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Indoor Visible Light Communication Prototyping

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Abstract

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This project is primarily comprised of research on Visible light communication systems and methods for developing two prototypes in order to test out the link between them.

This is accomplished using various components such as LEDs, two different photodetectors and other passive components. The microcontrollers used are Arduino Uno's and thus programs are written in C++. OOK-NRZ is used for modulating the data. The photoresistor prototype worked as expected, but the photodiode prototype failed to output any useful data.

Further testing of the links in terms of the SNR and BER could be beneficial in future projects. A good understanding of transimpedance amplifiers will prove to be useful in the design of a VLC system using a photodiode.

Keywords: VLC, OOK, LED, Arduino, photoresistor

Contents

List of Abbreviations

VLC:	Visible Light Communication
RF:	Radio frequency
OWC:	Optical Wireless Communication
LED:	Light Emitting Diode
OOK:	On-off Keying
IOT:	Internet of Things’
MRI:	Magnetic resonance imaging
ECG:	Electrocardiogram
EMI:	Electromagnetic Interference
PD:	Photodiode
LDR:	Light dependant resistor
LOS:	Line-of-sight
TX:	Transmitter
RX:	Receiver
SNR:	Signal-to-noise ratio
IM/DD:	Intensity Modulation/Direct Detection
PAM:	Pulse Amplitude Modulation
OOK-NRZ:	On-off Keying Non return Zero
OOK-RZ:	On-off Keying Return Zero
PSD:	Power Spectral Density
LLC:	Logical Link Control

MAC:	Medium Access Control
SSCS:	Service-specific Convergence Sublayer
PHY:	Physical Layer
VPPM:	Variable Pulse Position Modulation
CSK:	Colour Shift Keying
SMD:	Surface mounted device
ASCII:	American Standard Code for Information Interchange

1 Introduction

This thesis focuses on the function of light as a means to transmitting data between electronic devices. It also covers various theoretical aspects of Visible Light Transmission (VLC) in order to provide the reader with sufficient understanding of why and how to use such a technology. The theoretical section will cover the prerequisite information in order to better understand the practical parts. This thesis also provides reasoning for why this method of data transmission may be viable in today’s society of radio wave congested data transmission. The practical aspect is a simple one and is an attempt at devising a simple usage case of data transmission via VLC and the possible problems that will be highlighted throughout the project.

The effect of radio waves in the form of electromagnetic interference on high precision equipment is an important issue that has to be continually addressed and visible light communication is a potential candidate in terms of offering a viable alternative to Radio Frequency (RF) communication.

The main purpose of this work is to identify gaps of knowledge of various methods of communication, with a focus on VLC. An additional function is the practical implementation, which includes an attempt putting together two prototypes of said system in order to compare the efficacy using different components.

The entirety of this project covers theoretical knowledge as well as a practical implementation of a simple VLC system in order to demonstrate the simplicity and efficiency of using light as a means of communication. The goal being to be able to actually transmit some form of information through free space using some simple code, light, and some photodetector.

2 Theoretical Background

This project draws on the knowledge covered in various courses taken in Metropolia UAS and will also attempt to expand upon some of them. The topics that have been covered throughout the education that pertain to this subject matter include digital circuits, state machines, C++ programming, network architecture, microcontrollers, timings, sensors, and various topics covered in telecommunications and radio technology. Other relevant topics that have been introduced throughout the project will be included in this section of the theoretical background.

2.1 Visible Light Communication

2.1.1 What Is VLC

Visible light communication (VLC), also referred to as Optical Wireless Communications (OWC), is a system of communication operating in the visible light band, between approximately 400 nm and 700 nm wavelength, which is depicted in figure 1 below [1]. With the advent of Light Emitting Diodes (LED) through solid state technology, light sources have the ability to emit visible light at very high frequencies which enables the modulation and demodulation of these signals. This ability contributes to the capability of data transmission through light propagation.

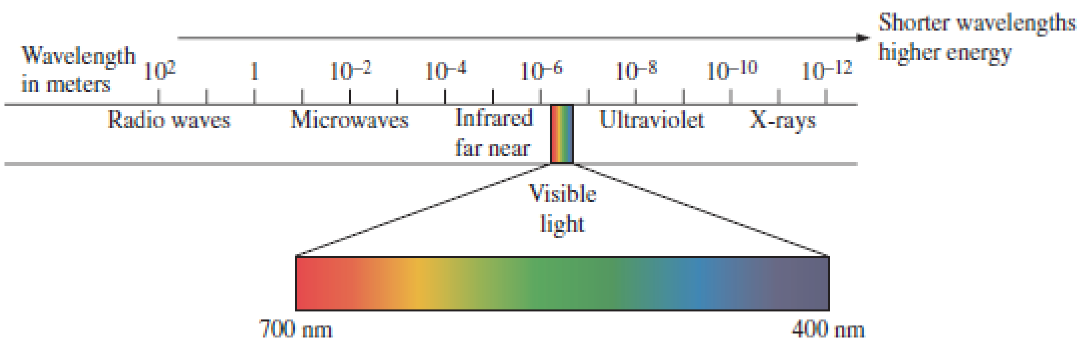

Figure 1. Band spectrum of visible light. Reprinted from [1]

2.1.2 How Is VLC Used?

The fundamental concept of VLC comprises of at least two main components, LEDs and photodetectors. The idea is that since LEDs have short rise and fall times, enabling fast switching, data can be transferred using certain modulation techniques such as on-off keying (OOK) modulation to represent the data as the light hits some form of photodetector.

2.1.3 Why Use VLC?

The reasons for using VLC as an alternative to or as supplemental to existing technology are plenty. The existing and developing wireless technologies for data communication are primarily utilizing the radio wave and microwave frequencies. At the pace of this development, it is inevitably leading to spectrum congestion, especially in urban areas [2]. According to the Cisco Annual Internet Report, by 2023, 5.3 billion people will be using the internet in contrast to 3.9 billion users from 2018. With the implementation of Internet of Things (IOT), connected home applications will have the largest share of Machine-to-Machine connections by 2023, making up a share of 48%. Over 70% of the world population will have access to mobile connectivity by 2023, at about 5.7 billion people. Figure 2 depicts the upward moving trend of global internet users compared to each year.

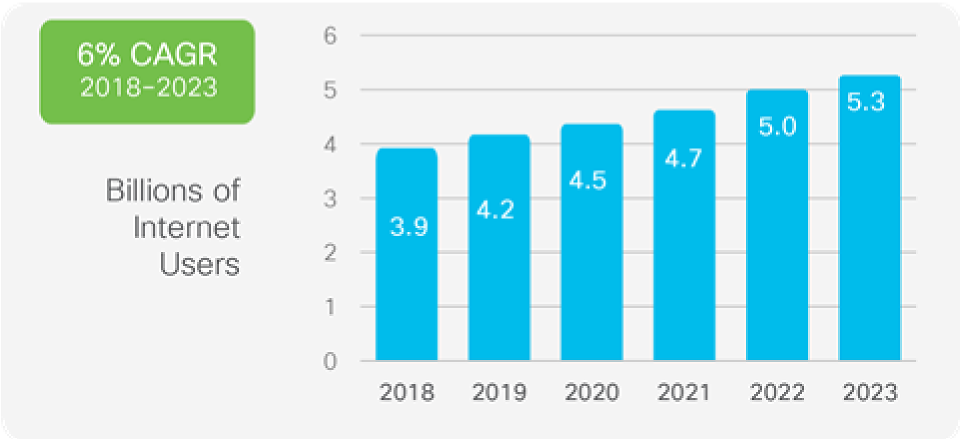

Figure 2. Representation of number of internet users. Reprinted from [3]

The number of untapped users in the internet space is still large considering the world population and the varying user percentages with respect to the region of the world. This information is evident in table 1 below.

Table 1. Internet users as a percentage of regional population. Modified from [3]

Region	***2018***	***2023***
Global	51%	66%
Asia Pacific	52%	72%
Central and Eastern Europe	65%	78%
Latin America	60%	70%
Middle East and Africa	24%	35%
North America	90%	92%
Western Europe	82%	87%

With the information provided in the table 1 above, it is evident that there is still room for growth, especially in Middle East and Africa region, which holds a predicted estimate of only 35% internet users by 2023 [3]. According to the data shown, by 2023 the global internet users will be 66%, still leaving 34% potential increase in the future [3]. With these estimates, it is reasonable to assume that increase in infrastructure is pending. The global traffic is capable of this consistent increase due to the development of different kinds of wireless devices and systems. However, with this increased networking infrastructure, a potential congestion is a serious problem to consider. A great effort is spent in managing the current radio spectrum in order to maintain efficiency and mitigate interference, but even this management has its limits. Because of this, efforts in exploring new avenues of data transmission have increased, with some efforts focusing on different spectrums, such as the visible light spectrum. This has spawned a technology colloquially known as Li-fi, or Light-fidelity. It should be noted that this emerging technology is not intended to be a complete replacement to RF transmission, but rather complementary to it. Currently the advantages it poses make it an attractive suggestion.

Some of the advantages it has are for instance the fact that there are no licensed channels for it to function.

Applications for VLC are plentiful due to certain advantages it poses in comparison to radio frequency communication. It is very energy efficient, cost efficient and does not require any special regulation or licensed channels.
Due to the nature of light being unable to pierce through walls and solid objects, it has intrinsic security in the sense that the waves will not propagate past a desired area, as long as it is blocked physically, whereas radio frequencies are more difficult to limit in that regard.

The frequency bandwidth of radio frequency ranges from approximately 3Hz to 3THz, whereas visible light frequency ranges from 400THz to 750THz. This high bandwidth shows the high potential capacity for VLC and is one reason that it is attractive.

Another factor to consider is the overall power consumption in relation to the function. VLC has been considered to be applied as a means of data transmission as well as providing illumination. This multi-purpose application makes it highly power efficient.

Areas where it may prove useful are healthcare facilities where healthcare equipment, such as magnetic resonance imaging (MRI) and electrocardiograph machines (ECG) are very sensitive to electromagnetic wave interference (EMI). For devices such as these, VLC may be desirable since it does not produce interference with the mentioned machines [4,2].

Another application could be in vehicle communication due to traffic light infrastructure. VLC could be used in safely communicating with vehicles, traffic, and traffic infrastructure in order to provide safe and efficient transportation.

VLC can also be applied to various industrial sites where RF transmission may cause hazardous chemicals to ignite, such as in petrochemical plants, mines, and explosive devices plants [4,5].

2.2 Common Hardware Used In VLC system

2.2.1 Semi-conductor Materials and the P-N junction

In order to understand the inner workings of the LED and the PD, it is helpful to first understand what semiconductors are. Semiconductors are materials classed in between a conductor and an insulator, such that they do not conduct current as well as conductors but also do not resist the flow of current as well as insulators.

Silicon, a common semiconductor element, has 4 electrons in its valence shell. This means that there is space for 4 more electrons in its outermost shell. Each of these additional electron slots are referred to as holes and can be filled by borrowing electrons from nearby atoms. Pure silicon has a tendency to form strong covalent bonds with nearby silicon atoms to form a stable crystalline lattice that is not a good conductor, by borrowing an electron from each neighbouring atom until the valence shell is full. However, by introducing different atoms into the lattice, with differing number of valence electrons, a so-called doped semiconductor can be formed. The number of valence electrons in these atoms would be either 3 or 5. For instance, boron, an atom with 3 valence shell electrons, can be injected into a silicon lattice, forming covalent bonds with nearby silicon atoms, but leaves a hole due to having an unbonded electron as shown in the figure 3 below**.**

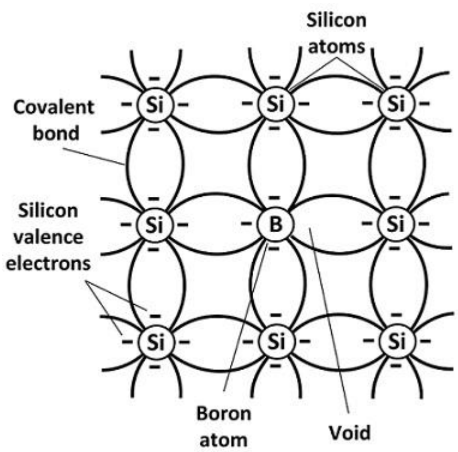

Figure 3. A depiction of boron doped silicon lattice structure. Reprinted from [5]

These are called P-type semiconductors and have a deficit of electrons and can therefore attract free electrons, which results in “hole” current.
On the other hand, N-type semiconductors are formed when silicon is injected or “doped” with an atom consisting of 5 electrons in its valence shell, such as an antimony atom.

What results is a structure depicted in figure 4 below, where there are 4/5 electrons of the antimony atom forming covalent bonds with the surrounding silicon atoms, leaving the remaining 1/5 electron in the structure free to roam, allowing electrical conduction.

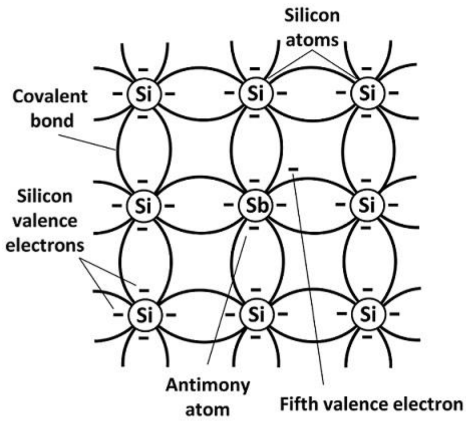

Figure 4. A depiction of antimony doped silicon lattice structure. Reprinted from [5]

In thermal equilibrium, what naturally occurs in a P-N configuration is that the electrons from the N-type will be attracted to the holes near the junction in the P-type. The N-type electrons start filling these holes in the P-type across the junction, in a process called recombination. As the recombination is occurring near the junction, this leaves the surrounding space empty of free carriers (electrons and holes). This results in the formation of the depletion region which is essentially an electric field formed between the recombined carriers that prevents further recombination. This inability to further recombine is what gives diodes their fundamental ability to resist current flow unless a voltage bias greater than the strength of the resisting electrical field is applied.

Three different voltage conditions can be applied to diodes, *forward bias*, *reverse bias* and *breakdown voltage*.

Forward bias is when enough voltage is applied across the diode for it to conduct current in the anode to cathode direction. This requires the minimum voltage which is the *cut-in voltage* and it refers to the amount of voltage required to bypass the resisting P-N junction electric field. In forward bias condition, the diode looks like a short-circuit.

Reverse bias means applying voltage in the opposite direction of the diode and this prevents the flow of current. This is also due to the P-N junction, or the depletion region widening.

Breakdown voltage is when a large negative voltage is applied to the diode and the diode essentially breaks down and allows current to flow in the opposite intended direction.

This usually results in the diode breaking and occurs when a large enough reverse-bias voltage is applied. This maximum voltage is referred to as the *Peak Inverse Voltage* [6].

2.2.2 LEDs

LEDs are similar to other forms of diodes, but what is dissimilar about them is that they have a transparent package that permits either infrared or visible light to pass, and the P-N junction area can be tailored to specific applications.

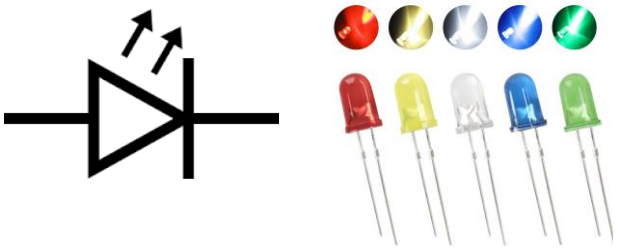

Figure 5. An illustration of an LED circuit symbol and also the physical components. Reprinted from [15]

An LED is a P-N junction diode that can utilize the photon emission process described earlier. The LED works under forward bias conditions, and an external power supply provides the necessary voltage for current conduction. The electrons passing through the junction undergo a process called *radiative recombination*. When an electron passes through the junction, it can emit photons. The photon can be reabsorbed by another electron, which can pass through the junction and emit another photon. This process continues until all the energy of the electron is released in the form of photons.

2.2.3 Photoresistor

Photoresistors, also known as Light Dependant Resistors (LDR), are components that exhibit varying values of resistance depending on the incident light intensity. The value of resistance increases with a decreasing light intensity, and decreases with increased light intensity. Unlike LEDs and photodiodes, they are passive semiconductor components and do not contain a P-N junction. For this reason, their function is very simple and easy to implement.

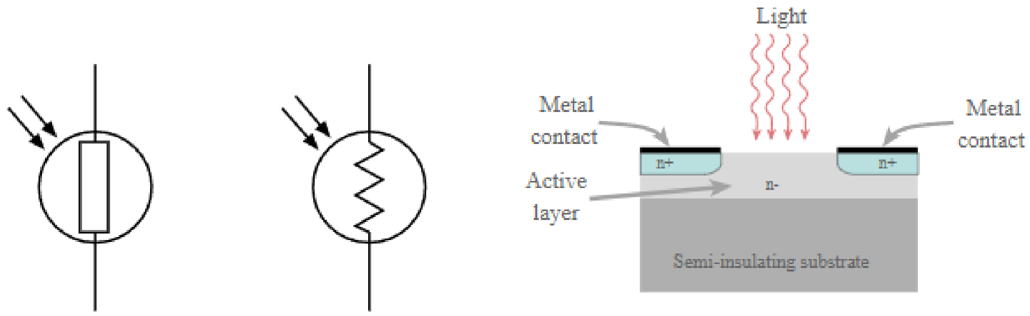

Figure 6. A depiction of photoresistor symbols and structure. Reprinted from [7]

The first two images from the left on figure 6 above depict the resistor symbols for a photoresistor while the image furthest to the right shows the physical structure.

An important factor regarding photoresistors is their resistor latency. This is essentially the time it takes for the resistor to change its resistance once the amount of the incident upon it has changed. This response time can vary from 10s of milliseconds up to a second. This characteristic prevents photoresistors from being used in high bit rate communications.

2.2.4 Photodiode

Photodiodes are semiconductor components that possess a P-N junction, but as opposed to LEDs, where there is a process of radiative recombination of electrons to produce photons, photodiodes take advantage of a radiative recombination in reverse. This means that when a photodiode is exposed to photons, these photons will provide electrons in the valence band with enough energy to become conductive. This effect is known as photon absorption. This process is further illustrated in figure 7 below.

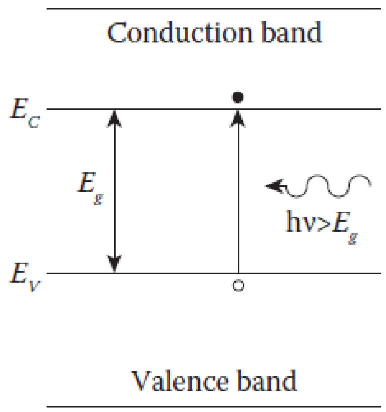

Figure 7. Depiction of a photon entering and exciting electrons. Reprinted from [2, 61]

Photodiodes generally do not suffer from the same high latency issues as photoresistors do. Their response time varies as well, but in the µs range. Typical response time for a photodiode is about 1µs. One important factor to consider for photodiodes is their spectral efficiency that is usually denoted in their respective datasheets. The spectral efficiency provides information regarding how much current it produces with respect to the wavelength of light incident upon it.

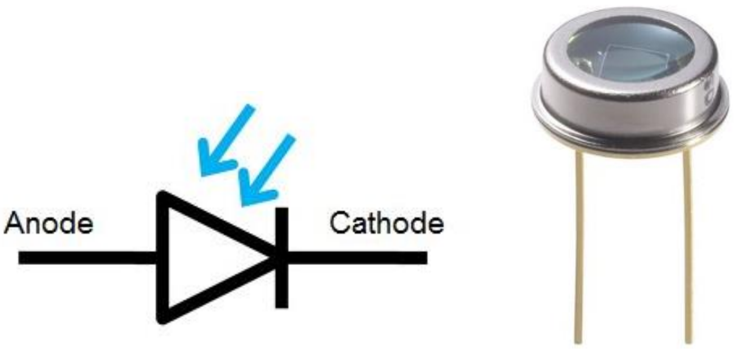

Figure 8. Depiction of a photodiode symbol and component. Reprinted from [8]

Figure 8 above on the left displays the photodiode circuit symbol, while the image on the right displays an example of the physical component.

2.3 Channel Modelling

Signal propagation can be defined as the method in which a signal is communicated in terms of the positioning of the transmitter relative to the receiver. Certain characteristics of the transmitter/receiver system also belong to this definition, such as field-of-view, divergence angle, emitter beam angle, and the existence of line-of sight.

2.3.1 Signal Propagation

Signal propagation can be defined as the method in which a signal is communicated in terms of the positioning of the transmitter relative to the receiver. Certain characteristics of the transmitter/receiver system also belong to this definition, such as field-of-view, divergence angle, emitter beam angle, and the existence of line-of sight.

The fundamental models for signal propagation are directed line-of-sight propagation model, nondirected-line-of-sight model, and diffuse model. LOS signal propagation can further be classified into 3 different links; full tracked, half tracked and non-tracked. These 3 links refer to the facing direction of the TX and RX. A visual representation of these models is displayed in figures 9 and 10.

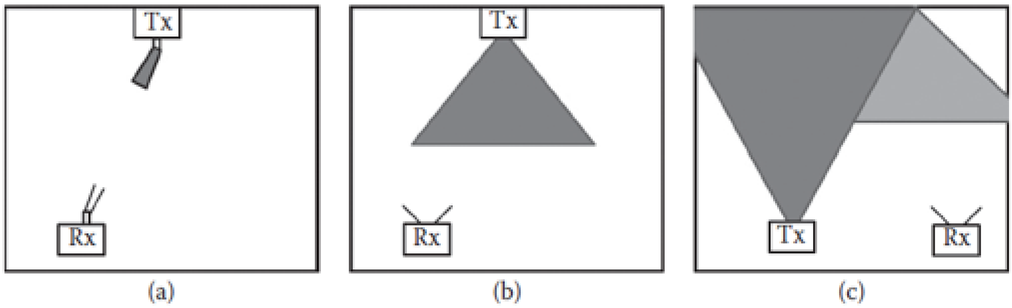

Figure 9. Link configurations: (a) directed LOS, (b) nondirected LOS, (c) diffuse. Reprinted from [2,73]

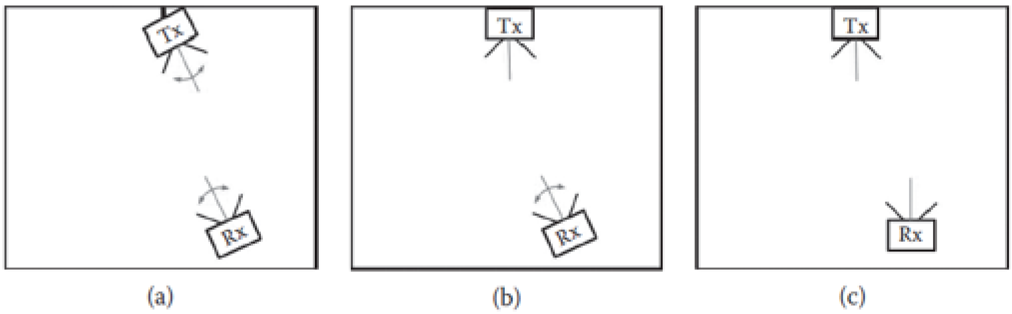

Figure 10. Link configuration with respect to mobility. (a) full tracked (b) half tracked (c) nontracked. Reprinted from [2,73]

LOS model is useful in the sense that it provides higher received light intensity, leading to higher SNR, data rate and link budget at the cost of possible beam blockage and mobility. Mobility is the capability of the TX and RX to be able to track each other in order to optimize the link strength. However, mobility is not an important factor in the scope of this thesis.

2.4 Modulation Techniques

In order to transmit digital data and have it transmitted as light waves for a receiver, that data must be modulated. This implies encoding the light waves to carry information. This information, after being transmitted, will then eventually be delivered to the receiver and will then be decoded in order to be able to read the message. There are many ways to convert this electrical signal, or to modulate it, but the most common and cost-effective method is intensity modulation (IM) / direct detection (DD) [9,81].

Table 2 below compares the various modulation techniques with respect to their SNR, bandwidth, power efficiency and cost.

Table 2. Comparisons of Different Modulation Schemes. Reprinted from [9,162].

MODULATION TYPE	SNR	BANDWIDTH EFFICIENCY	POWER EFFICIENCY	COST
AM	Low-moderate	High	Low-moderate	Low
FM/PM	Moderate	Moderate	Moderate	Moderate
DIGITAL	High	Low	High	High
OOK-NRZ	Moderate	R_b	P	Low
OOK-RZ	Moderate	2 Rb	P-3	Low
PPM	Low	R_b L/Log_2L	P-5log10[(L/2)Log_2L]	Moderate

IM/DD is a form of modulation in which the brightness of a light source is varied in accordance with some characteristic of the modulating signal. Information is transmitted by the light source. A local oscillator is not used in intensity modulation/direct detection systems. Information must have certain attributes to be encoded on the light source. These attributes allow the information to be retrieved from the intensity variations of the light source.

The receiver is comprised of some type of photodetector which senses the light and converts it into electric current. The current is directly proportional to the amount of light that hits it. This means that the current is proportional to the square of the light that hits it. An illustration of an IM/DD implementation is show in figure 11 below

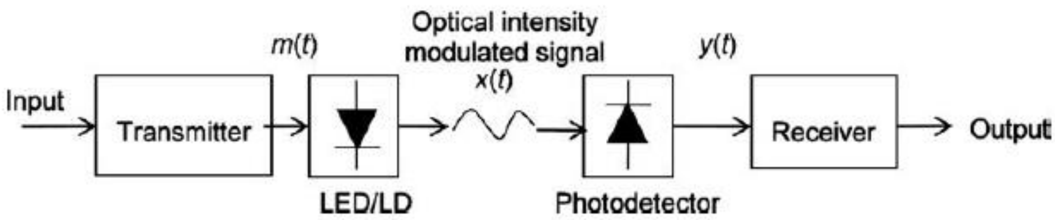

Figure 11. A block diagram of an IM/DD system. Reprinted from [9,82]

Because of the simplicity and cost efficiency of the IM/DD method of signal transmission, the most popular and most reported modulation technique for VLC is the on-off keying (OOK) scheme. In this scheme, also known as Binary Pulse Amplitude Modulation (2-PAM), a binary 1 denotes an optical pulse that is on, while a binary 0, denotes an optical pulse that is off [2,98].

The length of the on-time of the optical pulse is called the duty cycle. The duty cycle is defined as the ratio between the optical pulse time and the bit time. The non-return-to-zero (NRZ) OOK has a duty cycle of 1 and the return-to-zero (RZ) OOK has a duty cycle <1 [2,99].

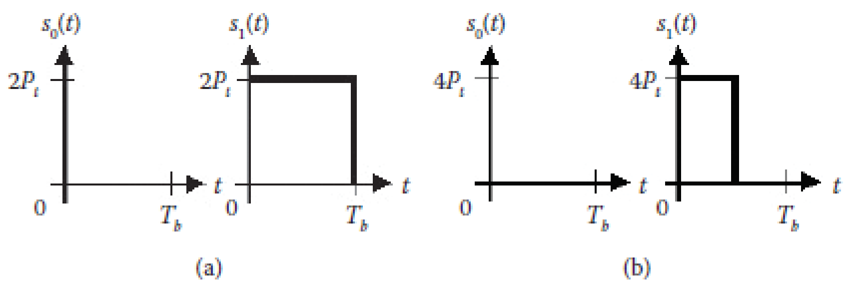

Figure 12. Time wave-forms of (a) OOK-NRZ (b) OOK-RZ. Reprinted from [2,99]

The time waveforms in figure 12 above represent OOK-NRZ and OOK-RZ with a duty cycle of 0.5.

2.5 Noise Analysis

In any electronic devices, any undesirable disturbance is generally defined as noise. In data transmission, noise will likely affect the integrity of the information signal and is therefore unwanted. The types of noise and their sources depend on various factors. The most relevant noise sources in OWC are essentially shot noise, thermal noise and flicker noise. The combination of these different noises has large implications for the receiver front-end and are sought to be mitigated [2,59].

2.5.1 Shot noise

Shot noise is important. It occurs when there are junctions, when there are transition events, and it also occurs when there are recombination and generation events. It generally occurs when there are distinct events of losing charge and/or gaining charge. Since some of the components used in this project employ P-N junctions, they are also susceptible to shot noise, especially in photodiodes. Shot noise is also known as quantum shot noise, at least in the case of photodetectors. The cause of this noise is due to the quantum nature of light and how it propagates towards the photodetector. The photons of light strike the photodetector in such a way that they appear to arrive at random. Although the average number of photons arriving do so at a relatively constant rate, each individual photon arriving is separated from the next by some miniscule interval. This randomness of arrival of the photons results in a photocurrent that fluctuates and the result appears as shot noise. The noise power spectral density (PSD) of shot noise can be expressed as in the equation (1) below**.** The PSD of any signal provides a breakdown of the distribution of power over the total frequency spectrum.

$$\sigma_{sh}^2 = 2qI_s \tag{1}$$

where σ represents the noise power spectral density, q is the electron charge, I_s is the reverse saturation current. The unit for σ_{sh}^2 is [W/Hz].

$$i_{sh}^2 = \sigma_{sh}^2 B \tag{2}$$

The shot noise current is given in equation (2) where B represents the receiver electrical bandwidth.

2.5.2 Thermal Noise

Thermal noise, also known as Johnson-Nyquist noise, is the random fluctuations of the electrical resistance in conductors and is caused by the motion of charge carriers as they jiggle through the conductive material and bump into the neighbouring atoms of the substance. Thermal noise is regarded as white noise because the power spectral density is independent of frequency [9]. The PSD of thermal noise can be characterized by the equation (3) below,

$$\sigma_{th}^2 = \frac{4kT}{R_L} \tag{3}$$

where k is the Boltzmann's constant, R_L is the load resistor, and T is the absolute temperature. The unit for σ_{th}^2 is [W/Hz].

$$i_{th}^2 = \frac{4KTB}{R} \tag{4}$$

The thermal noise current is provided in equation (4) above where B represents the post detection bandwidth of the system.

2.5.3 Dark Current Noise

Even when there is no light incident on the photodetector, a small dark current noise exists in the form of reverse leakage current. The amount of dark current depends on the structure of the P-N junction, the temperature, and also the dopant levels. The PSD can be can be characterized by the equation (5) below [10, 146], where I_D signifies the dark current.

$$\sigma_{dk}^2 = 2qI_D \tag{5}$$

The dark current noise is given by equation (6),

$$i_{dk}^2 = 2qBI_D \tag{6}$$

2.5.4 Optical Signal to Noise Ratio

In any optical communication system, the Signal-to-Noise (SNR) ratio is a determinant factor in the quality of the signal transmission. The key constituents to a high SNR are high responsivity and low noise level of the photodetector.

In order to understand the responsivity of a photodetector, it is important to first understand efficiency.
Efficiency, η, is simply defined as the number of electrons produced for every photon that enters the active area of a photodiode and if every photon is converted to an electron, then $\eta = 1$.
Thus, the responsivity of a photodetector, often denoted by $\Re$, refers to how many milliamperes of photocurrent can be generated for every milliwatt of input signal optical power. The optical power is given by equation (7) [10,139].

$$P = N \times \frac{hv}{\Delta t} \tag{7}$$

where Δt is the difference in time, N is the number of photons received, and hv is the photon energy.

The photocurrent is given by equation (8) below,

$$I = N \times \frac{q}{\Delta t} \tag{8}$$

With the help of the equations above, the responsivity can now be calculated with the following equation (9) below,

$$\Re = \frac{I(mA)}{P(mW)} = \eta \frac{q}{hv} \tag{9}$$

Finally, in order to calculate the SNR, which is the ratio between the signal electrical power and the noise electrical power, and is also equivalent to the ratio of the mean-square currents, equation (10) can be applied [10,147].

$$SNR = \frac{i_s^2(t)}{i_{sh}^2 + i_{th}^2 + i_{dk}^2} \tag{10}$$

2.6 VLC Standards

The standards set forth for VLC are defined in the network architecture of IEEE 802.15.7 along a number of layers, each with their own particular responsibilities. Figure 11 demonstrates a block diagram of the architectures various layers and their relation to neighbouring blocks.

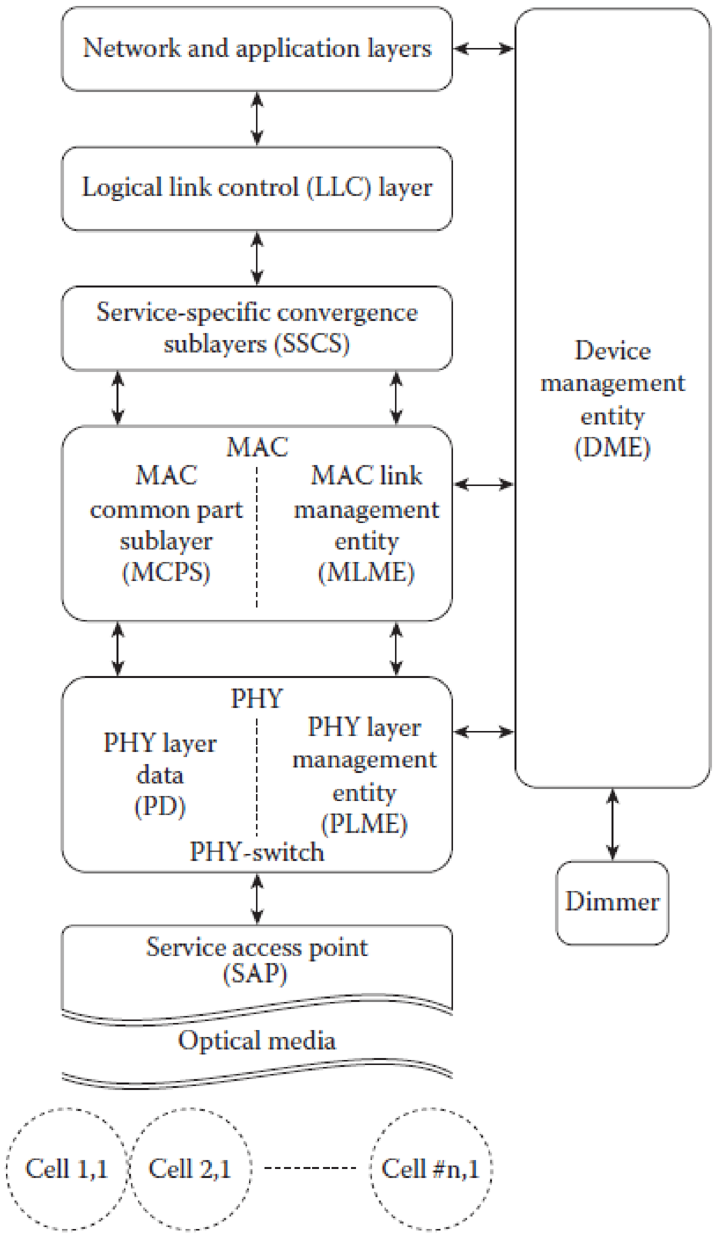

Figure 13. VLC Architecture block diagram. Reprinted from [2,149]

2.6.1 Upper Layers

The network and applications layer that can be seen in figure 13, provide the network configuration and configuration of the device respectively. The logical link control (LLC) layer is the link that connects the upper layers to the Medium Access Control (MAC) layer through the service-specific convergence sublayer (SSCS) [2,171].

2.6.2 MAC Layer

According to [11], three network topologies are defined:

Peer-to-peer, where two devices are communicating bi-laterally and one acts as a co-ordinator.
Star Communication, which is emplyed using multiple devices and one acts as a co-ordinator.
Broadcast One, where one device, usually a co-ordinator, transmits data to multiple devices.

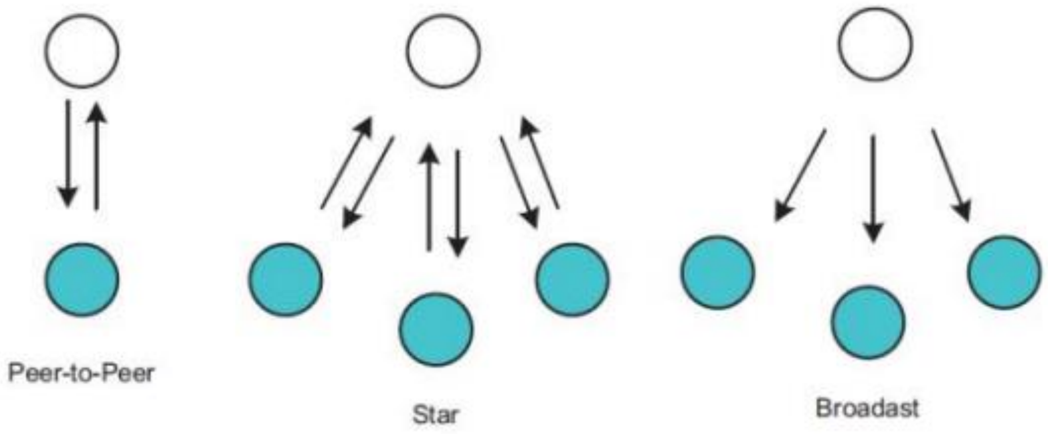

Figure 14. Network topologies. Reprinted from [16]

Figure 14 above depicts the MAC network topologies for simplicity. The white ball represents the co-ordinator and the blue represent the agent devices.

2.6.3 PHY layer

The Physical (PHY) layer functions in 3 different modes. These modes are in charge of the transmission, reception, verifying the state of the transmitting module, as well as the initiation and stopping of the transceiver. The three modes are defined as follows:

PHY I, uses OOK and Variable Pulse Position Modulation (VPPM) and was designed for outdoor applications with relatively low bit rates, ranging from 11.67kbit/s to 266.6kbit/s.

PHY II, also uses OOK and VPPM and was designed for indoor applications with higher bit rates, ranging from 1.25Mbit/s to 96Mbit/s.

PHY III, uses Colour Shift Keying (CSK) modulation and aims to achieve bit rates ranging from 12Mbit/s to 96Mbit/s.

3 Methods and Materials

What follows is an implementation of a simple visible light communications system in order to understand the underlying principles behind the electronic and coding aspects of designing such a system. Two models were designed and attempted. A crude and simple model based on a photoresistor and a basic 465nm wavelength pin LED was implemented with the use of two Arduino Uno's to handle the transmission and reception. The second model involved using the same two Arduino Uno's but this time around an attempt was made at designing a transimpedance amplifier to enable the usage of a photodiode due to the high latency, or low responsiveness of the photoresistor.

Parts from the project were primarily gathered from a personal stash of components. This personal stash included the knock-off Arduino Uno, photoresistor, 465nm PIN LED, resistors, jumper wires and breadboards. The rest were purchased from retailers, with the exception of the operational amplifier and photodiode which were borrowed from school since ordering parts at that point was not feasible due to time constraints.

3.1 Materials

The tools, devices, and components are all listen in the table 3 below, with each column indicating the use case.

Table 3. A table of components, devices, and tools used.

Model 1 Transmitter	Model 2 Receiver	Model 2 Transmitter	Model 2 Receiver	Other tools
Knock-off Arduino Uno (ATMEL mega328P)	Original Arduino Uno (ATMEL ATmega328P)	Knock- off Arduino Uno (ATMEL mega328P)	Original Arduino uno (ATMEL ATmega328P)	Personal computer
YSL-R542B5C-A11 (465nm LED)	5MΩ Photoresistor	APTD1608SEC-J3 625nm Red LED SMD	Unknown photodiode	Mastech MY74 Multimeter
330Ω resistor	10kΩ resistor	330Ω resistor SMD	LM747CN Operational Amplifier	
Jumper wires	Jumper wires	Breakout board	2x 1MΩ resistors	
Breadboard	Breadboard		Jumper wires	
			Breadboard	

The majority of the prototyping was handled from the home environment. The breakout board was created at work since it was possible to get the surface mount LED installed with the use of some work tools.

The practical aspect of this project was rather straightforward. The prototypes were assembled with minimal amounts of soldering and mainly just connecting the jumper wires to their appropriate places. The codes were uploaded into the microcontrollers of the Arduino Uno’s using the Arduino IDE. The code was slightly tweaked in order to better suit the varying components used in the program and it can be viewed in the appendix 1 and 2 with a link to the original source.

3.2 Explanation of code

3.2.1 Synchronization

In order for the receiver to read the data being sent by the transmitter, it needs to know when to start sampling the data. Since there is no clock signal to synchronize the transmission and reception, another method is applied. Asynchronous serial communication is the method of choice. As long as the two devices share the same time period for each bit, the data can be transmitted synchronously. The period is set by the ‘PERIOD’ variable in each of the codes shown in appendices 1 and 2 and it defines the time period for each bit**.** The start of the sampling is triggered by a falling edge of the initial transmission, followed by a ‘*delay’* function of 1.5 times the ‘*PERIOD’*. This delay ensures that the sampling occurs in the centre of the sampled bit. The falling edge of the signal is the start since the transmitter always ends the transmission with signal HIGH and this can be seen in the second last line of code in the transmitter in appendix 1. Thus, as long as the receiver and transmitter share the same period, they will remain synchronized.

3.2.2 Transmitter

The transmitter code in appendix 1 initially defines the pin that the LED is connected to on the Arduino and the line below defines the period of transmission. The next block sets a character string which can be defined by the user, and will subsequently be sent to the LED. The length of the string is initialized by creating the variable *‘string_length’.* In *‘void setup()*’, the ‘*pinMode’* defines which pin is used and whether it functions as an input or an output, and in this case it functions as an output. The next line creates a variable for the length of the initial string through the function ‘*strlen’*. The for loop iterates over the string array and sends each character to the serial port. The delay function at the end of the loop waits for 1 second before starting the next iteration.
As for the transmission of the bytes, in order to send the individual bits, a bitwise ‘AND’ operator and a bitwise shift operator is used and this can be seen in the following line of extracted code from appendix 1,

```
digitalWrite(LED_PIN, (my_byte&(0x01 << i))!=0 );
```

In the *‘send_byte’* function the LED is first turned off, a delay is introduced to create the necessary spacing between the bits, and then the byte is iterated through, turning the LED on if the bit is 1, and off if the bit is 0. Finally, the LED is turned off, and the delay is introduced again.

3.2.3 Receiver

The receiver code shown in appendix 2 starts with some basic definitions of the photoresistor analogue pin number, the threshold voltage for the output of the photoresistor, and the period. Two Boolean variables are created indicating which state the photoresistor is in. The data rate in bits per second is set by the *‘serial.begin()’* function.

The *‘void loop’* takes the voltage from the LDR, which is a light dependent resistor. This voltage is then compared to a threshold value. If the voltage is greater than the threshold, the state is true, otherwise it is false.

The *‘get_byte’* function will return a byte of data taken from the LDR. The function first takes the LDR readings and stores them in an array, then computes the sum of the array and shifts the bits to the left. This is done because the LDR readings will be in binary, but we want the return value to be in decimal. Finally, the function returns the sum of the array.

‘print_byte’ is a function that takes a single parameter, a *‘char’*, and prints out the ASCII representation of that character, one character at a time. The *‘buff’* is a ‘*char’* array with a length of two. It is used to store the ASCII representation of a single character.

‘*sprintf’* takes a buffer and a format, and prints the result of applying the format to the buffer. In this case, we are using the format *‘%c*’, which means "*a single character*". The ‘*buff’* buffer contains the character we want to print, and the *‘%c’* format is applied to the buffer. The result is printed on the serial port which the shows up on the Serial Monitor.

3.3 Methods for the transmitter of both prototypes

The transmitting circuit is the same for both of these prototypes due to the simple nature of the transmitter. The main part of the transmitter is in the code and the circuit aspect consists of nothing but an LED and a current limiting resistor. An illustration of the circuit is shown in the figure 15**.**

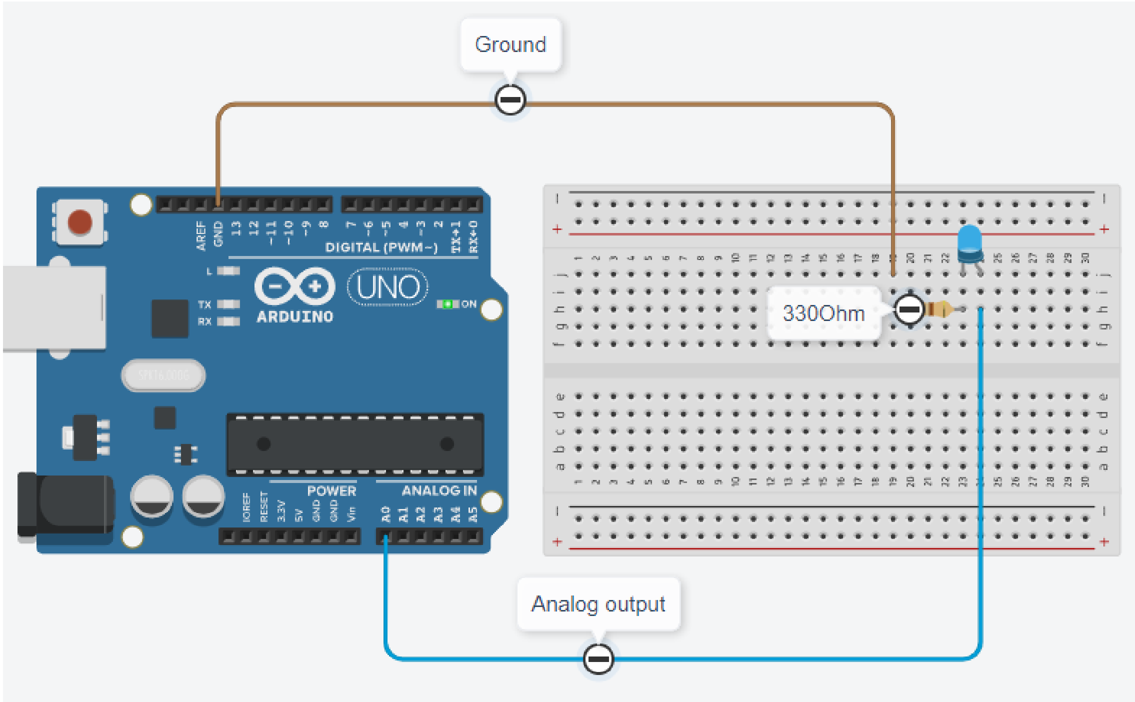

Figure 15. A depiction of the transmitter circuit

As can be seen in the figure, this simple model has a current limiting resistor with a value of 330Ω, limiting the current to approximately 13mA at peak transmission. Another set-up was also used, but instead of a 465nm blue LED being used, a 650nm red surface-mount LED was used. The setup was identical to the one depicted in figure 15 except for the fact that it was made using a small breakout board since there was not a rated pin LED available.

3.4 Methods for Photoresistor Receiver Prototype

The connection for the receiver circuit is depicted in the figure 16 below.

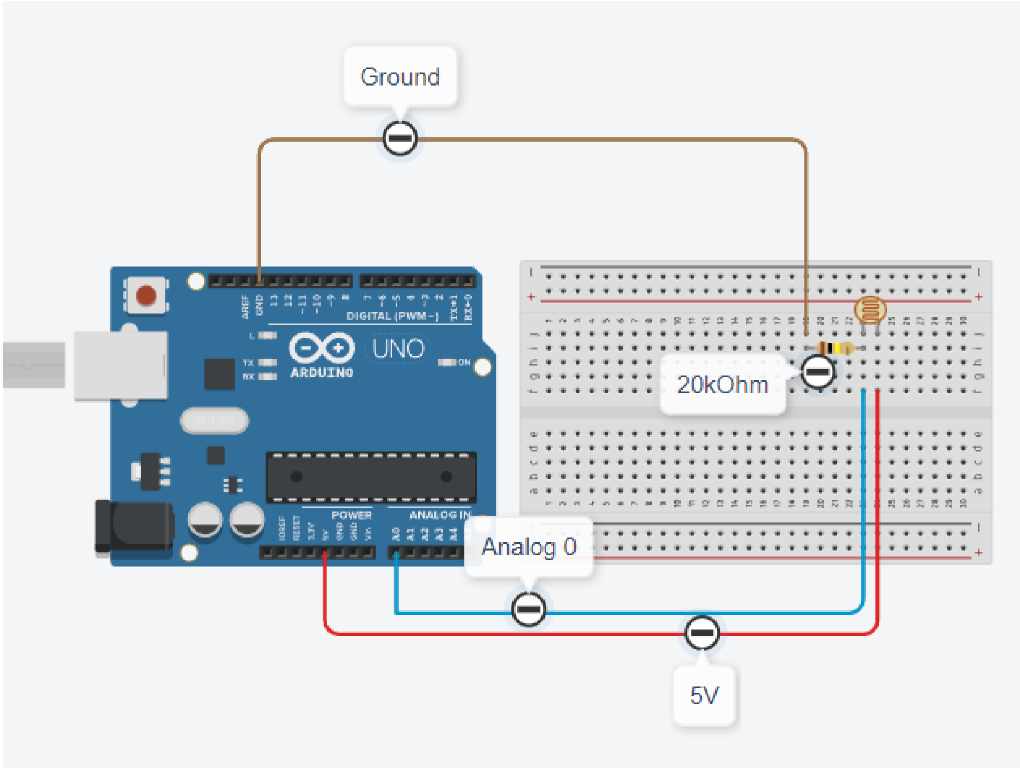

Figure 16. A depiction of the receiver circuit

The photoresistor is connected in series with a 20kΩ resistor as can be seen in figure 16**.** The one end of the resistor is connected to ground and the one end of the photoresistor is connected to 5V. This configuration provides an analogue voltage between 0V and 5V. The resistor in series with the photoresistor acts as voltage divider and furthermore, the value sets the sensitivity of the photoresistor. Values below 10kΩ affected the sensitivity too much and would not reach the peak output. Hence 20kΩ was used since it provided the maximum output voltage and higher sensitivity.

3.5 Methods for Photodiode Receiver Prototype

The design of this circuit was based on a design from [12] on how to create a transimpedance amplifier. This circuit was assembled on a breadboard using an Arduino with the same code as in appendix 2**.**

4 Results

4.1 Photoresistor Prototype

The photoresistor prototype produced positive results. With the photoresistor connected in series with a 20kΩ resistor, it still managed to detect the bits being sent without any errors with up to 12cm separation between the receiver and the transmitter. The initial testing was done at a time period of 15ms and a threshold value of 80 units, which is equivalent to 392mV. This threshold limit did not produce any results on the Serial Monitor. The threshold limit was subsequently increased to 200 units or 980mV, but this still produced nothing measurable at the output. Through trial and error, a working threshold limit of 1000 units (equivalent to 4.9V) resulted in the Serial Monitor producing the expected string. This successful run was executed at a transmitter-receiver distance of less than 1cm. What followed was a test to see how much the distance can be increased and still maintain a functional link. The result was approximately 12cm. Anything beyond this would result in misread data and the output would be similar to the output of the Serial Monitor shown in figure 17 below following the correct output.

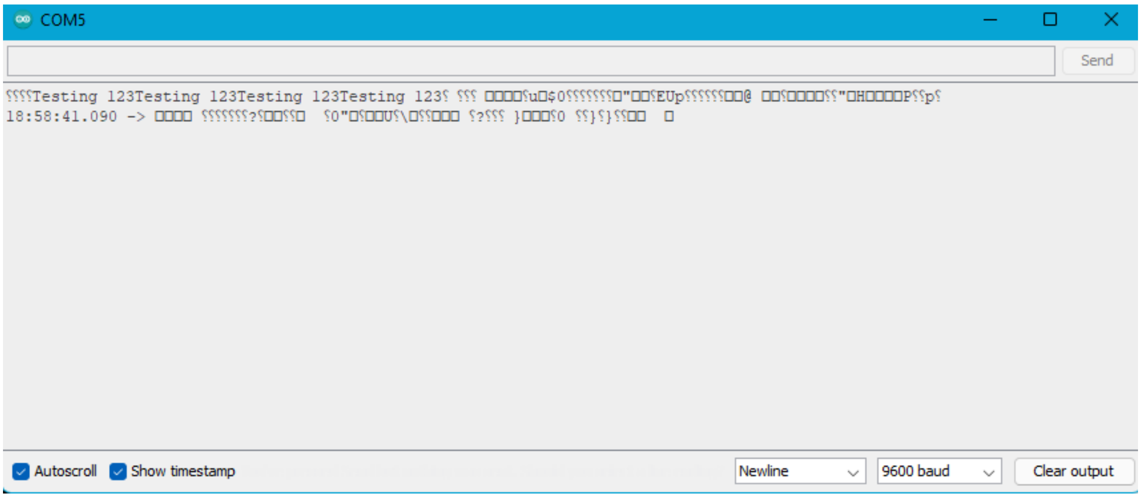

Figure 17. Serial monitor output of the receiver

Any deviation from the line of sight at 12cm would also result in the same false readings as shown in figure 17.

4.2 Photodiode Prototype

The photodiode prototype failed to produce any measurable readings when using the appendix 2 code that was applied to the photoresistor model. However, a simple test to measure the light intensity partially worked. Although it was not part of the scope of this project, the code can be found in the appendix 3**.** The reason for its use was to be able to quickly test the receiver without having to run the transmitter. The result of the readings indicates that at ambient lighting, the photodiode obtained a reading of approximately 196mV. When 465nm blue LED was directed at it, the reading increased to approximately 294mV. Since the photodiode was of unknown origin, it was difficult to figure out its spectral response. For this reason, the APTD1608SEC-J3 625nm red LED was also used. The results were indistinguishable from the 465nm. The photodiode prototype failed.

Despite the failure of this prototype, the project overall was successful given that the goal of this project was to have at least a single functioning prototype as well as being an excellent opportunity to do extensive research into the topic of Visible Light Communication.

5 Discussion

The results of the photoresistor prototype were successful in the sense that it produced the expected output on the receiver end. With a 20kΩ resistor in series with the photoresistor, it proved to be effective up to 12cm of link distance. However, as soon as the LED angle of incidence altered even slightly, the message would become scrambled. This is very likely due to the very narrow relative power output of the LED in relation to the incident angle. The half-power angle of the LED is extremely low at 10 degrees, which implies if the light beam is shifted by only 10 degrees to either side, the power at the receiver end will be halved. An LED with a much higher half-power angle would probably give this transmitter more mobility. Another potential solution to this problem would be to attach some form of collimator, funnel or ball lens to the head of the photodetector in order to redirect the stray beams directly to the head. This could potentially amplify the transmitted signal and also increase the link distance.

The spectral response of the photoresistor was also unknown. This meant that it was not possible to determine the ideal wavelength for the transmitter. Therefore, a point to maximise efficiency for potential future projects would be to clarify what the spectral response is, and then design the transmitter accordingly.

Another drawback with the photoresistor was its responsiveness. Given that some photoresistors have a latency of up to 1 second, the one used in this project seemed to have much lower, approximately 8ms. Although 8ms is relatively fast for photoresistors, it still was a bottleneck when it came to the transmission.

The photodiode prototype was improperly planned. The initial idea was to purchase an after-market VLC development kit with pre-defined characteristics in order to have something to compare the photoresistor prototype to. Due to time constraints and the fact that these VLC development kits are relatively expensive, the decision to attempt to build another one based on photodiodes was made. This was not too far fetched of an idea; however, it does require more research in the fundamental characteristics of designing a transimpedance amplifier from an operational amplifier. The use of the feedback resistor, feedback capacity, the reverse biasing of the photodiode, and certain characteristics of the operational amplifier were not properly understood. A good attempt could be to follow a working circuit model, ordering all the defined parts, assembling the circuit and proceed to run some tests and experiments. Unfortunately, in the case of the photodiode prototype in this project, the operational amplifiers of interest were not readily available. Perhaps the LM747CN could function very well as a transimpedance amplifier with a deeper understanding of the required components, but it failed in this attempt. However, another important note is that the photodiode itself could not be identified, which also prevented access to some important information that could have aided in the development of the circuit.

6 Conclusion

In conclusion, given that the photoresistor prototype proved to be functional and was able to transmit strings of text using light as the medium for communicating the data, this project may be deemed successful. Due to the slow nature of the data transmission of the photoresistor prototype however, it cannot be said that this project made any major contributions to the development of VLC system considering the existence of 10Gbps VLC.

This project drew on a lot of the teachings and lab work throughout the Electronics degree program, especially analogue design, digital technology, microcontrollers, programming, sensors and telecommunication.

The main limitations of this project were the lack of proper planning in acquiring some components. Also, another limitation is that the scope of the project may be considered somewhat wide and could be narrowed down to some specific area such as testing the line quality with regard to bit-error-rate and signal-to-noise ratio.

The strengths are that despite the wide scope, this project could prove to be useful for some in that it may provide good introductory information to VLC systems, having touched upon many theoretical aspects to some degree. Something that could be studied and worked on for future projects, in order to increase data transmission rates, could be to apply CSK for modulation since according to [9], the speeds appear to be significantly higher than with OOK.

Although the photodiode prototype was unsuccessful, the attempt at the execution of this entire project required a great deal of research and provided great learning opportunities with regards to VLC systems.

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8 Appendix

1 Transmitter code, [13]

```
#define LED_PIN A1
```

```
#define PERIOD 15

char* string = "Testing 123";
int string_length;

void setup()
{
  pinMode(LED_PIN, OUTPUT);
  string_length = strlen(string);
}

void loop()
{
  for(int i = 0; i < string_length; i ++)
  {
    send_byte(string[i]);
  }
  delay(1000);
}

void send_byte(char my_byte)
{
  digitalWrite(LED_PIN, LOW);
  delay(PERIOD);

  for(int i = 0; i < 8; i++)
  {
    digitalWrite(LED_PIN, (my_byte&(0x01 << i))!=0 );
    delay(PERIOD);
  }
  digitalWrite(LED_PIN, HIGH);
  delay(PERIOD);
}
```

2 Receiver code, [13]

```
#define LDR_PIN A0
#define THRESHOLD 80
#define PERIOD 15

bool previous_state;
bool current_state;

void setup()
{
    Serial.begin(9600);
}

void loop()
{
  current_state = get_ldr();
  if(!current_state && previous_state)
  {
    print_byte(get_byte());
  }
  previous_state = current_state;
}

bool get_ldr()
{
  int voltage = analogRead(LDR_PIN);
  return voltage > THRESHOLD ? true : false;
}

char get_byte()
{
  char ret = 0;
  delay(PERIOD*1.5);
  for(int i = 0; i < 8; i++)
  {
```

```
   ret = ret | get_ldr() << i;
   delay(PERIOD);
  }
  return ret;
}
void print_byte(char my_byte)
{
  char buff[2];
  sprintf(buff, "%c", my_byte);
  Serial.print(buff);
}
```

3 Light intensity test code, [14]

```
void setup() {
  Serial.begin(9600);
}

void loop() {
  // reads the input on analog pin A0 (value between 0 and 1023)
  int analogValue = analogRead(A0);

  Serial.print("Analog reading: ");
  Serial.print(analogValue);   // the raw analog reading

  if (analogValue < 10) {
    Serial.println(" - Dark");
  } else if (analogValue < 200) {
    Serial.println(" - Dim");
  } else if (analogValue < 500) {
    Serial.println(" - Light");
  } else if (analogValue < 800) {
    Serial.println(" - Bright");
  } else {
    Serial.println(" - Very bright");
```

```
  }

  delay(500);
}
```