six crystals. A voltage of $0 - 5V$ is applied in steps of $0.1V$, after which the color is captured using a camera, while light is shining through on the other side.**

spectrum of Figure 3.9. When looking closely at Figure 3.9, we can see that for a stack of six crystals, this region is just inside the spectrum (at a voltage of 5 V). Therefore, to satisfy ②, the maximum number of crystals is six. ③ has to be done empirically, because data sheets of the LCs are not available. Therefore, we look at Figure 3.8 and check whether the intensity of the signal is lower compared to fewer crystals. When looking at the X channel of Figure 3.8f, we notice that the height of the peaks is around 1.63 V. When we compare this with the X channel in Figure 3.8d, where the peak has a height of around 1.64 V, it is clear that intensity is lost when adding extra crystals. However, the number of transitions that could be used for modulation, is doubled, from two to four. Therefore, the choice is made to use six crystals.

3.3.2 Modulation

The system uses a similar modulation technique as ChromaLux in order to transmit data. Figure 3.10 shows the response for six liquid crystals in a stack. This response is created by applying 0 V, 5 V and 0 V to the stack, and measure the red light on the other side of the stack. As can be seen, there are multiple locations in the plot that could be used to have a high contrast between two symbols, without the need for a full voltage swing.

In this case, the voltage levels 2.2 V and 2.7 V for symbols A and B are chosen, because the edges of the transition region are more stable than the middle region. For a further description we refer to Section 4.1.1. For higher speeds, the symbols can be closer together to improve data rate, at the expense of SNR. Another observation is the fact that the response is not symmetrical, that is, the rising edge is faster than the falling edge.

When the aforementioned voltage levels are directly used for modulation of the signal, the response would be slow, because of the capacitive behaviour of the LCs. Therefore, the choice is made to apply 5 V and 0 V for a certain

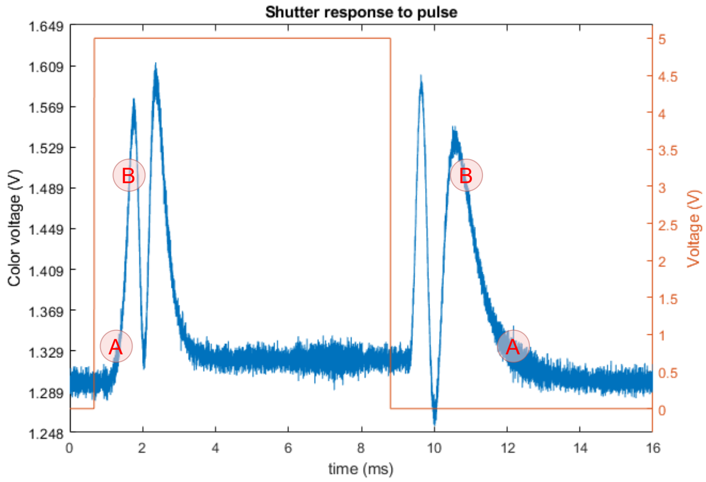


Figure 3.10: **The response for a stack of six liquid crystals. This plot is created by applying a 5 V pulse, followed by 0 V (in orange). The light at the output of the liquid crystals is measured using a red color sensor (blue line). Multiple high contrast regions appear. These regions can be used to modulate information, for example symbol *A* and symbol *B*.**

duration, depending on the data rate, to charge and discharge faster.

Capitalizing on the previous observations, we make use of three voltage levels, 0 V, 5 V, and a middle voltage 2.2 V. To send a *'0'*, the system is simply kept at the middle voltage, at symbol A, resulting in a straight line. To send a *'1'*, an A-B-A transition is created by applying 5 V for the proper duration to reach symbol B, and then apply 0 V for the proper duration to reach symbol A again. This way, a *'1'* can be seen as a /\ shaped signal. However, this is the approach that is used for ChromaLux. For the new system, a feedback controller is used to create the A-B-A transitions. The precise approach will be described in Chapter 4.

3.3.3 Demodulation

The main building block of the demodulation algorithm, is a function that detects peaks. The difference between consecutive peaks is saved as t_{dif}. A new variable *bitdif* is then created, which is dependent on t_{dif} as well as the frequency of the transmitted signal, f_{signal} (e.g. 1000 Hz for a 1 kbps signal), and is shown by Equation 3.5, in which round is a function to round the number to the nearest integer.

$$bitdif = round(t_{dif} \cdot f_{signal}) \tag{3.5}$$

When *bitdif* equals 1, meaning only one period between two consecutive peaks, a *'1'* is detected. Otherwise, a *'1'* followed by a number of *'0'*s is detected. The number of *'0'*s is equal to the value of $bitdif - 1$. As a result of this method, a transmission always has to end with a *'1'*. This is so the system is able to demodulate the final bit(s). However, because there is little to no drift, large messages can be transmitted at once, so this does not pose a real issue. This bit can be seen as a stop bit. There is no start bit.

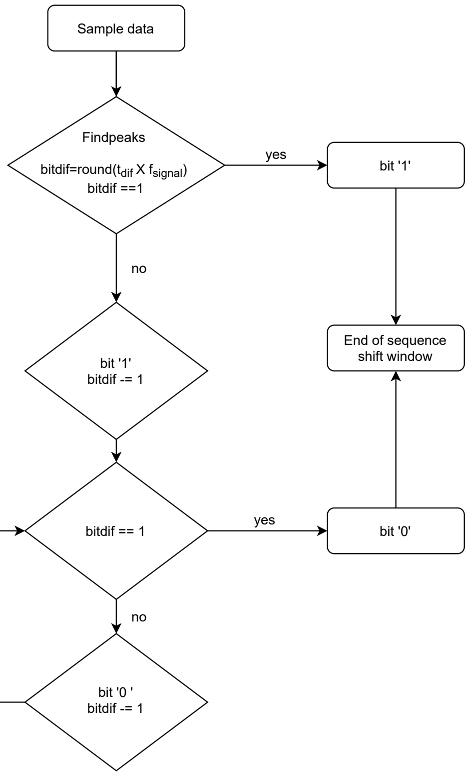


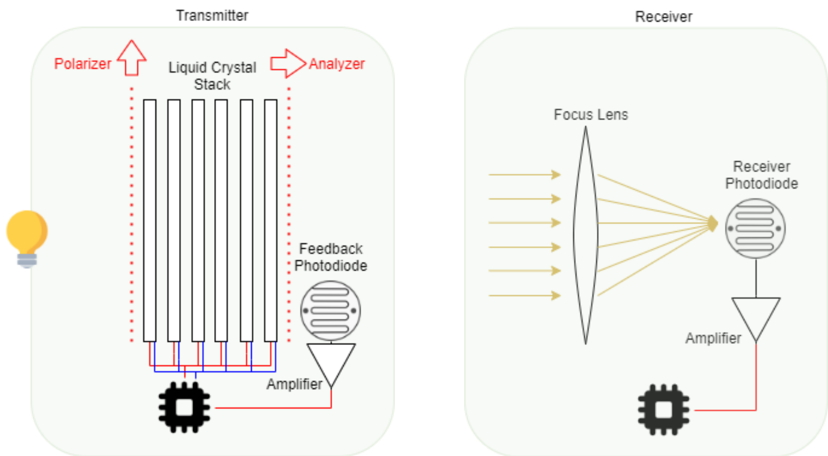
Figure 3.11: **Demodulation scheme. First, the findpeaks algorithm is invoked. The difference between two consecutive peaks is then saved as t_{dif}.**

3.4 The system

To incorporate both the stabilizing feedback mechanism and the SNR improving idea, a new system is created. This system consists of a new transmitter and a new receiver.

3.4.1 Transmitter

The transmitter is built upon a STM32H750VBT6 microcontroller. The Digital Analog Converter (DAC) of this board is used to create the proper signals that are required for controlling one a stack of LCs. As this DAC can only supply $0 - 3.3V$ and the system requires $0 - 5V$, an extra amplification stage is added, which uses a simple LM6132 operational amplifier with an amplification of 1.5x. The shutters that are used are taken from 3D glasses [1]. In addition, to make feedback possible, the transmitter also incorporates a photodiode that is placed directly behind the stack of LCs. The current from this photodiode is converted into a voltage level by using a transimpedance amplifier. This voltage is then fed into an integrated voltage follower, after which it is measured using the 16-bit Analog Digital Converter (ADC) from the microcontroller. Figure 3.12a shows a schematic view of the transmitter system. The flashlight from a phone is used as a light source. The system is programmed to continuously send the same message, so any drift can be immediately identified.



(a) **Schematic view of the transmitter. Six crystals are placed in a stack, in between a polarizer and an analyzer film. A photodiode is placed directly behind the analyzer in order to provide feedback to the microcontroller, so that the microcontroller can adjust the voltage on the stack.**

(b) **Schematic view of the receiver. Light beams are directed towards a photodiode using a lens. The photodiode is connected to a microcontroller using a transimpedance amplifier.**

Figure 3.12: **Transmitter and receiver of the created system.**

3.4.2 Receiver

The receiver is built upon an STM32F446RE microcontroller. This microcontroller can be different to the one used in the transmitter, since the receiver requires less processing power. A photodiode is connected to the microcontroller through a transimpedance amplifier, from which the output is connected to the internal operational amplifier of the board. The output of this amplifier is then connected to a 12-bit internal ADC of the microcontroller. To focus the light, and to achieve a higher SNR, a lens is placed in front of the photodiode. Figure 3.12b shows a schematic view of the receiver system.

To create a simpler, cheaper system, the color sensor from the ChromaLux system has to be replaced with a photodiode. In this case, the choice is made to use a photodiode with a color filter prefitted, the CLS15-22C/L213X/TR8 [12], in order to make use of the color properties of the LCs. To transform the current that the photodiode generates to a voltage that is within range of the

ADC, the circuit of Figure 3.13 is created. First, the current generated by the photodiode is converted to a voltage using a transimpedance amplifier. Instead of biasing the voltage to ground, the voltage is instead biased to 1.65 V, half of the voltage that is supplied. This way, voltage swing is allowed from the plus and minus sides without saturating the opamp. The component values are based on the necessary bandwidth and the amplification. The resistor value is set by trial and error, but as the speed that is required is not that high, a high amplification factor can be used in the first stage. This creates a circuit that requires fewer components. The sweet spot for the resistor is found to be 500 kΩ.

The capacitor value can be calculated by looking at the bandwidth β. Equation 3.6 [25] shows the equation that is used. The preferred bandwidth will be 10 kHz, because this is the speed that the microcontroller sends measurements to the computer. Filling in the resistor value, as well as the bandwidth, we end up with 32 pF for C.

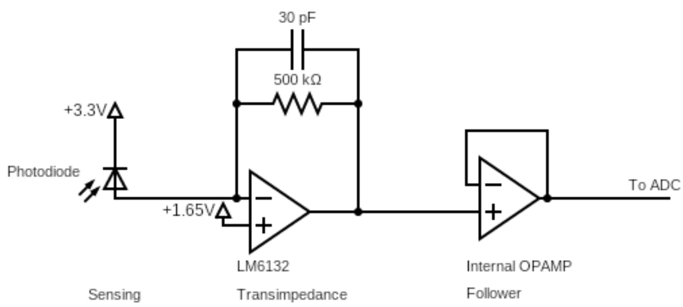


Figure 3.13: **Sensing circuit for the photodiode. First the current is converted into a voltage using the transimpedance amplifier. Second, the voltage is buffered by a voltage follower, after which it is fed into the ADC converter of the microcontroller.**

$$\beta = \frac{1}{2\pi \cdot R_f \cdot C_f} \tag{3.6}$$

3.4.3 Connection to the pc

As stated in the problem statement in Section 1.3, a new communication method between the receiver and the computer is used. The previous system could not achieve real-time communication because of the limited speed of the used protocol, as well as the limited speed of the microcontroller itself. The microcontroller takes 3000 samples, after which a transfer is initiated. The transfer itself takes numerous seconds. To solve this issue, the USB protocol is used. Instead of sending the data in one bunch, the data is now transferred at a rate of 10,000 measurements per second as soon as a new measurement is made. On the PC side, a serial oscilloscope is used [34], which plots the data as soon as it arrives. Figure 3.14 shows a sample of this program while it is receiving data. However, at this time, the computer is not able to demodulate the signal in real-time.

Figure 3.14: **The Serial Oscilloscope program. Sample data consisting of *’0’*s and *’1’*s is sent and shown here.**

Another improvement that this approach incorporates is that the data is already filtered at the microcontroller. Instead of sending every measurement of the ADC, which would be very noisy, the data is oversampled at the microcontroller itself. This means that the average value of multiple measurements is taken. This way, a large portion of the noise is already filtered away, which reduces the need for a filter on the PC side.

Chapter 4

Feedback of the transmitter

As stated before, the system is unstable. This chapter will describe a way to stabilize it. First, in Section 4.1 the problem will be further explained. Then in Section 4.2 a possible solution will be created. Finally, in Section 4.4, results of the feedback system will be described.

4.1 Working in the unstable region of LCs

An LC is designed to have slow response times with a high contrast. It is not designed for other transitions, especially not staying in the middle of the response curve. This causes an unstable signal. Especially when higher switching speeds are required, issues arise because of the capacitive behaviour of an LC. There are multiple reasons for this unstable response.

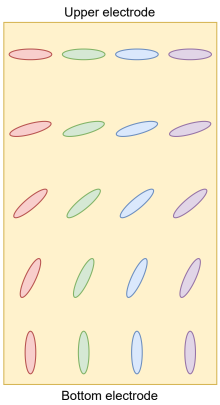
4.1.1 Reverse flow in liquid crystals

One of the main causes of the unstable response of LCs is reverse flow that is induced when a voltage is applied. This is called the backflow effect [8]. In an ideal scenario, we would expect the response of an LC to be like in Figure 4.1a. The molecules inside the LC are nicely aligned. However, in the real world, a backflow effect occurs, represented in Figure 4.1b by black arrows. This backflow has an 's' shape, which causes the molecules to shift, and causes distortion. This flow is temporary, and is mostly present in the middle of the transient state. In a lower frequency system, this backflow will not cause significant issues, because the system will have enough time to reach its steady state again. However, in our system, the frequency with which the LCs are modulated is high, which causes issues. Also, the more LCs are added, the more this backflow will be present.

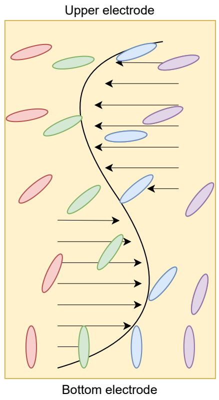
This backflow effect also impacts our choice of symbols to use. As the middle region is more unstable, the first peak that occurs in the transient state is used to transmit data.

4.1.2 Timing issues

Another cause of the drift could be timing issues. ChromaLux uses a set timing that is only adapted to data rate. However, even a slight misalignment with the



(a) **Simplification of the cross-section of the ideal response of a Liquid Crystal cell when an electric field is applied on the upper and bottom electrodes. All molecules nicely align, and achieve a 90° rotation of the molecules.**



(b) **Simplification of the cross-section of the true response of a Liquid Crystal cell when an electric field is applied on the upper and bottom electrodes. An s-shaped backflow (represented by the black arrows and black line) is induced, causing misalignment.**

Figure 4.1: **Simplification of the cross-section of a Liquid Crystal when an electric field is applied.**

actual liquid crystal cells could cause drift. To further explain this, we take a look at Figure 4.2. In this figure, the response for a stack of six liquid crystals is plotted. This response is created by applying a pulse of 5 V followed by 0 V, while a red color sensor measures the light at the output of the liquid crystals. In addition, two symbols A and B that could be used in the system are inserted into the figure. As explained before, a *'0'* can be sent by staying at symbol A, while a *'1'* can be sent by an A-B-A transition. Now imagine that, while sending a *'1'*, the second part of the transition is not quite able to make it all the way back to symbol A, but only to symbol A' in the time that is given, and then another consecutive *'1'* is sent. It is easy to see that, because the A-B-A transition does not start at symbol A, but at symbol A', the system will never be able to reach symbol A again, when consecutive *'1'*s will be sent. The third consecutive *'1'* might only be able to reach symbol A'', and so it goes on. Similarly, this also causes symbol B to shift up to B' and B''.

When after a consecutive set of *'1'*s, *'0'*s are sent, these *'0'*s also have a tendency to drift, because they want to get back to symbol A. This whole phenomenon can be seen in Figure 4.3a.

In addition, as soon as symbol B gets too high, a second peak occurs. This can be explained by the symbol overshooting, and reaching symbol C in Figure 4.2. The resulting output will look like Figure 4.3b. This second peak will cause difficulties in demodulating the signal. The inverse of this can also be true. When the time that 0 V is applied is too long, the *'1'*s cause a downward slope, and as a consequence, the *'0'*s can cause an upward slope.

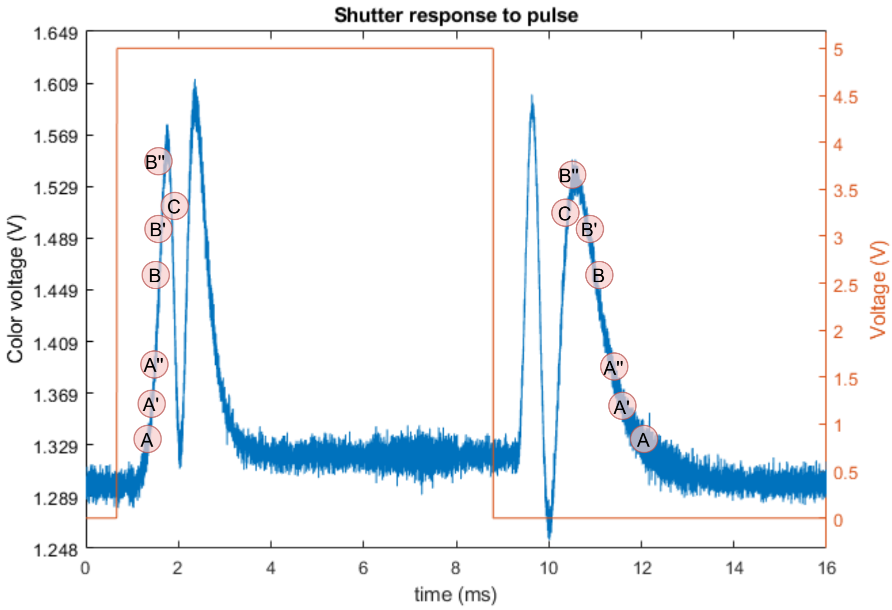
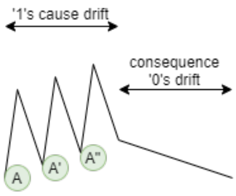
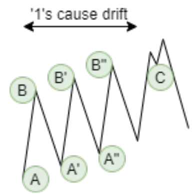


Figure 4.2: **The response for a stack of six liquid crystals. This plot is created by applying a 5 V pulse followed by 0 V (in orange). The light at the output of the liquid crystals is measured using a red color sensor (blue line). Drift occurs when a series of *'1'*s is sent.**



(a) **Consecutive *'1'*s cause an upward trend. As a consequence, when *'0'*s are transmitted right after a sequence of consecutive *'1'*s, they tend to drift as well, in order to get back to symbol *A*.**



(b) **Drift that occurs after a long series of *'1'*s is transmitted. This drift creates a second peak, because symbol *B* overshoots into the \ part of the signal, reaching symbol *C*.**

Figure 4.3: **Different forms of drift that could occur during transmission.**

4.2 Feedback controller

To solve the open-loop issues that cause drift in the system, a feedback controller is created. This controller measures the light that comes through the stack of crystals using an extra photodiode. Using these measurements, the system can be adapted in real-time.

4.2.1 The controller

The feedback system has to be able to remove the drift that occurs during transmission of symbols. When a *'1'* has to be transmitted, the controller continuously measures the amount of light that passes through the LCs. After a certain peak height is measured (not to be confused with the peaks that can be seen in the response of the crystals), the controller will bring the system back to symbol A. To transmit a *'0'*, the system will remain at symbol A. A state machine for this process is given in Figure 4.4.

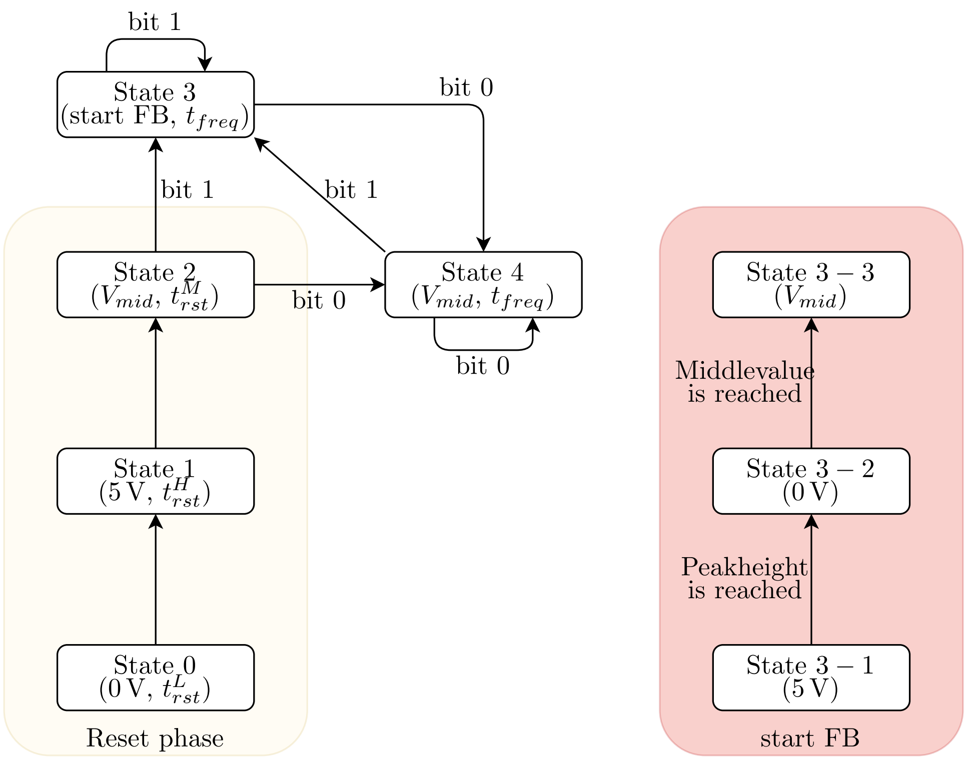


Figure 4.4: **State machine for the feedback mechanism in our system. First, the system is reset in the reset phase. Then the system is ready to start transmitting data. When a *'1'* has to be transmitted, the feedback (FB) state machine on the right is invoked. The system will remain in this state machine for a duration of t_{freq}. For a *'0'*, the middle voltage V_{mid} is applied for a duration of t_{freq}.**

In this state machine, the following variables are present:

- t^L_{rst}: Worst-case time that should be applied on the stack to remove all stored charge on them. For the used LCs, this value is 8 ms. This can be seen by looking at Figure 4.2.

- t^H_{rst}: Time that 5 V has to be applied in order for the LCs to reach symbol A from steady state. This value is also based on the response found in Figure 4.2 and is set to 0.8 ms.

- V_{mid}: Middle voltage that is applied for symbol A. This will be the voltage that is used to send *'0'*s and will also be used in the feedback mechanism for sending *'1'*s. This value can be adapted during transmission.

- t^M_{rst}: Duration that is required for the system to measure and save the $Middlevalue$. This value can be short as the system is already at symbol A when this state is incurred, and is set to 1 ms.

- t_{freq}: Time depending on the desired data rate. It is defined as $t_{freq} = \frac{1}{datarate}$. This means that for a data rate of 1 kbps, t_{freq} will be 1 ms.

- *Peakheight*: Peakheight that the system should reach when a *'1'* has to be sent (symbol B). It is defined as $Peakheight = Middlevalue + desiredpeakheight$, in which *desiredpeakheight* can be set.

- $Middlevalue$: Value that is measured in State 2, defining the baseline signal level for symbol A.

To be able to start transmission of symbols, the LCs first have to be reset, so that there is no residual charge left. This is because these crystals behave like capacitors, and can have a random charge left on them. It might seem strange to still use timing in this reset phase, but this is simply to make the transition towards V_{mid} faster.

The reset phase goes as follows:

0. *State 0*: apply 0 V for a duration of t^L_{rst}.
1. *State 1*: apply 5 V for a duration of t^H_{rst}.
2. *State 2*: apply V_{mid} for a duration of t^M_{rst}. This time can be short, because the system has already been brought to symbol A by State 1 and State 2. In this state, the first measurement is done using the photodiode. This measurement will be saved in the microcontroller, and will be known as *Middlevalue*. This will then be used as a baseline for the feedback mechanism.

After this reset phase, the system is ready to start transmitting bits. When a *'0'* has to be transmitted, the system traverses to State 4, in which the middle voltage V_{mid} is applied for a duration t_{freq}, depending on the set bit rate of the transmitter. When a *'1'* has to be transmitted, State 3 is initiated. This state invokes the *Start FB* state machine on the right of Figure 4.4, for a duration of t_{freq}. This *Start FB* state machine consists of three states.

3-1 5 V is applied on the stack of LCs. As soon as the system reaches $Peakheight$, the system goes to the next state.

3-2 0 V is applied on the stack of LCs. As long as the system does not reach its starting point, the system stays in this state.

3-3 V_{mid} is applied on the stack of LCs. The system will stay in this state until the main state machine has to transmit its next bit.

The value for V_{mid} has its own simple feedback mechanism, so that when a *'0'* is transmitted, the system will see this as a flat line. This mechanism is described in Section 4.2.2.

4.2.2 Reconfigurability

Another improvement of this system is its form of reconfigurability. Because of its simple nature, there are multiple parameters that can be configured, some manually, and some automatically. The first and most important parameter is the height of peaks that should be reached when sending a *'1'*. As shown in Figure 4.4, the system will apply a 5 V signal until it measures a peak of V_{middle} + *Peak_difference*. By adjusting the value of *peak_difference*, we automatically adjust the peak height, or symbol B, that we want the system to reach. However, special care must be taken when setting this value, as it is easy to set it too high. A too high value can easily lead to the same issues that ChromaLux experienced, double peaks or drift, as shown in Section 4.1.2. Another issue that could arise is the skipping of symbols, because the system is not able to reach the peak height at all, and therefore never reaches the second part of the transition of an *A*-*B*-*A* transition.

The second part of the reconfigurability is the adaptation of the middle voltage V_A itself, the voltage that is applied to the stack of crystals to create symbol A. By changing this voltage, drift in sending *'0'*s can be completely mitigated. There are two options for this voltage to change:

Adjust the value of V_A *manually*: by sending a command over the serial bus to the controller, the value of V_A can be manually tweaked. This way, the system can be very precisely tuned for specific circumstances. This is not the ideal method, because it defeats the purpose of automatic reconfigurability.

Automatically adjust the value of V_A *during runtime*: During runtime, every time a *'0'* is sent, the current light intensity is measured using the feedback photodiode. Halfway through the transmission of this *'0'*, the light intensity is measured again. These two measurements are then deducted (V_{diff}), after which three possible measures can be taken:

1. $|V_{diff}| < threshold$: No further action is taken.

2. $V_{diff} < -threshold$: This means that the system has a drift that has an upward trend. To solve this, V_A is decreased by 0.005 V. This value can be tweaked, but for our system this works well.

3. $V_{diff} > threshold$: This means that the system has a drift that has a downward trend. To solve this, V_A is increased by 0.005 V.

This process is also shown in Figure 4.5. The three actions are numbered, and describe the process stated before.

4.2.3 Adaptability to light

One more improvement over ChromaLux is the adaptability of our system to changes in light intensity. Because of the feedback loop that is implemented, the system is always aware of its status. Therefore, it is able to react to changes in light intensity relatively easy. In our implementation, every time the system starts up, it measures the current light intensity that comes through the stack of crystals when the middle voltage is applied. This measurement will then be used as a baseline.

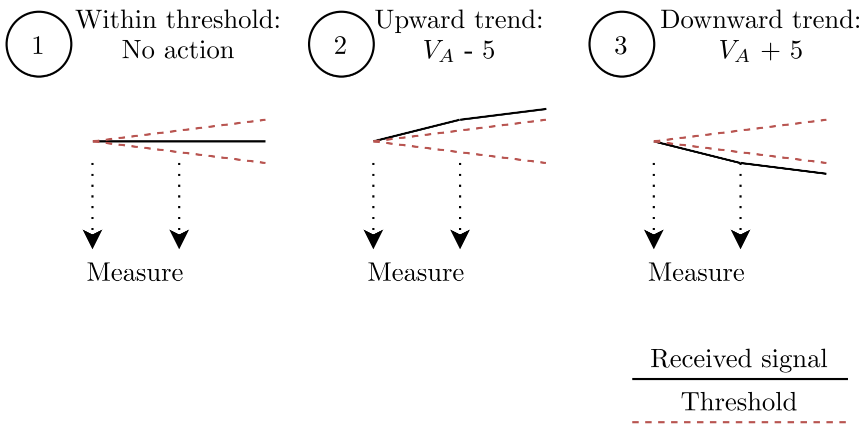


Figure 4.5: **Three versions of actions to change the value of V_A automatically. When the drift is within the threshold, no action is taken (①). When the drift has an upward trend, the value of V_A will be decreased (②). When the drift has a downward trend, the value of V_A will be increased (③).**

4.3 Benchmarking ChromaLux

To be sure that the circumstances of our measurements are comparable to those of ChromaLux, the ChromaLux system has been recreated, after which several measurements have been conducted in order to check if the results are similar to the results reported by the authors of ChromaLux.

We conducted benchmarking tests at two distances, 1 meter and 5 meters at a data rate of 1 kbps. We continuously send the same message, after which we use the demodulation code of ChromaLux to demodulate the signal and calculate the BER. Then we compare our results with the results from ChromaLux. Figure 4.6 shows an example of the bit sequence, and its demodulation by ChromaLux.

At 1 meter, we have found no errors during transmission of 81 test messages, each 14 bits long. This means a BER of 0%. At 5 meters, we found one error in 109 test messages, each 14 bits long. This means a BER of 0.06%.

The comparison of the results can be found in Table 4.1.

Table 4.1: **Comparison between our measurements of the ChromaLux system and the measurements from the paper [13].**

	BER (%) 1m	**BER (%) 5m**
Paper	0	0.0016
Measurements	0	0.06

For a range of 1 meter, the BER is exactly the same. For a range of 5 meters, the BER is not the same, but this can be contributed to the (lower) number of messages sent, as well as the circumstances that the measurements are conducted. As the BER for 5 meters is still low enough, and we only do measurements for our system up to 5 meters, we can conclude that the results

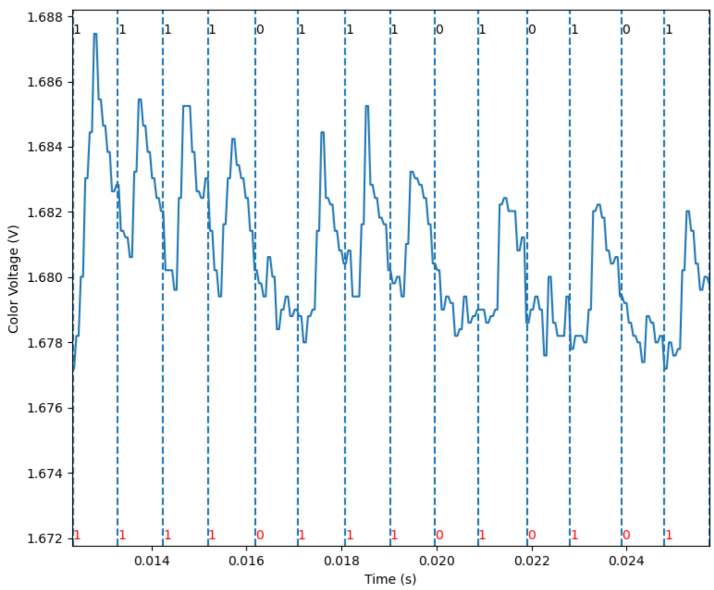


Figure 4.6: **Demodulation of ChromaLux while transmitting a message at** 1 kbps **at a range of 5 meters. The blue line shows the received signal. The top row of *'1'*s and *'0'*s (in black) shows the demodulated bits, while the bottom row (in red) shows the values that they should be.**

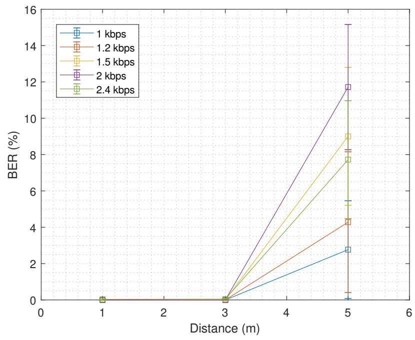
are comparable, and we can use the results from ChromaLux itself to compare to our system. This does mean that ChromaLux has a small advantage.

4.4 Feedback results

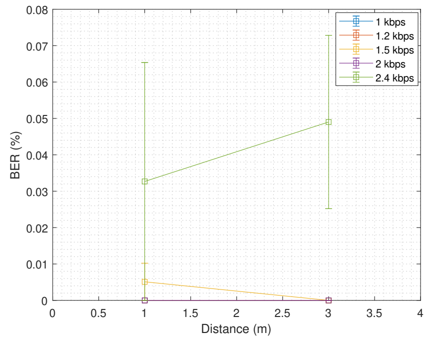
To test our improved system, five different messages were transmitted. These messages were chosen so that all sort of transitions are present, as well as transitions that ChromaLux struggled with. Included are sets of *'0'*s, sets of *'1'*s and sets of *'01'*s. The total message size is 48 bits, 6 bytes. These messages are then received for 3 seconds, after which the first 51 messages are decoded. This means that the total message size is 2448 bits. Using this many messages in one go will also test if there is any drift present, because our simple demodulation scheme is not able to cope with drift, and thus will result in a high BER.

These measurements are conducted at speeds of 1 kbps, 1.2 kbps, 1.5 kbps, 2 kbps and 2.4 kbps, at ranges of 1, 3 and 5 meters. This maximum range is due to limitations of the room in which the measurements are done. Due to covid, this was the only possibility to do the measurements. In addition, also the minimum speed that the system is capable of is investigated, to see whether the feedback system is capable of keeping the system stable while operating in an unstable region of the LCs. Finally, also the maximum speed that the system is capable of is investigated. All tests are performed while artificial light with a brightness between 700 and 1000 lux shines through the stack of crystals. Therefore, the system can be compared to ChromaLux, which uses similar light intensities.

The next step is to test our system. The results for these tests are shown in Figure 4.7a. The mean BER of all messages is shown by the small squares, while the minimum and maximum BER of a single message can be seen by the vertical lines. Notice that the system struggles for ranges larger than 3 meters. Therefore, another plot is created with only one and three meters of range, so the results are more clear. The results for 1.5 kbps are strange, because these show a lower BER for a higher range. Our hypothesis is that this is caused by the placement of the lens. A small misalignment will already cause issues. To test this hypothesis, we did more tests with this particular scenario. We have sent another 7200 bits of the same message that previously had an error in it, and found no bit errors. It is therefore plausible that this one erroneous bit was random noise.



(a) **Zoomed plot with error bars for different transmission speeds at distances of 1, 3 and 5 meters.**



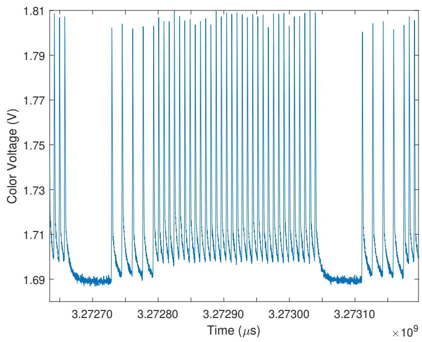
(b) **Line plot with error bars for transmitting different speeds at distances of 1 and 3 meters.**

Figure 4.7: **BER for different speeds at different ranges. The square in each plot shows the mean BER. The lines above and below shows the standard deviation of the BER during transmission of the different messages.**

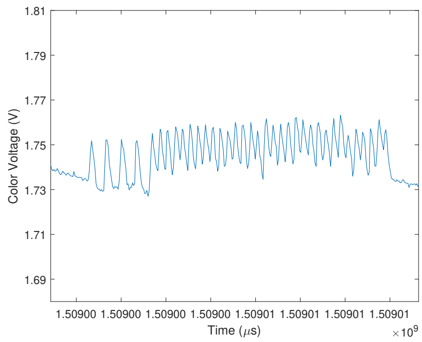
We have also investigated the minimum data rate that the system is still able to operate at. This minimum data rate could be used to reach longer ranges, because for our modulation scheme, the SNR of a lower speed signal is higher. A sidenote is that this does not scale up endlessly. As soon as the whole first peak of the transition region (in Figure 3.10) is used, the SNR will not rise anymore.

Figure 4.8a shows the received signal for a pattern of *'01'*s, followed by a set of *'1'*s, and ended with *'0'*s. As can be seen, the signal is stable, has little to no drift, and can be easily demodulated. Even slower speeds are also possible, so we have found no limit on lower speeds of the system. However, as this data rate already utilizes the maximum peak height of the transient region, there is no real need to go any lower. This signal results in a BER of 0 %.

The maximum speed of the system is also tested. This maximum speed can only be reached at a distance of 1 meter, because the SNR will rapidly decay as the distance increases. This higher speed will also cause a higher BER. The maximum speed that we have been able to achieve is 3 kbps. The signal for the same message as for the low speed signal can be found in Figure 4.8b. The first observation shows that there appears to be a lot of drift in the system. However, when the complete signal is shown, the signal will still remain in this intensity range, and will not drift any further. It does make the signal more difficult to demodulate. This results in a mean BER of 0.33 %.



(a) **Received signal for a** 125 bps **message. The signal is stable and can be easily demodulated.**



(b) **Received signal for a** 3000 bps **message. The signal starts to become unstable, and is more difficult to demodulate.**

Figure 4.8: **Comparison of the maximum speed of** 3000 bps **and a speed of** 125 bps**, the speed at which the maximum SNR can be reached.**

4.5 Discussion

As can be seen in Figure 4.7a, the system is able to reach speeds of up to 2.4 kbps, while keeping the BER under 0.08 % at distances up to 3 meters. However, the system struggles to reach higher distances. This is caused by the fact that we block the stack of LCs partly, causing the SNR to go down. Another reason is that our demodulation scheme is not as sophisticated as the scheme that ChromaLux uses, and is not capable of coping with a lot of noise. Finally, as ChromaLux resets the system every time one message has been transmitted, it is easier to demodulate the signal, as small drifts and noise can already cause issues in our demodulation system. However, we still made the choice to do the measurements using a large message size, to test the system up to its limits.

The maximum speed that is reached is mainly throttled by noise in the feedback system. Because of this noise, we need multiple processing cycles to check if the peak height has really reached its maximum. This impacts the ability to keep the peaks at stable heights, as well as reduces its maximum reachable speed.

When comparing the results to the ChromaLux system, we see a speed improvement at 1 meter from 1.25 kbps to 3 kbps, which is 140 %, while keeping the mean BER at similar levels. At a range of 5 meters, the mean BER of our system is too high for communication purposes because of the blocking of the LCs, so ChromaLux shows the best results there.

Chapter 5

Improving the contrast of ChromaLux

As explained in Chapter 4, the SNR of the system is low because we partially block the LCs with our feedback photodiode. This causes a lower achievable range than the ChromaLux system. Therefore, we need to find a way to improve the SNR of the system in order to make a higher range possible. This chapter will describe differential amplification, which can be used to improve the SNR of the system, and therefore can accomplish our goals. First, Section 5.1 will describe the idea, and will state the maximum theoretical improvements of this method. Section 5.2 then continues by explaining a method to incorporate the differential amplification theory into our system, after which the system itself is described in Section 5.3. Finally, Section 5.4 shows the results of the system, while Section 5.5 discusses these results.

5.1 Differential amplification

A standard method to decrease noise and therefore increase the SNR is the use of differential amplification. We can use this method here as well. The idea is simple: by subtracting two completely opposite signals, we can double the output signal. As an added benefit, any common noise that is created by the photodiodes and the Analog-Digital Converters, will be filtered out. The idea is shown in Figure 5.1.

Two signals, V_1 and V_2, which are completely inverse, are subtracted from each other. These signals also have common noise. This common noise is then filtered out. The process can be described by the following Equations:

$$\begin{aligned} V_{diff} &= (V_1 + noise) - (V_2 + noise) \\ V_{diff} &= V_1 - V_2 + noise - noise \\ V_{diff} &= V_1 - V_2 \end{aligned} \tag{5.1}$$

As $V_1 = -V_2$, the resulting signal will be $2V_1$, resulting in the doubling of the signal amplitude, as well as a reduction in noise.

This is of course the perfect scenario, in which both signals are completely aligned. Figure 5.2 shows what happens when the two signals, V_1 and V_2 are not

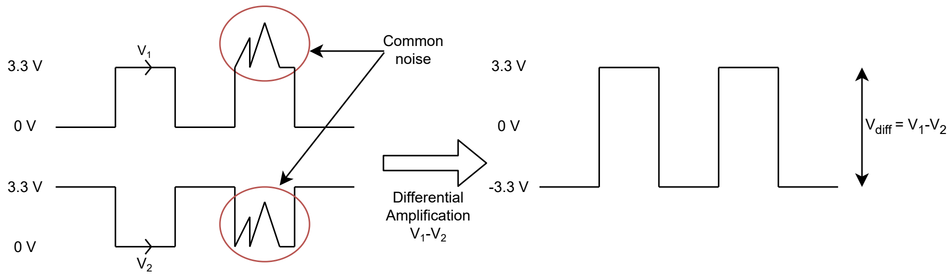


Figure 5.1: **Differential amplification. Two inverse signals are subtracted, removing common noise, as well as doubling the signal amplitude.**

perfectly inverse. As can be seen, the output signal still has the same maximum value of V_{diff}. However, the more the signal is shifted, the smaller the peak will be when a square wave is used, up to the point where the two signals are the same, creating a horizontal 0 V line. It is therefore important to have well aligned inverse signals. Section 5.2 describes our method to keep the signals aligned.

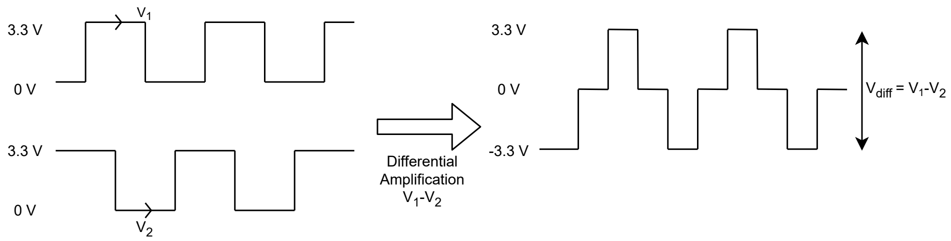


Figure 5.2: **Differential amplification when the two signals are misaligned.**

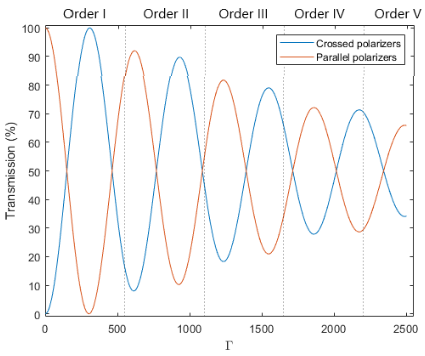
5.2 Response of crystals

As explained in the previous section, we can increase the SNR by using differential amplification. However, this means that we have to find a method to create two inverse signals. One option would be to add a second stack of crystals, and operate this stack in a slightly different region to create a \/ shaped signal instead of a /\ shaped signal. However, as we have also discussed in Section 5.1, the signals have to be perfect inverses of each other. Misalignment will quickly cause difficulties in demodulation, and will not have any added benefits. Therefore, a second feedback mechanism would have to be created to make sure that the two signals are aligned, which would make the system unnecessarily complicated.

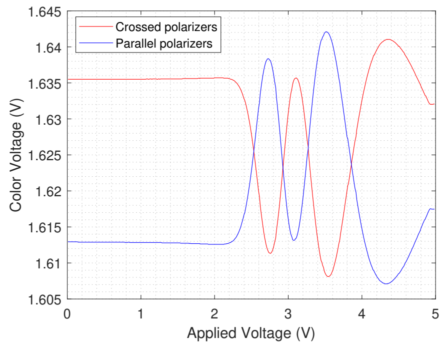
A better method would be to make use of the properties of the crystals itself. In Section 3.2.2, important aspects of these crystals are overlooked. In Equation 3.2, we have only considered the case when the polarizer and analyzer are perpendicular. Equation 5.2 shows the transmission when the polarizer and analyzer are parallel to each other [36]. In this equation, Γ is the same as in Equation 3.3.

$$I = cos^2(\frac{180 \cdot \Gamma}{\lambda}) \tag{5.2}$$

When we apply a similar reasoning as in Section 3.2.2 to create the theoretical response, we end up with the response in Figure 5.3a. In this figure, the theoretical response for the red color channel from Section 3.2.2 is plotted against the theoretical response that is calculated using Equation 5.2. As can be seen, the two signals are completely inverse, which means that in theory they can be used in conjunction with each other by using differential amplification. The same reasoning applies to the other color channels.



(a) **Theoretical response for the red color channel of parallel polarizers vs crossed polarizers. As can be seen, the signals are completely inverse.**



(b) **Measured intensity for crossed polarizers (red) and parallel polarizers (blue). This measurement is done using a single color channel.**

Figure 5.3: **Theoretical and measured response for crossed polarizers vs parallel polarizers**

To verify this behaviour, a small test has been conducted, in which a $5V$ pulse is applied to a stack of six LCs, while the red color channel is measured. The results can be found in Figure 5.3b. For the first measurement, the polarizer and analyzer are crossed, resulting in the red line. The second measurement is done with the polarizer and analyzer in parallel, resulting in the blue line. The signals are almost perfect inverses of each other. To quantify the results: the peaks are three samples apart, with a sample size of 500. This means they are shifted by $\frac{3}{500} = 0.6\%$. We do not expect this to give any issues.

5.3 The system

To incorporate the theory from Section 5.2, the transmitter and receiver have to be slightly altered. First, the analyzer from the transmitter has to be transferred to the receiver. This will give an issue for the feedback photodiode, so the photodiode will be covered with a small piece of polarizing film. For the receiver part, an extra photodiode has to be added. In front of each photodiode is an analyzer, with directions perpendicular to each other. Both will then be connected to the receiver board, after which differential ADC is used. The used microcontroller is already capable of subtracting two ADC channels to create a new signal with an amplitude double the amplitude of the original signal. Figure 5.4 shows the new system.

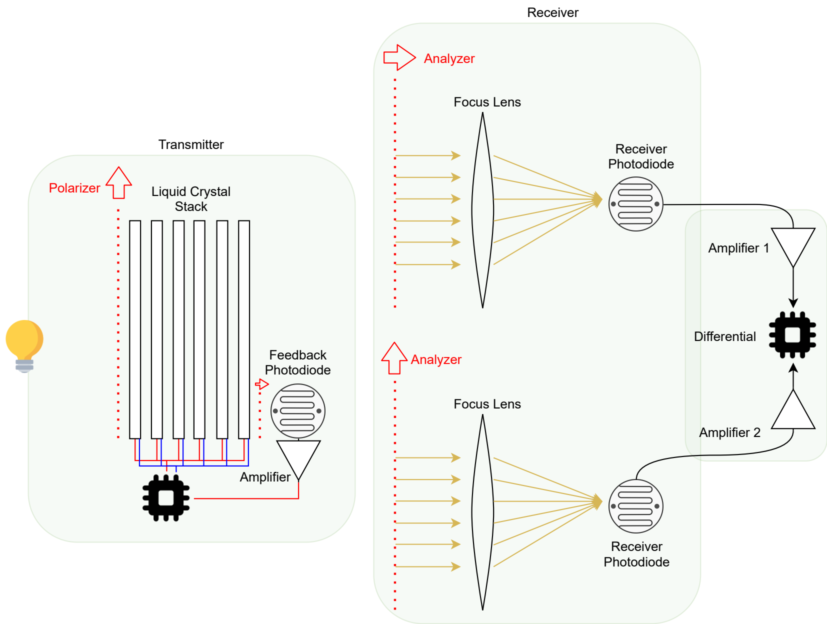


Figure 5.4: **Adapted receiver and transmitter system, to use for differential amplification.**

This method could also be used to create more color channels, when it would be used in conjunction with color filters on the transmitter side. Another major benefit of this method, is that it could be used in almost all the other VLC systems from Section 2.5 to improve performance.

5.4 Results

The system is tested using the same approach as for the feedback system in Chapter 4. Figure 5.5 shows the results for the measurements.

Although still not perfect at a range of 5 meters, the system is able to keep the maximum BER under 0.2 % for speeds up to 2 kbps, while the mean BER is closer to 0.1 %.

As the majority of the state-of-the-art attempts to keep the BER under 1 % ([13, 31, 33]), we accept a BER of up to 1 % as well, to keep the comparison fair.

In addition, the measurement for 3 kbps at 1 meter has been redone as well, using the differential amplification method. This method decreases the mean BER from 0.33 % to 0.25 %. This improvement is less than expected. One explanation could be that the majority of the errors are already caused during transmission of the signal, because of noise in the feedback photodiode. We

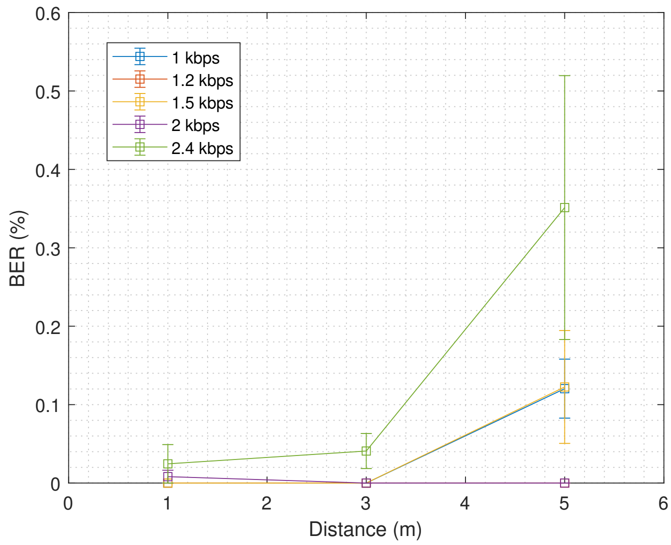


Figure 5.5: **Resulting BER using differential amplification. The mean BER is shown with a small square, while the minimum and maximum BER values are shown by the vertical lines.**

could use differential amplification again for the transmitter, but as the noise is mainly in the circuit of the photodiode, this would not be benificial.

5.5 Discussion

As the main goal of this chapter was to solve the issue that the feedback controller of Chapter 4 caused, we compare the results from the feedback controller to the results from the feedback controller with differential amplification. The expected improvement of the system can be calculated using Shannon's theorem [30]:

$$C = BW \cdot \log_2(1 + S/N) \tag{5.3}$$

where
C = channel capacity in bits/s
BW = bandwidth of the channel in Hz
S/N = SNR

Because of this equation, we expect the system to behave better than the feedback system from Chapter 4, with at least a factor $\frac{\log_2(1+2)}{\log_2(1+1)} \approx 1.58$, when the SNR is doubled. This means that for a similar range and speed, we expect the BER to be less than $1/1.58 \approx 0.63$, or reach 1.58 times the range with a similar BER as for only feedback. The main issue was at five meters, where no reliable data transfer was possible anymore. Therefore, we compare the BER from the measurements at five meters with and without differential amplification. The results can be found in Table 5.1. As can be seen, the improvements are huge, from 2200 % up to 7154 %. When comparing the results to ChromaLux, we achieve a data rate of 2.4 kbps with a BER of 0.35 % at 5 meters, while ChromaLux has reached a data rate of 1.25 kbps with a BER of 0.27 %. This means that we achieve a data rate which is 92 % higher, while maintaining a comparable BER. This BER could probably be even lower when a more sophisticated demodulation algorithm is used.

Table 5.1: **Comparison between feedback only and feedback in combination with differential amplification at a range of 5 meters.**

Data Rate (kbps)	**Mean BER (%) Feedback**	**Mean BER (%) Differential**	**Improvement (%)**
1	2.77	0.12	2200
1.2	4.28	0.00	–
1.5	8.89	0.12	7154
2	11.73	0.00	–
2.4	7.72	0.35	2106

The measurements gave some unexpected results. For 1 kbps and 1.5 kbps signals we have found 1 error, while for 1.2 kbps and 2 kbps no errors were measured. Some additional measuring was done, but unfortunately there was not enough time to do even more measurements due to the complicated way the measurements are done and the systems involved. The results are promising but may not be 100 % accurate. For more accurate results, additional measurements would have to be performed. However, the current measurements without doubt show the many capabilities of this system.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

Throughout this thesis, a method has been devised to improve the performance of ChromaLux [13], a system that uses ambient light in combination with Liquid Crystals to transmit data. Its main innovation is the use of a stack of Liquid Crystals instead of a single one, exposing a new transient region that could be used for transmission of symbols. Several challenges were encountered by the ChromaLux system, mainly an unstable operation resulting in bit errors due to drift in the system. We have made several contributions to the system, in order to address the problem statement:

How can we improve ChromaLux so that the data rate increases, the system becomes adaptive to changes in light intensity, and the bit error rate decreases.

In order to do so, the problem statement has been split into two parts. First, the drifting of the system was addressed while at the same time making the system adaptive to light changes. A feedback system has been created for this cause. The feedback system measures the light that is passed by the LCs in order to create an output signal free of drift. At every reset, the system measures the current light intensity, and adapts its feedback accordingly. This makes the system adaptive to light. Using this method, the data rate of ChromaLux has increased from 1.25 kbps to 3 kbps at 1 meters, at the expense of SNR, and therefore range. The maximum range that the system has is 3 meters as opposed to 10 meters for ChromaLux.

The second part of the thesis has addressed the issue of the lower range, and has created a method to increase the SNR by means of differential amplification. Using parallel and perpendicular polarization, two different channels can be created using a single transmitter and a single stack of crystals. At the receiver side, two photodiodes are present to receive the signal and perform differential amplification. Using this method, we have achieved a data rate of 2.4 kbps at a range of 5 meters, an improvement of 92 % over ChromaLux. Due to covid restrictions we could not determine the maximum range of our system as experiments could only be done in a single room. All this is in combination with a similar BER as ChromaLux has achieved at its highest data rate, 0.35 % vs 0.27 % for ChromaLux.

6.2 Future Work

While an increase in performance has been obtained, there is still room for improvement. Some improvements that could be made are:

- **Use comparators**: The current feedback controller continuously measures the light that passes through the stack of crystals. This gives high requirements on the microcontroller. One way that might solve this issue is to use comparators instead of continuously measuring. This would mean that a less powerful microcontroller could be used, decreasing the energy consumption and cost of the system.
- **Use multiple color channels**: As we currently only use one color channel, using multiple channels could mean that multiple bits can be sent at once. This would increase the data rate even further.
- **Redesign the feedback board**: Currently, noise in the feedback controller gives issues, because we have to oversample the signal, causing a slower response. This response causes slower data rates. By improving the design of the feedback board, this noise could be (partially) removed, hence giving rise to a higher data rate.
- **Improve the demodulation code**: By creating a more sophisticated demodulation code that would detect peaks better, the BER can be decreased, and the range could be improved.
- **Implement adaptive data rate in the system**: By transmitting certain bit sequences at the start of transmission, the data rate could be found at the receiver side. This would create a possibility to automatically adjust the data rate.

List of Acronyms and Abbreviations

Notation	**Description**	**Page List**
ADC	Analog Digital Converter	32, 33, 34, 48
BER	Bit Error Rate	2, 3, 4, 10, 11, 13, 15, 16, 17, 18, 41, 42, 43, 44, 48, 49, 50, 52
DAC	Digital Analog Converter	31
LC	Liquid Crystal	9, 12, 13, 15, 16, 17, 21, 22, 24, 27, 28, 29, 31, 32, 35, 38, 39, 42, 44, 45, 47, 51
LEDs	Light Emitting Diodes	1, 2, 8
RF	Radio Frequency	iii, 1, 17, 18, 19
SNR	Signal-to-Noise Ratio	iii, 3, 10, 22, 27, 28, 29, 31, 32, 43, 44, 45, 46, 49, 51
VLC	visible light communication	iii, 1, 2, 7, 8, 9, 10, 11, 12, 13, 17, 18, 19, 48

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