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Master of Science Thesis in Embedded Systems

Increasing the Performance of Passive Communication with Ambient Light

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Title

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Abstract

Most wireless communication technologies have been using the Radio Frequency (RF) spectrum for decades. Due to the popularity of the Internet of Things (IoT), the RF spectrum has started to become densely populated. Researchers have begun to explore other bands of the electromagnetic spectrum that can be utilized as a communication media. One of the promising choices is the visible light spectrum.

Visible Light Communication (VLC) refers to the wireless communication technology that utilizes the visible light spectrum. This spectrum is thousands of times wider than the Radio Frequency (RF) spectrum and is license-free. In VLC, data is transmitted by turning a light source on and off. However, not every light source can be controlled. Passive light sources such as the sun provide an immense amount of light that can be used for wireless communication if we can develop ways to modulate them.

One of the researches that use ambient light to create a wireless link is LuxLink. LuxLink uses liquid crystal shutters to control passive light sources and provides low energy, reliable, and flicker-free (safe) communication. This thesis addresses several problems that the current LuxLink system has.

We present LuxLink+, an extension of LuxLink that provides two main improvements. Firstly, the data rate of the system is relatively low (80 bps). To increase the data rate, we provide a thorough analysis of the systems bandwidth. Afterward, we modify the modulation technique, which increases the data rate to 1000 bps at a range of 1.5 m.

Secondly, the system has a static data rate, which means that the system cannot adapt its data rate to changes in the environment. We implement a rate adaptation algorithm that can change its data rate accordingly. LuxLink+ improves the average throughput of the system by up to 85 percent compared to LuxLink.

Preface

I have always been fascinated with wireless communication as it is invisible but means so much for us. This motivates me to work on that topic. When I talked to Marco Zúñiga regarding thesis possibilities in the Embedded Software group, I was interested in his idea of wireless communication using sunlight. After discussing further with Marco alongside Chaitra and Rens, who already worked on this project, I decided to continue their work. Even though the last ten months seem to pass by, I learned a lot during that period.

I want to express my gratitude to all of the people that helped me during this thesis project. First of all, I would like to thank Marco for his superb supervision during the project. He is always supportive of what I want to do and always try to motivate me to be a better person. Next, I would like to thank Rens and Chaitra for guiding me throughout the project. Without your help, I would not finish the project on time. I would also thank all my friends here in Delft, especially Adi, Anup, and Yonatan, who always give me inputs inside and outside my thesis. Next, I would like to thank my family and Caecilia for all the motivation and good wishes given to me during my ups and downs. Last but not least, thank you StuNed for providing me a scholarship. Without StuNed, the dream of studying abroad would not come true.

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Contents

Preface	v
1 Introduction	1
1.1 Problem statement	2
1.2 Contributions	2
1.3 Thesis outline	3
2 Background and related work	5
2.1 Active and passive light sources	5
2.2 Polarization in visible light communication	6
2.2.1 Controlling polarization direction	7
2.2.2 Liquid Crystal Shutter	7
2.3 Related works	9
2.3.1 Semi-passive systems	9
2.3.2 Passive systems	10
2.3.3 Summary	12
3 System design	13
3.1 LuxLink	13
3.1.1 Transmitter	13
3.1.2 Receiver	13
3.2 LuxLink+	15
3.2.1 Design requirements	15
3.2.2 Improving data rate: modulation technique	16
3.2.3 Adaptive system	16
4 Data rate improvements	19
4.1 Frequency Shift Keying (FSK)	19
4.2 Bandwidth analysis	21
4.2.1 Lower limit frequency analysis	21
4.2.2 Upper limit frequency analysis	23
4.2.3 Summary on bandwidth analysis	27
4.3 Multiple frequencies usage	28
4.3.1 M-ary Frequency Shift Keying (MFSK)	28

4.3.2	Multiple-Input Multiple-Output Frequency Shift Keying (MIMO FSK)	28
4.3.3	Comparison	29
4.4	Evaluation	31
5	Adaptability improvement	33
5.1	Adaptive data rate	33
5.1.1	Practical considerations	34
5.2	Adaptive Auto Rate Fallback (AARF)	35
5.2.1	Implementation details of AARF	35
5.3	Evaluation	36
5.3.1	Varying distance	37
5.3.2	Varying light intensity	39
6	Conclusions and Future Work	41
6.1	Conclusions	41
6.2	Future Work	41
A	Flicker mitigation: polarizer placement	47

Chapter 1

Introduction

Most wireless communication technologies have been using the Radio Frequency (RF) spectrum for decades, which enables us to transmit information over short distances (e.g., Wi-Fi, LoRa, and Bluetooth), or over long distances (e.g., deep-space radio communications). Due to the popularity of the Internet of Things (IoT), the RF spectrum has started to become densely populated. Researchers have begun to explore other bands of the electromagnetic spectrum that can be utilized as a communication media [10].

In the past, the visible light spectrum has been considered to be a viable option for communication. The British-Indian Army developed Heliographs [22], which used sunlight reflections to transmit Morse codes, as early as the 19th century. The reflections were manipulated by pivoting or blocking a mirror with a shutter. Another notable invention of communication using light was the Photophone [14], developed by Alexander Graham Bell in the 1880s, which used a vibrating mirror to modulate voice via sunlight reflections. These inventions demonstrated the potential of visible light as an alternative communication media.

Visible Light Communication (VLC) refers to the optical wireless communication technology that utilizes the visible light spectrum between 400 and 800 THz. This spectrum is thousands of times wider than the Radio Frequency (RF) spectrum, and is license-free. In VLC, data is transmitted by modulating a light source. The Light Emitting Diode (LED), an *active* light source, has become the most popular VLC transmitter [11] as it is already installed everywhere to provide illumination and can be turned on and off rapidly. In contrast, *passive* light sources, like the sun, are pervasive and offer more light compared to active light sources. It would be transformational if we can use them for wireless communication.

Unlike active light sources, passive light sources can not be easily controlled to modulate information [23]. However, we can borrow the idea of controlling light reflections to send information, similar to the Heliograph idea. Instead of pivoting a mirror to control the reflections, we can use ma-

materials that can vary its transparency level to either allow or block incoming light, like the Liquid Crystal (LC) shutter. There are several works which utilized the LC shutter to control light reflections, such as RetroVLC [18], PassiveVLC [25], PIXEL [26], and LuxLink [8]. This thesis focuses on improving the performance of LuxLink.

1.1 Problem statement

LuxLink [8] enables wireless communication by controlling the reflections of ambient light using LC shutters. It uses a frequency-based modulation to realize a flicker-free and reliable communication system. This thesis addresses several challenges that the current LuxLink system encountered.

Challenge 1: Maximizing data rate while maintaining flicker-free and reliable communication. The current data rate is relatively low compared to other similar VLC technologies [18, 25]. Higher data rates would enable a wider range of applications. Moreover, LuxLink utilizes frequency-based modulation to achieve a reliable and flicker-free (safe) communication [8]. We perform a thorough analysis of the modulation scheme to maximize the data rate while maintaining the reliability of the system.

Challenge 2: Adaptive data rates. The current system is designed to operate at a fixed data rate. This inflexibility results in a sub-optimal throughput when the environment provides good channel conditions that may allow the system to transmit at higher data rates. It is desirable to have a system that can adapt its data rate, given certain conditions (e.g., shorter distances and higher light intensities). This requires us to devise an adaptive data-rate algorithm to maximize the amount of information that can be sent.

1.2 Contributions

This thesis presents *LuxLink+*, which is an improvement of the LuxLink system. The contributions of this thesis are as follows:

1. We implement a modulation technique that increases the data rate of the system from 80 bps to 1000 bps. This is done by analyzing the bandwidth of the system and employing frequency multiplexing schemes (Chapter 4).
2. We implement an adaptive data rate algorithm that improves the average throughput by up to 85 percent (Chapter 5).

1.3 Thesis outline

Before going into the details of the system, background information and related works are presented in Chapter 2. In Chapter 3, the current LuxLink system and its potential improvement are described. The analysis of the modulation technique and how the data rate can be maximized are discussed in Chapter 4, including the evaluation of the modulation technique. In Chapter 5, we describe the adaptive data-rate algorithm employed in our system and evaluate its performance. Finally, the conclusion and future work of this thesis are discussed in Chapter 6.

Chapter 2

Background and related work

This chapter provides background information related to this thesis. First, information about active and passive light sources is given in Section 2.1. After that, Section 2.2 describes the use of polarization in visible light communication (VLC). In the end, Section 2.3 shows some related works on the topic of passive light communication.

2.1 Active and passive light sources

In VLC, there are two categories of visible light sources, active and passive light sources. Active light sources refer to light sources that can be controlled, such as light bulbs and LED lamps. These light sources transmit information by toggling the emitter at high frequencies to vary the light intensity. The modulated light is then propagated over the air and decoded by a photosensor at the receiver. An illustration of data transmission process using active light sources is shown in the upper part of Figure 2.1. We refer to this type of communication as *active VLC*.

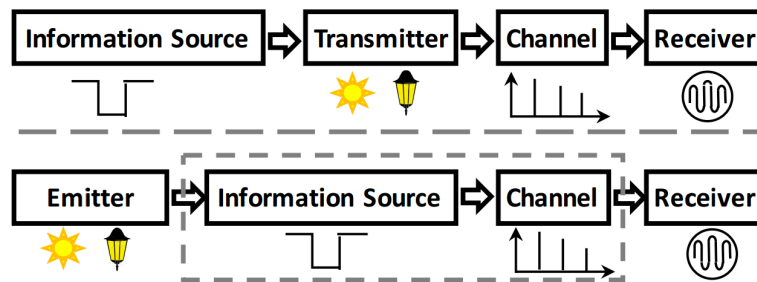


Figure 2.1: Active (above) and passive (below) VLC communication process [24].

Communication approach that is used in active VLC is not applicable for passive light sources as the emitter cannot be controlled. Instead, we

can modify the transmission process by alternating the position of the information source and the emitter, as shown in the lower part of Figure 2.1. The information source needs to be able to modulate the light sources by manipulating light reflections [24]. This type of communication is referred as *passive* VLC.

Passive VLC has desirable properties of using ambient light, as it is pervasive and can provide a higher level of illumination compared to its counterpart, almost a hundred times higher. Besides, passive VLC eliminates the energy consumption related to illumination, since active VLC needs to provide lighting (which consumes a few Watts) in addition to modulating data (which adds another hundred of mW [7]). The major drawback of passive VLC is that the communication system has no control over the light source. Therefore, control over the ambient light is essential to this type of communication.

There are several implementations of passive VLC such as [18], [25], [26], [8] which use materials that can allow or block light. Thus, the light intensity can be controlled, and information can be modulated. The details of these works are discussed in the following sections.

2.2 Polarization in visible light communication

A light wave consists of electric waves that oscillate perpendicular to its propagation direction. The oscillation directions are called the polarization directions [20]. Visible light produced by the sun or other light sources are randomly polarized, i.e., the light is composed of multiple waves with different direction of polarization. This light is called *unpolarized light*, as illustrated in Figure 2.2. On the other hand, light that oscillates at one direction is called *polarized* light.

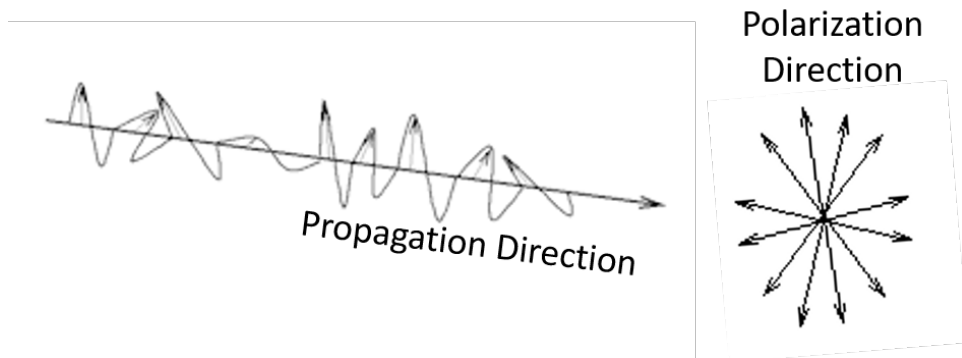


Figure 2.2: **Light wave (left) and its polarization direction (right)** [2].

2.2.1 Controlling polarization direction

Unpolarized light from sunlight that is reflected off a surface would be partially polarized, usually in the horizontal direction. This behavior is illustrated in Figure 2.3. In some applications, e.g., in photography, the reflection of sunlight is unwanted as it may distort the picture. To block the reflection, people use a polarizing filter (polarizer), which only allows a specific direction of polarization. For example, the camera can use a vertical polarizer to block the horizontal polarization.

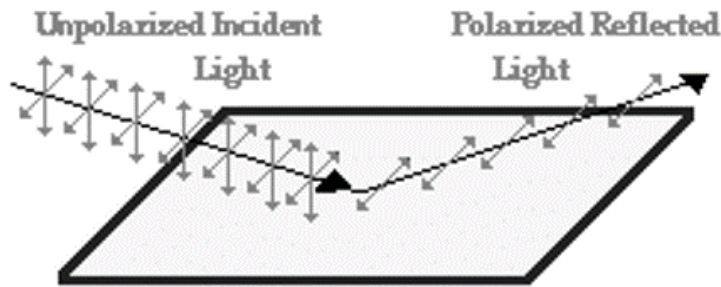


Figure 2.3: **Partially polarized light reflected off of a surface [2].**

The theory behind the polarizer is the Malus law which states that when a polarized light incident to a polarizer has an intensity of I_0 , the light that passes through will have an intensity of I_θ which is determined by the angle between the light's initial polarization direction (θ) and the polarization direction of the polarizer. This relation is described in (2.1).

$$I_\theta = I_0 \cos^2 \theta \quad (2.1)$$

If the incident light has a polarization direction parallel to the polarizer, i.e., $\theta = 0^\circ$, the light will pass through without any attenuation. Likewise, when the incident light has a polarization direction that is perpendicular to the polarizer, i.e., $\theta = 90^\circ$, the light will be attenuated entirely. This also implies that unpolarized light will be polarized in one direction as the polarization in any other direction will be attenuated. The effect of this polarizer is depicted in Figure 2.4.

2.2.2 Liquid Crystal Shutter

If we use two polarizers consecutively, we can control the light intensity that passes through the two polarizers. As seen in Figure 2.4, when both polarizers are parallel in their polarization direction, light can be detected on the other end. Conversely, light will be blocked when both polarizers are perpendicular in their polarization direction. This is the basic concept of the Liquid Crystal (LC) shutter.

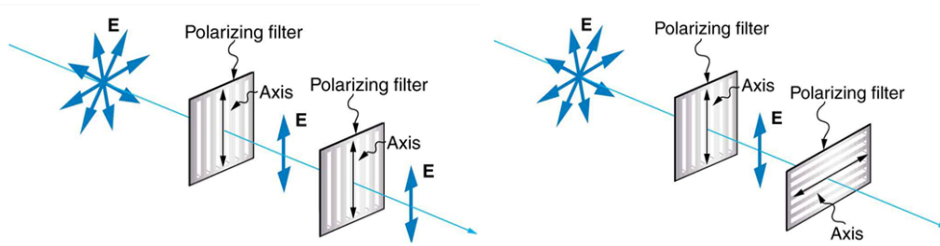


Figure 2.4: **Behavior of Polarizer** [20].

In a regular LC shutter, there are two polarizers which are perpendicular to each other, and there is a liquid crystal layer between the two polarizers. Most of the shutters use the Twisted Nematic (TN) liquid crystal as it is readily available and cheap.

The TN liquid crystal has a characteristic that allows its molecules to twist or untwist depending on the given voltage. Most of the TN liquid crystal will have a 90° twist when no voltage is applied, which means that polarized light passing through the layer will be rotated by 90° . On the other hand, when voltage is applied to the liquid crystal, the molecules will untwist, and the polarization direction is maintained.

The liquid crystal behavior implies that when no voltage is applied, light will pass through the shutter. When voltage is applied, the light will not come through the shutter as the second polarizing film blocks the light. This way, we can modulate information by varying the voltage applied to the shutter to encode bit '1' and '0' using the different light intensity on the receiving end. The shutter behavior is shown in Figure 2.5.

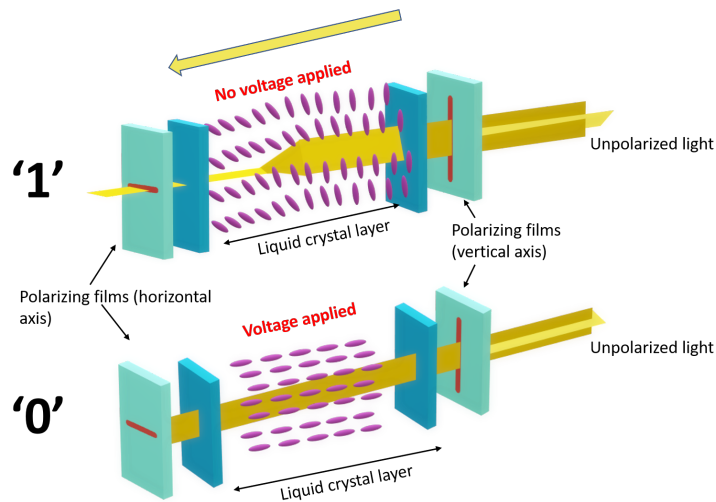


Figure 2.5: **Cross-section of Liquid Crystal Shutter** [8].

2.3 Related works

In this section, we will focus on some of the works that inspired our work, primarily in the area of semi-passive and passive light source communication.

2.3.1 Semi-passive systems

Semi-passive systems refer to visible light communication (VLC) systems that still use traditional active VLC on the downlink while utilizing materials such as liquid crystal shutter to control light reflections on the uplink.

Retro-VLC

The focus of Retro-VLC is to enable a bi-directional link in visible light communication systems [18]. The server, called the ViReader, consists of an LED and a photodiode. On the other side, the client, called ViTag, consists of a photodiode, a retro-reflective fabric, and an LCD shutter.

On the downlink, ViReader toggles the LED to modulate information, which is subsequently received by the ViTag. On the uplink, the client reflects the light to the ViReader using the retro-reflective fabric. ViTag uses the LCD shutter to modulate the reflected light. Finally, the modulated light is then received by the photodiode in the ViReader. The system components are depicted in Figure 2.6. The system can achieve 10 kbps downlink rate and 0.5 kbps uplink rate with a maximum distance of 2.4 m.

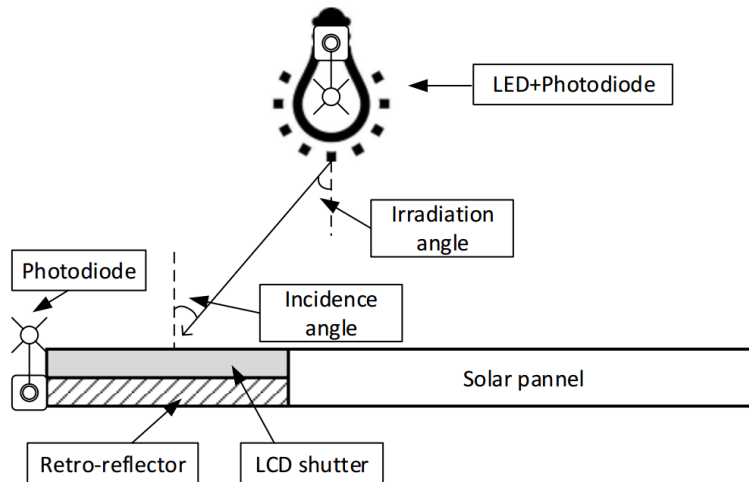


Figure 2.6: **Implementation of Retro-VLC system [18].**

Retro-VLC depends on the LED light from the downlink to transmit information back to the transmitter, unlike the work of this thesis, which uses ambient light to send data.

PassiveVLC

PassiveVLC [25] focuses on increasing the performance of the Retro-VLC mentioned above, specifically in the uplink data rate transmission. To achieve that goal, the modulation scheme is modified.

In Retro-VLC, the LCD shutter needs to wait until it completely changes its on/off state before transmitting the next symbol, which limits the data rate. As can be seen in Figure 2.7, it takes approximately $T_r = 4ms$ for the shutter to completely change its state.

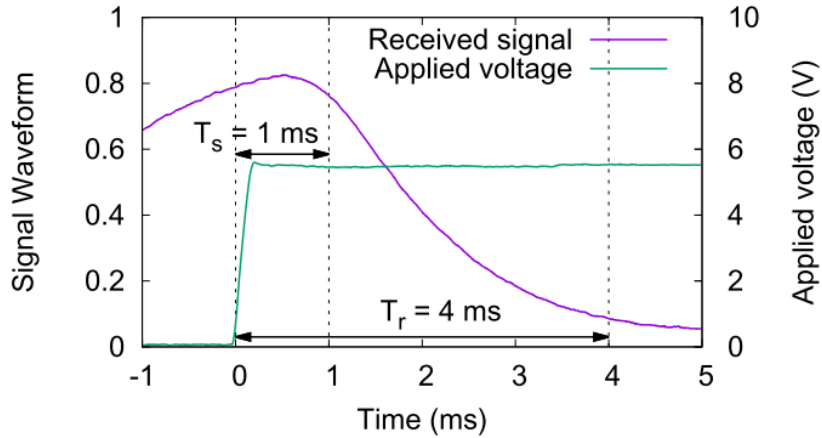


Figure 2.7: **Trend based modulation in PassiveVLC [25].**

PassiveVLC observed that when an LCD is discharged or charged, even if incompletely, its transparency level will change over a short time. The increasing or decreasing *trend* in the transparency level is enough to convey information. As an example, the decreasing *trend* during $T_s = 1ms$ in Figure 2.7 is sufficient to send data. This method increases the uplink data rate transmission to 1 kbps.

2.3.2 Passive systems

Passive systems refer to VLC systems that fully utilize passive light sources to convey information, both in the downlink and in the uplink.

Indoor positioning with visible light (PIXEL)

PIXEL [26] is a lightweight indoor positioning system that utilizes visible light. PIXEL eradicates the flicker effect observed in VLC systems by modulating the light's polarization instead of its intensity (discussed in Appendix A). Besides, it also eliminates the need for an accurate orientation between the transmitter and the receiver.

The transmitter consists of an LED light as a light source, modified liquid crystal (LC) shutters and an optical rotatory material (disperser) that dispersed white light to different colors of light. The disperser makes sure that the color for different bits will be distinct in any orientation of the receiver. The receiver is a smartphone with a polarizer attached to its camera that analyzed the received color. The system has a data rate of 14 bps and can reach up to 10 m of distance. The system diagram of PIXEL can be seen in Figure 2.8.

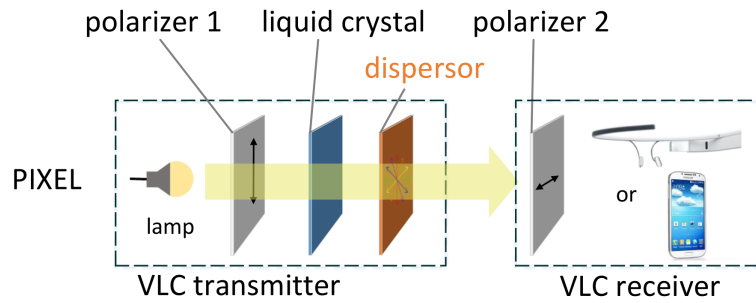


Figure 2.8: Indoor positioning system of PIXEL [26].

LuxLink

LuxLink [8] focuses on creating a wireless link using ambient light. It builds upon the concept of controlling the reflections of ambient light using a material that can be easily controlled.

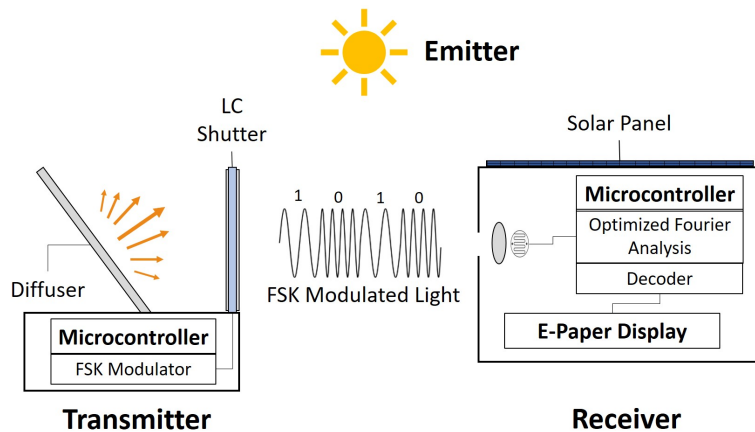


Figure 2.9: Wireless link using ambient light [8].

The LuxLink system, which is shown in Figure 2.9, consists of a transmitter and a receiver. The transmitter uses liquid crystal (LC) shutter, which is

controlled by a microcontroller to modulate data. Unlike other implementation, LuxLink uses Binary Frequency Shift Keying (BFSK) modulation technique to eliminate the flicker effect. The system toggles the shutter at two different frequencies (f_0 and f_1) to represent bit '1' and '0'. This way, the modulated light intensity will remain the same irrespective of the data, thus eliminating flicker. The receiver only uses a simple photosensor to decode the transmitted signal using the Fourier analysis. The system has a static data rate of 80 bps and can communicate at a distance up to 65 m at an outdoor setup.

The LuxLink system acts as the base of this thesis. We introduce several enhancements to the systems, which will be explained further in the following chapters.

2.3.3 Summary

Table 2.1 presents the summary of the semi-passive and passive VLC systems that were discussed above compared to our proposed system, LuxLink+. It should be noted that each system employs different modulation techniques which affect the characteristics of the system, such as flicker effect and data rate.

Name	Communication System	Data Rate	Range	Flicker Effect	Link Adaptability
RetroVLC [18]	Semi-passive	500 bps	2.4 m	Yes	Static
PassiveVLC [25]	Semi-passive	1000 bps	2 m	Yes	Static
PIXEL [26]	Passive	14 bps	10 m	No	Static
LuxLink [8]	Passive	80 bps	65 m	No	Static
LuxLink+	Passive	800 bps	1.5 m	No	Dynamic

Table 2.1: Performance Comparison Between Various VLC Systems

Chapter 3

System design

The system implemented in this thesis is built on top of the system architecture and hardware implementation of LuxLink [8]. Therefore, we have to understand the building blocks of the LuxLink system beforehand, which is described in Section 3.1. Afterward, we introduce the LuxLink+ system by defining the design requirements and its implementation in Section 3.2.

3.1 LuxLink

In this section, we look into the implementation details of the LuxLink system. As explained in Section 2.3.2, the system consists of a transmitter and a receiver.

3.1.1 Transmitter

The transmitter consists of two liquid crystal (LC) shutters that modulate ambient light using the Binary Frequency Shift Keying (BFSK) modulation. The LC shutters used are off-the-shelf 3D LCD shutters [1]. A regular operational amplifier (OPA2325) delivers the required power to the shutters in parallel. To ensure enough light is reflected through the shutters, a diffused white panel tilted at an angle of 45° is added. The whole setup is embedded in a 3D printed case, which can be seen on the right side of Figure 3.1. The transmitter is preprogrammed to transmit test messages periodically.

3.1.2 Receiver

The receiver captures the modulated light from the transmitter using a phototransistor (TEPT4400). The generated current from the phototransistor is converted to voltage using a trans-impedance amplifier and then filtered with an analog band-pass filter that isolates the FSK signal and removes noise. The signal is then amplified and fed to a 12-bit Analog to Digital Converter (MCP3201) connected to a low-power microcontroller (STM32L031)

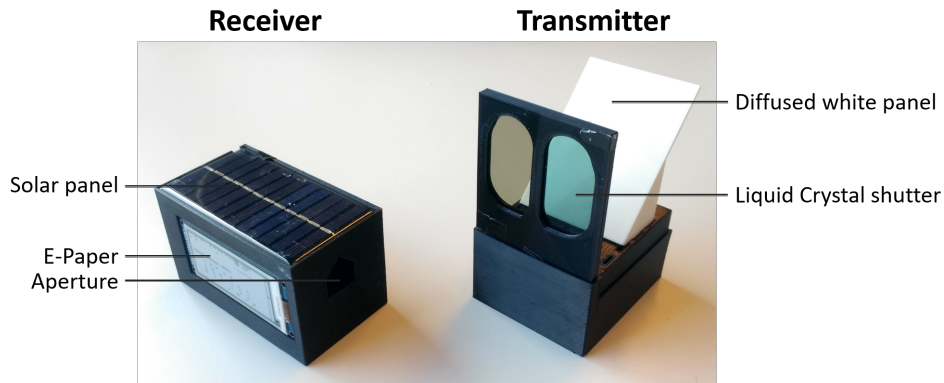


Figure 3.1: **Receiver (left) and transmitter (right) of the system.**

that samples at 10 kHz. The analog and digital circuits are powered separately by two 4.2V Lithium Polymer (LiPo) batteries to reduce the noise on the analog circuitry. The battery is charged by a solar panel, which is controlled by a battery charger module (TP4056). The receiver also includes an e-Paper to display information.

The receiver has a small aperture ($\sim 1^\circ$) to minimize the influence of noise and a lens is added to focus light from far distances, which in turn reduces the field-of-view (FoV), as illustrated in Figure 3.2. This increases the signal to noise ratio (SNR) in the receiver. The whole setup is enclosed in a 3D printed case, which can be seen on the left side of Figure 3.1.

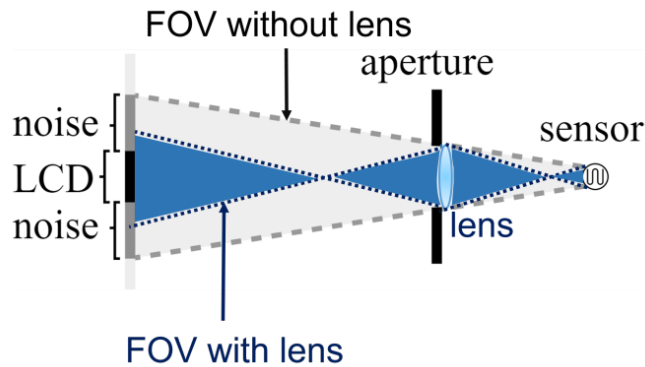


Figure 3.2: **The effect of limiting the aperture and adding a lens to the Field-of-View [8].**

Decoding algorithm

The basic block of the decoding algorithm is Fourier analysis. Fourier analysis decomposes a function, e.g., the received light intensity signal in our

case, into its constituent frequency components. Since we are dealing with discrete data, we are using the Discrete Fourier Transform (DFT) to analyze the signal's frequency components in terms of its magnitude and phase.

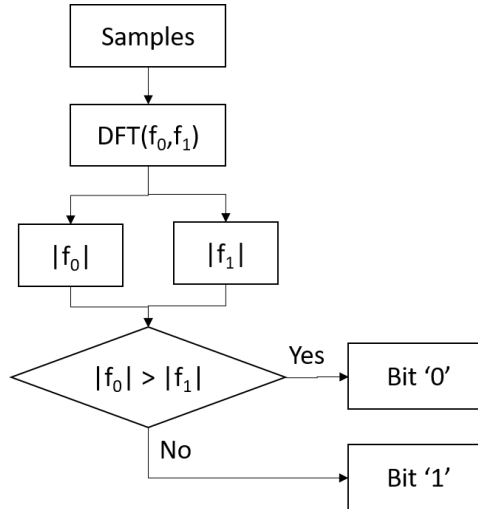


Figure 3.3: **Decoding algorithm of LuxLink.**

LuxLink only analyzes the modulating frequencies (f_0 and f_1 in BFSK) to save computation time. To decode the bit, the magnitudes of f_0 and f_1 from the DFT analysis are compared, and the highest value becomes the decoded bit. This efficient algorithm allows the system to decode data in real-time. The illustration of the decoding algorithm is shown in Figure 3.3.

3.2 LuxLink+

We build LuxLink+ on top of the LuxLink system. There are several modifications to the hardware and software with the goals of improving the data rate and enabling data rate adaptability, which is explained in this section.

3.2.1 Design requirements

Before describing how we achieve our goals, we define the design requirements for LuxLink+.

Design requirement 1: Higher data rate. The system should be able to transmit data using sunlight at a higher data rate compared to LuxLink. It also needs to use the system's basic components, i.e., using LC shutters to transmit data and photosensor to receive data. Furthermore, the system needs to remain flicker-free.

Design requirement 2: Adaptive system. Since there is a need to make the data rate adaptable to changes in the environment, the transmitter

needs to know the condition of the link. To assess this, feedback from the receiver is required. From the link condition, the system needs to be able to adjust the data rate automatically.

We take these design requirements into account and develop an improved system, as described next.

3.2.2 Improving data rate: modulation technique

As mentioned in Section 2.3.2, LuxLink uses Binary Frequency Shift Keying (BFSK) to modulate data. However, it only uses a narrow bandwidth, which produces a relatively low data rate. We can increase the data rate by widening the bandwidth. However, there is no information on how wide the bandwidth is. Thus, we perform a thorough analysis of the bandwidth, as shown in Chapter 4.

We also see the opportunity to further increase the data rate by utilizing the bands more effectively. To do this, we use two modulation techniques, called M-ary FSK and multiplexed BFSK. Both methods use multiple frequencies to transmit more data. The details and comparison of these methods will be discussed in Chapter 4.

3.2.3 Adaptive system

As explained in the design requirements, the transmitter needs feedback from the receiver to adapt its data rate. LuxLink only allows one-way communication from the transmitter to the receiver. They have to be able to transmit and receive data to enable two-way communication. Therefore, we design a transceiver on both ends. The feedback from the receiver can then be processed by the transmitter to adjust the rate dynamically using a rate adaptation algorithm. Even though the current system is peer-to-peer, we will use the terms server and client to differentiate the roles of the transmitter and receiver, respectively.

Transceiver

We combine the hardware and software of the transmitter and receiver of LuxLink with several modifications. The transceiver is controlled with a single micro-controller (STM32-F446RE), which has more clock speed and more timers compared to LuxLink's microcontroller. It is powered via the USB interface. Besides providing power, the USB is also used to send debugging information, which replaces the e-Paper display due to the low refresh rate (two seconds for a full refresh). The microcontroller is configured and programmed using the STM32CubeMX and VisualGDB software, respectively. The system diagram can be seen in Figure 3.4. The physical appearance of the transceiver can be seen in Figure 3.5

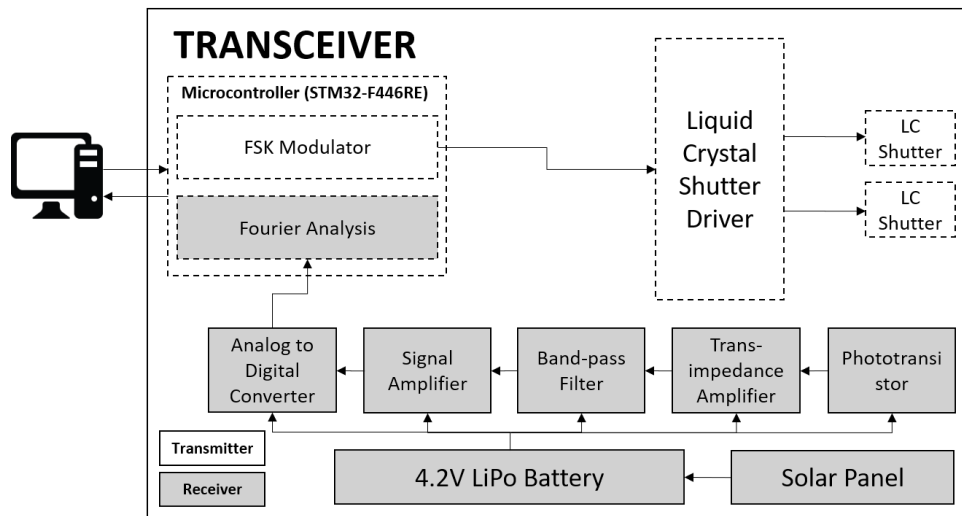


Figure 3.4: Components of the transceiver, the dotted parts represent the modified components with respect to the original LuxLink platform.

Transmitter. Multiplexed BFSK requires the transmitter to drive the shutters independently as each shutter is assigned to different frequency pair. Thus, each driver circuit is connected to a different pin on the microcontroller, which is controlled separately by independent timers.

Receiver. The new modulation techniques use more than a pair of modulating frequencies to transmit data. Therefore, we modify the Fourier analysis to evaluate all the used modulation frequencies. The modification details are discussed in Chapter 4.3.

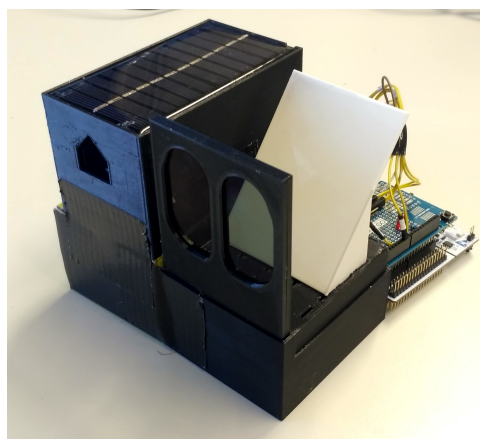


Figure 3.5: Physical appearance of the transceiver.

Communication protocol

Since the client needs to provide feedback to the server, the communication protocol of the system needs to be modified. We configure the client to send an ACK message back to the server as a packet(s) retrieval confirmation. The server is also allowed to re-transmit messages several times if an ACK is not received before dropping the messages. We set the retransmission threshold to four. The client needs to change its configurations, i.e., the modulation frequencies parameters, if the server wants to change the data rate. Therefore, the server can send a notification message to the client to change the settings. The illustration for the communication protocol is shown in Figure 3.6.

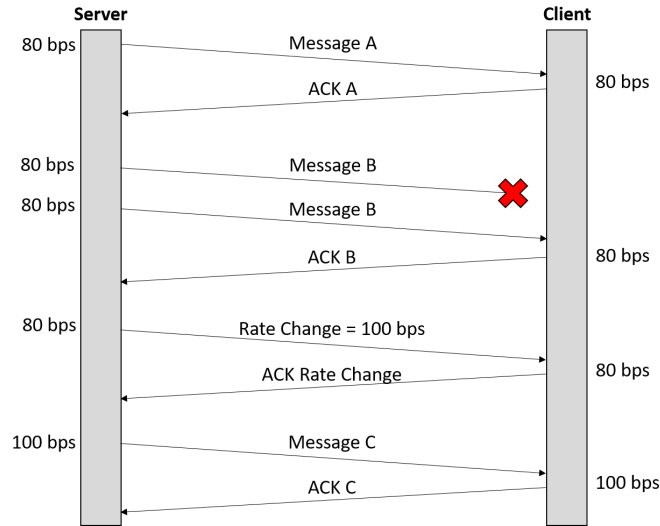


Figure 3.6: Illustration of the communication protocol.

Rate adaptation algorithm

The server can now assess the link condition from the feedback of the client. We can use this information to adapt the rate automatically. There are several rate adaptation algorithms, each having their own merits. Most of the algorithms are designed for the 802.11 wireless protocol (WiFi). However, we can employ the principles of those algorithms for our system. The details of the applied algorithm are discussed in Chapter 5.

Chapter 4

Data rate improvements

According to [8], the current LuxLink system can only transmit at 80bps, which is quite low compared to active light source communication systems like [18] and [25]. In this chapter, we look into the improvement of the data rate and how we can achieve that goal. Before describing the improvements, we provide background information relating to the modulation technique that LuxLink uses, the Frequency Shift Keying (FSK), in Section 4.1. Afterward, we present the analysis of the system's bandwidth in Section 4.2, which is needed to improve the data rate. From the previous information, we describe the optimal utilization of the maximum bandwidth in Section 4.3 to further increase the data rate. Finally, we evaluate the performance of our system, which is shown in 4.4

4.1 Frequency Shift Keying (FSK)

LuxLink uses the frequencies of 560 Hz and 640 Hz to yield 80 bps data rate, which is a relatively narrow bandwidth. However, it is unclear to why that specific data rate is chosen. Therefore, we look deeper into the modulation technique used, that is Frequency Shift Keying (FSK), and see which parameters affect the data rate.

In a regular binary FSK (BFSK), two different frequencies are used. By convention, the higher frequency (f_1), commonly called the *mark* frequency, is used to represent symbol '1' and the lower frequency (f_0), commonly called the *space* frequency, is used to represent symbol '0'.

As [8] suggested, when an electrical square wave is given to a liquid crystal (LC) shutter at a particular frequency, the generated signal (the light intensity) will follow a near-sinusoidal pattern. Therefore, we can generate FSK signals using the LC shutter. However, the shutter cannot abruptly transition between the two frequency signals as the shutter can only produce a continuous signal. Thus, the transition between the two frequencies can only happen after the oscillation period has ended.

We can adjust the number of oscillation periods to determine the data rate. For a constant data rate of R , the chosen frequency pair should be the integer multiple of R . The relationship between the modulation frequencies f_0 and f_1 , and their corresponding number of periods n_0 and n_1 , are given in Equation 4.1. As an example, if we set the data rate to 100 bps, we can choose f_0 and f_1 to be 200 Hz and 400 Hz with n_0 and n_1 to be 2 and 4 respectively. The resulting FSK signal is shown in Figure 4.1.

$$f_0 = n_0 \cdot R, f_1 = n_1 \cdot R; n_0, n_1 \in \mathbb{N} \quad (4.1)$$

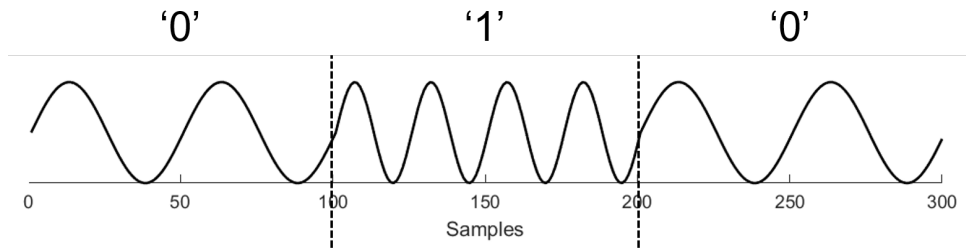


Figure 4.1: **FSK signal for $f_0 = 200$ Hz, $f_1 = 400$ Hz, $n_0 = 2$, $n_1 = 4$, $R = 100$ bps**

When determining the data rate, we need to consider some factors. First of all, the sampling frequency of the receiver. The current receiver samples the received light intensity at 10 kHz, which means that the highest frequency component of the received signal must be less than 5 kHz to satisfy the Nyquist theorem. We can see that the sampling frequency can limit the bandwidth that can be used by the system, which in turn determines the data rate.

Another factor that can influence the data rate selection is the decoding technique used. The receiver decodes the BFSK signal using the Discrete Fourier Transform (DFT). To get a correct decoding, the number of samples fed to the Fourier analysis has to correspond with the length of a symbol. Given a bit rate R and sampling frequency f_s , the number of samples per symbol N is given in Equation 4.2. As N needs to be an integer number, the bit rate is limited to the factors of the sampling frequency. Using the previous example, if we set f_s to be 10 kHz, the number of samples per symbol is 100, which is shown in Figure 4.1.

$$N = \frac{f_s}{R} \quad (4.2)$$

4.2 Bandwidth analysis

As explained in Chapter 3.2.2, LuxLink only uses a narrow bandwidth, which produces a relatively low data rate of 80 bps. We can widen the bandwidth to improve the data rate. However, there is no information on the minimum and maximum modulation frequency that the system can use. We observe that when the shutter switches at a frequency that is too low, flicker may happen. On the other hand, when the frequency gets too high, the contrast of the signal will become so low that we cannot decode the data correctly. We illustrate this problem with Figure 4.2. In this section, we investigate the lower limit frequency of the system that does not show flicker. Afterward, we evaluate the upper limit frequency.

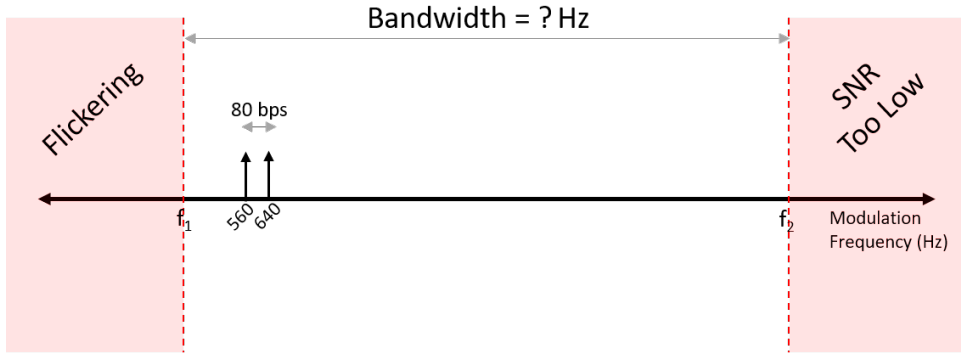


Figure 4.2: Illustration of the current bandwidth usage.

4.2.1 Lower limit frequency analysis

Before investigating the lower limit frequency, we have to understand the flicker effect. According to [21], flicker is “the variations of luminance in time.” Flicker at low frequency can cause harmful physiological effects to humans, such as headaches and epileptic seizures [5]. We have to make sure that the modulated light from the liquid crystal (LC) shutter is oscillating at a frequency that is high enough to avoid flicker. We can consider the minimum flicker-free frequency as the lower limit of the bandwidth. Investigating the minimum switching frequency can be tricky as flickering is perceived differently from one person to another [5]. Therefore, we need a way to measure the flicker effect quantitatively.

According to [5], flickering can be measured by calculating its percent flicker. Percent flicker, also known as modulation depth or modulation percentage (Mod%), is defined in Equation 4.3 where I_{max} , I_{min} , and I_{avg} represent the maximum, minimum, and average luminance respectively. In our case, the illuminance value is represented by the ADC value. Since the signal generated by the shutter is sinusoidal, the variables of Equation 4.3

serve as the peak, valley, and middle point of the sinusoid respectively. For this document, we are going to use the term Mod% to quantify the flicker effect.

$$Mod\% = \frac{I_{max} - I_{min}}{I_{avg}} \cdot 100\% \quad (4.3)$$

The guideline recommends any lighting systems to be operated under the low-risk or no-risk operating regions based on the modulation frequency used and the measured Mod%, which is shown in Figure 4.3.

Using this guideline, we can vary the modulation frequency, measure the Mod% and evaluate them with the defined regions. Since we are using FSK modulation, we use the center frequency $((f_0 + f_1)/2)$ as the modulation frequency. We measure the Mod% by setting the LuxLink transmitter to modulate data at various modulation frequencies. The receiver is placed 30 cm apart from the transmitter and is configured to log the received light intensity at 50 kHz over 20 seconds. The measurement is done indoors with the ceiling lights turned on. The measured Mod% over different modulation frequencies and different data rates can be seen in Figure 4.3.

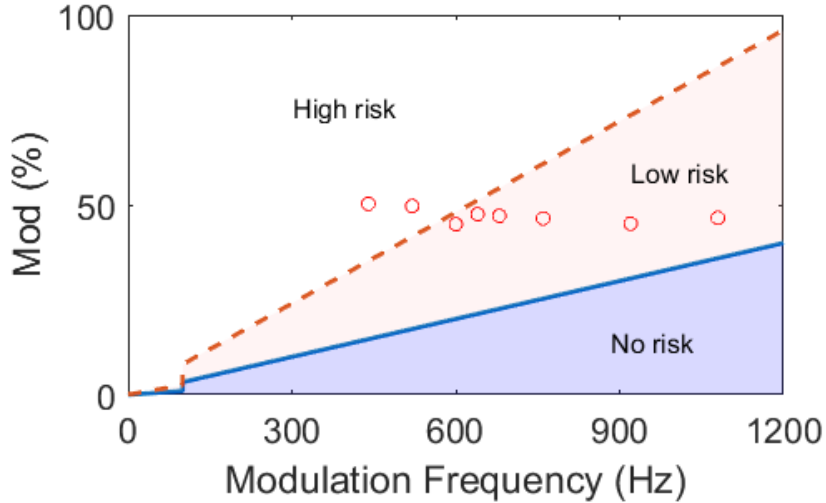


Figure 4.3: **Mod% for various modulation frequency. The Mod% should fall below the dashed red line to be considered low or no flicker risk.**

From the figure, we can see that when we increase the modulation frequency, the measured Mod% will eventually fall below the low-risk zone because the changes of light would be so rapid at high modulation frequency that humans cannot detect them. We can see that the system starts to display a low-risk flicker effect at around 600 Hz. Therefore, we can conclude that the lower limit frequency is at 600 Hz.

Finding a lower limit frequency is one of the ways to eliminate flicker. However, we can also remove flicker by moving one of the polarizing films of the LC shutter to the receiver, similar to what [26] does, but such an approach has some key disadvantages. The details of that method are discussed in Appendix A.

4.2.2 Upper limit frequency analysis

After investigating the lower limit frequency, we analyze the upper limit frequency. As [8] describes, when we increase the shutter’s switching frequency, the contrast between the transparent and opaque states produced by the shutter will decrease. This is because the shutter is not switching from a fully transparent to a fully opaque state, eventually producing a flat signal. The illustration of this effect is shown in Figure 4.4. As the contrast decreases, the signal-to-noise ratio (SNR) would also decrease, which would make the decoding on the receiver more challenging. Thus, there is a maximum frequency where the system can still decode the data correctly.

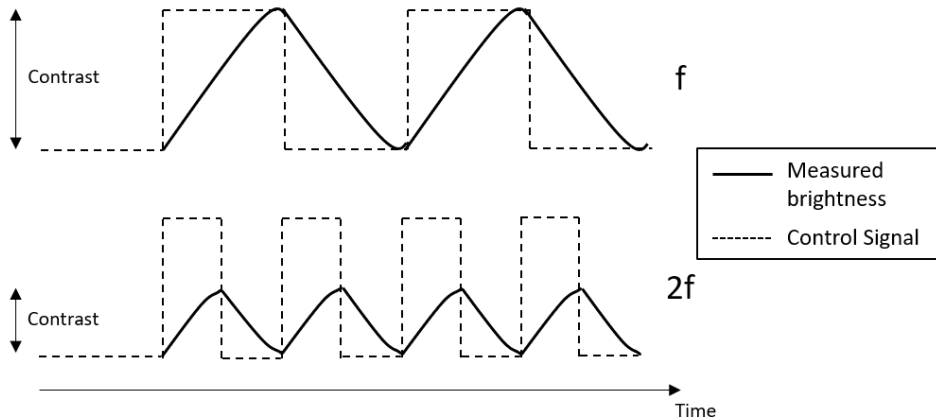


Figure 4.4: **Reduction of received brightness when the shutter frequency increases.**

We investigate the maximum switching frequency by increasing the modulation frequency until the receiver cannot decode the transmitted data properly. We consider the packet success rate (PSR), which is the ratio of packets successfully received to the total sent, as the metric for our measurements. The experiments are conducted using the LuxLink platform in a controlled environment (indoor) with the lights on the ceiling on. We measure the illumination at the transmitter to be 550 lux. For the experiment, 50 packets are sent using various data rates and modulation frequencies. Each packet is 12 bytes in size, including four overhead bytes. We put the transmitter and receiver 30 cm and 100 cm apart. The result of the experiment can be seen in Figure 4.5 and 4.6.

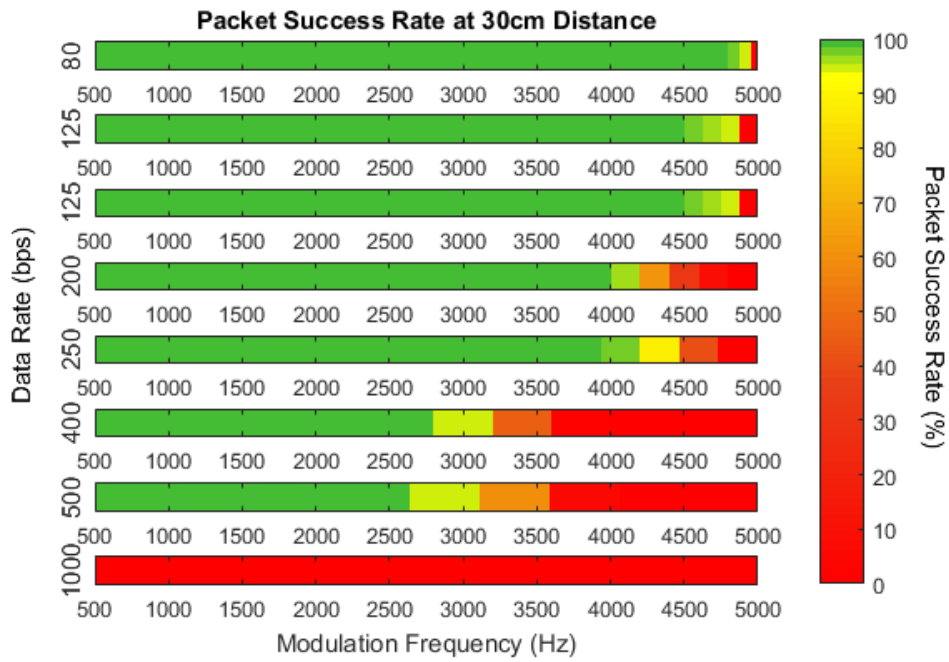


Figure 4.5: Packet success rates of the system at 30cm distance.

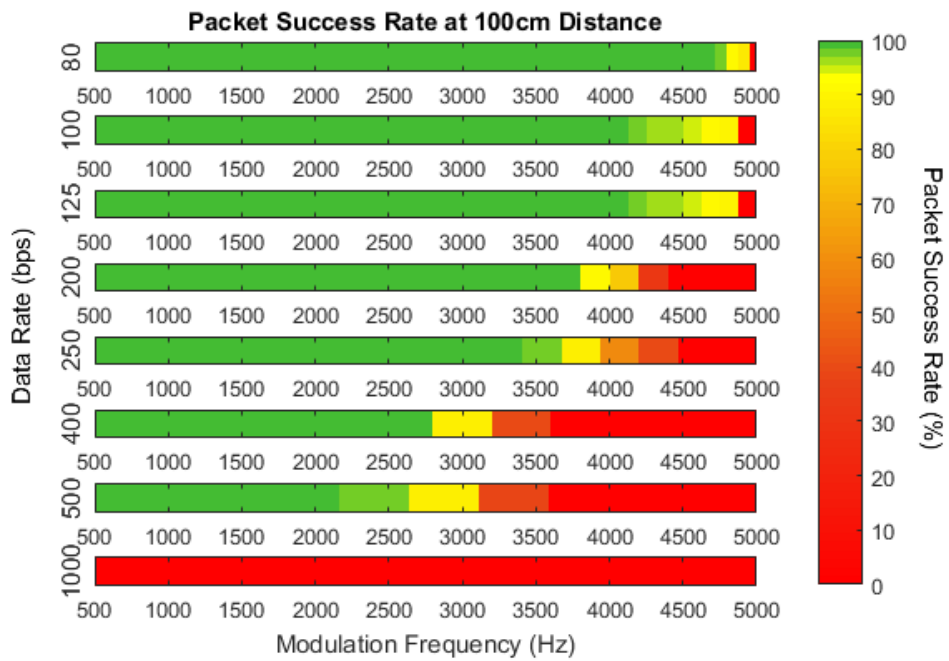


Figure 4.6: Packet success rates of the system at 100cm distance.

From both figures, we can see that the upper limit frequency decreases when the data rate increases. This is due to the limitation of the Discrete Fourier Transform (DFT) used to decode the signal. The computation of the DFT is given in Equation 4.4.

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-\frac{i2\pi}{N}kn} \quad (4.4)$$

The DFT computes the frequency content of a discrete signal, in our case, the sampled light intensity. The illustration of the DFT is shown in Figure 4.7. Since the DFT is a summation function, the magnitude of a particular frequency will be lower if the number of samples decreases.

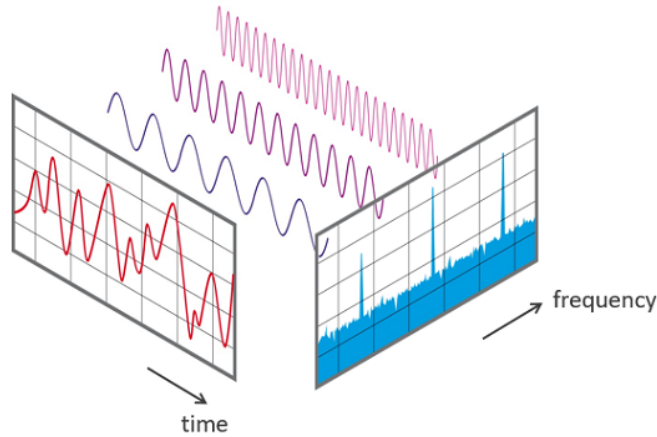


Figure 4.7: **Illustration of the DFT [3].**

As explained in Section 4.1, the number of samples (N) has to correspond with the length of a symbol. As the data rate increases, the number of samples per symbol will decrease, as implied by Equation 4.2. There will be a point where the number of samples is not sufficient to make a clear distinction between the magnitude of the modulating frequencies (f_0 and f_1), which can cause incorrect decisions.

If we compare Figure 4.5 and 4.6, we can also see that the upper limit frequency decreases when the distance increases. This is due to the higher SNR requirement that the system needs to have reliable communication. As the distance increases, the SNR requirement would also increase, and vice versa. From this observation, we can see that there is a trade-off between distance and data rate. This experiment concludes that multiple factors influence the upper limit frequency, i.e., the communication distance and the data rate. Therefore we cannot set a definite value for the upper limit frequency.

Sampling frequency

In the previous experiment, we have seen that as the data rate increases, the upper limit frequency would decrease due to the insufficient samples fed into the DFT algorithm. To increase the number of samples while maintaining the data rate, we can increase the sampling frequency to get more samples in the same interval, thus increasing the magnitude of the DFT. In this section, we analyze the effect of changing the sampling frequency to the upper limit frequency.

The current ADC (MCP3201) allows us to sample the signal at a higher frequency. For the experiment, we vary the sampling frequency while maintaining the data rate of 250 bps and 400 bps. We place the transmitter and receiver 30 cm apart. The result of the experiment can be seen in Figure 4.8 and Figure 4.9.

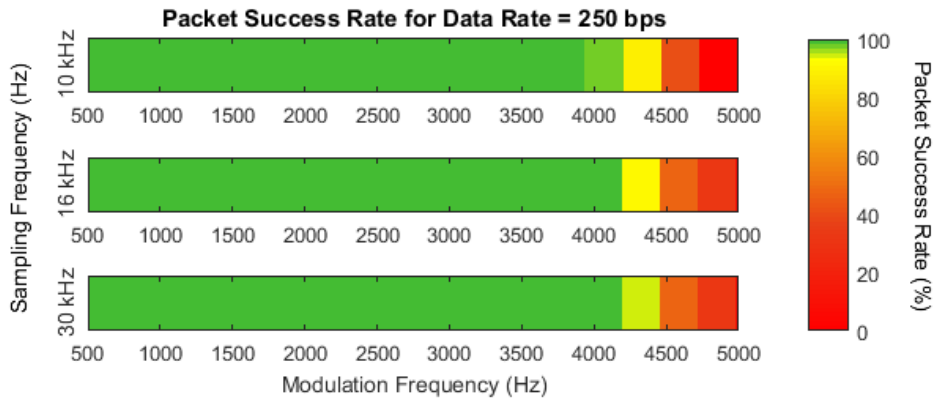


Figure 4.8: **Packet success rates of the system for data rate of 250bps.**

From both figures, we can see that the increase in sampling frequency causes the bandwidth to increase. This also means that the distance will increase as well. However, as we increase the sampling frequency further, the number of samples per symbol would also increase, as we recall from Equation 4.2. The extra samples will add more computation time, thus more energy. We can consider the sampling frequency as one of the parameters that can influence the trade-off between data rate and distance. We decided to use the 10 kHz sampling frequency as the upper limit frequency of the data rate (400 bps) still falls well below the Nyquist frequency (2800 Hz compared to the Nyquist frequency of 5000 Hz).

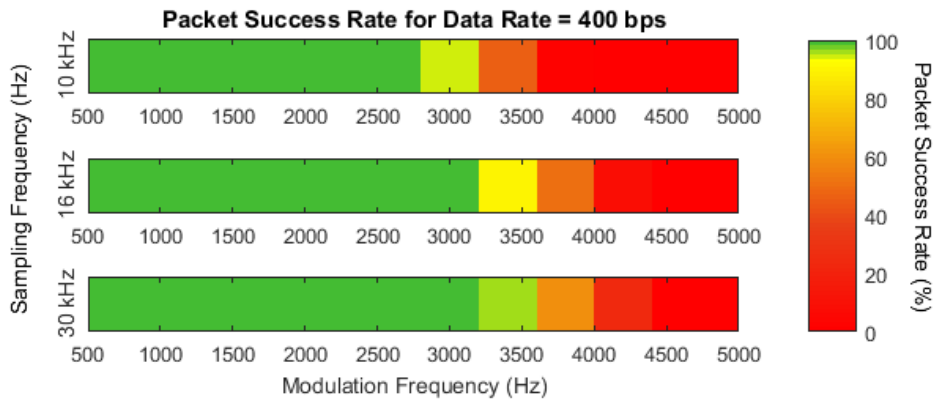


Figure 4.9: Packet success rates of the system for data rate of 400bps.

4.2.3 Summary on bandwidth analysis

By analyzing the lower limit and the upper limit frequency of the bandwidth, we can see that the highest data rate we can get using the BFSK modulation is 500 bps since the next data rate we can choose from, 1000 bps, always yield errors when decoding.

However, we are only using a small portion of the bandwidth available, as we only use a single frequency pair. This is illustrated in Figure 4.10. If we set the data rate at 200 bps, we can see from Figure 4.5 that we are using only 200 Hz of bandwidth ($f_0 = 800$ Hz and $f_1 = 1000$ Hz). We still have unused band between 1000 Hz and 4000 Hz. We can exploit the band by utilizing more frequencies in our transmission, which will be discussed in the next section.

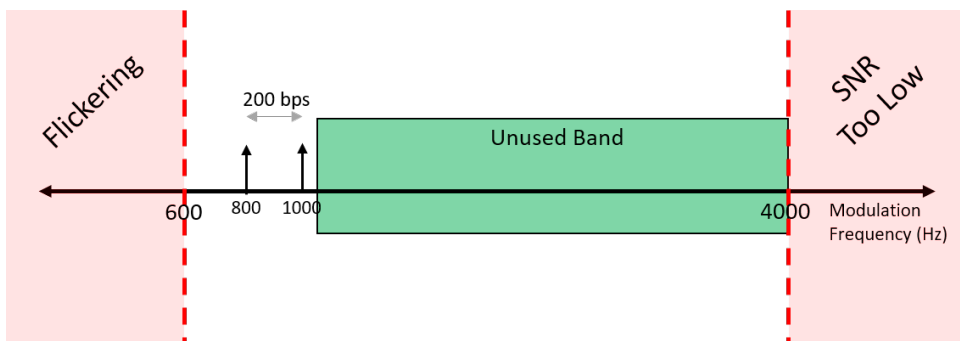


Figure 4.10: Unused band when a single frequency pair is used.

4.3 Multiple frequencies usage

As explained in the previous section, the system is now capable of transmitting data at 500bps. However, there are still unused bands that can be utilized. Thus, we try to use those bands by using more frequencies. Two methods can be employed for this situation, M-ary Frequency Shift Keying (MFSK) and Multiple-Input Multiple-Output (MIMO) FSK. In this section, we look into these two methods and compare them.

4.3.1 M-ary Frequency Shift Keying (MFSK)

BFSK does not utilize the whole bandwidth of the system because it only uses two frequencies (f_0, f_1) to represent different bits (0 or 1). These frequencies can also be called symbols. One symbol is transmitted at a symbol rate R_s . BFSK only sends one bit per symbol, which means that the data rate equals to the symbol rate.

Alternatively, we can use more frequencies (symbols) using the same symbol rate to represent more bits. As an example, we can utilize four different frequencies of f_0, f_1, f_2, f_3 to represent bits 00, 01, 10, and 11 respectively. The illustration of this is shown in Figure 4.11. Since we encode more bits in each symbol, we effectively increase the overall data rate. This approach is called *M-ary FSK (MFSK)*. Given M symbols, the data rate will be $\log_2(M)$ times the symbol rate, which is the original BFSK data rate.

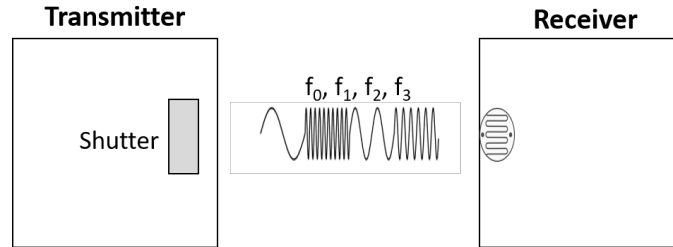


Figure 4.11: Illustration of M-ary FSK modulation technique.

4.3.2 Multiple-Input Multiple-Output Frequency Shift Keying (MIMO FSK)

Beside MFSK, there is also an alternative where we could use different frequency pairs that transmit different data. To do this, we use different shutters that use different frequency pairs, similar to the MIMO method with a slight difference (we only use a single receiver). Each shutter is still transmitting one bit per symbol. However, since we are transmitting different data per shutter, we effectively send multiple bits at once, similar to MFSK.

We call this method *MIMO FSK*. The illustration of this method is shown in Figure 4.12.

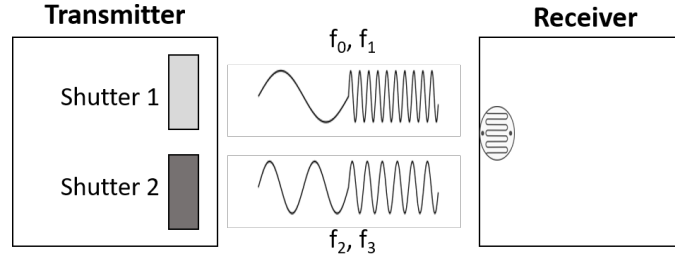


Figure 4.12: **Illustration of MIMO FSK, each shutter transmits different symbols.**

By using MIMO FSK, the data rate would increase linearly with the number of frequency pairs used. The increase of data rate will be $M/2$, where M represents the number of symbols (frequencies) used, and M is an even number.

4.3.3 Comparison

As explained in the previous section, MIMO FSK is better at improving the data rate as the increase of data rate is linear compared to the logarithmic gain of MFSK. Besides that, MIMO FSK is more spectral efficient compared to MFSK when the number of frequencies used increases. Spectral efficiency refers to the bit rate over a given bandwidth, which is measured in (bits/s)/Hz. According to Carson's rule [9], the bandwidth of a frequency-modulated signal can be approximated using Equation 4.5, where Δf refers to the peak frequency deviation and R_s refers to the symbol rate. The frequency deviation refers to the difference between the center frequency and the modulating frequency (mark or space frequencies).

$$B = 2(\Delta f + R_s) \quad (4.5)$$

According to [6], given the number of modulation frequencies M , the spectral efficiency for MFSK and MIMO FSK can be calculated as $\log_2 M/(M + 1)$ and $(M/2)/(M + 1)$, respectively. As can be seen in Table 4.1, the bandwidth efficiency of MFSK decreases as M increases, while the opposite happens for MIMO FSK. In other words, MFSK consumes more bandwidth to achieve the same data rate gain as MIMO FSK.

However, MFSK only needs one shutter to increase the data rate while MIMO FSK needs multiple, which will consume more energy. Besides that, MIMO FSK needs to make sure that all of the shutters are in the field-of-view (FoV) of the receiver to get the data rate improvement. As mentioned

Number of Frequencies	Bandwidth Efficiency	
	MFSK	MIMO FSK
2	0.5	0.33
4	0.4	0.4
8	0.33	0.44
16	0.24	0.47

Table 4.1: **Bandwidth efficiency for different frequency usage.**

in Chapter 3.1.2, the receiver has a small detection area (FoV). Therefore, we need to move the receiver further back to ensure all of the shutters are on the FoV, as shown on the left side of Figure 4.13. However, when the receiver is at a closer distance, the FoV will decrease, and smaller portions of the shutters will fall under the FoV, which will reduce the SNR, as shown on the right side of Figure 4.13. This effect limits the mobility of the receiver, as we cannot point the FoV to any part of the surface. The FoV must always cover some part of all four shutters. One solution to this problem is to add an adjustable lens, which can vary the FoV. However, that topic is outside the scope of this thesis.

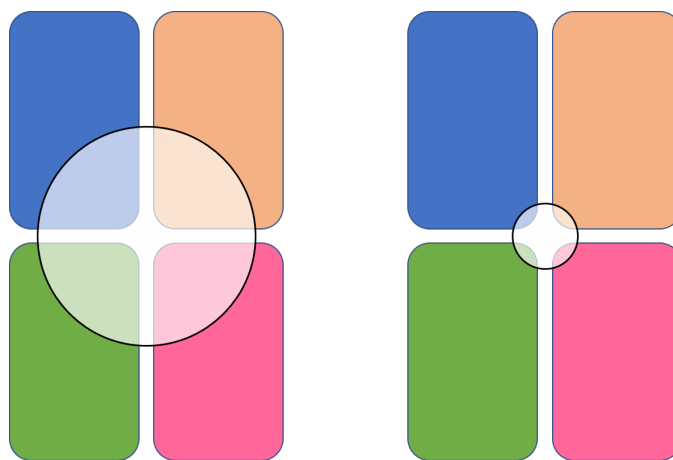


Figure 4.13: **Field of view (FoV), indicated by the white shade, of the receiver at far distances (left) and short distances (right). Each color represents different frequencies. The FoV has to cover at least partially all four shutters.**

We choose to apply MFSK in our system because of the mobility issue of MIMO FSK. Besides, if we limit the number of frequencies used in our system to four, we will have the same bandwidth efficiency as the MIMO FSK. Using the frequency selection guidelines in Section 4.1 and the bandwidth analysis in Section 4.2, we can use a symbol rate of 500 bps and utilize four

frequencies of 1000 Hz, 1500 Hz, 2000 Hz, and 2500 Hz to yield a total data rate of 1000 bps.

4.4 Evaluation

In this section, we evaluate the performance of our system in terms of distance. The experiment is done indoor and uses artificial light sources. We closed all the windows to make sure the light intensity is constant throughout the test.

We devise three different scenarios. For the first scenario, we turn on all the ceiling lights. The measured light intensity on the surface of the transmitter is 500 lux. We call this setup as the regular indoor scenario. After that, we turn off half of the ceiling lights for the second scenario, which resulted in light intensity of 150 lux. On the third scenario, we turn on all the ceiling lights and add additional DC light sources above the transmitter. This setup produced a light intensity of 2000 lux, which is roughly the typical illuminance on an overcast day. We send 50 packets and measure the packet success rate at different distances for each scenario. We test our system using various data rates (from 50 bps up to 1000 bps). The result of the experiment is shown in Figure 4.14. We only plot the distance up to 6 m due to the limitation of the indoor space.

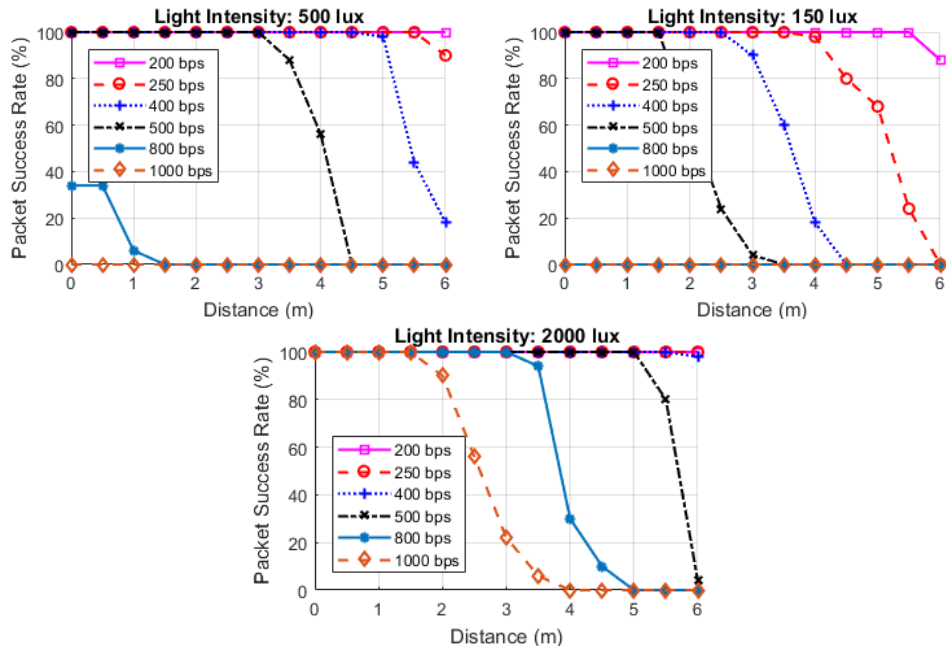


Figure 4.14: Range performance.

We are only showing the result for data rates above 200 bps since all the data rates below 200 bps always yield perfect packet success rate. From the figures, we can see that as the light intensity increases, the packet success rate will also increase due to better SNR. This allows the system to transmit using higher rates at the same distance.

We also observe that the MFSK modulation (800 bps and 1000 bps data rates) needs higher light intensities to transmit at a decent packet success rate. At 500 lux, none of the MFSK modulations produce packet success rates above 50 percent. When we increase the light intensity to 2000 lux, we can use MFSK to transmit data at 1000 bps properly until a distance of 1.5 m after which the SNR deteriorates, and packets start dropping.

From the measurements, we conclude that our system can transmit data reliably at a data rate of 500 bps with a range of 3 m in a regular indoor scenario. The system can even achieve higher data rates or higher distances if placed outdoor.

Chapter 5

Adaptability improvement

This chapter focuses on implementing a rate control algorithm suitable for LuxLink+. First, we provide some background information on the concept of adaptive data rate algorithms. From the available algorithms, we select an appropriate scheme for our system based on some practical considerations, which is described in Section 5.1. Afterward, we describe and implement the chosen method in Section 5.2. Finally, we evaluate the behavior of LuxLink+ in Section 5.3.

5.1 Adaptive data rate

As described in Chapter 4, the system now has multiple bit rates to choose from. Higher data rates allow the system to transmit more data on high-quality links (e.g., when ambient light is bright). However, they provide low throughput on poor links (e.g., when the receiver is far away). On the other hand, lower bit rates have a lower loss probability on low-quality links. We want to maximize the throughput on any link condition. Therefore, designing an automatic data rate selection that yields the maximum throughput for a specific situation is central for our system. We decide to borrow the concept of rate adaptation algorithm from the 802.11 wireless protocols.

To correctly choose the data rate, the algorithm needs to collect information on the current link conditions. Based on the link quality metric, there are several groups of algorithms:

1. **Acknowledgement (ACK) based mechanisms.** ACK based mechanisms, such as AARF [17], AMRR [17], and Onoe [4], adapt data rates from the results of successful transmissions (e.g., packet loss ratio), which are estimated based on received acknowledgments.
2. **Signal to noise ratio (SNR) based mechanisms.** SNR based mechanisms, for example, RBAR [12] and CHARM [15], select their data rate based on the measured SNR.

5.1.1 Practical considerations

To select the appropriate rate adaptation algorithm, we have to look into several practical considerations.

Difficulty of measuring SNR. As mentioned in Chapter 3.1.2, the receiver only analyzes the modulating frequencies to save computation time. To measure the SNR, we have to analyze the whole spectrum of the received signal, which adds additional processing power. We aim our system to consume as little energy as possible, therefore using SNR as a metric for the rate control algorithm is not preferable.

Preconfigured receiver. Each data rate has a different symbol period and uses different modulating frequencies. Our receiver can only use one data rate configuration at a time. The transmitter needs to inform the receiver regarding its transmission configuration (data rate and frequencies). Several rate control algorithms (AMRR and Onoe) use a multi-rate retry (MRR) approach, illustrated in Figure 5.1. In MRR, each data transmission has four pairs of data rate and number of retries $(r_0/c_0, r_1/c_1, r_2/c_2, r_3/c_3)$. First, the data is transmitted with the rate r_0 . If the transmission fails (no ACK is received), the hardware will retransmit the data with the rate r_0 up to $(c_0 - 1)$ times. If the transmitter is still unsuccessful, the hardware will try the rate r_1, c_1 times, then r_2, c_2 times, and finally r_3, c_3 times. If the transmission still fails at the last pair, the packet will be discarded. This allows the system to deal with short-term fluctuations in the channel condition.

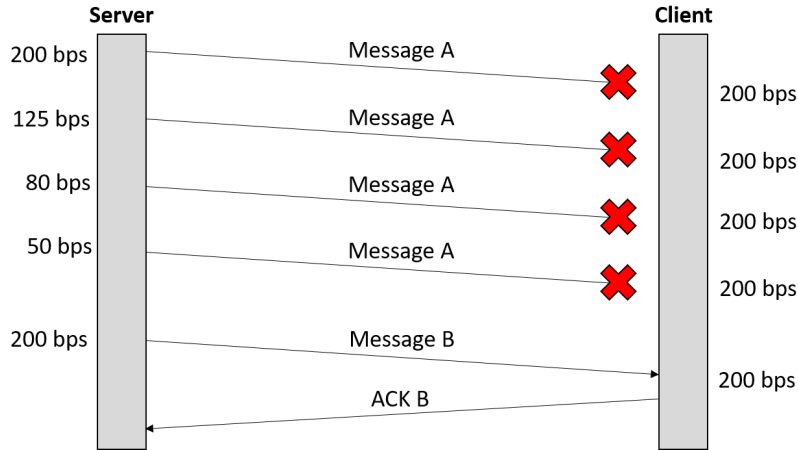


Figure 5.1: Multi rate retry (MRR) illustration with $(r_0/c_0, r_1/c_1, r_2/c_2, r_3/c_3) = (200/1, 125/1, 80/1, 50/1)$.

Our receiver does not know the transmitter's current state, i.e., the rate configuration. When the transmitter fails to transmit data at r_0 and retransmit at r_1 , the receiver is still configured to receive data at r_0 and cannot decode

the retried data at r_1 , as shown in Figure 5.1. Therefore, algorithms that use multi-rate retry approaches such as AMRR and Onoe do not apply to our system.

Knowing the practical considerations of our system, we decide to implement the AARF algorithm as it only uses an ACK metric to change the rate. We present the details of the algorithm in the following section.

5.2 Adaptive Auto Rate Fallback (AARF)

Before understanding AARF, we have to consider its predecessor, the Auto Rate Fallback (ARF) algorithm. ARF is the first rate adaptation algorithm to be published [16]. Given the number of retries of data transmission and whether it was successfully acknowledged, ARF adjust the bit rate using the following criteria:

- Reduce bit rate if the packet never gets acknowledged.
- Increase bit rate if a threshold of X successive transmissions has occurred without any retransmissions. Usually, X equals to 10.
- Else, continue at the current bit rate.

The algorithm has a downside where if the channel quality is static, it will try to use a higher rate every ten successful attempts and will fail to transmit. This effect decreases the overall throughput as more re-transmissions are done.

AARF [17] tries to overcome this problem by increasing the threshold X exponentially when the algorithm tries to increase the bit rate and the subsequent packet, called the probe packet, fails to be transmitted. It solved ARF’s problem as the algorithm will wait exponentially longer before trying to increase the bit rate. This effect allows the system to avoid frequent re-transmissions, thus better throughput.

5.2.1 Implementation details of AARF

After understanding the basic concepts of AARF, we implement the algorithm in our system. In our setup, we consider ten different data rates: 50, 80, 100, 125, 200, 250, 400, 500, 800, 1000 bps. We number these data rates as “Modes”, so a 50 bps data rate is “Mode 1”, 80 bps is “Mode 2” and so on. We will discuss some of the implementation details in this section.

Eliminating flicker. Since we implement an ACK based transmission, the transceiver’s shutters will be turned off they do not transmit, making the shutters translucent. The shutters’ contrast will be different when it is transmitting data. We can consider this as flicker as we can see the change of light intensity between the two states. To get around this, we set the

shutters to send synchronization messages when they are idle. This way, the shutters' contrast will be constant, thus eliminating flicker.

Preventing interference. Each data rate has its configuration of frequency pair(s). If both of the transceivers use the same frequency pair, interference will happen, which can distort the signal. To prevent interference, we set different modulating frequencies for the server and client. As an example, if we set the data rate to be 100 bps, the server uses 600 Hz and 700 Hz frequency pair to transmit data while the client uses 800 Hz and 900 Hz frequency pair.

ACK timeout period. During the implementation, we have to decide the ACK timeout period effectively. To do this, we measure the duration of a full data transmission, including synchronization, message transmission, and confirmation period, and add an extra second to get the timeout period. Since the length of the message is constant, the transmission duration will be consistent. However, lower data rates have longer durations, which means more extended timeout periods as well. If we use the longest timeout period, i.e., the timeout period for the lowest data rate, the server will be waiting for an extended time when using higher data rates, as the transmission duration will elapse faster. Therefore, we configure the server to select the appropriate timeout period according to the data rate.

Handling ACK losses. During the implementation of the algorithm, we observe a corner case in our system, which is illustrated in Figure 5.2. As an example, we configure our system to transmit and receive at 80 bps. When the server decides to change the data rate to 100 bps, it will send a "change-rate" message to the client. When the client tries to send an ACK back, the server might not receive the ACK due to a sudden change of link condition. Since the client has no information on the state of the server, it will change its configurations to 100 bps regardless of the client condition. When the server's ACK timeout period expires, the server will try to resend the same message again, using the 80 bps settings. Since the configurations are different between the two ends, they would not decode any data. This cycle continues forever. To get around the problem, we implemented a timeout period for the client. The timer starts when the client does not receive any synchronization message from the server. When the timer expires, the client will change its data rate settings to a lower one. We choose the timeout period empirically.

5.3 Evaluation

For the evaluation, we implement the AARF algorithm in our system and benchmark its behavior. We test the algorithm at indoor settings for two different scenarios. In the first scenario, we make the lighting condition constant and vary the distance. We did the opposite for the second scenario.

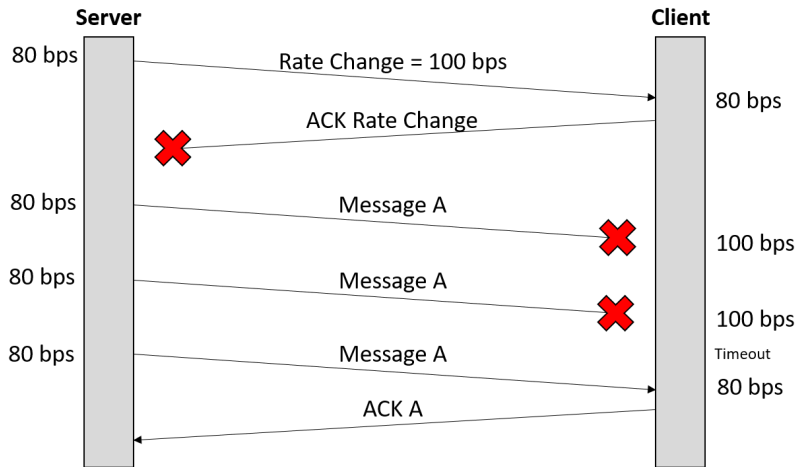


Figure 5.2: Illustration of handling ACK losses.

5.3.1 Varying distance

In this scenario, we turn on all the lights in the room. The illumination is 550 lux. To see the dynamics of the data rate, we vary the distance every five minutes. In the beginning, we put the transceivers 2 m apart. We move the client backward to a 3 m distance after five minutes. Afterward, we shorten the distance by placing the client at 1 m distance. Finally, we put the client back to its original position. The result of the test is shown in Figure 5.3. We also compared it to LuxLink’s data rate.

As can be seen in the figure, when the distance is at 2 m, the data rate oscillates between 250 bps and 400 bps. When the range increases, we see an immediate drop in data rate to 125 bps, sometimes to 0 bps, because the client is disconnected from the server due to poor link. When we place the client closer at 1 m, the data rate slowly increases and reaches a maximum of at 400 bps. There are several instances where the data rate dips to 0 bps. This happens due to the corner case we described previously. After we place the client back to its original position, the data rate drops back to 250 bps.

We also plot the average throughput per five minutes, which is shown in the dotted line. When the distance is at or below 2 m, the average throughput of LuxLink+ will be above LuxLink’s. However, when the gap is increased to 3 m, LuxLink+’s throughput falls below LuxLink’s.

By calculating the area below the curve (i.e., the number of packets sent), we can figure out the improvement of LuxLink+ to LuxLink for this specific setup. We measure an increase of 85 percent in the number of packets sent for our scenario, which corresponds to the rise in throughput. The improvement of performance can be more significant if the lighting condition is better.

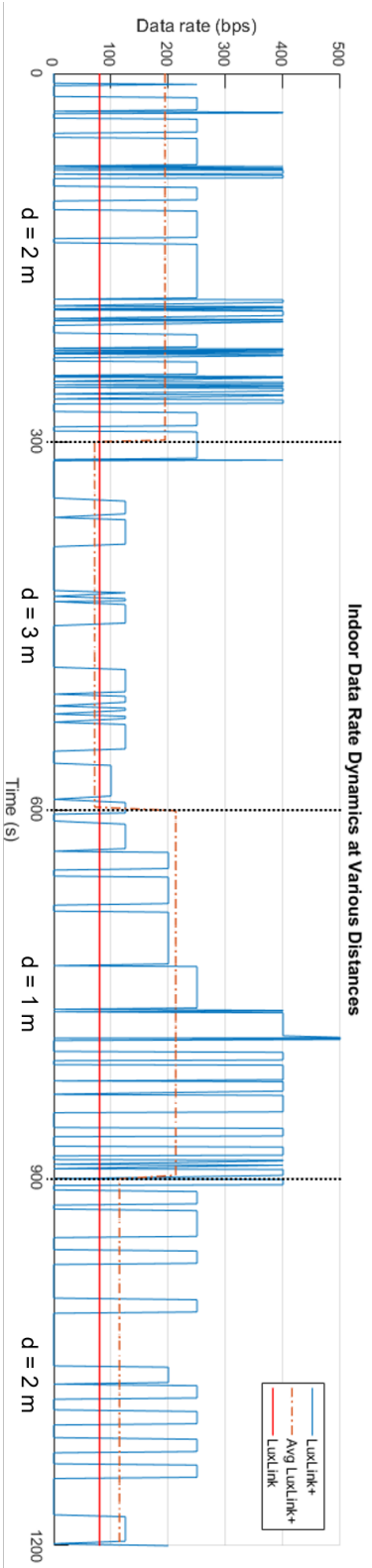


Figure 5.3: Indoor data rate dynamics for various distances. The dotted orange line represents the average throughput per 5 minutes.

5.3.2 Varying light intensity

Besides evaluating the system for different distances, we also evaluate it under different light intensities. We put the transceivers at 2 m distance. Using the same interval as the previous experiment, we change the light intensity of the room by controlling the light fixtures. We changed the illumination of the room to match 190 lux, 55 lux, 550 lux, and back to 190 lux consecutively for each interval. The result of this evaluation is shown in Figure 5.4.

We can see the same trend as the previous experiment, where when the light intensity is low, the system will decrease its data rate step-by-step and vice versa. This effect, however, restrains the system from using the highest data rate as the adaptation process is fast to decrease the rate but slow to increase it. We can see this effect when the light intensity switches to its highest (550 lux) at $t = 900$ s. Theoretically, the system can achieve a data rate of 400 bps in this lighting condition. However, the system drops its data rate down to the lowest data rate (50 bps) during the previous interval ($t = 600 - 900$ s, when the illuminance is at its lowest). Since the algorithm increases the data rate one mode at a time, it can only use the highest data rate at the end of the 900 - 1200 s interval, reducing the average throughput. However, we observe that the average throughput during this interval is still above LuxLink's. We also observe that the data rate never gets to the maximum data rate (1000 bps) due to insufficient lighting condition.

We also calculate the improvement of LuxLink+ using the same method as the previous scenario. We measure an increase of 45 percent compared to LuxLink in this specific scenario. We note that the result will vary due to the probability of encountering the corner case mentioned above, which can affect the outcome.

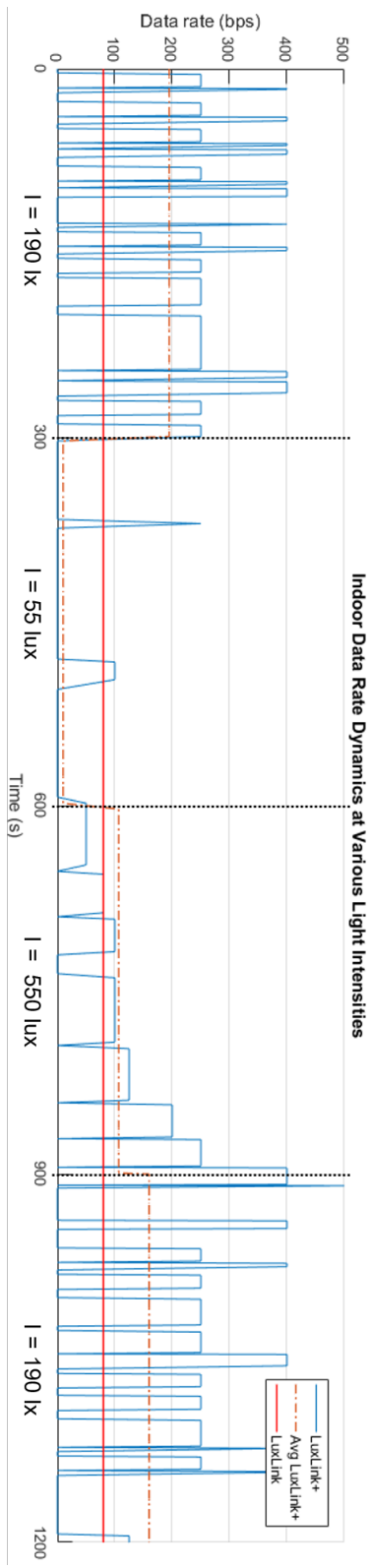


Figure 5.4: Indoor data rate dynamics for various lighting condition. The dotted orange line represents the average throughput per 5 minutes.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

This thesis shows the performance improvement of LuxLink [8], which is one of the passive communication systems that use ambient light. There are several challenges that the current LuxLink system encountered, mainly the relatively low and static data rate. We made several contributions to address those challenges.

We presented LuxLink+, an extension of LuxLink that provides two main improvements. Firstly, we provided an analysis on the modulation technique used by LuxLink, the Frequency Shift Keying (FSK). Based on that, we conducted a thorough analysis of the bandwidth of the system by investigating the upper and lower limit frequency. Using this information, we looked into multiple-frequency based modulation schemes, in which we chose M-ary Frequency Shift Keying (MFSK). The performance of the new modulation scheme was then measured at various conditions. The data rate of the system increased from 80 bps to 1000 bps at 1.5 m distance under a lighting condition that simulated an overcast sky.

Secondly, we presented LuxLink+, which is the extension of LuxLink. LuxLink+ implemented an adaptive data rate algorithm that maximizes the channel capacity based on the decoding quality. We implemented the Adaptive Auto Rate Fallback (AARF) algorithm and managed to increase the average throughput by up to 85 percent in various fluctuating environments.

6.2 Future Work

The presented work resulted in the performance increase of LuxLink, especially on the data rate and the adaptability of the system. However,

we observe that there is still room for improvement. Some possibilities for future work are:

- **Use of other materials.** The current transmitter uses off-the-shelf liquid crystal shutters, which has a limited switching speed. There are other fast-switching materials such as Pi-Cell [19] that can be used as a transmitter. However, there are no information regarding the switching speed. Therefore, research on that can be beneficial as additional switching speed will translate to the increase of data rate.
- **Adjustable receiver.** In our implementation, we configure the signal amplifier on the receiver for indoor usage. When we move the receiver outdoor, we have to change the hardware so that the signal would not saturate. Having a receiver that can adjust the amplifier gain according to the ambient light intensity could allow the system to be used in various use case without the need for any hardware modifications.
- **Better use of rate adaptation algorithm.** The current algorithm adjusts its data rate step-by-step, which resulted in a slow-changing data rate, as explained in Chapter 5.3.2. Research on other rate adaptation algorithm that uses different metrics (e.g., SNR) may alleviate this problem, which would allow the system to achieve better channel utilization.
- **Power optimization.** The current implementation is not optimized for power as we are running the microcontroller at full power. Usage of low-power microcontroller and optimizations on the software can reduce the power consumption of the system.
- **End-to-end communication.** The current LuxLink+ already supports the physical layer of the communication system. It would be ideal to add our physical channel to existing operating systems, such as Linux, to enable end-to-end communication. To achieve that, it is necessary to write a network driver so that applications on a higher layer can access our physical layer.

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Appendix A

Flicker mitigation: polarizer placement

To mitigate flicker effect, we could revisit one of the techniques used by [26], that is to move one of the polarizing films of the LC shutter to the receiver. The illustration of this method is shown in Figure A.1.

As mentioned in Chapter 2, the second polarizing film filters the polarized light to determine if the light is passed through or blocked. If we move the second polarizing film to the receiver, the light coming out of the LC shutter would be polarized, but in different directions (horizontal or vertical depending on the voltage applied). Humans cannot perceive the changes in polarization [13]; thus, the flicker effect should not be apparent to human eyes.

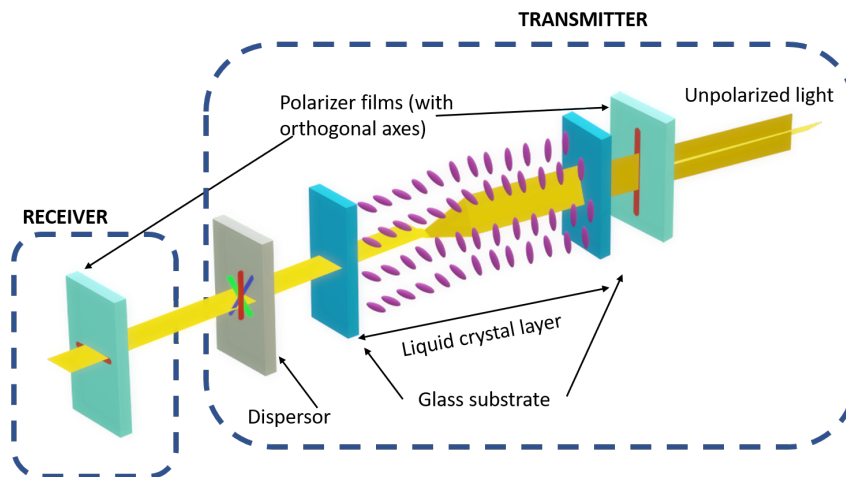


Figure A.1: **Placing the polarizing filter at the receiver to mitigate flickering.** [8].

The method, unfortunately, has a downside in terms of mobility. If we

recall, the two polarizing films have to be perpendicular to each other. If the receiver is rotated relative to the transmitter, the polarizing films will not be perpendicular anymore. We tested this effect by moving one of the polarizing films from the transmitter to the receiver. We placed the transmitter and the receiver at two different distances, 50cm and 100cm. We evaluated this effect in a controlled environment (indoor) with the ceiling lights turned on. The result of the experiment is shown in Figure A.2

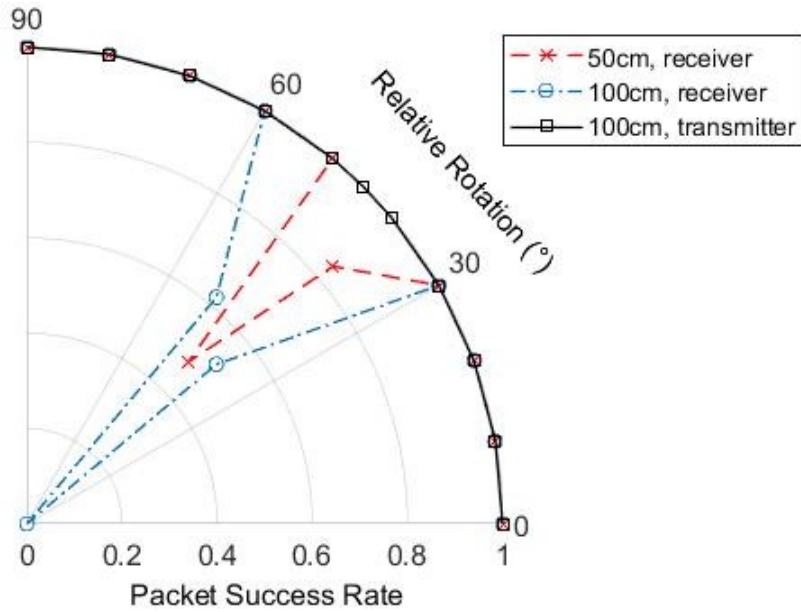


Figure A.2: **The effect of rotation of polarizing film to packet success rate.**

As can be seen from the figure, when we move the polarizing film to the receiver, the packet success rate drops when the relative rotation is at around $45^\circ \pm 15^\circ$, even dropping to 0 when the distance is farther. At that relative rotation, the polarizing films are not orthogonal anymore. Thus, there is no clear distinction between the different states of the shutters. In contrast, when both of the polarizing films are located at the transmitter, the packet success rate stays at 100 percent regardless of the relative rotation.

We can counter the problem using a dispersor at the transmitter, employ the CSK encoding, and decode the signal using a camera, similar to [26]’s solution. However, as [8] suggests, the solution consumes more power as a camera is used to decode the signal. Moreover, the system does not exploit the full energy present in ambient light since the system decodes the data by sensing the difference in color, which only uses a narrow portion of the total energy contained in the light spectrum. If we use the FSK encoding, the system will utilize the energy from the whole light spectrum, which

yields better signal decoding. From the experiment, we can conclude that placing the polarizing film at the receiver can severely limit the mobility of the system.