Delft University of Technology
Master’s Thesis in Embedded Systems

Visible Light Communication with Mobile Lights

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TU Delft Delft University of Technology

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Abstract

Artificial lights in our buildings have always been designed to be static for one purpose only; illumination. With the increasing interest in Visible Light Communication (VLC) and a crowded radio-frequency spectrum, static lights in our offices and rooms might not be ideal anymore. VLC can add extra services like high quality communication and localization. These services benefit from optimal circumstances as we can find in the hot spot below the lights. Outside the hot spot, the intensity of the lightbeam starts to drop rapidly. This research is dedicated to the aspect that the static lights are lacking which is mobility. Instead of having static lights we create a light source that is able to move along with persons in a room.

In this work, which consists of the design and evaluation of our system, we create a mobile platform which includes enhancement of an existing gondola system, the design of a small mobile LED-transmitter and a smartphone as receiving device. We designed a system for the light to follow a user. The smartphone can locate the light and it calculates the location offset through image processing. New coordinates for the light are send to the gondola system to move the light and keep the transmitter and receiver in sync.
The system was tested by installing it in the Embedded Systems laboratory of the TU Delft and evaluated in terms of illumination, communication and energy efficiency compared to a static light network. We can conclude that a mobile light can add extra services to VLC by ensuring a constant high illuminance and signal-to-noise ratio by using individual focused hot spots that follow the user in real-time, with an average position error of 1.74 cm, which the static light network can not do causing a performance degradation. The mobile light is in most cases also more energy efficient than a full hot spot static light network coverage. Besides that, we obtain a 3.91 centimeter precision indoor localization as an extra result.

Preface

This Master of Science thesis is the result of the time I spent at the Embedded and Networked Systems group for the past year. My interest in Visible Light Communication was sparked after having an orientative talk with Marco Zuniga who then became my supervisor. The concept of moving a light around the room seemed really interesting with all the benefits that could bring to the table compared to the static lights that we are used to.

For the duration of this project, a number of people have provided me some support or good laughs. First of all, I would like to thank my supervisor Marco Zuniga for guiding and helping me through this thesis. Further, I would like to thank my parents and more recently my girlfriend for their patience and support throughout all these years that it took me to reach this point. Third, I want to thank Ioannis for his tips and insights which helped me during this project. I would also like to thank all members from the VLC and ENS group that I met and gave me some useful suggestions and I would like to thank all my friends for their support and encouragements during the thesis. Also Eric could always provide me with some quality 'gratis' coffee and some good laughs. Not to forget I want to thank Christoph for being my third member of the thesis committee. Finally, I would like to thank Koen for sustaining the high quality of this Masters study and being the chair of my defense.

Delft, The Netherlands
25th June 2019

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Transatlantic

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Introduction

1.1 Motivation

For decades, artificial lights in our buildings have been designed to be static. These static lights in offices and rooms have been designed for two purposes only; illumination and decoration. To provide illumination, multiple static lights are needed to get full coverage of a room, which usually requires a minimum illuminance of around 500 lux. The lights provide us with enough light to carry out various tasks throughout the day. Since static lights are necessary, most of the research time spent on lights were for decorative purposes instead of focusing on possible other features of a light bulb.

After the recent replacement of incandescent light bulbs by Light Emitting Diodes (LEDs) these static lights gained some new interesting features. Besides having a longer lifetime expectancy and consuming less energy than incandescent bulbs, one of the most important aspects of LEDs is the fact that they can instantly turn on and off which allows us to communicate with them. This is the key principle of Visible Light Communication (VLC) which uses the instant on and off state of the LEDs to send 0's and 1's and create a communication protocol.

With an increasing interest in Visible Light Communication (VLC) and a crowded radio-frequency spectrum, the concept of having static lights in our offices and rooms might not be ideal anymore. This triggers us to look at more efficient solutions to maximize the benefits from the services that LEDs and VLC can offer.

Adding communication to the lights means that we want optimal circumstances to achieve a highest efficiency resulting in a highest possible throughput. This is possible when we are within the so-called hot spot of a light, directly below the light where the maximum intensity can be found as seen in figure 1.1. Here the yellow curve is the intensity of the light related to where we stand below the light.

Outside the hot spot, the light intensity of the light beam decays fast from the center, which reduces the signal strength and minimizes the signal to noise ratio (SNR). This means that we need to be in the hot spot at all times if we want a high SNR resulting in a high throughput, since the lights can not move along with us. For this thesis, the hot spot is defined as the region where the luminous intensity is always at least half of the maximum intensity.

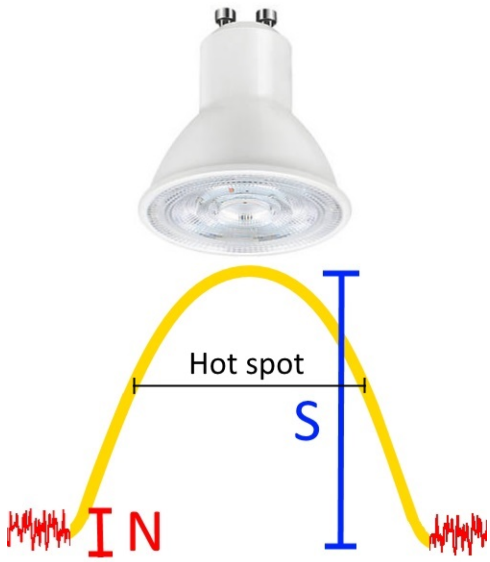

Figure 1.1: Hot spot and SNR.

1.2 Research goal

Therefor this research focuses on an aspect that static lights are lacking and which can possibly be exploited: mobility. Instead of having static lights installed in rooms we could create a light source that is able to move along with persons in the room. By having a mobile light we could not only reduce the manufacturing, installation and recycling of light bulbs (although we do need to install a mobility system), but we can also add several other useful features such as improved illumination, communication and as bonus feature a form of indoor localization.

This is possible due to the fact that the light source will be hovering directly above the user which significantly increases the light intensity for the user compared to walking in a room with static lights. Figures 1.2 and 1.3 show a comparison between the static and mobile lights situations.

We see that the room with static lights is creating the hot spots directly below the lights (the blue beams). The user however is not directly below a static light and does not gain the benefits that a hot spot can offer.

In the room with the mobile lights we see that the user has a light assigned to him which will follow him. This ensures that the user always benefits from being in the hot spot of the light and can move wherever he wants through the room. To be able to achieve lights that are mobile we exploit a mechanical system that is able to move these LEDs around the room.

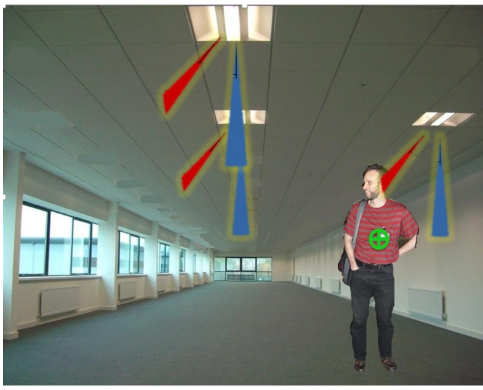

Figure 1.2: Static light hot spots.

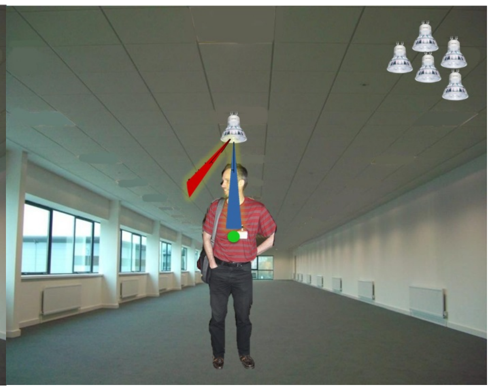

Figure 1.3: Mobile light assigned.

Since light has a different place in the electromagnetic spectrum, it does not interfere with the radiofrequency-spectrum. This spectrum is already really crowded with WiFi, GSM, Bluetooth and many more different signals, so having an alternative for communication is really precious. And last, due to the nature of light radiation patterns and communication techniques, they can also be used for localization techniques. All together this could create a new standard for illumination of rooms and offices.

1.3 Contributions

This work proposes to use (swarms of) mobile lights which track and follow persons in a room. These mobile lights are created by grouping an LED, a battery supply and an Arduino Pro Micro together to create a mobile light source that is able to communicate. The light is moved by an Arduino driven gondola system [3], which is a system of motors and wires, that can move the light fully within a 3D space. To group it together the contributions made in this thesis are as follows:

1. The creation of a mobile platform. This includes enhancement of the existing gondola system, the design of a small mobile LED-transmitter and receiving device.

2. Design of a system for the light to follow a user. Through image processing the smartphone locates the light, calculates the offset and sends new coordinates to the gondola, so the light can be maintained on top of the user as he/she walks around. The system also provides the location of the user as an extra feature.

3. Evaluation of the system in terms of illumination, communication and energy efficiency compared to a system with static lights.

1.4 Thesis organization

This thesis is organized as follows. In chapter 2 the principles of lights/LED's and VLC are explained and related projects are discussed. Following that, chapter 3 describes the components and setup used to get a working mobile platform. In chapter 4 the method to follow the user is explained while chapter 5 will explain how the measurements have taken place and evaluation of the results of these measurements will be done. Finally we conclude with general remarks, limitations and future work in chapter 6.

2
Background

This chapter will give a brief explanation of Visible light communication in section 2.1 and a background on the behaviour of light in section 2.2 and how it can be used for illumination, localization and communication on which this thesis is focused. Section 2.3 will discuss related works done in this field.

2.1 Visible light communication

Visible light communication (VLC) [17] has gained a lot of interest in recent years. This is mostly due to the fact that visible light does not interfere with the radio frequency spectrum which is getting crowded so alternatives are appreciated. Another welcome fact is that light sources can already be found everywhere. Light is an essential part of the human existence and being able to use it for communication could improve our lives significantly.

VLC works by switching an LED on and off really fast. Therefor the on-state can be seen as a logical 1, while the off-state acts as a 0. Since this switching happens very fast it can not be seen by humans, unless it is not properly executed which can cause flickering of the light. By capturing the modulated light with a photodiode we can set up a communication protocol. This creates the basis for VLC and is currently being explored to maximize its potential.

An alternative for the photodiode is the use of a camera and a smartphone to capture the VLC transmissions using the rolling shutter effect [11] of the camera.

2.2 Light characteristics and behaviour

This thesis is highly based on the characteristics and behaviour of visible light. We want to gain as much profit as we can from visible light. To get a better understanding of how we can achieve this we will take a look at some basic principles of light, i.e. Lambert's Cosine Law [22], size and shape of the light source, illumination requirements and signal-to-noise ratio.

2.2.1 Lamberts Cosine Law

Any surface which obeys Lamberts law is called a Lambertian. The official law is stated as follows:

> *The radiant intensity or luminous intensity observed from an ideal diffusely reflecting surface or ideal diffuse radiator is directly proportional to the cosine of angle between the direction of the incident light and the surface normal.*

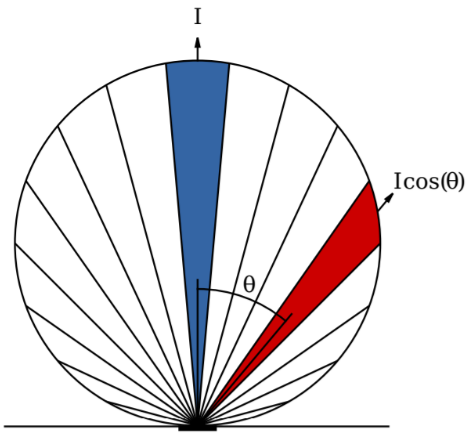

Figure 2.1: Lambert's cosine law [7]

Figure 2.1 shows the radiation pattern of a light source. With this figure the cosine law is easily understood. If we take a look at the blue region we observe an intensity I in the hot spot. The cosine law states that the intensity of light in the region described in red is directly proportional to the cosine of the angle formed between itself and the surface normal.

This means that when a person walks across a static light source it creates an angle θ and together with an increasing distance between the light and user this means a rapid drop in luminous intensity.

A special angle is the semi-angle, where the intensity is halved compared to the maximum intensity. This angle defines our hot spot region and is thus of great importance for this thesis.

2.2.2 Size and direction of the light source

Different light sources have their individual optical characteristics which define their radiation patterns. This is due to their size, the amount of LEDs inside the bulb and in the way they reflect the light out of the (glass) panel. If the glass panel scatters the light beams in every direction you will not have as much luminous intensity as a glass panel that is more focused and sends the light beams straight to the ground.

Another aspect to take into mind is the influence of the distance on the luminous intensity. When moving away from a light source the intensity will start to drop rapidly. Of course when moving sideways (out of the blue region in figure 2.1, changing the angle) it also follows Lambert's cosine law, but as can be seen in figure 2.2 if we change the distance to the light source from 5 to 20 centimeters we have lost around 85 percent of the luminous intensity. This is the same principal as the well known exponential decay of electromagnetic waves.

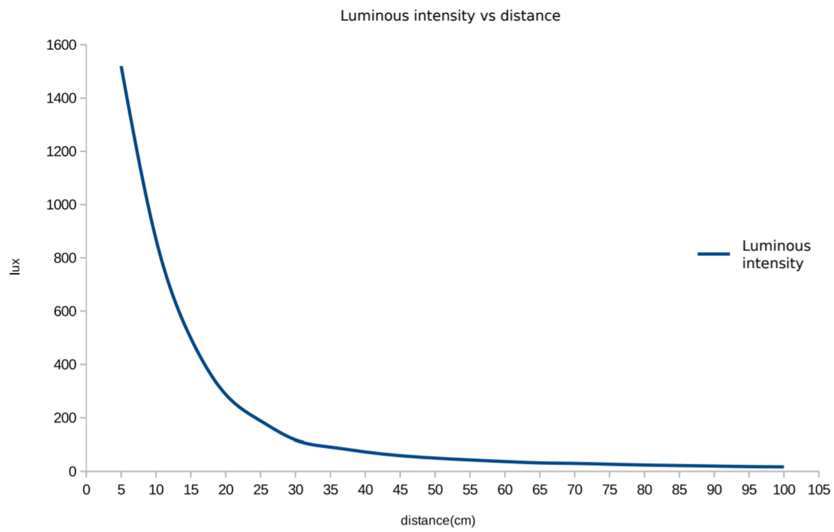

Figure 2.2: Luminous intensity vs distance [6]

2.2.3 Recommended light levels

The outdoor light level is approximately 10,000 lux on a clear day. In buildings, in the area closest to windows, the light level may be reduced to approximately 1,000 lux. In the middle area of a room it may be as low as 25 - 50 lux. Additional lighting equipment is often necessary to compensate for these low levels.

To accommodate this, certain illuminance standards have been developed over the years to improve the working and living experience of humans. The authors of [15] for example have listed illuminance requirements starting from early 1900 stating how many foot candles should be lit to have enough light up to the early 80's where a minimum amount of lux is required for certain activities.

Table 2.1 shows the recommended light levels in different workspaces that we use as of today. We can see that for normal office work we would like an average illuminance of 500 lux at the spot. To illuminate the whole room to get an average illuminance of 500 lux means that we need to place several static lights around the room.

However, if we take a look at the fact that we need 500 lux at our workspace for office work while simple orientation and navigation through the room needs less lux, this means that we could place a single light at or above our office desk if we are alone and have to move occasionally through the room.

The problem is that people move around often, so if we could make this single light mobile, we could carry this 500 lux with us around the room and always have sufficient illumination and be guaranteed of hot spot benefits. Besides that, this mobile light could be dimmed or brightened (or placed further/closer to the user) to get a desired recommended light level for our task at that specific location, which could also be used to increase the bitrate for communication purposes.

Activity	**Illumination (lux)**
Public areas with dark surroundings	20 - 50
Simple orientation for short visits	50 - 100
Working areas where visual tasks are only occasionally performed	100 - 150
Warehouses, Homes, Theaters, Archives	150
Easy Office Work, Classes	250
Normal Office Work, PC Work, Study Library, Groceries, Show Rooms, Laboratories	500
Supermarkets, Mechanical Workshops, Office Landscapes	750
Normal Drawing Work, Detailed Mechanical Workshops, Operation Theatres	1,000
Detailed Drawing Work, Very Detailed Mechanical Works	1,500 - 2,000
Performance of visual tasks of low contrast and very small size for prolonged periods of time	2,000 - 5,000
Performance of very prolonged and exacting visual tasks	5,000 - 10,000
Performance of very special visual tasks of extremely low contrast and small size	10,000 - 20,000

Table 2.1: Illumination requirements [21]

2.2.4 Signal quality

To get a better insight whether the signal quality is excellent or very low, we will make use of the Signal-to-Noise Ratio or in short SNR, which shows the amount of noise compared to the signal strength. Obviously, the more noise is added to the received signal, the worse the overall signal will become. Just as with Wi-Fi signals [5] and other signals in general, the SNR can give a quick understanding of the quality of the signal.

Table 2.2 therefor lists SNR values versus the quality it can guarantee for Wi-Fi signals, which we use as a reference for our VLC measurements in section 5.2.

SNR	**Quality**
>40dB	Excellent signal; always associated; lightning fast
25dB to 40dB	Very good signal; always associated; very fast
15dB to 25dB	Low signal; always associated; usually fast
10dB - 15dB	Very low signal; mostly associated; mostly slow
5dB to 10dB	No signal; not associated; no go

Table 2.2: Signal-to-noise ratio vs quality of the signal.

Besides the SNR there also exists the SINR, which is the Signal-to-Interference-plus-Noise Ratio. This means that the quality of the signal is determined by the power of the signal of interest divided by the sum of the interference power (from all the other interfering signals) and the power of some background noise. Other lights can cause interference on the receiver of the user and thus the SINR will be used if this is the case. If no interference is detected in the channel, then the SINR will automatically be reduced to the SNR.

The SINR describing the quality of the signal differs slightly from the SNR. Therefor the SINR dB level vs. quality is also summed up in table 2.3 below.

SINR	**Quality**
$\geq$ 20 dB	Excellent ; Strong signal with maximum data speeds
13 dB to 20 dB	Good ; Strong signal with good data speeds
0 dB to 13 dB	Fair to poor ; Reliable data speeds may be attained, but marginal data with drop-outs is possible. When this value gets close to 0, performance will drop drastically
$\leq$ 0 dB	No signal ; Disconnection

Table 2.3: Signal-to-interference-plus-noise ratio vs quality of the signal.

2.3 Related works

This section will show related work trying to improve illumination, indoor localization and visible light communication.

2.3.1 Improving illumination and communication

With the phasing out of the incandescent light bulbs and the use of LEDs, illumination has already become a lot more efficient this last decade as the authors of [20] showed. Several studies focus on the type,color and placement of the light and the impact that has on the human performance like the study of the authors of [8] which concludes that there are at least ten mechanisms that contribute to the increase of human performance after improving the lighting. Besides a boost for the human performance, this is also likely to boost the quality of the communication structure for VLC.

Illumination

Static lights and their illumination patterns have been extensively researched and many enhancements and optimizations were found. For example, the authors of [12] show that a better illumination coverage can be realised through optimizing LED arrangements, using the semi-angles and controlling the height of the LEDs in communication and illumination networks. About 75 percent coverage improvement was achieved under their assumed room condition with illumination requirements fulfilled by this optimization. Basically, this idea hopes to ensure that the user is always within the semi-angle of a static light by passive rearranging. Still, we lose half of the intensity when close to the semi-angle. Active rearranging of LEDs is exactly what we can do with a mobile light. If done well, we could prevent ever reaching the semi-angle and always have more than half of the intensity.

Another illumination improvement was found by the authors of [9], which propose an improvement of illumination uniformity for LED flat panel lights by using a micro-secondary lens array which minimizes hot spots. Their results showed a 61 percent enhancement of illumination uniformity on the floor and a 20.5 percent enhancement of illumination uniformity on the walls compared to a normal LED panel. However due to the effects of Lambert's Cosine Law we still suffer from losses when not directly below the LED panel, which happens when the user/receiver is mobile. For normal illumination purposes this might not be a big issue, but the performance of VLC can decrease drastically when an angle is created between the transmitter and receiver. Besides that, hot spots provide high luminous intensities which we can exploit by being able to move the hot spot to the user instead of getting rid of it.

Communication

Besides aiming for illumination improvements, researchers also try to achieve optimal circumstances for VLC and important parameters like throughput and failure rate. The authors of [18] tried to exploit hot spots to increase the communication performance by placing the LEDs in a centralized manner pointing at all directions as can be seen from figure 2.3. Important parameters such as the average outage area ratio, root mean square delay, the minimum number of LEDs required for outage free communication, the impact of semi-angle variation and signal-to-noise ratio have been analyzed for the models below.

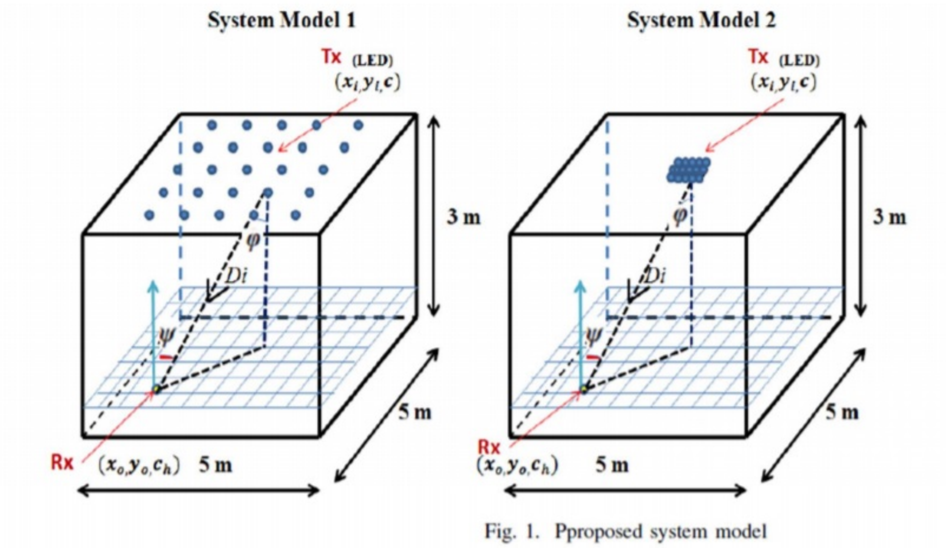

Figure 2.3: Uniform vs centralized LED distribution models.

It was observed that at higher semi-angle values (ψ), the centralized LED configuration (system model 2) exhibits better performance levels as compared to uniform LED distribution (system model 1). However, at semi-angle values lower than 18 degrees, the uniform LED distribution model outperforms the centralized LED model. This system has a drawback however as the lights are pointing from the side and can directly fall on the human eyes instead of from above and this can be perceived as annoying and troublesome, possibly blinding the person when looked at it too long.

Since the previous studies all still show some drawbacks, we could also try to benefit from the hot spots by putting the lights close to each other causing hot spots to overlap. This creates a new problem for communication due to overlapping illumination areas. The authors of [19] created a method to address the issue of an overlapped-illumination area as seen from figure 2.4.

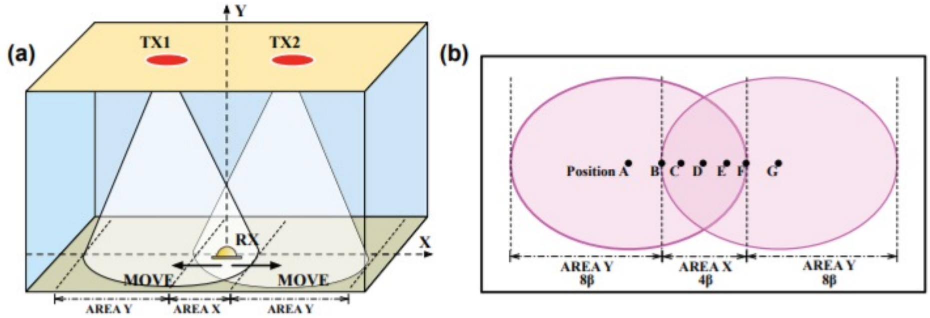

Figure 2.4: Overlapping illumination area with mobile user.

Their proposed algorithm induces the performance degradation in the border of the overlapping area, which is similar with the case of the cellular handover. However, with this solution we still need to place a lot of static lights to get a full hot spot coverage, as is calculated in subsection 5.3.

In conclusion, most, if not all, studies like the ones above focus on the use of static lights with a mobile user and no one has yet tried the case where both the light and the user can be mobile!

2.3.2 Localization

Another service that VLC brings to the table is localization. When driving around with the car many people are using some navigation devices to get to their destination. Almost all outdoor navigation devices use GPS to get a relatively accurate localization. However, GPS has the disadvantage that the signal can not really penetrate thick walls and thus does not work indoors. Therefor a lot of research has been done to achieve indoor localization.

While some other RF techniques have been tried for years to get some accurate indoor positioning, VLC has come with some new options for indoor localization using the characteristics of light and the high availability of already installed light sources. The authors of [10] for example used a VLC smartphone camera based indoor positioning system to achieve a position estimation of 4.81 cm and 6.58 cm for a distance between transmitter and smartphone of 50 cm and 80 cm, respectively. This is already sufficient to be used for indoor navigation.

A whole different way of achieving localization was done by the authors of [16], which made use of the placement of multiple static lights with their own unique message (fingerprint) and were able to achieve an accuracy of 0.56m in their validation experiments. Besides fingerprinting, we can also use the shape of the illumination pattern in overlapping areas when using two LEDs as has been done by the authors of [6]. They were able to achieve an position error of around 3cm.

And last, time distance of arrival can also be used to obtain a localization result as the authors of [14] have showed. This method can acquire a simulated accuracy of less than 2cm.

So in summary VLC can play an important role for localization techniques, both indoors with the already available lights and outdoors, by sunlight modulation/reflection techniques. Our research however is not focused on improving localization results. With our technique to obtain the user-light synchronization as explained in chapter 4 we move the light through the room to match the position of the user. Since the mobility system knows the location of its movable object (the light), we obtain a position estimation result as a side feature.

3

System setup

This chapter describes the gondola system (1) that provides mobility in section 3.1 and explains the transmitter (2), which is the light, in section 3.2 and receiver (3), which is the smartphone, in section 3.3 used to achieve the interplay between a user and the light. Figure 3.1 shows all three components in an overview of the system.

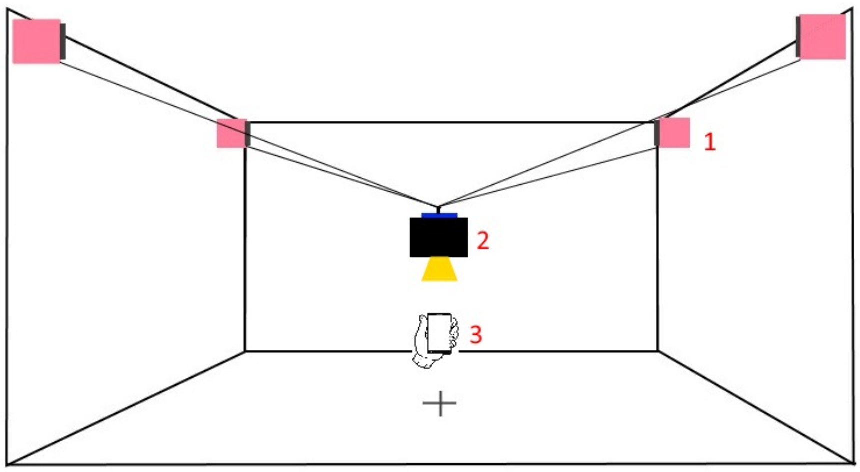

Figure 3.1: Mobile light system.

3.1 Mobility

For a light to move, we need a flexible dynamic structure. For this thesis project a gondola system is used to provide mobility.

3.1.1 Gondola

Gondola consists of four 12V stepping motors, commonly used in 3D-printers, which are turning spools that can lengthen or shorten a fishing wire by rotating the spool and winding the wire. These four motors together then can move an object through the 3D-space created between the four motors and the ground as can be seen in figure 3.1.

The motors are embedded in a case which can be screwed on the walls or ceiling. The wires go out of the case through a hole which is the anchor point for the motor. The exact locations of the anchor points are required for the system to be accurate.

The Gondola is controlled by an Arduino Mega board which determines the direction and speed of the rotating motors depending on where the object at point 2 in figure 3.1 needs to move to. The anchor points are used to calculate the distance between the current and a new position. New coordinates are translated by the Arduino to a certain amount of steps for the motors to rotate the spools and achieve the requested distance.

The gondola system has been mounted in multiple rooms over the course of this thesis. The calibration point can be seen in figure 3.1 on the floor. This is the point where the four wires meet and the object should be placed at this location at the start-up of the system.

3.1.2 Mechanical issues and limitations

Gondola had a few issues and limitations before the start of this thesis, which are listed below with their solutions.

1. The first issue was the fact that the spools and cases are 3D printed plastic. Long term use of the gondola system has taught us that the wires tend to cut into the plastic case. This also caused the wires to be damaged over time and ultimately break.

    - To avoid the wires cutting into the plastic case the holes have been reinforced by metal nuts through which the wires will go out. This prevents the cuts in the plastic case and damaging of the wires.

2. Second, while the Gondola moves close to a wall, the wires are pulling at each other with a lot of force that can cause the motors to skip some wire and thus lose its correct position.

- These tension problems are solved by enhancing the code for Gondola such that it is only able to move to positions at least 1.75 meters from a wall. This creates an area of 3 by 4 meters in the ES-lab for which the Gondola can move freely and where the person should stand to be detected. The calibration spot is in the middle of this area.

3. Next is the weight limit of the Gondola. The object at point 2 in figure 3.1 will add extra weight to the system that will pull on the wires. This creates the same tension on the wires as moving close to a wall or the ceiling and will cause the motors to skip or not even hold the object anymore.

    - Weight experiments were performed to determine a safe weight threshold for the object. This was done by equipping a tray on the Gondola and then fill it with rice until it could not be moved smoothly anymore. This experiment taught us that the weight of the object should not exceed 500 grams to be able to move high enough and not hit persons standing below it.

4. The Gondola is designed to be controlled by a user sitting at his desk and requesting new coordinates by inputting it on his/her keyboard. The Gondola is connected by a USB-cable to the computer/laptop and thus mobility is limited. We want to move throughout the room without being connected by a wire, also without the need of using a computer in between.

    - To address this mobility problem an HC06-Bluetooth module has been connected to the Arduino to enable Bluetooth communication between the smartphone and the Arduino. The software is altered to include the Bluetooth serial connection besides the USB serial connection, which can still be used for testing purposes. Also, the software of the Arduino has been extended to include a discovery routine search to get a rough location of the user. This discovery function is triggered upon receiving a 'discovery' signal from the smartphone and is further explained in chapter 4.

5. A last physical limitation of the Gondola is its speed. The Gondola can move the object only with a maximum of 10 centimeters per second. This is a limitation of the motors and can not be enhanced. This 0.1 m/s (or 0.36 km/h) is way less than the average walking speed of humans which is 1.4 m/s, or 5 km/h. Therefor for this project the person should keep this in mind and move fairly slowly for the Gondola to be able to keep following him or her.

3.2 Transmitter

In traditional VLC, lights are static. This allows them to be connected to power and network wires. In our case, the light needs to be mobile. Because of this reason, there are some constraints on designing such a light transmitter. We need to find a solution to include power and add Visible Light Communication while maintaining a weight close to or less than 500 grams.

3.2.1 Power

First of all the transmitter needs to be powered. As static lights are directly connected to the power grid and we need mobility, one can argue to use a longer power cord and extend it to reach every spot in the room. However, this creates the need to wind up the power cord, otherwise it would be dangling from the transmitter and hinder movement below the transmitter. For this an extra motor with spool is needed which is to be controlled by the Gondola. This would cost too much time to implement.

Another option is to replace one of the fishing wires with a power cable. This option was also not chosen, because the power cable would be way thicker than a fishing wire, which means that it would not fit on the spool and it would increase the effective radius of the spool. For example figure 3.2 shows that a fully wound up spool increases the radius by 1 centimeter. This means that the circumference increases by 2π, which is roughly 6.28 centimeters and this creates a large positioning error. The fishing wire is thin enough to neglect this error. Since we cannot use cables to power our mobile light, our only option is using a battery to power the transmitter.

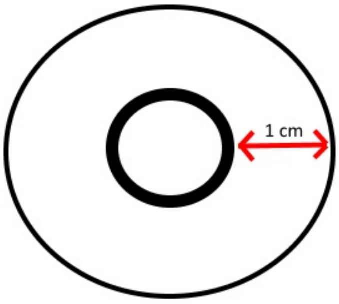

Figure 3.2: Spool radius increase.

3.2.2 LED and communication

To modulate the LED in the mobile light, an Arduino pro micro is used with a mosfet to toggle the LED on and off. This Arduino has an operating voltage of 5V, but has an on-board voltage regulator that can accept voltages up to 12V. This means that the LED that is used for communication can be powered from 5V up to 12V and thus we need to find a suitable LED that can work within this range and the 123led GU5.3 led-spot glass 3W LED [1] has been chosen for this project, because it works within this range and can be easily connected to the Arduino mini.

The LED works as expected when powered directly from the raw 6V voltage input supply from the battery case. However, when VLC was added and the LED had to toggle on and off very quickly it was noticed that the LED does not switch on and off instantly, but looks like it is charging and discharging. This means an extra circuit is inside the lamp containing a capacitor that acts as a battery preventing instantaneous toggling. Therefor this circuit was taken out of the lamp leaving only the PCB with the LEDs on it.

However, these LEDs on the PCB light up when supplied with a voltage of around 24V which is significantly higher than the 5-6V from the batteries. Therefor a DC-to-DC converter, or booster circuit, was added before the mosfet switch to boost the battery voltage to 24V. This has a disadvantage that, while the voltage will be stepped up from 5 to 24V, the current will be stepped down (P = U*I) because of the limitations of our battery, causing the LEDs to have a lower luminous intensity. However, since the goal is to compare the mobile light with static lights and not to have a fully functional prototype for the real world, we have to match the luminous intensity of the mobile light with the luminous intensity of the static lights or vice versa to attain apples-to-apples comparison in sections 5.1 and 5.2.

3.2.3 Weight

Using a battery means adding more weight to the transmitter. As mentioned before this creates more tension on the wires so the battery pack should not be too heavy. A battery holder containing 4 Eneloop AA-batteries [2] is chosen for this. To group it all together and form a transmitter, a lightweight plastic case for all the components was designed in OpenSCAD [13] and then 3D-printed such that all components fit in. Together with the batteries, LED, Arduino, breadboard and wiring to connect everything this adds up to around 280g which is light enough to be moved above the user without complications.

3.2.4 Final result

With all the above mentioned restrictions and additions the transmitter ultimately turned out as seen in figure 3.3, where the 10 centimeters height includes the LED.

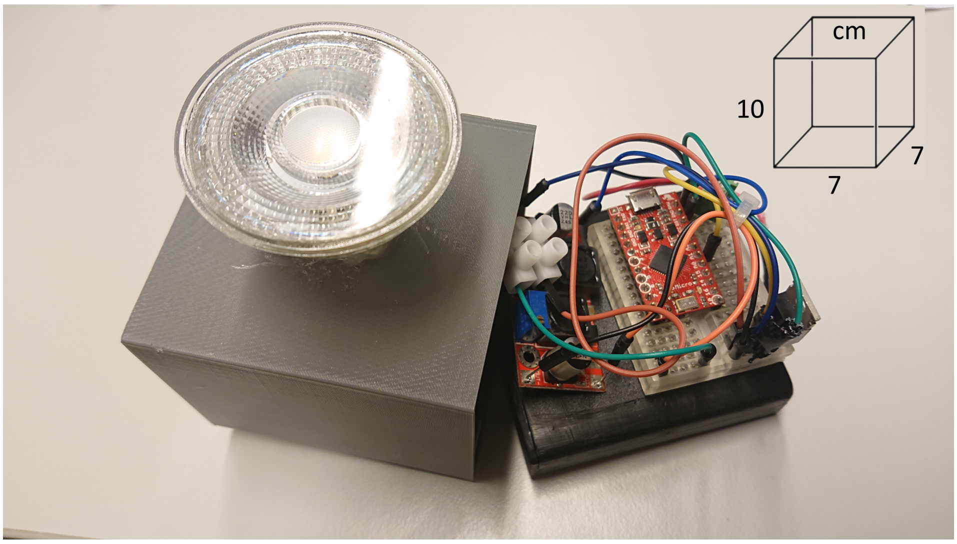

Figure 3.3: Final result for the LED transmitter.

Since the transmitter is close to the maximum weight of 500 grams, to avoid skipping of the wires the Gondola is programmed to move the transmitter at a height of 190 cm. Placing the transmitter higher creates too much tension on the wires. Beside this mobile transmitter, four extra static transmitters have been created (without cases) for direct comparison measurements between static lights and a mobile light.

3.3 Receiver

For this project two different receivers are used. The main receiver is the smartphone that was mentioned before. However, smartphones use cameras as receivers and cameras are known to have limited communication ranges.

With a camera, the communication range depends on the size of the light and the resolution of the camera, because the light is seen as a blob. If the light is small, the blob is too small at long distances and can not be decoded. If the camera has a low resolution, the blob is blurry and hard to decode.

In our case, the light is very small which only allowed us a communication range of 15 centimeters, as will be explained in chapter 5. To be able to detect the VLC at longer ranges, an extra receiver, based on a photodiode, is designed.

3.3.1 Smartphone

For our system to work, a key requirement is to develop a mechanism that allows a light to follow a user. Although the blob, created by the light, is too small to detect communication, it is very suitable for image processing purposes. Therefor, an Android app has been developed for this project called 'Mobile Lights'. This app uses Bluetooth and the front camera of the smartphone, which is a Sony Xperia XZ2 Premium in this case. Through image processing certain features like localization and communication can be extracted, which will be explained further in chapter 4 and 5.

The smartphone is to be held in hand without blocking the camera with the head. It can be placed freely through the available space in the room.

3.3.2 Photodiode

As mentioned before, to obtain the light communication for larger distances a photodiode is used in combination with an Arduino to sense the luminous intensity. The setup for the photodiode can be seen in figure 3.4.

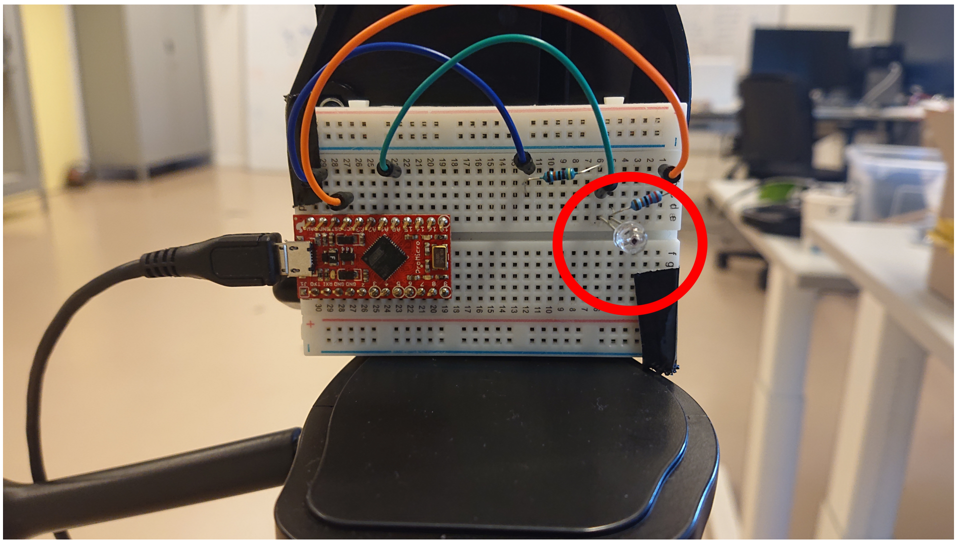

Figure 3.4: Photodiode receiver for sensing VLC.

4
Following system

This chapter describes the following system that is used to keep the light directly above the user. Section 4.1 gives an overview of the following system while section 4.2 goes into more detail on the image processing part. In section 4.3 the correction method is explained, while section 4.4 shows the results for our following system. Section 4.5 closes the chapter by stating the restrictions and assumptions made for the system to work properly.

4.1 Overview

The main goal of this thesis is to have a light following a person and evaluate its performance compared to static lights which makes the synchronization part crucial in achieving a good result. In order to synchronize with each other, the light and person need to be able to communicate. Since the light is controlled by the Gondola and the smartphone of the user is our reference point for the user, we can establish a Bluetooth connection between the two as shown in figure 4.1 which shows the messages that are interchanged between the two devices and a basic timeline overview.

The purpose of this following system is to get (and maintain) the light blob in the center of the camera stream, right above the camera, because that maximizes the illumination lobe. This is achieved in the following matter: The user connects its smartphone to the Gondola and sends the message that it wants to synchronize (the discovery signal). The light is conveniently positioned by the door and thus, upon entering the room, the smartphone's camera will capture the light hovering upon it and sends a message stating that it has seen the light.

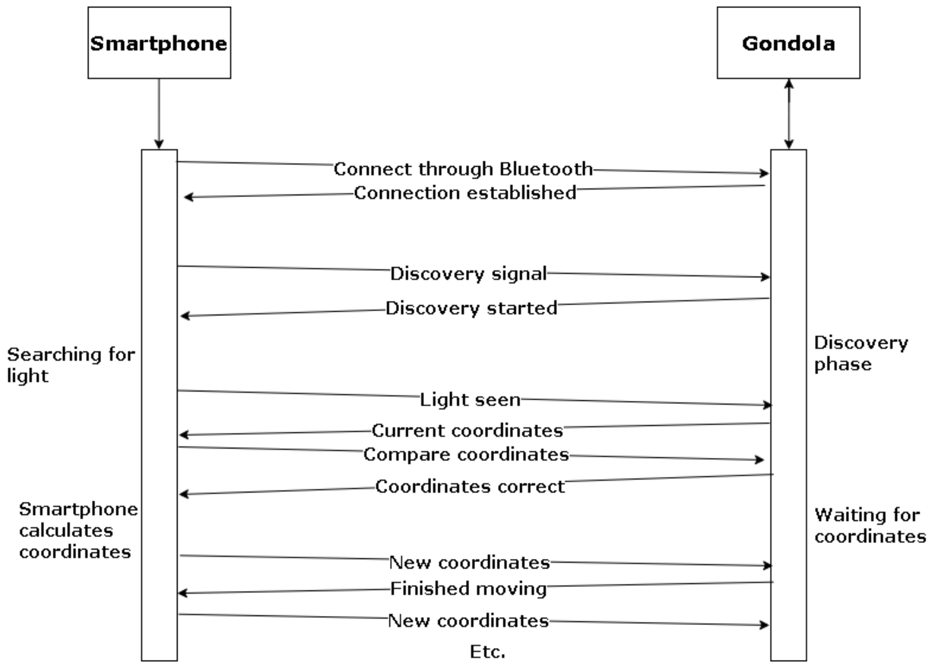

Figure 4.1: Communication between the smartphone and Gondola.

At this point and when the person moves, the light is highly likely not in the center of the camera or it will move away (relatively speaking) from the center. To correct this offset, geometric calculations are performed by the smartphone to guarantee that the light is moved in the correct direction and reach the center.

The role of the Gondola in this system is shown in figure 4.2. It will act differently based on the received messages. When asked to synchronize (Discovery) it moves the light to the door position, since it starts at the calibration spot at the ground in the middle of the room. In rare occasions where the user is not positioned by the door the Gondola starts moving the light through the room in a spiral manner to ultimately end up in the camera stream. Then, the Gondola stops movement and sends its coordinates when the light has been seen (Seen), which will be double checked by the smartphone afterwards through comparison (Compare) and re-transmitted if not correct, since these coordinates will be used to calculate the direction. Any other message (Else) should be new coordinates for the light. The Gondola expects coordinates for the x-, y- and z-plane as well as the speed for the movement. Anything other than these coordinates will be ignored and the Gondola goes back to waiting for a message.

As mentioned, the smartphone is tasked with detecting the light and performing the geometric calculations. These tasks will be explained in more detail in sections 4.2 and 4.3.

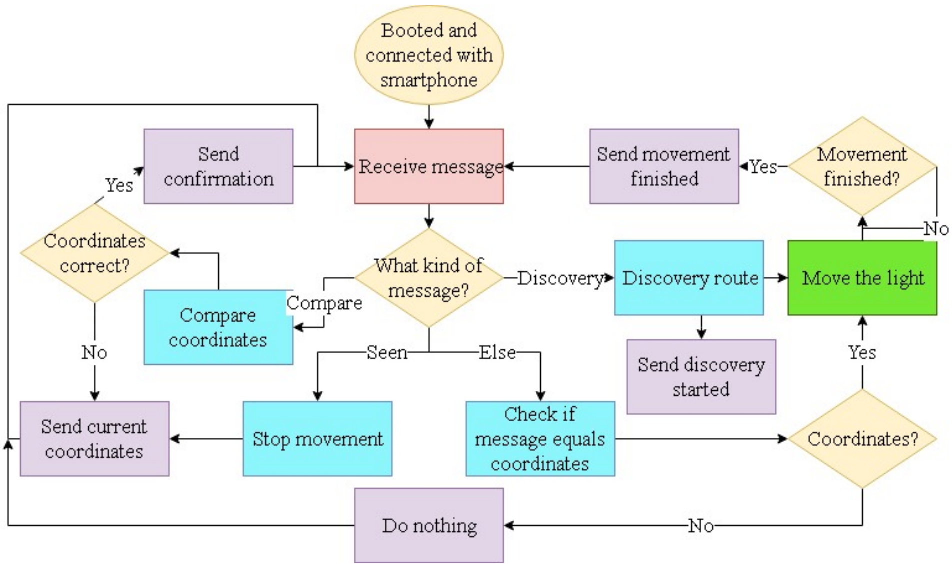

Figure 4.2: Working of the Gondola.

4.2 Image processing

To detect the light in the camera stream we need to use image processing. The open platform OpenCV for Android provides all functions needed and is integrated in the app that has been created for this project.

Since we deal with a light source, which is the only object of interest in the camera stream, a threshold filter is applied to a gray-scaled image of the stream to blacken out all pixels that have a brightness level lower than 254 out of the possible 255. This leaves only light sources like our transmitter as can be seen in figure 4.3, since the ambient light present in the room, for example the light coming in through windows and flickering of computer screens, is usually not bright enough to reach a brightness level of 255.

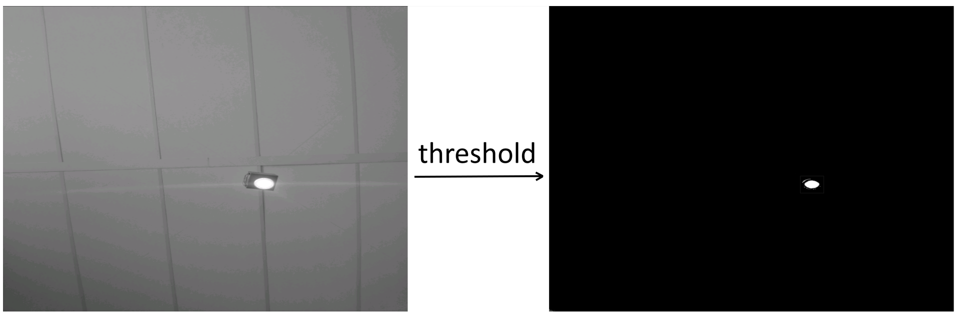

Figure 4.3: Thresholding

On our black and white image we can use the findContours function from OpenCV to get coordinates of the contours of all white areas, which are light sources. Usually the only light source is the transmitter, but the biggest contour is selected in case a light disturbance, for example reflections, cause an extra contour. Then, we iterate through all coordinates and calculate the average x- and y-position which is the center of the contour and the position of the light. The contour and the light position can be seen in figure 4.4 as the green circles.

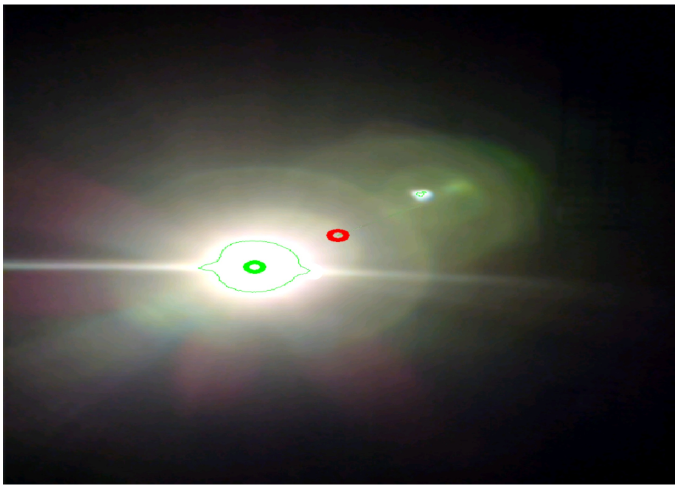

Figure 4.4: Light position calculated by the smartphone.

4.3 Correction calculation

With the position of the light in the camera stream known, the smartphone now needs to calculate the direction and distance, translated to coordinates for the Gondola, to move the light to the middle of the camera stream, which is the red circle in figure 4.4. In the case of this figure, the light is positioned in the lower left part of the camera stream, which makes the desired movement in the opposite direction.

To translate this movement to coordinates for the Gondola, we look at the distance as seen as amount of pixels between the two locations. If we zoom in on the situation from figure 4.4, we can create a triangle as shown in figure 4.5. From this triangle we can obtain the distance d by using the formula of Pythagoras with the offset in the x- and y-direction x_{offset} and y_{offset}:

$$d = \sqrt{{x_{offset}}^2 + {y_{offset}}^2} \tag{4.1}$$

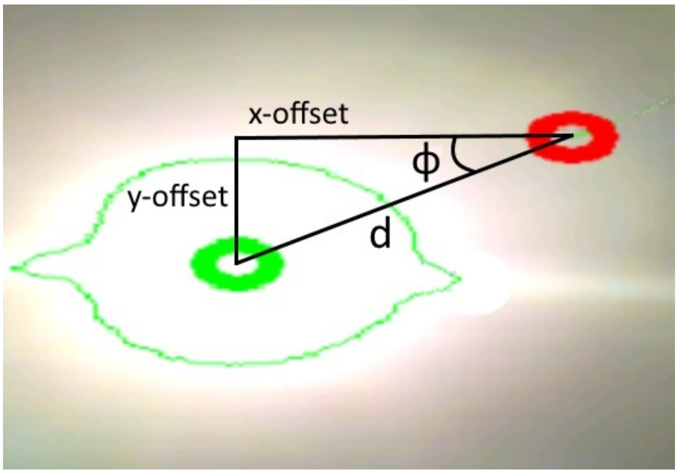

Figure 4.5: Calculating the distance and angle for the correction in the camera stream.

Next, we need to know the direction for our movement and we can calculate this from figure 4.5 as well. The angle ϕ can be calculated with the 2-argument arctangent of the x_{offset} and y_{offset}. Since the movement has to be in the opposite direction we need to subtract 180 degrees which gives us the following formula:

$$\phi = atan2(y_{offset}, x_{offset}) - 180^{\circ}; \tag{4.2}$$

With d and ϕ known, we need to convert d from pixels to centimeters. This conversion was found by moving the light ten times for one centimeter and writing down the difference in amount of pixels. This resulted roughly in a 9.5 pixels per centimeter conversion, which gives us a real distance $r = \frac{d}{9.5}$. Then, with the help of polar coordinates we can obtain our correction for the x- and y-plane with the following equations:

$$x_{diff} = r \cos \phi \tag{4.3}$$

$$y_{diff} = r \sin \phi \tag{4.4}$$

Now we can add the calculated difference to the current coordinates of the Gondola and obtain the new coordinates as shown in the formulas below. However, the Gondola system was installed with an inverted x-axis, which just means that we need to subtract the x-plane difference instead of adding.

$$x_{coor} = x_{coor} - x_{diff} \tag{4.5}$$

$$y_{coor} = y_{coor} + y_{diff} \tag{4.6}$$

After the Gondola moved the light with these new coordinates it has hopefully reached the center. If not, or due to new movement of the user, the whole process is repeated until the light has reached the center.

This correction works when the smartphone keeps the same orientation throughout the whole process. However, this is not a realistic situation, because the user of the smartphone often changes orientation and a small change already causes a difference in the x- and y-pixel value resulting in a large error in the calculated coordinates. This means that the orientation of the smartphone needs to be put in the equation as well.

Figure 4.6 shows the Embedded Systems-Lab in the EWI-building of the TU Delft with our Gondola mounted in it. First, we need to allign the x- and y-axis of the Gondola system to true north, because the lab has a natural offset α which is an addition of around 70 degrees. Second, the user creates an orientation angle β when turning, which is opposite to the polar coordinate system and means that this angle will be subtracted.

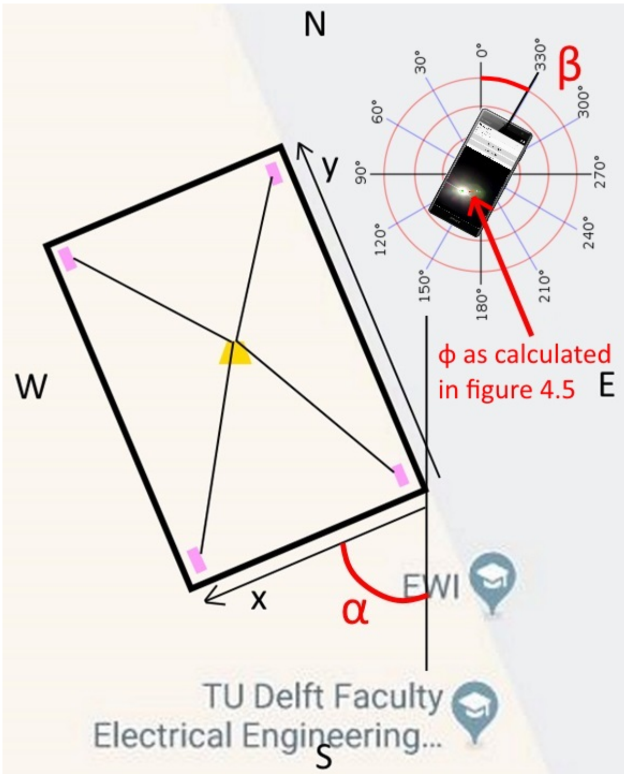

Figure 4.6: Natural offset of EWI-building.

Together with the calculated ϕ from figure 4.5 this creates a new final angle θ and updated correction coordinates as follows:

$$\theta = \alpha - \beta + \phi \tag{4.7}$$

$$x_{diff} = r \cos\theta \tag{4.8}$$

$$y_{diff} = r \sin\theta \tag{4.9}$$

4.4 Restrictions and assumptions

In order for the system to work properly some restrictions and assumptions are needed as we did not address all possible real life scenarios in the coordinate calculations.

First, and the most important one, is the restriction that the smartphone should not be tilted, but always pointed upward with the front camera facing the ceiling. Tilting the smartphone causes perspective errors as well as image blurring etc. which can be seen from figure 4.7, resulting in incorrect new coordinates.

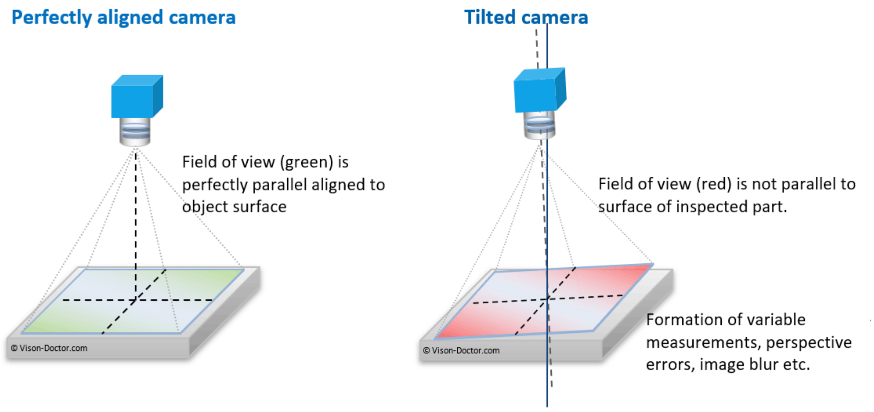

Figure 4.7: Tilting the smart phone [4].

Second, we assume that the height of the smartphone, with respect to the floor, is constant throughout the evaluation. The smartphone is roughly 1m above the ground, while the light moves at 2m, creating a distance of 1 meter. When increasing this distance, the pixel to centimeter conversion will not be accurate anymore and the system may need some extra movements to arrive at the desired point, because it has not moved far enough. Decreasing the distance creates a same pixel to centimeter conversion problem, but not only will it move the light further away than is needed, it can also cause the light to move out of the camera frame. This results in restarting the system to rediscover the light.

Finally, the Gondola can not keep up with the smartphone in terms of walking speed and object movement, as previously explained in chapter 3. Since the smartphone immediately overwrites the current coordinates with the new coordinates after calculation, it will not immediately calculate new coordinates during movement, but it waits until the Gondola sends the message stating that it has finished movement. If this is not done, the coordinates of the moving light do not match the coordinates of the smartphone which results in incorrect new coordinates and the system starts to drift.

4.5 Results of the following system

With the restrictions and assumptions clear, we can test the following system and measure its performance. To get the results clear, the goal of this following system is to move the light to the exact same location of the smartphone and thus have a location error as small as possible. The Gondola uses coordinates to move the light that are calculated by the smartphone. These coordinates are known by both the smartphone and Gondola and thus count as an extra feature to be used as result for indoor localization, but can differ from the real location of the user/smartphone.

For the experiment there are two situations:

1. Best case - The user connects with the Gondola and enters the room through the door causing immediate synchronization with the light, because the light is positioned by the door.

2. Worst case - The user stands somewhere else in the room and tries to synchronize with the light. The Gondola needs to move the light in a spiral form through the room to get in the camera stream of the smartphone before it can synchronize.

The Gondola always has to boot up from the calibration spot after receiving the 'discovery' message and move to the starting position before it can synchronize, which is the position of the door. If the smartphone has not seen the light at the starting position, the spiral form will be executed.

After the light and smartphone are synchronized, a laser measurement tool is used to measure the exact location in the x- and y-plane of both the smartphone and the light and the coordinates known by the smartphone and Gondola are taken for comparison. This is done 3 times for different end-positions of the user and one time where the user visits three different locations in one run. Finally, one worst case situation is also measured.

4.5.1 Results

The testing of the following system showed the following results as seen in table 4.1. Here measurements 1 to 3 represent the synchronization at starting position and movement to different end-positions, while 4 to 6 represent the three locations that the user visits in one run. Measurement 7 represents the worst case situation where the user is not found at the starting position.

Figure 4.8 shows all these 7 measurements with corresponding traces for a better overview. These measurement were performed in the working area of 3x4 meters in the ES-lab as was shown before in figure 4.6. Figure 4.9 has zoomed in on measurements 1 and 5 to have a more convenient look at the measured locations for the smartphone, light and corresponding Gondola coordinates.

Nr	Smartphone location (cm)	Light error	Coordinate error
1	x: 397.5 y: 520.9	0.85 cm	2.16 cm
2	x: 227.7 y: 231.3	1.02 cm	6.74 cm
3	x: 248.0 y: 425.3	1.36 cm	5.01 cm
4	x: 409.1 y: 323.0	1.80 cm	3.69 cm
5	x: 438.4 y: 486.2	2.60 cm	3.00 cm
6	x: 295.9 y: 328.3	2.01 cm	3.96 cm
7	x: 430.0 y: 354.0	2.53 cm	2.83 cm
Avg.	N.A.	1.74 cm	3.91 cm

Table 4.1: Synchronization error results for the light location and corresponding coordinates.

Light location error

The results show that the light often stays within 2 centimeters reach of the smartphone, with an average position error of 1.74 centimeters. Since our LED-light illumination surface has a diameter of roughly 4 centimeters, this ensures that the smartphone stays within the hot spot of the light and the following system succeeds in fulfilling its task.

Besides that, achieving millimeter precision is very difficult with this system, since the Gondola always needs to move the light for at least one centimeter. It could be more accurate with a better mobility system, since the 9.5 pixels per centimeter ratio is close to a 1 pixel per millimeter ratio.

Coordinate location error

The calculated coordinates for the light that we can take from the smartphone and Gondola show a larger error, with an average position error of 3.91 centimeters compared to the smartphone location. These coordinates thus do not equally match the real location of the light as can also be seen from the close up in figure 4.9. This difference is caused by weaknesses of the gondola system like, for example, skipping of the wires or placing the light not exactly at the calibration spot which causes the Gondola to obtain inaccurate coordinates.

For the evaluation in the next chapter this difference between coordinate output and light location does not matter, since our system is based on the synchronization between the light and smartphone and not on finding the exact location of the smartphone. However, since these coordinates of the Gondola can be used as a form of indoor localization for users in a room this means that we have a localization estimate that has an average error of 3.91 centimeters. This is actually a good result, since other indoor localization techniques usually struggle to obtain centimeter level precision.

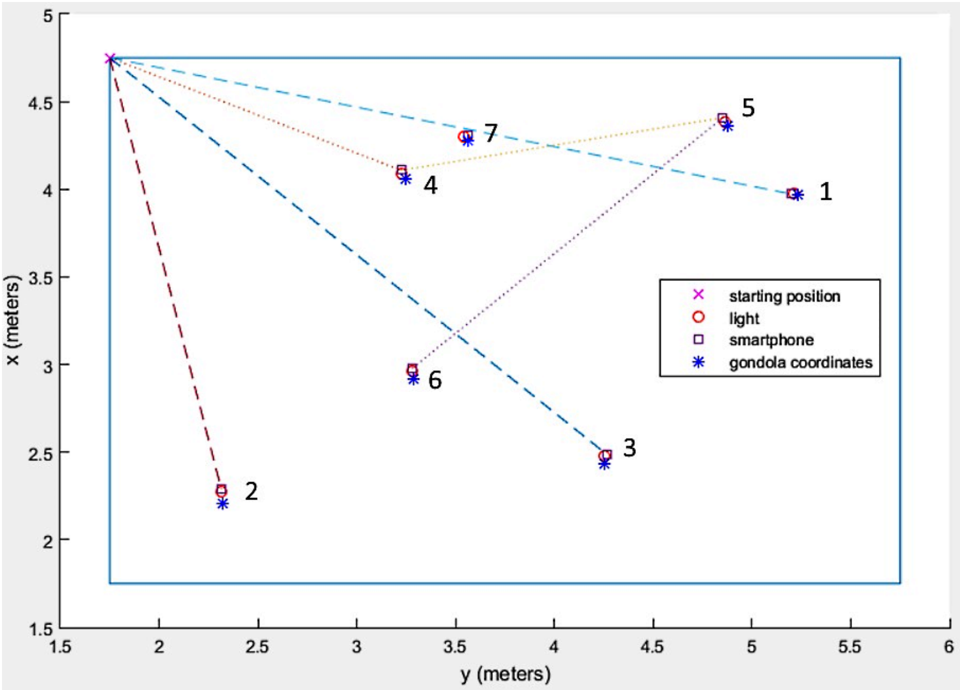

Figure 4.8: Measured locations for the light, smartphone and output of the Gondola

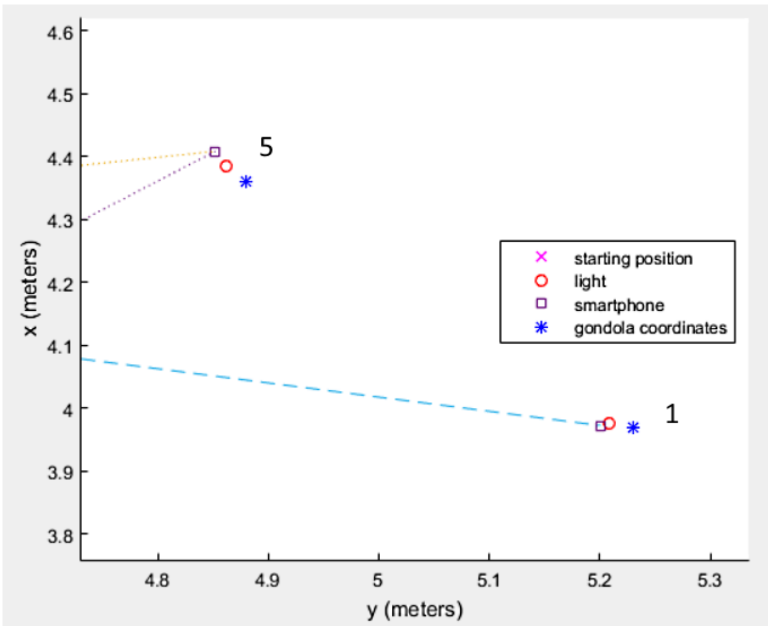

Figure 4.9: Zoomed in location results for measurements 1 and 5.

5
Evaluation

This chapter shows the measurements and results to evaluate the performance of the system in terms of illumination in 5.1, communication in 5.2 and energy consumption in 5.3.

5.1 Illumination

In order to compare the mobile light against static lights, we need to make sure that both have the same illumination level so we can compare apples with apples. To do that, we measure the illuminance of the mobile light first in the following manner:

First, the mobile light is placed at the same height as it would operate when synchronized with the smartphone and it is turned on as shown in figure 5.1. Turning the mobile light on means that it is sending data.

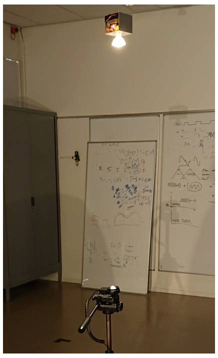

Figure 5.1: Measuring the illuminance of the mobile light.

The illuminance is measured with a same distance between light and lux meter as for the following system (1m) and is measured directly below the mobile light in the hot spot. The illuminance was measured as 96 lux. Then, the illuminance of each static light, i.e. the four extra transmitters, is fine tuned to be the same as the mobile light by performing the same measurement and tuning the booster circuit to match this 96 lux.

To get the coverage and the semi-angle of the transmitter, it is moved around the lux meter and the illuminance value is measured at every two centimeters in all directions. This results in a luminance heat map as can be seen in figure 5.2.

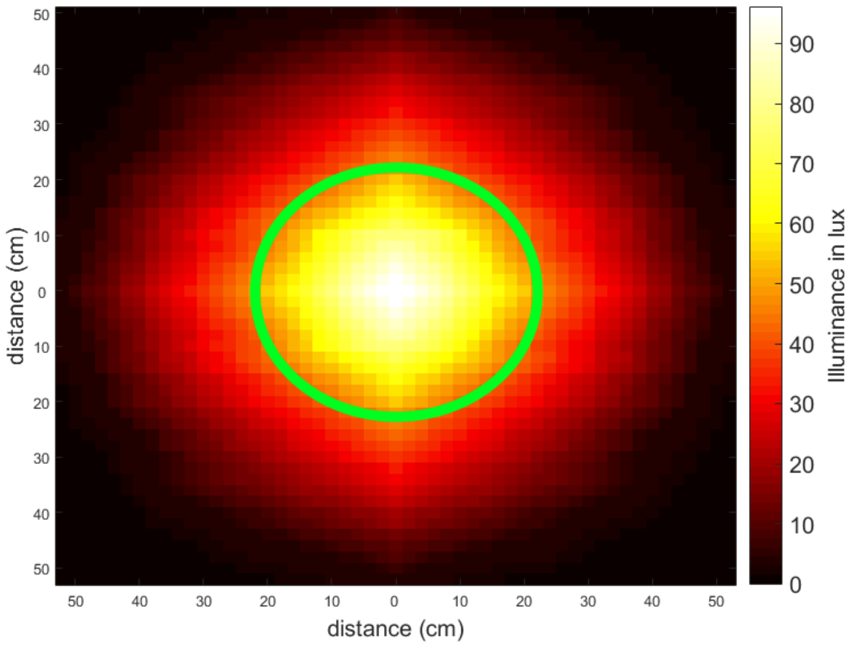

Figure 5.2: Luminance heat map of the mobile light.

The semi-angle is found by calculating the angle at the point where the illuminance dips below $\frac{96}{2} = 48$ lux. This point is found at 24 centimeters away from the transmitter. Together with the 100 centimeters distance from the light source this creates the angle ψ_{mobile} as follows:

$$\psi_{\text{mobile}} = atan2(24, 100) = 13.5^\circ \tag{5.1}$$

Staying within this 13.5° radius of the transmitter ensures that we have at least 50 percent of the maximum intensity and stay in the hot spot which is shown by the green circle in figure 5.2.

The results of our following system show that the smartphone and transmitter can stay synchronized within a 1.74 cm position error on average. This guarantees that it will always stay within the hot spot. This 1.74 cm error would even be small enough to almost always guarantee a maximum intensity as we see from figure 5.2.

However, it can be observed that the mobile light cannot provide the 500 lux necessary for working spaces. This is mostly due to using a battery and the size of the LED which is small compared to normal office lights.

To get a comparable result for a 500 lux coverage of our mobile light, a fluorescent light in the ES-lab was measured at 1 meter to find the semi-angle and the distance where the intensity has dropped to 500 lux. The semi-angle was measured at 40 centimeters and 500 lux was measured at 50 centimeters, creating an extra distance of 10 centimeters or an extra quarter of the semi-angle distance.

We know that the semi-angle for the mobile light was found at 24 centimeters, so adding a quarter to that distance gives 30 cm. If we take a look at the luminance heat map of the mobile light at 30 cm this means that we would need an intensity of around 30 lux to compare with the 500 lux.

With the four extra transmitters a setup for the static lights is created. Since the area where the mobile light operates has a surface of 3x4 meters we need to place the lights at convenient spots to try to cover the whole area, which is done by placing them each at one third of the length and width of the area. This results in an illuminance heat map of the static lights as can be seen in figure 5.3.

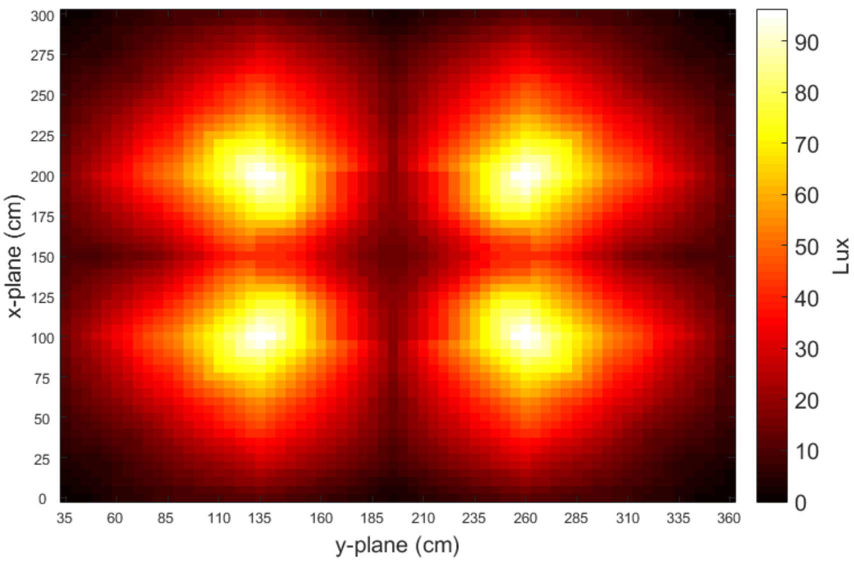

Figure 5.3: Static lights illuminance map.

From this illuminance heatmap the 30 lux requirement is not easily seen. Therefor the cumulative distribution function (cdf) of this heatmap is calculated to see the percentage of the area which is covered by at least 30 lux. This cdf is shown in figure 5.4 and it can be seen that at least 45 percent of our area is covered with 30 lux or more.

This also means that 55 percent of the area is not illuminated well enough and more static lights would be needed for proper lighting if we would use it in real life, possibly with better and bigger lights.

The cdf also shows that the area is only covered for around 22 percent with 48 lux and therefor hot spots. More dramatically is the fact that 90+ lux is only found in 2 percent of the area. This could mean that the mobile light could perform better in 98 percent of the area compared to static lights.

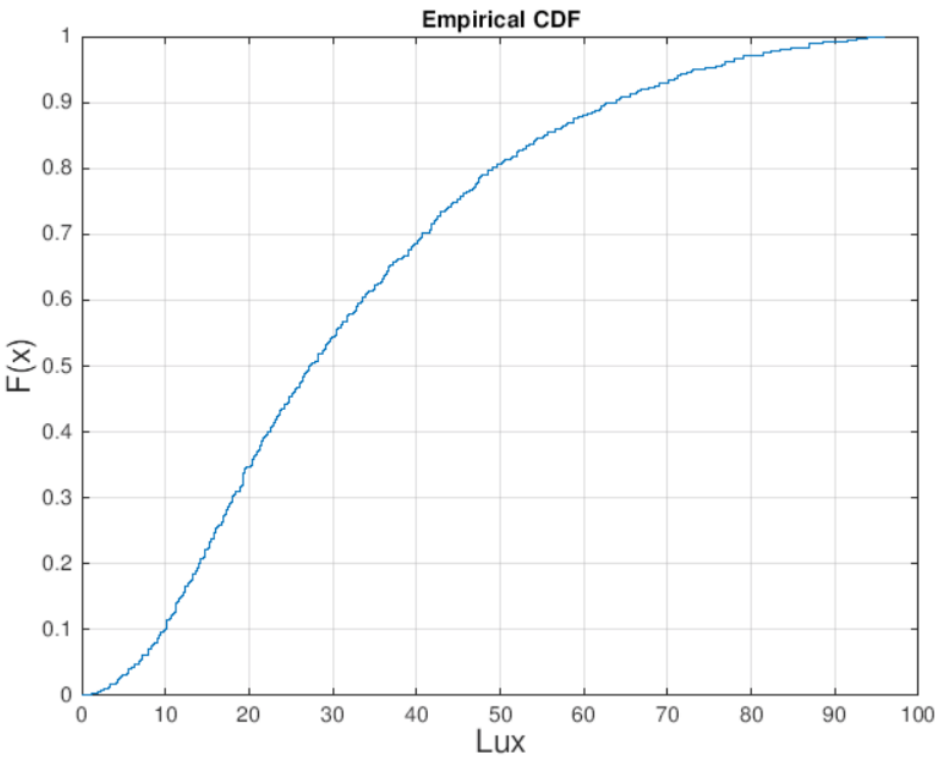

Figure 5.4: Cumulative distribution function for the static lights illuminance.

5.2 Communication

The communication measurements are performed with the same setup as for the illuminance measurements. First we take a look at how and what we are communicating.

5.2.1 Protocol

In order to transmit data, the Arduino needs to modulate the LED in such a way that symbols can be decoded accurately by a receiver and at the same time not to generate any noticeable flickering.

On-Off Keying (OOK) is the most basic approach, where the digital data "1" and "0" are represented by turning the LED ON and OFF respectively. Since it was decided, in order to avoid extending time for this thesis, to not create a receiver that can accurately decode our signals due to the design of our transmitter (low intensity and small LED), we have chosen for OOK such that we can quickly identify our bitstream with our camera or photodiode.

The data that is continuously transmitted is the bitstream "101100" which is transmitted at 250 Hz and can be seen in figure 5.5. The 250 Hz ensures that we do not notice any flickering effects and we can more easily detect the bitstream on the camera. The photodiode measures the light through a serial connection with a limited speed, so if the light transmits at a lower frequency we can get more measurements during the "ON" and "OFF" state of the transmitter compared to higher frequencies.

With more measurements during the "ON" state of the transmitter we can more easily measure and calculate the signal-to-noise ratio which gives us a lot of information about the signal quality.

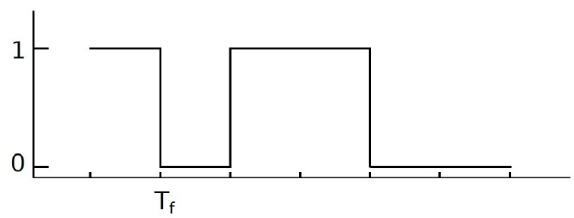

Figure 5.5: OOK encoding for the bitstream 101100.

5.2.2 Camera as receiver

First we will try to capture the data by using the camera of the smartphone. As mentioned before, the camera of the smartphone uses the rolling shutter effect to capture the VLC transmissions such that it could be decoded in, for example, Matlab.

The example that is shown below is performed with the same smartphone, the Manchester Encoding (MAE) technique at 3000 Hz and with a distance of 5 centimers. This gives a better overview of how this smartphone capturing works. The real tests were done with the OOK-technique at 250 Hz, but similar results were found with the MAE technique.

Figure 5.6 shows, as an example, how the VLC capturing can be done by grayscaling the *original_image* first which creates the *detector_image*. Then we use a threshold value to determine if the pixel should be black or white after which we can take a slice out of the image. For example the *line_image* took a slice out of the top row of the *adaptive_threshold* image which gives us a clear black/white image and thus 0/1 bitstream which then can be decoded.

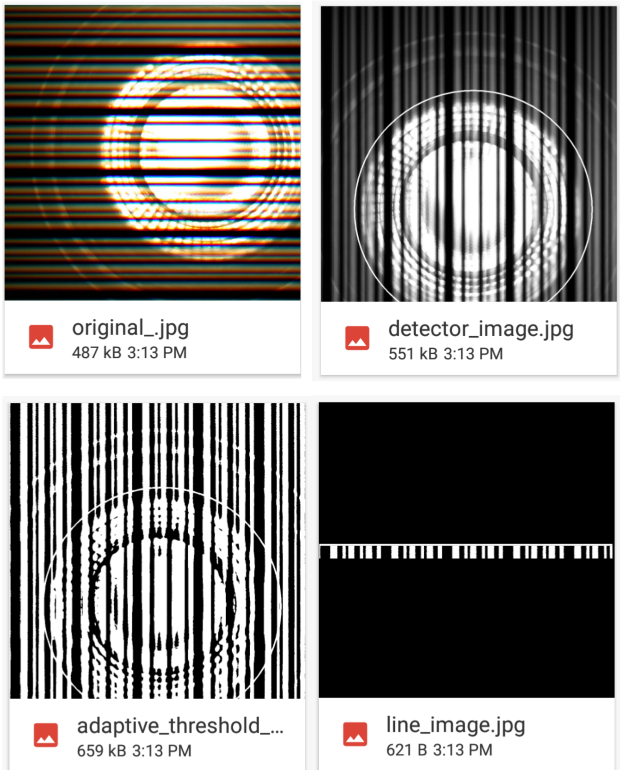

Figure 5.6: Converting the rolling shutter effect to a bitstream.

To try exploiting the rolling shutter effect, we hold the camera directly in front of the LED. A photo is taken of the LED after which we increase the distance between the LED and camera to see whether we are able to detect the bitstream or not. The result of this can be seen in figure 5.7.

At 3 cm distance we can reliably detect our bitstream in the image. The borders of the "ON" and "OFF" state are very clear which helps with the image processing in obtaining the bitstream.

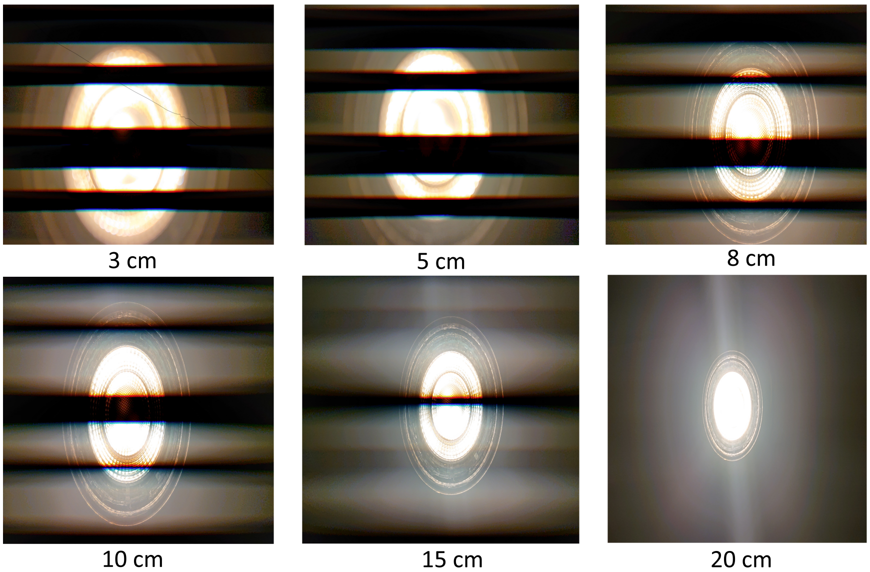

Figure 5.7: Camera captured VLC transmissions with rolling shutter effect for increasing distance.

As we move further away from the LED we notice that the previously mentioned borders begin to bend and the "ON" state gets more blurry. However, up to 10 centimeters we can still reliably detect the bitstream. At 15 centimeters the borders begin to fade and detecting the bitstream becomes very difficult and at 20 centimeters we can not detect any communication at all.

Since the Gondola system is designed to have a distance of 1 meter between the smartphone and the mobile light, this means that the camera of the smartphone is not suited to carry out the measurements. This is a drawback of the design of our transmitter and it cannot be changed, because it has to weight less than 500 grams to be able to move with the Gondola.

5.2.3 Photodiode measurements

Since the camera has been found unusable for our communication measurements, because of its short range, we will use the photodiode setup to perform our measurement scenarios, since we can boost the voltage output of the photodiode by changing the resistors which enables us to capture the light at larger distances.

Mobile light

The mobile light will be measured first. To do this, the Gondola system is booted and after the light has fully synced with the smartphone we place the photodiode at the exact spot of the camera to measure the VLC. This results in a photodiode measurement as shown in figure 5.8. The values of the photodiode are dimensionless and do not compare to luminance levels, but to the voltage level that the photodiode creates.

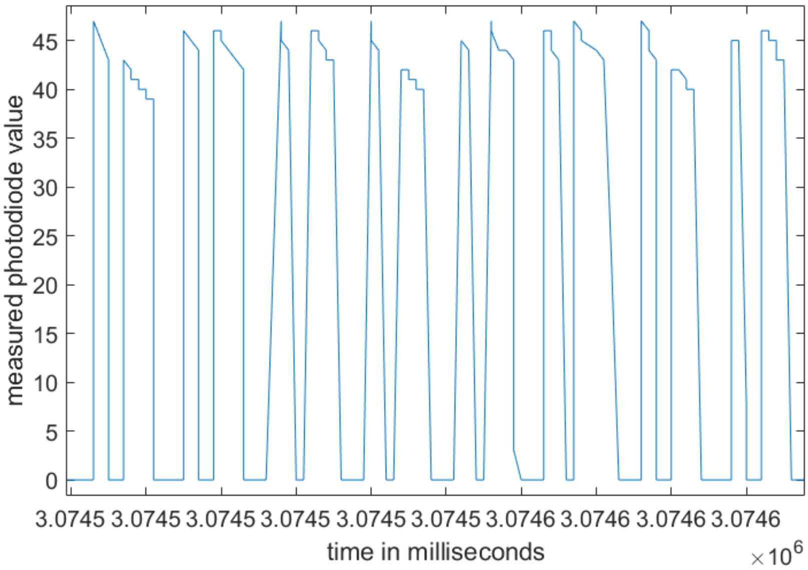

Figure 5.8: VLC communication of a synchronize mobile light.

In the received signal the ever repeating bitstream "101100" can be detected. The measured "1" for the signal however shows some noise through the inconsistent photodiode levels. To get a comparable evaluation in terms of signal quality the signal-to-noise ratio SNR needs to be calculated from this signal.

To be able to calculate the SNR, we need to get clear what the signal and noise levels exactly are. To see this more easily, the normal (or Gaussian) distribution is extracted from the signal as shown in figure 5.9, which shows the normal distribution and the signal and noise amplitudes.

From figure 5.9 the SNR can be calculated by obtaining the amplitude level A_S of the signal, which is 44, and the noise amplitude A_N, which is N_{max} - N_{min} = 47 - 39 = 8.

The SNR is then calculated with the following formula:

$$SNR = (\frac{A_S}{A_N})^2 \tag{5.2}$$

This ultimately results in a SNR of $(\frac{44}{8})^2 = 30.25$ or 34.1 dB which we are guaranteed to have with a synchronized mobile light.

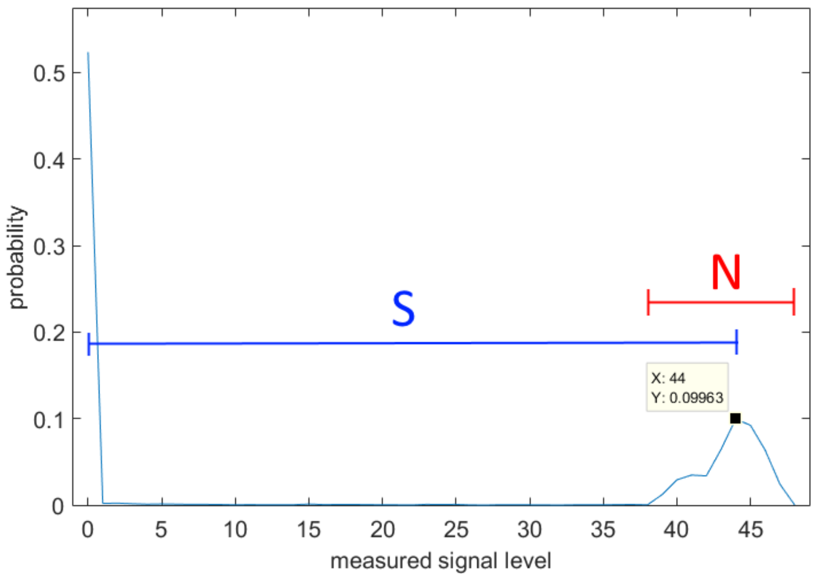

Figure 5.9: VLC communication when the light is synchronized with the smartphone.

Static lights

With the SNR of the mobile light measured, the static lights are measured next to compare the results. Firstly a SNR heatmap of the static lights area of 4x3 meters will be made. This is done by measuring the incoming light signal(s) for every 10 centimeters of a single static light. Since these static lights are tuned to all have the same luminous intensity and are sending the same message, the results of the single static light are equal to the other static lights and can be mirrored to get a full SNR heatmap.

During inspection of the measured photodiode values it became clear that the other three static lights and reflections of the lights cause interference on the channel of the receiver. This can be seen in the Gaussian distribution, as example shown in figure 5.10, by having multiple signal peaks. This means that for these cases we have to calculate the SINR instead of the SNR, as explained before in chapter 2, by dividing the amplitude of the signal with the amplitude of the noise and the interferences.

For this example this results in a SINR as follows:

$$SNR = (\frac{17}{6+9+3})^2 = 0.89 \tag{5.3}$$

Since the SINR is lower than 1 this results in a negative dB level and therefor reliable communication is not achievable at that particular location.

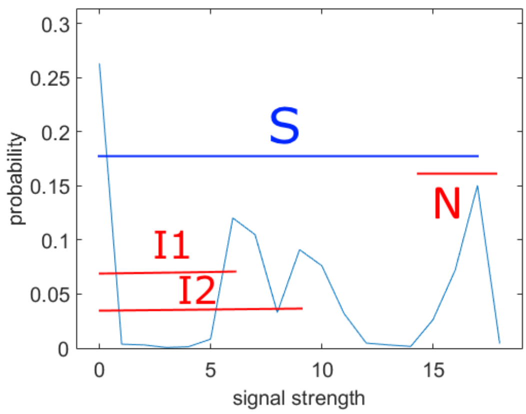

Figure 5.10: Interference caused by the other static lights and reflections.

By performing the SNR and SINR calculations, the SNR heatmap is created for the 4x3 static lights area, which is shown in figure 5.11. The interference is clearly noticeable here, since the whole middle of the area shows a SNR of 0 and thus no communication is possible there. However, when the interference is no longer noticeable in the measurements, the SNR immediately goes from 0 to a reliable 20+ dB around the locations of the static lights.

The interference is a problem when the lights are sending messages at the same frequency. A solution for this can be realized by using different frequencies for every light, also known as fingerprinting. Besides the interference, Lambert's cosine law and the increasing distance between transmitter and receiver definitely show in the heatmap as the SNR drops when moving away from the transmitter.

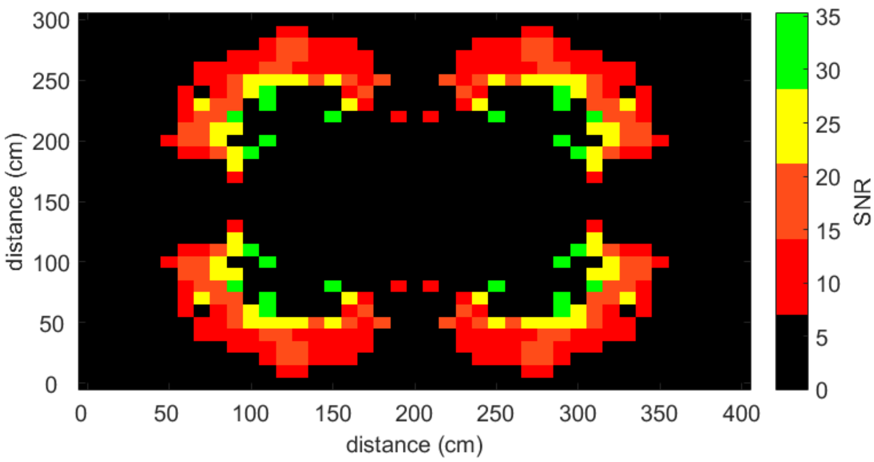

Figure 5.11: Static lights S(I)NR heatmap.

As figure 5.11 already shows, a big portion of the area is not suited for communication. For better investigation of the heatmap a cdf graph is made again and is shown below in figure 5.12. This graph immediately shows that 70 percent of the area holds a SNR of 0 and only 7 percent of the area can guarantee a SNR of 20+ dB, which means that we would have a strong signal.

For a decent signal quality, meaning a SNR of at least 13 dB, only 18 percent of the area is suited. This makes the mobile light in the other 82 percent of the area the better option for communication. To investigate if this is actually true, two user traces are created in subsection 5.2.4 where the user starts at the door position and moves through the area towards an end position.

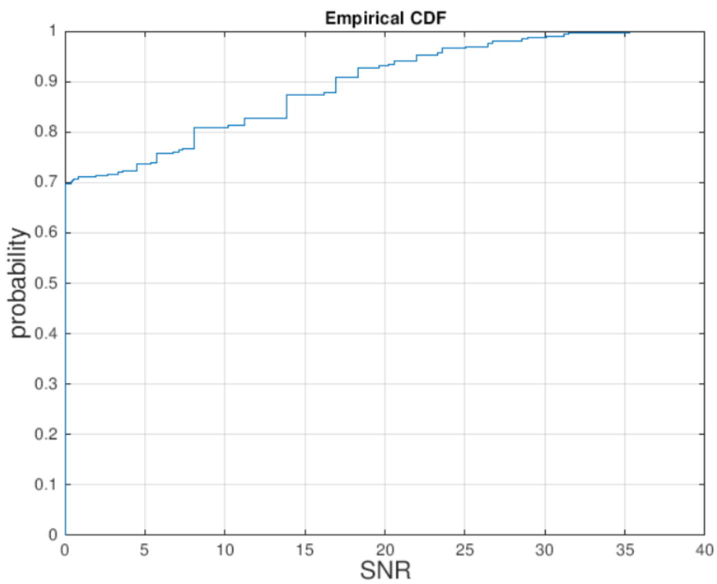

Figure 5.12: Static lights S(I)NR cdf.

5.2.4 User traces

To simulate a more real-life scenario, two user trace scenarios are created. Figure 5.13 shows the 4x3 area where the Gondola system operates which is now used as an office. The four yellow crosses in circles resemble the static lights and their positions. In case the mobile light is used, these four static lights are turned off and the mobile light syncs with the user at the door.

Trace 1 resembles a user entering the room through the door and walking immediately to his desk. Trace 2 resembles a user entering the room through the door, walking past two desks and taking a seat at his/her desk in the back. For both the mobile light and the static lights the user will follow the same path.

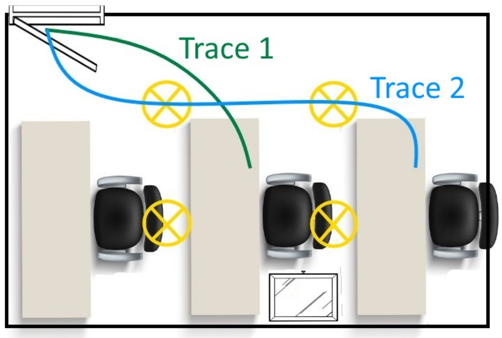

Figure 5.13: Measurement scenarios.

To get a SNR for the mobile light during movement, the photodiode is placed right beside the smartphone and the measurement is started after the light and smartphone have synced and the user begins to move and is stopped after the user has stopped moving and the light is stable at the user's position again. For the static lights the photodiode is just moved across the area.

Then, after the measurements are performed, the SNR is calculated at 25 timeslots of the received signal. This will give an overview of the SNR during the movement. Figure 5.14 shows the signal traces of the mobile light and the static lights and the corresponding SNR for each timeslot for trace1.

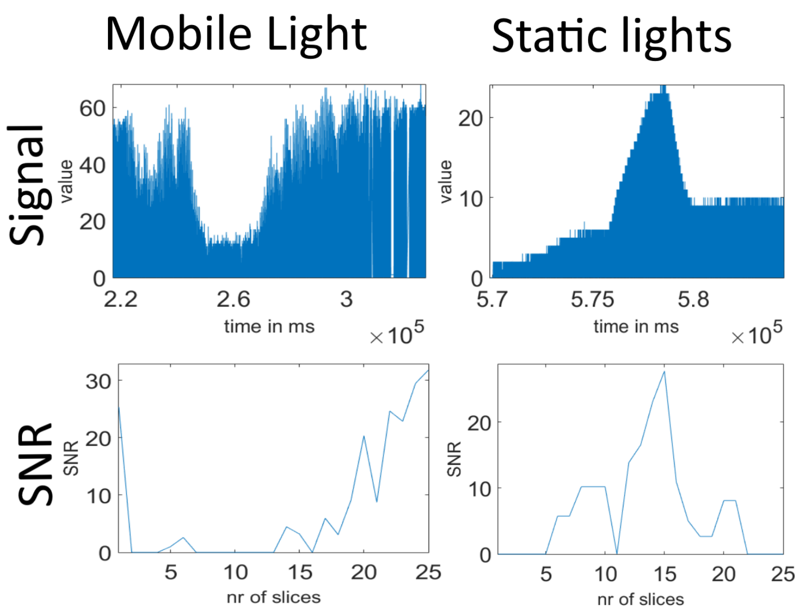

Figure 5.14: Captured trace 1 signal and SNR for mobile and static lights.

It is observed that the mobile light does not generate a high SNR during movement. This is the fault of the Gondola. As mentioned in chapter 3, the Gondola can not keep up with the average human walking speed and, although the user can compensate for this, it will still lag behind the user, because it has to correct the users position relative to the light. This also creates a larger distance which further decreases the SNR.

The mobile light also swings around heavily during movement, because it is attached to the four wires of the Gondola which is an unstable situation. The swinging causes the light beam to often miss the photodiode which drastically decreases the SNR. As the user has reached its end position and the mobile light closes in on the user, it is observed that this results in an increasing SNR. When both the user and mobile light are fully synced and the swinging has stopped, the SNR is 30+ dB and good communication is achieved again.

For the static lights it is observed that there is only proper communication possible when the user moves near the static light. Since the user does not walk directly below the static light, the SNR never reaches a dB level above 30 dB. Also, at the end position, the user will not be able to communicate anymore. This is not desirable, since the end position in this case is the user's desk where the user will probably spend a few hours working.

Figure 5.15 shows the same received signal and corresponding SNR values for trace 2. During this trace the user walks directly below two static lights when moving to its end position.

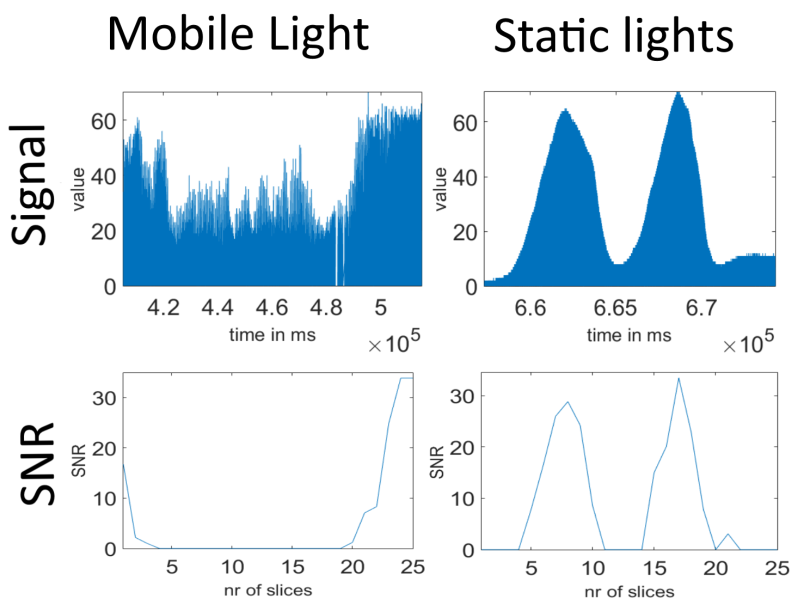

Figure 5.15: Captured trace 2 signal and SNR for mobile and static lights.

Again, the mobile light is not able to provide reliable communication during movement, but can provide it only after the user has stopped moving and the light and user are in sync again. For the static lights the SNR only spikes again when walking close or directly below the static lights. The user is still not able to communicate after reaching its end position. Only when this end position is close to a static light this will be possible.

Overall we can conclude that the mobile light offers us reliable communication with a high SNR when we are not moving. During movement however, the Gondola has so many drawbacks that communication is not reliable. A different mobility system could possibly solve this issue.

For example, a robot moving on the ceiling while holding the transmitter could move the transmitter almost instantly when a user moves. Besides that, the transmitter will not swing around heavily, since it will not be connected to wires anymore. Therefor it is quite possible that we can maintain the high SNR values that we obtain when the transmitter and user are synced during the full movement.

The static lights only generate a high SNR when close or directly below a light. Therefor communication is obviously restricted to the hot spot areas created below the static lights. The mobile light however can match the SNR of the static lights hotspots and if the mobility system can be improved it will outperform the static lights at any point in the area.

5.3 Energy and costs

Figure 5.16 shows our 4x3 area, but now fully covered by hot spots which ensures that the user always has at least 50 percent of the maximum luminous intensity. As the results for the illumination and communication measurements showed, we want to exploit these hot spots for the high SNR obtained in it and don't want to constrain the users to specific places within the area. To do this,more static lights need to be placed in the room. It can be seen that 5*5 = 25 lights need to be installed to get a hot spot coverage for the full area.

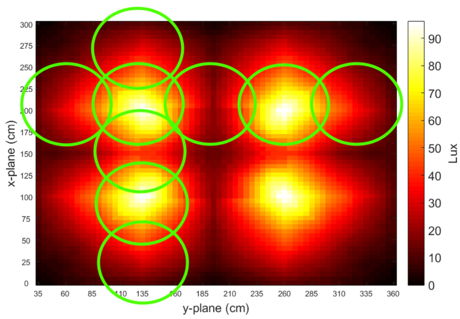

Figure 5.16: Full hot spot coverage.

Not only would this mean that we need to have 25 static lights installed, the energy bill would also rise with that many turned on static lights, whereas the number of turned on mobile lights could be related to the amount of users in the room. For our chosen LED bulb of 3W, this already means that we have a total power of 75W.

For a perfect mobility system for the mobile light, the energy usage could be reduced to the power needed to move the transmitter plus the power used by the transmitter multiplied by the amount of transmitters. For such a system, where mobility is close to perfect in terms of energy waste and the transmitter consists of the 3W LED plus an Arduino to toggle it, we take a look at the Power needed to move the LED.

Here the following standard formula is used:

$$Power = \frac{Force * Displacement}{Time(s)} \tag{5.4}$$

where Force is the mass of the transmitter in Newton, which is 281g. Displacement is in line with the average walking speed of a human, which is 1.4 m/s, so this creates a displacement of 1.4 meters and a time of 1 second, so we can ignore the fracture.

If we fill this in, we get a total power $P = \frac{2,7557*1.4}{1} = 3.86$W when moving for a full hour. The transmitter uses around 3W and the smartphone with a capacity of 3540mAH will use around 13W if we completely deplete the smartphone in an hour. In total this means we use around 16W to operate one constantly moving mobile light.

This creates a situation where adding a light means that we add 16W + 3.86W * t/3600 for every second 't' that we move. If we plot this out to see how many mobile lights we could use before we equal the 25 static lights, we obtain the plot in figure 5.17 with the dashed line representing the 25 static lights.

It can be observed that we could have 3 users walking around in the room for a full hour with their own personal mobile light and still use less power than the 25 static lights. Only when a 4th person joins the room with a mobile light and walks for at least 2500 seconds, or 42 minutes, we will start to use more energy. Adding a fifth person will always generate a higher electricity bill.

The Gondola as mobility system is of course less efficient than a perfect system. The Gondola was measured to operate at 12 Volts with 0.94 Ampere at all times, netting up to 11.26W. This 11.26W, instead of the calculated 3.86W for a perfect system, is also plotted in figure 5.17 as the '-.' line. For the Gondola it is observed that 2 users can walk the room with a mobile light for a full hour and be more energy efficient than 25 static lights. It can also handle 4 persons with a personal mobile light, but only when movement is limited.

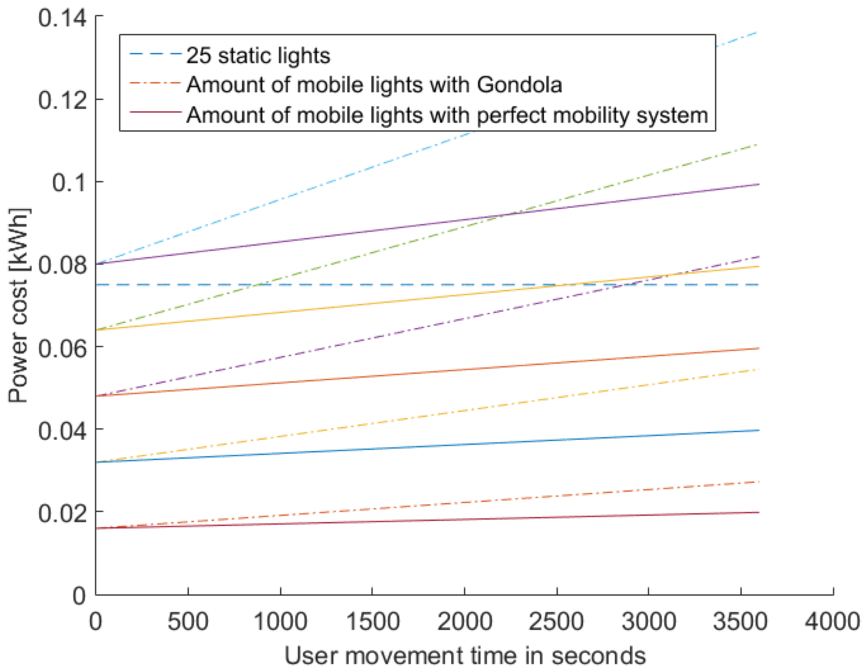

Figure 5.17: Nr of mobile lights vs full hot spot coverage by static lights.

Furthermore, if the smartphone can be replaced by a simple micro controller with a camera, we can further reduce the overall power of the system, ultimately coming close to the 3W of the transmitter plus 6.86W * t/3600 for every second 't' we move the light with a perfect system. In this case the system can handle up to 20 different mobile lights with limited movement and be equally efficient as 25 static lights. Of course, fitting 20 persons in the 4x3 area will not happen that often.

This calculation shows that for quiet workplaces, where people can sit for a few hours behind a computer for example, the overall power consumption of the system is almost equal to an office with static lights, but now with all the benefits that being in a hot spot can bring to the table. Also, with less people in the room than there would be static lights, we can even save on the electricity bill while being guaranteed of high illuminance and SNR values.

6 Conclusions and Future Work

6.1 Conclusions

With the evaluation of chapter 5 done we can conclude that a mobile light, doubling as a transmitter, can definitely add some extra benefits to a future system using VLC.

While static lights create only a few hot spots below the lights where illumination and communication can be optimal, moving a few (tens of) centimeters away from those spots will result in a dramatic loss of illuminance and communication reliability as the SNR quickly drops to 0. Especially with multiple static lights and their interference only 18 percent of our 4x3 test area was evaluated as suited for communication, while only 7 percent of the area could generate a strong signal with a S(I)NR of 20+ dB.

The mobile light was found to stay on average within 1.74 centimeters of the location of the user, resulting in a highest intensity and SNR at all locations within the test area. If we can design a close-to-perfect mobility system, the energy consumption can even be decreased in relation to the amount of people in the room, especially when requiring high illuminance and SNR values, at the cost of buying and installing the mobility system.

Since the position of the light comes as a result of the correction method, we also generate a form of indoor localization with an estimation error of 3.91 centimeters. This is quite accurate compared to other indoor (RF) localization techniques which struggle to obtain centimeter precision.

Grouped together we can conclude that a mobile light can add extra services to VLC by ensuring a constant high illuminance, SNR and quite a good localization result which clears the way to improve the bandwidth and bitrate for VLC by using individual focused hot spots.

6.2 Future Work

Now that this project was full-filled by using the Gondola system, it must be noted that this system is far from perfect. Most limitations of the system are caused by the Gondola, like the working speed and the height, weight and brightness of the transmitter, because it uses fishing wires for movement. Improving all these factors could lead to a better working prototype.

Therefor future studies could try to implement a different kind of system that provides mobility, such as an extra ceiling with a small robot driving on top of it which is holding the transmitter with, for example, some magnets while powering the transmitter through the ceiling. This is not a cheap solution of course which is why the Gondola was used for this project.

Another contribution for this project could be the addition of the influence of the height and tilting of the smartphone. For this project the distance between the smartphone and transmitter was always around 1 meter, while in reality people differ in height and do not always hold their phones still. This creates a difference in the pixel to coordinates calculation which could possibly be addressed by using barometers, accelerometers and gyroscopes.

Also, since we are moving lights around the room, we could add other hard- and software to our transmitter. For example we can add Wi-Fi or Bluetooth communication and have it focused on the user. This could improve their throughput significantly and possibly remove the need of having a router transmitting in all directions to reach the user, with a lower energy consumption and less crowded RF-spectrum as a result.

Bibliography

[1] 123led.

[2] Eneloop Pro HR06 1.2V.

[3] Marco Cattani and Ioannis Protonotarios. Gondola: a parametric robot infrastructure for repeatable mobile experiments: Demo abstract. pages 298–299, 11 2016.

[4] Vision Doctor. Perfect alignment of the camera system.

[5] Wi-Fi: Define Minimum SNR Values for Signal Coverage.

[6] Ander Galisteo, Qing Wang, Aniruddha Deshpande, Marco Zuniga, and Domenico Giustiniano. Follow that light: Leveraging leds for relative two-dimensional localization. pages 187–198, 11 2017.

[7] Inductiveload. A diagram showing a cross section of the radiaton from lambertian surface - that is, directly propertional to the cosine of the angle between the observer's line of sight and the surface normal., 2008.

[8] Henri Jusln and Ariadne Tenner. Mechanisms involved in enhancing human performance by changing the lighting in the industrial workplace. *International Journal of Industrial Ergonomics*, 35(9):843 – 855, 2005.

[9] Hsiao-Wen Lee and Bor-Shyh Lin. Improvement of illumination uniformity for led flat panel light by using micro-secondary lens array. *Opt. Express*, 20(S6):A788–A798, Nov 2012.

[10] Y. Li, Z. Ghassemlooy, X. Tang, B. Lin, and Y. Zhang. A vlc smartphone camera based indoor positioning system. *IEEE Photonics Technology Letters*, 30(13):1171–1174, July 2018.

[11] Chia-Kai Liang, Li-Wen Chang, and Homer H Chen. Analysis and compensation of rolling shutter effect. *IEEE Transactions on Image Processing*, 17(8):1323–1330, 2008.

[12] Jianhui Liu, Qing Li, and Xiao-Yi Zhang. Cellular coverage optimization for indoor visible light communication and illumination networks. *Journal of Communications*, 9:891–898, 11 2014.

[13] OpenSCAD The Programmers Solid 3D CAD Modeller.

[14] J. H. Y. Nah, R. Parthiban, and M. H. Jaward. Visible light communications localization using tdoa-based coherent heterodyne detection. In *2013 IEEE 4th International Conference on Photonics (ICP)*, pages 247–249, Oct 2013.

[15] W. K. E. Osterhaus. Office lighting: a review of 80 years of standards and recommendations. In *Conference Record of the 1993 IEEE Industry Applications Conference Twenty-Eighth IAS Annual Meeting*, pages 2365–2374 vol.3, Oct 1993.

[16] K. Qiu, F. Zhang, and M. Liu. Let the light guide us: Vlc-based localization. *IEEE Robotics Automation Magazine*, 23(4):174–183, Dec 2016.

[17] Sridhar Rajagopal, Richard D Roberts, and Sang-Kyu Lim. Ieee 802.15. 7 visible light communication: modulation schemes and dimming support. *IEEE Communications Magazine*, 50(3):72–82, 2012.

[18] R. Sharma, A. C. Kumari, M. Aggarwal, and S. Ahuja. Performance analysis of led based indoor vlc system under receiver mobility. In *2017 International Conference on Computing, Communication and Automation (ICCCA)*, pages 945–950, May 2017.

[19] J. Shi, Y. Wang, X. Huang, and N. Chi. Enabling mobility in led based two nodes vlc network employing self-adaptive stbc. In *2016 Optical Fiber Communications Conference and Exhibition (OFC)*, pages 1–3, March 2016.

[20] P. K. Soori and S. Alzubaidi. Study on improving the energy efficiency of office building's lighting system design. In *2011 IEEE GCC Conference and Exhibition (GCC)*, pages 585–588, Feb 2011.

[21] Engineering ToolBox. Illuminance - recommended light level.

[22] AG Worthing. Deviation from lamberts law and polarization of light emitted by incandescent tungsten, tantalum and molybdenum and changes in the optical constants of tungsten with temperature. *JOSA*, 13(6):635–649, 1926.