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BEng Hons Project Report
Development of a Visible Light Communication (VLC) System using LED Modulation
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Mission Statement

Background

Wireless communication using electromagnetic waves are a common way of transmitting information across electronic devices. Visible light as the higher frequency spectrum in electromagnetic waves emerges as a fairly new technology to transmit information. Transmitting information using visible lights,promotes security due to fact that they can be highly directional and cannot penetrate opaque obstacles. Data being transmitted will not be picked up easily by other devices.

Project Definition

The aim of the project is to prototype the Visible Light Communication System. Using LED as a transmitter, digital information such as audio signal and images would be modulated and trans- mitted. By using photo diode, the signal is then received and demodulated by a micro controller. Various digital signal processing techniques would be used to ensure that the communication of the system is successful. Simulation of the system would be done using MATLAB, after which, a hardware prototype would be implemented. It is then tested in the Museum of Communication in Burntisland, Scotland. The visitor would receive images and also audio signal related to the exhibits by using the embedded device as a medium.

Objectives

- To prototype a transmitter that transmit encoded signal using a LED(s).
- Data being transmitted are audio recordings and images.
- To prototype a receiver that decodes the signal using photo-diode(s).
- To build a hand-held embedded device as the receiver that includes ways of replaying the audio signal and images.

Preparatory Task

- Finding optimal way of processing and encoding information into frequency modulated signal that is being transmitted and then demodulated.
- Model and simulate the modulation and demodulation of the digital signal being transmitted.
- Designing the amplification and filtering of the signal by using various electronic components.
- Interface the electronic components with a micro controller which contains LCD and audio jack output.
- To design and manufacture the printed circuit board (PCB) layouts

Main Tasks

- Simulation of the digital signal processing would be done using MATLAB and LT Spice.
- The aim of the simulation would be to maximize the signal to noise ratio (SNR).
- The micro controller being used would be an Texas Instrument (TI) chip. The launchpad of TM4C123GH would be used in the prototype.
- The PCB layout of the embedded device would be designed using Eagle CAD or TARGET
- The overall system would then be tested using lab tools such as oscilloscope and signal generator in the labs.

Interim Targets

Having researched on different LED modulation such that a feasible and optimal way of encoding the information into modulated digital signal. A simulation of the transmitter and receiver will hopefully be done by the end of this term. A full hardware schematic on both the amplifier, filtering and the embedded device would then done. Hardware components would then be decided for the embedded system.

Scope for Extension

- Low resolution videos as part of the information being transferred.

Background Knowledge

- Digital Signal Modulation
- Embedded Systems Interfacing

- C-Programming
- PCB Design

Location

The prototype would be designed and built in the Kivlin Suite TLA/B/C Labs in King's Building.

Abstract

This project aim to design uni-directional visible light communication system (VLC) to demonstrate the capabilities of transmitting information using LED. This document goes through details to design the VLC system from the physical layer till the application layer. The design was prototyped and tested to made sure that the system was able to meet the functional requirements needed for the application. Physical transmission speed of 50kHz and distance of up 50cm between the transmitter and the receiver were achieved. This document also show that the findings of the key components that needs to be calibrated properly or precisely in order to achieve high quality performance of the entire system. The junction capacitance of the photodiode, trans-impedance amplifier design of the receiver, filtering external noise caused by other lights are the key components for designing the VLC system. The pcb design source code and the implementation of the software back-end of both the transmitter and receiver are located in github[1].

Declaration of Originality

I declare that this thesis is my
original work except where stated.

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Statement of Achievement

In this project, I have researched and gain a huge understanding over digital communication systems. I have designed and prototyped a uni-directional visible light communication system (VLC) using LEDs. The system consists of a transmitter that transmits data periodically and a receiver that receives the data. Both the transmitter and the receiver are designed and prototyped using a Texas Instruments ARM Cortex M4 microprocessor. The final system is able to transmit files and also transmitting real time text or audio signal.

In the transmitter, I have designed a system to drive the LED by using analogue components such as operational amplifiers and a n-mosfet. The system is able to transmit logic signals driven by the microprocessor with a speed of 50kHz. I also have designed and programmed the microcontroller to encode data using Manchester Encoding.

As for the receiver, I have designed a analogue system to amplify the signal received from a photodiode using operational amplifiers. The system is able to transmit at 25kbps at the physical layer. In terms of the software, I have programmed the microcontroller to process and decode the logic signal using either ADC sampling or Input Edge Capture.

The source code of for both the transmitter and the receiver are available in Github [1] . I have designed a PCB for both the transmitter and the receiver using the EAGLE CAD design software. The PCB design had been sent to be manufactured by SEEED Studio.

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Glossary

AGC Automatic Gain Control.

BER Bit Error Rate.

CPU Central Processing Unit.

CRC Cyclic Redundancy Check.

DAC Digital to Analogue Converter.

DMA Direct Memory Access.

EEPROM Electrically Erasable Programmable Read-only Memory.

EM Electromagnetic Spectrum.

FAT File Allocation Table File System.

FPGA Field Programmable Gate Array.

GPIO General Purpose Input Output.

ISR Interrupt Service Routine.

LCD Liquid Crystal Display.

LED Light Emitting Diode.

MCU Micro Processing Unit.

MISO Master-In Slave-Out.

MOSI Master-Out Slave-In.

MUTEX Mutual Exclusion.

NMOSFET N-Gate Metal-Oxide Semiconductor Field-effect Transistor.

OOK On-Of Keying Modulation.

OP-AMP Operational Amplifier.

OS Operating System.

RAM Randomly-Accessed Memory.

ROM Read-Only Memory.

RTOS Real-time Operating System.

SD Secure Digital.

SNR Signal to Noise Ratio.

SPI Serial Peripheral Interface Bus.

SRAM Static Randomly-Accessed Memory.

TIA Trans-impedance Amplifier.

VLC Visible Light Communication.

Chapter 1

Introduction and Background

1.1 Introduction

Wireless communications has becoming a huge part of our daily life in terms of communicating or exchanging informations. The usage electromagnetic (**EM**) waves such as radio waves and micro waves to transmit digital data provides different kinds of service to users. However, availability of bandwidths in these EM spectrum does not cope with the increasing global internet traffics. A recent report shows that the global internet traffics increases by 24% every year[2]. This is due to the increased in electronics devices over the year. In addition, interference of radio or micro waves is also a huge problem in communication systems. This would further degrade the quality of the communication systems. This is done by introducing different types of interference avoidance techniques by trading off data rates. Furthermore, the ability of penetrating through the walls introduce more issues with security due to the fact that someone else could be eavesdropping the signal being transmitted.

With increasing capabilities for LED [3], illumination options are mostly replaced by LEDs. This change in commercial lighting shows that the capability of using LED to transmit information. However, the challenge of this is to implement communications capabilities into LED which is an add-on to illumination. VLC is one of the options to be able to solve the EM spectrum bandwidth crisis for radio waves communication system, due to the broad available bandwidth of visible light spectrum. VLC provides a good networking security due to the fact that VLC does not pass through opaque objects. This makes eavesdropping to be impossible if the light source is not in vicinity.

This project aims to design a visible light communication systems that could easily demonstrate the capability of **VLC** systems. The focus of this project would be to design a uni-directional VLC system. This project is part of a collaboration with the Museum of Communication in Burntisland, Scotland. An example of using the system is shown as follows. Transmitter of the system is setup to transmit data by driving the light source at each independent exhibits. A visitor visiting a museum would be able to use the receiver, an enclosed embedded device to retrieve more informations of a particular exhibits by aligning the receiver to the light source. The system is modelled and designed such that it would be easy and simple for the visitor to use.

1.2 Background

1.2.1 Visible Light

Visible light which is part of the EM spectrums with wavelength range of 380nm and 760nm. By replacing radio waves and microwaves with visible light, the problems mentioned could be solve. First, the huge bandwidth of visible light which is around 390 THz provides more than enough bandwidth for coping with the global internet traffics. Second, interference problems could be avoided due to the fact that visible light does not penetrate through walls. Naturally, this also solve the security issues introduced by radio waves. As a result, visible light is a good candidate to be used as medium to transmit information.

1.2.2 Light Emitting Diode

Light Emitting Diode (LED), is a p-n junction diode that emit lights when current passes through. LEDs are now more widely used due to the low energy consumption and longer lifetime compared to commercial light sources. LED tend to overtake the old illumination technologies due to the improved high power efficiency. In this project, a commercial high powered LED has been used as the transmitter.

The LED used in this project is a high power blue LED which is rated 0.5W with wave length of 470nm.

1.2.3 Photodiode

Photodiode is a device that converts photons or light into electrical current. This is one of the light sensing electronics that is used in this project. The photodiode have to be connected in the reverse biased direction [4] in order for it to function normally. However, the current generated by the photo diode is usually small and the current has to be amplified using trans-impedance amplifier (TIA). It is important to notice that the feedback resistor in the TIA and the junction capacitor of the photodiode greatly affects the amount of noise that is introduced in the TIA [5].

The photodiode used in this project is VTP1188SH photodiode [6].

1.2.4 Modulation

In communication system, modulation is a process to embed information to a carrier signal by varying different properties of the signal. This could be done by varying frequency, phase or amplitude of the signal. In this project, we would modulate digital bit streams into visible light by using On-Off Keying [7] and Manchester Encoding. On-Off Keying (OOK)is one of the simplest digital modulation scheme. In our case, the LED is switched on to transmit logical ’1’ and LED is switched off to transmit logical ’0’.

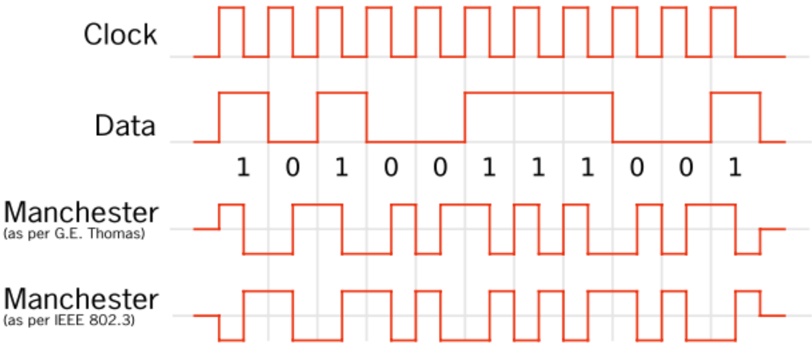


Figure 1.1: Manchester Encoding Conventions [8]

Manchester Encoding

Manchester Encoding is a digital modulation encoding scheme that is widely used in early Ethernet physical layer [8]. A digital '1' would be encoded as '01' and a digital '0' would be encoded as '10'. This could be seen in the Figure 2.1 below. Manchester encoding had been used due to the following reasons. Firstly, the frequent transition of signal removes flickering of LED even when burst streams of '1's or '0's are being transmitted. This removes the requirement of scrambling the data. Secondly, the demodulation for this method is not dependent on the system clock. The transmitter and the receiver does not have to have a synchronised clock to achieve data transmission. The decoder could make use of this property to easily decode the data. This could be done by capturing the rising or falling edge of the data stream. Thirdly, the average power and the intensity of the light would stay constant due to the frequent transition of the digital signal.

1.2.5 Micro-controller

Micro-controller [9] is a small processor that contains multiple **CPU** cores. They are normally used in embedded systems applications and it is programmable due to having internal memory such as Read-Only Memory (**ROM**) and Random-Access Memory (**RAM**). In our project, micro-controller had been chosen rather than a Field Programmable Gate Arrays (**FPGA**). This is because micro-controller offers easier programmable, and debugging capabilities compared to FPGA. Future implementations or extensions could be added to the system easily. Furthermore, parallelism provided by the FPGA is not required and the design of the system is more sequentially focused.

In this project, a Texas Instruments (TI) micro-controller (TM4C123GH6PM 32-bit ARM® Cortex®-M4F based **MCU**) [10] had been chosen and used to prototype the whole system. This micro-controller offers high performance capabilities of up to 80MHz clock processor. It also provide multiple programmable **GPIO**. The micro-controller provides 32KB of single cycle **SRAM**, 256 KB of flash memory and also 2KB of **EEPROM**. This would be sufficiently enough to be able to handle the task needed for our application. The low static RAM could be compensated by using external memory modules such as SD cards. The micro-controller also provides different serial communications peripherals and one of which that is used mostly in this project is the Serial Peripheral Interface Bus (**SPI**).

1.2.6 Serial Peripheral Interface Bus (SPI)

SPI [11] is one of the most commonly used serial communication protocol used by peripherals such as Secure Digital (SD) cards and Liquid Crystal Display (**LCD**). In SPI, a single master can communicate with multiple slave modules. Figure 1.2 shows a typical connection between a master module and a slave module. Both module have their own internal memory and also an internal circular shift register. The shift register are used to buffer data that needs to be transmitted or received. The master module sends data through the Master-Out-Slave-In (**MOSI**) connection and the master module receives data through the Master-In-Slave-Out (**MISO**) connection.

In this project, the micro-controller provides multiple SPI module and all of them act as a master module that communicates with one or multiple slave modules (SD card, LCD and **DAC** Chip).

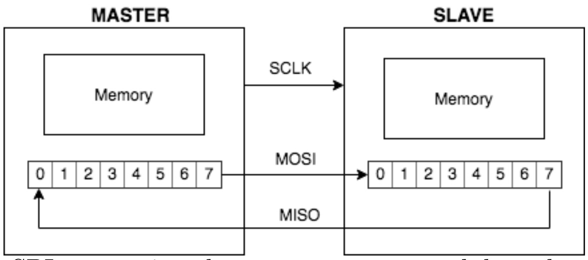
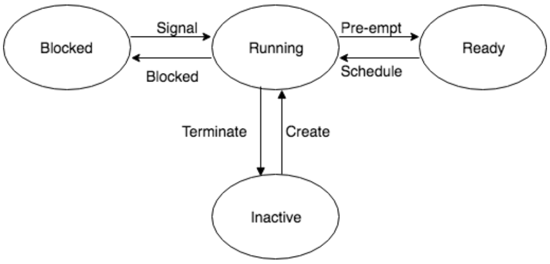


Figure 1.2: SPI connections between a master module and a slave module

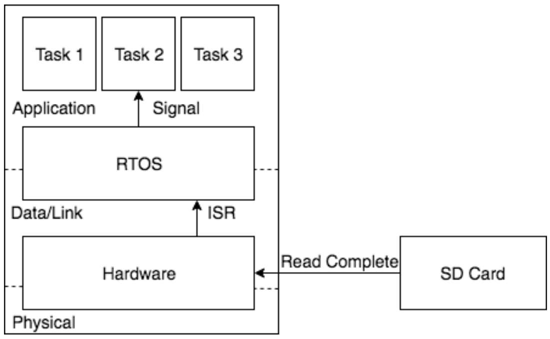
1.2.7 Real-Time Operating System (RTOS)

RTOS is an **OS** mainly written for applications that need to meet real time requirements. This could be processing data that comes in at a specific period. If an application requires that a certain task that needs to be done in a fixed time window, we can say that it is an hard real-time application. This could be safety critical systems that could cause lost of life. The application is considered to have failed if it does not complete its function within the fixed deadline even once. If the system allows some fixed deadline to be missed, the system is considered to be firm/soft real-time system. The main difference between firm or soft real-time system is that the value of the tasks that does not meet the deadline is reduced to zero for the former case where in the latter case the value decreases as the deadline is missed. In our application, firm real-time system is needed. This is because missing the deadline would cause the data to lose their value.

Tasks are scheduled with the scheduling algorithm that is used in the RTOS. This could be event-driven or time-sharing. Event-driven focuses on completing tasks that need to be done where as time-sharing focuses more on fairness. In this project, event-driven scheduling algorithm are used. Priority scheduling which is one of the example of an event-driven scheduling algorithm schedule tasks based on



(a) Task State Diagram



(b) An Example of SD Card triggering ISR

Figure 1.3: Figures to Illustrate Functionality of RTOS

the priority being assigned to them. Normally, tasks that have a harder real-time are assigned higher priority. However, these tasks are designed to be short tasks such that it does not take most of the cpu cycles. To further increase the performance of the system, tasks that are waiting for resources to be done such as reading data from a SD card, are blocked and no longer being scheduled.

Figure 1.3a shows the state diagram of a typical task. Firstly, a task are created an set to be in ready state. When the scheduler happens to schedule the task based on the scheduling algorithm, the task is then transitioned into running state where the task are allocated a certain fixed time to run. When the task have to wait on other resources, it is then blocked into blocking state. When the task finishes its assigned tasks, it would then terminate itself and pass the control to the RTOS to allow other tasks to be scheduled. External hardware uses hardware interrupts in order to signal tasks that requires external resources. For an example, a hardware interrupt is triggered when a block of data has been done reading from the SD card. The Interrupt Service Routine (**ISR**) would then be triggered and a signal is sent to a task to process the block of data. This is illustrated in Figure 1.3b.

1.2.8 Producer-Consumer Problem

Global resources such as global variables and global buffers are shared in order to pass data between tasks. This would potentially a problem if each tasks tries to access the global resource without proper synchronisation. For an example, when task 1 and task 2 tries to write to a same global variable, this would lead to a condition which is called racing condition. This would lead to nondeterministic data being written to the variable. The cause of racing condition is because writing to a variable consist of multiple lines of assembly code and the task might be pre-empted between line of execution of the assembly code.

Producer-consumer problem [12] is a common problem when a task tries to insert data into a global buffer and another task tries to retrieve data from the global buffer. The common approach to solve the producer-consumer problem is by using mutual exclusion object (**MUTEX**). Mutex is a synchronisation primitive provided by most RTOS.

1.3 Project overview

In this paper, we start with Chapter 2 that discuss the general impact that would have made with this project. This would include how the project would benefit the academic, economic or the industry. Later on, we would define the problem scope and also discuss about the design requirements needed by the application in Chapter 3. We then talk the design in more details in Chapter 4. The design description is separated into two different aspects of the system which are digital components and analogue components. An example of a typical use case is also included in this chapter. In Chapter 5, the system is prototyped and tested to measure the performance of the design. Extensions to this project is also discussed in 5.5. An assessment had been done to determine if the design meets the required design requirements. Finally, Chapter 6 gives out a conclusion and summary to this project.

Chapter 2

Impact and Exploitation

2.1 Where does the project fit in the Research and Development Process?

This project focuses on designing a Visible Light Communication (VLC) system that would be used as a information retrieval system for a museum. This project would be based on research papers that researched on VLC system implementations that is already being done. The system would then be modified and improved to fit the specification and requirements needed for this application. In a typical research and development process, this project would focus on designing the VLC system to meet the requirements needed. The system would then be prototyped and tested to check if the system would meet the requirements of the design. This project also involves design for manufacturability as an addition to have an prototype example of a working VLC system.

Further design of the system is required in order to meet the required specifications or requirements. If all of the core requirements are met, a more robust design for manufacturability should be done in order to take the design to production stage.

This project would be the first to implement a VLC based system to replace embedded systems to retrieve informations for exhibits in a museum. The main focus of this project would be to design the VLC system such that most of the functionality are met.

2.2 What form of Economic or Societal Impact is the outcome of the project likely to have?

VLC systems that is used as a information retrieval tool can show that the capabilities of VLC systems and give out a basic knowledge for wireless communication protocols. The society would also be introduced the current spectrum starvation of radio wave EM spectrum [2]. This project would also show that VLC might be a candidate to replace radio wave communication technologies.

This project is part of a collaboration project between the Museum of Communications in Burntisland, Scotland. The museum would greatly benefit from this project outcome. The goals to this project is to design a working VLC system that could be produced and manufactured in the future.

The VLC system implemented would be able to show that the capabilities of VLC system as to other applications. Other researcher or student would be able to quickly grasps the concept on how VLC systems are implemented without any knowledge of VLC systems.

The project would not have any adverse effects to the society. However, safety health regulations over light should be followed to prevent harming eye sight of a human.

Chapter 3

Problem Definition

3.1 Problem Scope

The aim of this project is to prototype the whole communication system that transmit simple data. The system would then be tested and used in the the Museum of Communication in Burntisland, Scotland. The system would be used to help visitors to receive extra information about an exhibit. This could be in text or audio speech. In this project we would design a VLC system that would be fit to be used in the museum of communication. The design should be modular and at the same time have different functionalities to improve user experience. This design also aim to implement a VLC system in a simple and understandable manner. The problem that this project would focus on would be "How to implement a uni-directional visible light communication system using LED and photodiode without having to compromise the illumination functionality of a LED?".

3.2 Technical Review

The following paper shows the capabilities of VLC systems. This paper [13] implemented VLC uni-directional communication using **OOK** modulation to transmit ascii characters and also unicode chinese characters using 2 raspberry pi with transmission speed of 5KBytes/s. Furthermore, this paper [14] uses DuoBinary Pulse Position Modulation (DuoPPM) technique to implement a VLC with capability of transmitting up to 14Mbit/s using FPGA boards. In addition, this paper [15] implemented and prototyped a VLC system that is based on Orthogonal Frequency Division Multiplexing (OFDM) that achieves 80Mbit/s. More over, this paper [16] had designed and implemented VLC systems that allows bi-directional communications of up to 500Mbits/s using RGB LEDs with Wavelength-division multiplexing (WDM). Next, this paper [17] demonstrates capability of VLC systems that transmit up to 1Gbits/s using Multiple-Input-Multiple-Output OFDM modulation technique. Finally, this paper [18] implemented VLC system by using PS-Manchester coded Nyquist PAM-8 modulation with hybrid time-frequency domain equalisation scheme and achieved data rate of 4.05Gbits/s.

These papers shows that the large variety of applications by using VLC systems. [19] implemented a positioning system using VLC using Arduino Nano as the transmitter and Rasberry Pi as the receiver using bandwidth in between 30kHz and 40kHz. [20] designed a system enable vehicles to communicate at night peer to peer using VLC system. [21] implemented VLC system that uses OOK modulation and also provides a receiver design that reduce interference effects from low-frequency noises such as ambient light or fluorescent light.

3.3 Design Requirements

The project would have the following core design requirements. They are split into two categories which are functional and non-functional requirements. The functional requirements describes the behavioural requirements of the communication system. As for the non-functional requirements describes the performance of that the system.

3.3.1 Functional Requirements

- The system should be able to transmit information in a single direction (uni-directional communication) using visible light.
- Both the receiver and transmitter should be able to read and store a file stored in an SD card.
- The receiver should be able to display text informations on a LCD screen.
- Both the receiver and the transmitter should let the user to interact with the system using switches.
- The receiver should be able to play audio files stored in a SD card.

3.3.2 Non-Functional Requirements

- The physical layer transmission speed should be at least 100kbps.
- The data transmission speed should be at least 10kbps.
- The distance between the transmitter and the receiver should be at least 1m apart.
- The receiver should be able to transmit a file of at least 1 Mega Bits without error.

Chapter 4

Design Description

4.1 Design Overview

The design focuses on achieving a uni-directional communication system. The transmitter of the system consist of both analog and digital components. The digital component is made and managed by an ARM Cortex M4 Microprocessor.

The transmitter are programmed as a few different modes. The idle mode, transmit consecutive '01's in order to preserve the illumination of the **LED**. The file transfer mode, transmit raw data of a specific file that needs to be sent in a loop. Real-time transmission mode, transmit raw data of a certain text file in a consecutive matter. There is a slight difference in the last two modes whereas the file transfer mode transmit an actual file of any format including txt and format. As for real-time transmission mode, ascii code of a string are transmitted byte by byte serially to the receiver.

The receiver are programmed into few different modes as well and they are described as follows. The file receiving mode, where the receiver receive a file of any format. The file reading mode, where the receiver reads a text file and display the raw text of the text file on the LCD screen. The audio player mode, where audio are played through the audio jack of the receiver. Lastly, the real-time transmission mode, where real-time raw text data are received and displayed on the LCD screen at the same time.

For the transmitter and the receiver, the design of both the data layer and the physical layer are the similar. This is because the data layer and the physical layer only describes and define the low level functionality of the data transmission. In Section 4.2, we would focus on the design of data layer and the physical layer of the system. In Section 4.3, a higher level description of the system such as the description of each different modes would then be discussed.

4.2 Detailed Description

In Figure 4.1 describes the high level modular components of the system. We would first describe the detailed implementation of the analog components with the transmitter. This is then followed with the analog components with the receiver. We would then talk about the implementation of the digital components for both the transmitter and the receiver. Furthermore, a detail description of interfacing the LCD screen is also discussed in Section 4.2.2. Lastly, Section 4.2.2 discuss the design of interfacing an audio jack to the receiver.

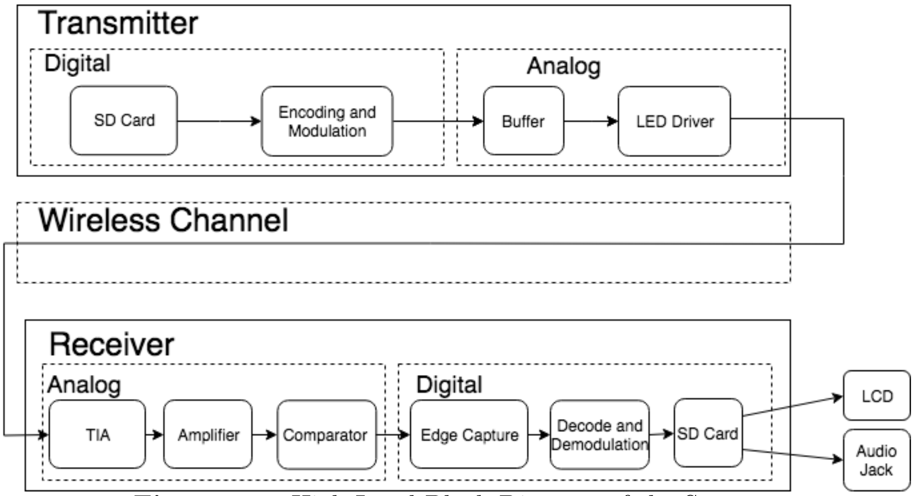


Figure 4.1: High Level Block Diagram of the System

4.2.1 Analog Components

Buffer Amplifier

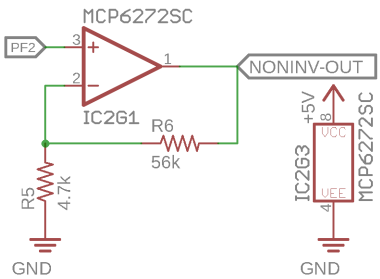


Figure 4.2: Buffer Amplifier

Figure 4.2 shows the schematic of the buffer amplifier. The buffer amplifier is used to buffer the digital signal from the GPIO (PF2) of the micro-controller to the LED driver circuit. The signal is also amplified such that the voltage would be sufficiently high enough to turn on the n-mosfet in the LED driver which would be discussed later. It also provide a low impedance input to the LED driver. This further increase the modularity of the design.

The buffer amplifier uses a non-inverting amplifier circuit topology. The gain of this circuit is calculated as follows. $\frac{V_{OUT}}{V_{IN}} = 1 + \frac{R_6}{R_5} \approx 13$. Hence, since the digital signal from the micro-controller is a square wave of amplitude 3.3V, the output voltage is going to be a 5V square wave. The amplification is sufficient to ensure that it would be enough to switch on the mosfet. This is discussed in more detail in the next section. The **OP-AMP** that had been chosen has to be powered with a 5V single power supply. The MCP6272 rail-to-rail op-amp [22] would be a good choice due to the high gain bandwidth product of around 2MHz. Therefore, this is going to be sufficient in our application since the frequency of the square wave is at 50kHz.

LED Driver

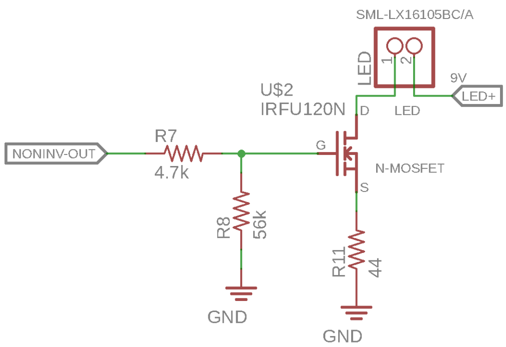


Figure 4.3: LED Driver

The LED driver of the transmitter consists of a enhancement n-gate mosfet that function as a switching component. When the digital signal from the micro-controller is logic 'high', the mosfet would be 'switched on'. The drain (D) and the source (S) of the mosfet would then be conducting and current would start to flow which would cause the LED to turn on at the same time.

As shown in Figure 4.3, the output signal from the buffer amplifier would pass through a voltage divider and connected to the gate of the n-gate mosfet. The drain of the mosfet is connected to the cathode of the LED being driven. A source resistor R_{11} of 44Ω is connected to the source to stabilise the mosfet.

The mosfet that had been chosen is a IRFU120 [23] manufactured by Vishay, that is readily available in the lab. In addition, the mosfet also provide fast switching of up to 100MHz. Therefore, this mosfet is a good fit for this system. However, the IRFU120 mosfet have a rather high $V_{GSth} \in [2.0V, 4.0V]$ (Gate to Source Threshold). Due to the fact that, the micro-controller outputs digital logic 'high' of 3.3V, an amplification is required in order for the mosfet to function properly. This could be avoided, if a n-gate mosfet of low threshold voltage is used.

Trans-impedance Amplifier (TIA)

The trans-impedance amplifier (**TIA**) is used to convert the current received by the photodiode into a voltage signal. Due to the linear response of the current to voltage, the TIA is a good fit to connect to the photodiode. The cathode is connected to the non-inverting input of the TIA. The schematic [24] of

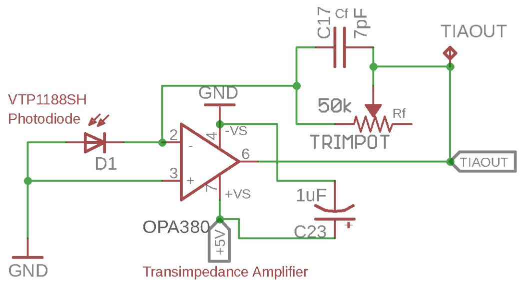


Figure 4.4: Trans-impedance Amplifier (TIA)

the circuit is shown in Figure 4.4. A variable resistor of $R_f = 50k\Omega$ is used to control the gain of the circuit. A capacitor $C_f = 7pF$ is connected in parallel with R_f to improve stability. The bandwidth of the circuit is calculated as follows $f_{cut} = \frac{GBW}{2\pi R_f C_f}$ where GBW is the gain bandwidth of the op-amp being used.

OPA 380 [25] manufactured by Texas Instruments (TI) have been chosen and suits the criteria needed by a current to voltage converter. The OPA 380 provides a large transimpedance bandwidth of greater than 1MHz and low input noise. The gain bandwidth of OPA380 is of 90MHz, of which makes the frequency cutoff to be more than 40THz. The OPA380 is powered with 5V single voltage supply.

Amplifier

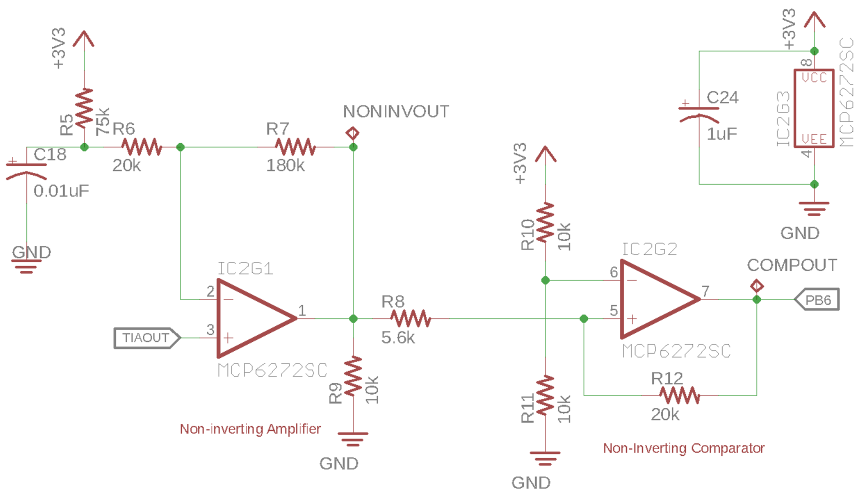


Figure 4.5: Non-Inverting Amplifier and Analog Comparator with Hysteresis

A non-inverting amplifier has been used to further amplify the signal from the TIA output. The gain of the amplifier can be calculated as follows $A_v = 1 + \frac{R_7}{R_6} = 10$.

Analog Comparator

Subsequently, the output from the amplifier is connected to a analog comparator. The comparator converts the signal to a stable digital square waves. When the input voltage goes above threshold voltage V_{TH}, the output goes to logical 'high'. Identically, when input voltage goes below V_{TL}, the output goes to logical 'low'. This comparator design provides hysteresis between the transition between them and thus decrease instability of the output due to noisy input signals. Figure 4.6 shows the transition between the threshold voltages. The threshold voltages can be calculated as follows:

$$V_{TH} = ((R_8 + R_{12}) * V_{REF} - (R_8 * V_{cc}))/R_{12} = 1.97V$$
$$V_{TL} = ((R_8 + R_{12}) * V_{REF} - (R_8 * 0.1V))/R_{12} = 1.18V$$
$$Hysteresis = V_{TH} - V_{TL} = 0.784V$$

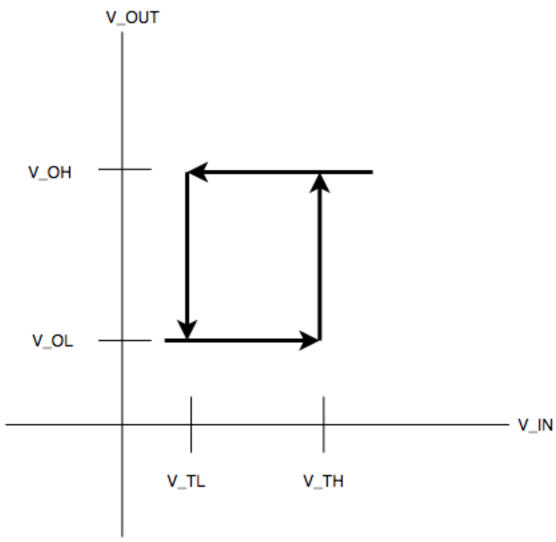


Figure 4.6: V_{OUT} to V_{IN} of the Comparator with Hysteresis

The same MCP6272 [22] manufactured by microchip has been selected due to the high gain bandwidth. The MCP6272 comes in a dual op-amp package. Therefore, the non-inverting amplifier and the analog comparator uses the same chip.

4.2.2 Digital Components

The digital components of the system are separated into few blocks including retrieving data from the SD card, encoding and modulating the raw data into carrier square waves. Lastly this signal would then be transmitted to the analog buffer amplifier through the GPIO port of the micro-controller.

The base of the software consist of a light weight Real-time Operating System (RTOS). The RTOS provides 2 different type of scheduling method such a round-robin scheduling and priority scheduling. In this project, the priority scheduling is used in both the transmitter and emitter. The OS is discussed further in the background section.

In each block, contains 1 or more threads that is independent with other threads. Each of them has been assigned a priority based on the functionality and the importance of that particular thread.

Secure Digital (SD) Card (Transmitter)

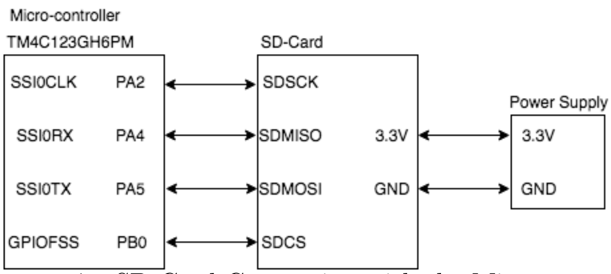


Figure 4.7: SD Card Connection with the Micro-controller

Due to the lack of large non-volatile memory in the micro-controller, a SD card is needed to store interesting data to be transmitted. The micro-controller are setup such that the transmitter are transmitting the same file repeatedly. As for the receiver, the data received are going to be reused in a repeatedly matter. Therefore, the SD card is a good option to replace the small non-volatile memory of a micro-controller.

In the transmitter, raw data that needs to be sent are stored in the SD card. This is the same for the receiver, as the data received are stored instead. This could be any file format and file size that is smaller than 50 MBytes. The application layer would decide the file format that needs to be stored in the SD card. Due to the design requirements, we would want to store txt format and mp3 format files. This would be discussed in further detail in the application layer section.

Serial Peripheral Interface (SPI) protocol is used to interface with the SD card. Figure 4.7 shows the connection between the micro-controller. The file system architecture used to format the SD card is **FAT**32. Files that wants to be sent are saved to the SD card using another computer system before inserted into the transmitter. Hence FAT32 file system is used. In addition, most computer system can read or write to FAT32 file system. This ease the process of adding new files to be sent or transmitted. The FatFs [26] module, which is a light weight implementation of FAT32 file system is used in the micro-controller to interface with the SD card.

In the transmitter, a thread is created with high priority at the start of the program. This thread which is the producer, is responsible to read a specific named file of a fixed amount of bytes from the SD card and pass it into the a global buffer (comBuffer). This buffer is used to pass raw data to be sent to the encoder and modulator thread which function as the consumer. Synchronisation primitives provided by the OS such as mutex or semaphores have been used to synchronise between the producer and the receiver.

Encoding and Modulation (Transmitter)

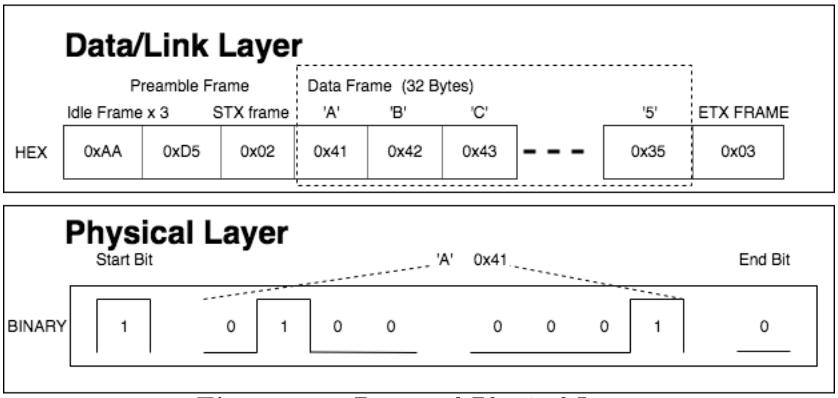


Figure 4.8: Data and Physical Layer

Encoding and modulation are designed into different layers such that the software is modular and easy to maintain. It is made up from 2 individual layers which are the physical layer and the data/link layer. In the physical layer, the format in which a raw byte is transmitted is defined. As in the data layer, the data frame is wrapped around with header data to assist in synchronisation between the transmitter and the receiver.

In the physical layer, each byte of raw data is wrapped with a start bit and a end bit. The physical frame of size (10 bits) are converted into Manchester Encoding and it is then fed into the GPIO output of the micro-controller serially. Figure 4.8 shows the frame format of the physical frame in detail.

In the data layer, the total size of the frame is of 38 bytes. 32 bytes of data frame are wrapped with 3 idle frame, a preamble frame, a STX frame and an ETX frame. As shown, the header information takes up 6 bytes of the whole data frame. Figure 4.8 also shows a graphical view of the whole data frame in the data layer. The coding rate of the data frame when sending 32 Bytes of data is calculated as shown:

$$Rate = \frac{data_{size}}{total_{size}} * 100\%$$
$$Rate = 84\%$$

By taking the specification mentioned in the requirements section, the speed of transmitting data is in the physical layer is 50 kbps. By using Manchester encoding the speed would then be divided by half (25 kbps). The data transmission speed in the data layer would then be around 16.8 kbps. This speed specifies the speed of transmitting useful or actual data excluding header information.

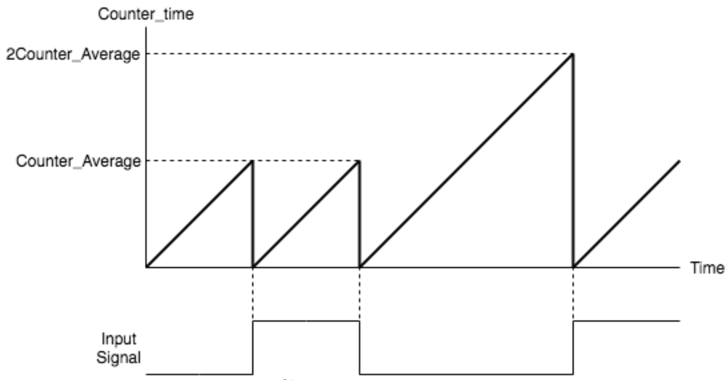


Figure 4.9: Input Capture Edge-Time Mode Example

Edge Capture

Edge capture or also known as Input Edge-Time Mode, is a functionality provided by the micro-controller (TM4C123GH6PM)[10]. In this mode, one of the general-purposes timer are configured to detect rising or falling edge. The timer or the counter would increment on each system clock cycle (80MHz). When a rising or falling edge is detected, the counter would then be recorded and later on reset to 0. The counter, C_t would then indicate the number of system clock cycles between 2 edges. Figure 4.9 shows an example of how the input edge-time mode works graphically. This mode is particularly useful to decode Manchester encoded data, since they encodes logical signals into rising edges and falling edges.

Decoding and Demodulation (Receiver)

By using the edge capture functionality, an decoding process is then implemented to decode the received signal. The software that is responsible to decode the signal takes into account the average system clock cycles, C_{avg} between edges by using the idle frame which consists of consecutive '01's. By using C_{avg}, the decoded determines if the data received is not corrupted. C_{avg} is also used to determine if there are 2 consecutive '1's or '0's in the signal. This happens when C_t received is approximately $2C_{avg}$.

An extra feature of detecting changes in transmitting frequency is also implemented in the decoder. When the clock cycle C_t differs by a certain threshold C_{thresh} from C_{avg}, in a consecutive matter, the decoder than register a change in transmitting frequency and recalibrate the internal settings of the decoder.

SD Card (Receiver)

In the receiver, the decoded data is then stored in the SD card. A thread with high priority is responsible to take the raw data and write them into the SD card. This thread function as the consumer and the producer being the decoder thread that was discussed in the previous section.

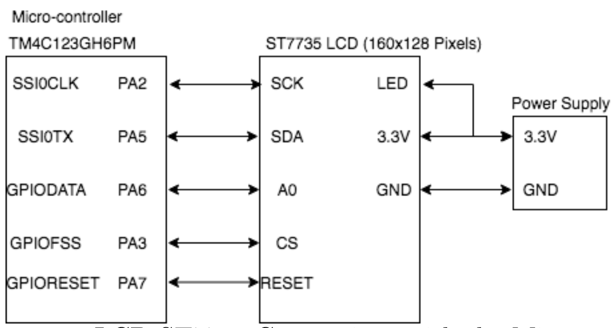
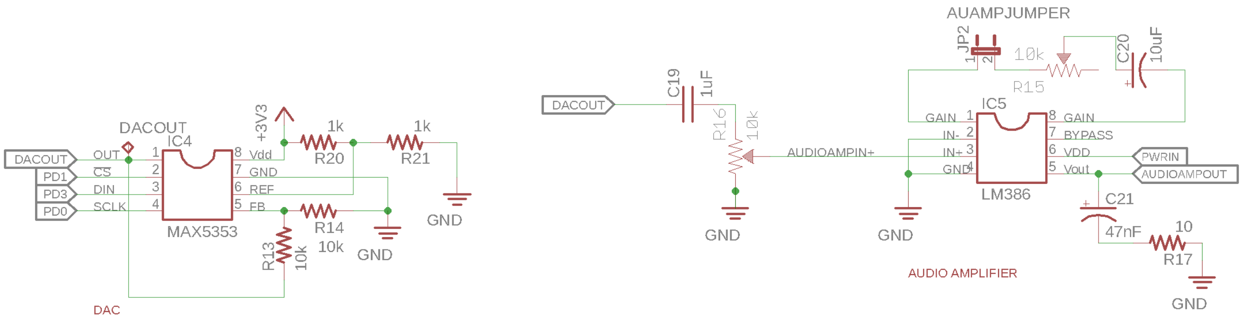


Figure 4.10: LCD ST7735 Connections with the Micro-controller

LCD Interfacing

A 1.8 inch LCD display module (ST7735) [27] is used to display text or images to interact with the user. The ST7735 module uses SPI protocol to interface with the micro-controller. Figure 4.10 shows the connection between the module and the micro-controller.



(a) Digital to Analogue Converter MAX5353 **(b)** Audio Amplifier LM386

Figure 4.11: Schematics of both DAC and the audio amplfier

Audio Jack Interfacing

In order to play audio files such as MP3 or WAV, an audio jack is added to the receiver of the system. This section consists of interfacing with a DAC chip, audio amplification and connections with the audio jack system.

Due to the lack of DAC functionality from the micro-controller used, a DAC chip has been chosen to convert digital bits of an audio file into analog signals. The MAX5353 which is a 12-Bit Digital to Analog Converter (DAC) [28], would suit our application since it work in 3.3V logic. Figure 4.11a shows the connections between the DAC with the micro-controller. The SPI protocol is also used. The connections used is based on the preferred connections in order for the DAC to work as unipolar rail-to-rail output circuit.

The output from the DAC is then amplified using a audio amplifier should be used in order to ensure a good quality of the audio signal. The LM386 [29] which is a low voltage audio power amplifier has been used. The Figure 4.11b shows the schematic of the audio amplifier chip. The default gain of circuit is $G = 20$, A jumper JP2 has been included to allow adjustment of gain of range $G \in [20, 200]$ by varying the variable resistor R_{15}.

The audio jack used is a general 3.5mm female audio jack. The SJ1-3523NG [30] without switches has been used. Figure 4.12 shows the schematic of the audio jack that connects the output from the audio amplifier.

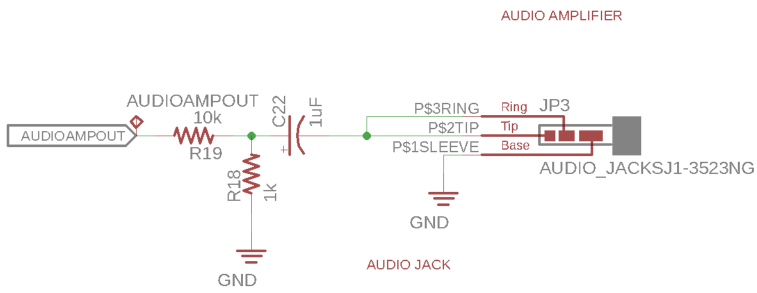


Figure 4.12: Audio Jack Connections

4.3 Application Layer

Figure 4.13 shows the state diagram of both the transmitter and receiver. In a higher level overview, the transmitter are programmed to work in few modes to fully demonstrate the functionality of the communication system using visible light. In default, the transmitter is setup in file transfer mode. Where as the receiver is setup with the file reading mode. Different modes can be switched in both the transmitter and receiver by physically pressing a the left switch (SW1). In this section, we would discuss the applications by going through each mode in the transmitter.

4.3.1 File Transfer Mode

In this mode, file of any format is able to be transferred. However, in this design the file that needs to be transmitted have a fixed name. The name is configured as follows: audio.mp3 and text.txt. The right physical switch (SW2) could be used to toggle between them. Extensions of the system of having other wireless connectivity such as bluetooth could be used to to allow configuration of picking which files to be transmitted by using other mobile devices.

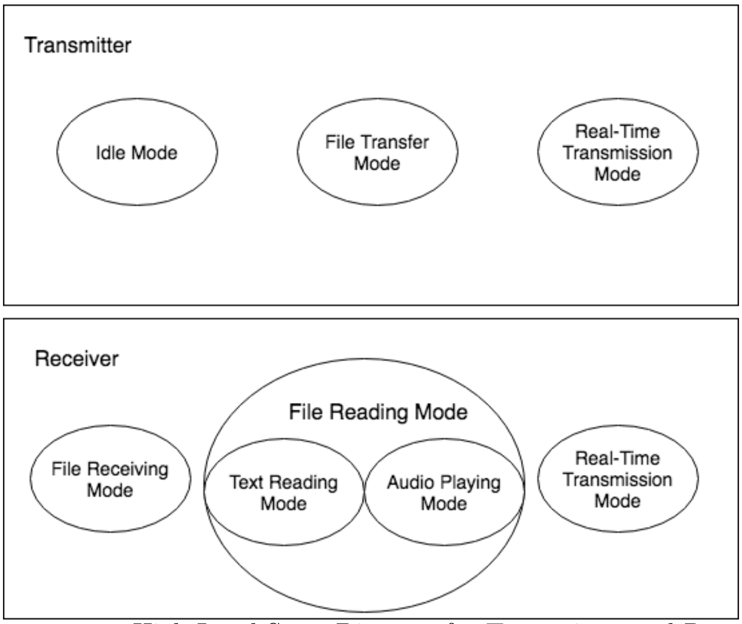


Figure 4.13: High Level State Diagram for Transmitter and Receiver

The receiver have to be set up in the file receiving mode in order to receive a file from the transmitter. The transmitter first sends a data frame that includes the header information such as file name and size of the file that is going to be transmitted. The transmitter would then start to transmitting raw data bits of the file till the End of File (EOF). The receiver would wait for the header information of the file and start to write received raw bits into the SD card.

The file maximum size that needs to be transferred is of 1MegaBits. By assuming the data transmission speed is 16kbps, the time required to send the file is approximately 1 minute. This will be tested to ensure that the non-functional requirements is met.

4.3.2 Real-time transmission Mode

In this mode, a text file of named realText.txt is read from the SD card in the transmitter. The receiver have to be setup into real-time transmission mode. In this mode, the transmitter would transmit the string of text from realText.txt repeatedly and receiver would display the text on the LCD screen in a real-time manner. In the receiver, the right switch (SW2) can be used to clear the text of previously received text on the LCD screen.

Since the speed of the transmission is 16kbps, the maximum speed of the text transmission is 16 characters per second.

4.4 Use Case

In this section, a typical use case of the system in different operating modes are shown.

4.4.1 Real-time Transmission Mode

1. A text file of name realText.txt with text contents are saved in the SD card and the SD card is formatted in FAT32 file system.

2. The transmitter have to be switched to real-time transmission mode. This could be done by pressing the left switch (SW1) of the transmitter. The LCD screen of the transmitter should display "Real-Time Transmission Mode".

3. The Receiver have to be switched to real-time transmission mode. This could be done by pressing the left switch (SW1) of the receiver. The LCD screen of the receiver should display "Real-Time Transmission Mode"

4. The user would then align the receiver until text information is starting to be displayed on the LCD screen.

4.4.2 File Transfer Mode

1. A text file of text.txt and audio.mp3 that needs to be transmitted have to be saved in the SD card and the SD card is formatted in FAT32 file system.

2. The transmitter have to be switched to file transfer mode. This could be done by pressing the left switch (SW1) of the transmitter. The LCD screen of the transmitter should display "File Transfer Mode".

3. The Receiver have to be switched to real-time transmission mode. This could be done by pressing the left switch (SW1) of the receiver. The LCD screen of the receiver should display "File Receiving Mode"

4. The user would then align the receiver and a string of "receiving file.." should be displayed on the LCD screen to indicate the start of receiving a file.

5. A string of "File Name: xxxx.xxx received" is then displayed on the LCD screen to indicate the finished process of receiving a file.

6. The receiver would then be automatically be switched to the file reading mode or audio playing mode depending on the format of the file being received.

7. In file reading mode the, text of the file would then be displayed on the LCD screen on the receiver. The right switch (SW2) could be used to switch between pages of the text.

8. In the audio playing mode, the audio is then played through the audio jack of the receiver. The right switch (SW2) could be used to pause or play the audio file.

9. The user could switch back to the file transfer mode by using the left switch (SW1) of the receiver.

Chapter 5

Evaluation

5.1 Overview

The design is tested mostly using prototype testing method. The Table 5.1 shows the 2 core requirements that need to be tested. The physical layer speed and the distance between the transmitter and the receiver were test by measuring the frequency response of each analog front-end blocks. Data of 1 Mbits were also sent to check the application requirements of the system were met

Table 5.1: Core Requirements

Requirements	Target	Testing Method
Physical Layer Speed	100 Kbps	Prototype Testing
Distance	1 m	Prototype Testing

5.2 Prototype

A prototype of the design was made to be able to test the functionality of the system. This prototype would be used to test out the requirements that was defined in Chapter 3. This prototype would also be tested in the Museum of Communication, Burntisland. The system would be used to receive extra informations about a particular exhibits in the museum. This would be able to demonstrate the concept of visible light communications to the visitors in the museum.

A printed circuit board (PCB) had been designed using EAGLE CAD software. The transmitter would be powered using wall plug power supply and the receiver would be powered either using wall plug power supply or an external battery pack. The full design of the schematic and the design of PCB has been included in the appendix section. The source code of the PCB design is located in the following GitHub repository [1].

The source code of both the transmitter and the receiver can be found in the following GitHub page [1]. The design was implemented in C and compiled using Keil [31].

5.3 Testing and Results

In this section we start of by measuring the performance of each analog components. Basically, we would start with measuring the performance of the LED driver at the transmitter. Similarly, the performance of the TIA was measured. Finally we then measure the performance of the amplifier with the comparator.

5.3.1 LED Driver

Introduction

LED driver is one of the analogue front-end block that drives the LED using the micro-controller in the transmitter. This circuit consist of a non-inverting amplifier and a **NMOSFET** that act as a digital switch that drives the LED.

Method

Firstly, the threshold level of the n-mosfet was measured and recorded. Secondly, the frequency response of the LED driver was measured by transmitting 1kHz of square waves and 50kHz of square waves using the micro-controller.

Result

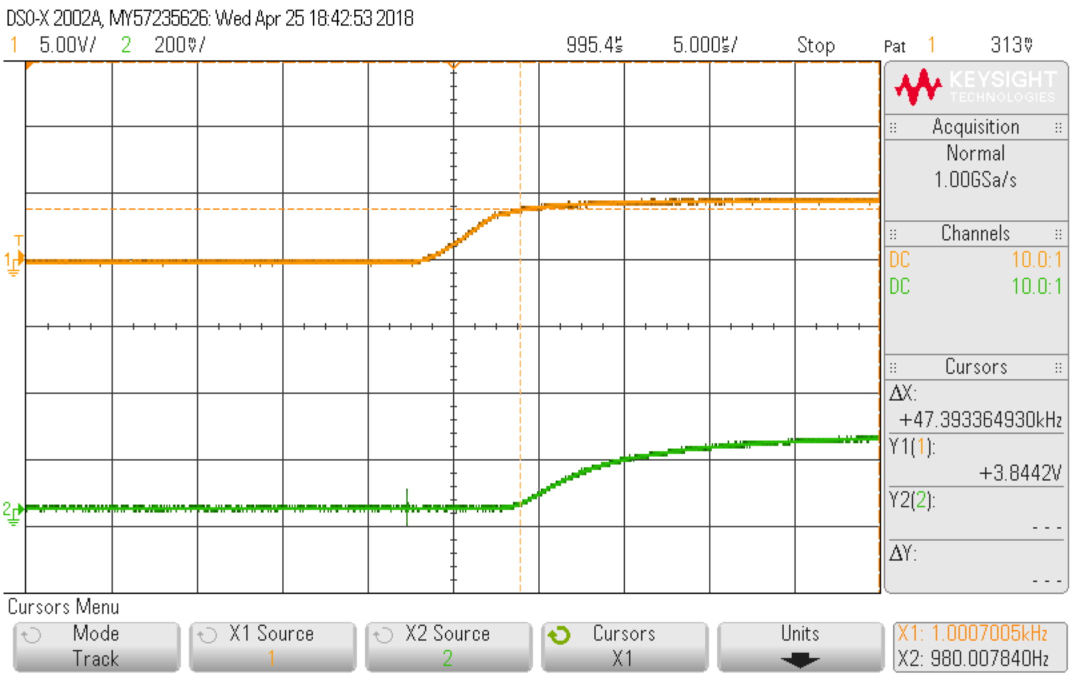
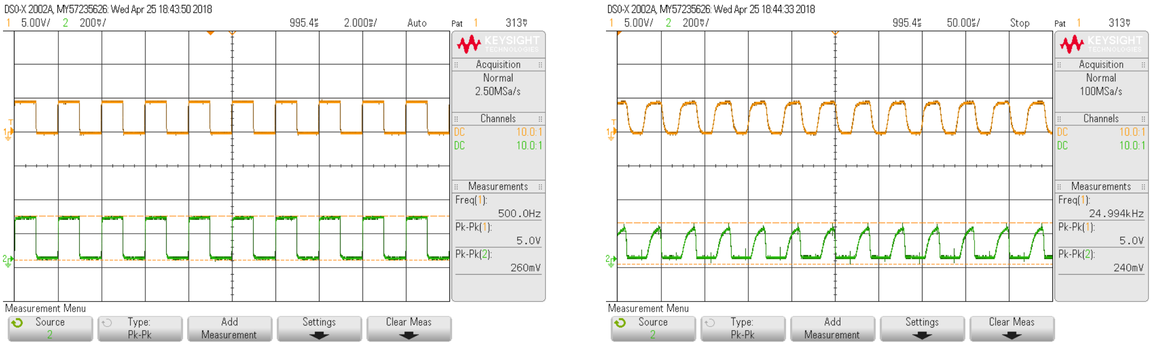


Figure 5.1: Voltage Level of the Gate of the N-MOSFET and across the Source Resistor in reference to GND



(a) 1kHz

(b) 50kHz

Figure 5.2: Frequency Response for LED driver

From Figure 5.1, we can see that the the threshold voltage, $V_{TH} \approx 3.8V$. The threshold voltage falls into the range of the IRFU120 NMOSFET [23] $V_{GSth} \in [2.0V, 4.0V]$ (Gate to Source Threshold). This shows that the buffer amplifier before the nmosfet is required in order to properly drive the LED since the voltage level of the micro-controller in reference to ground is 3.3V.

Figure 5.2 shows the frequency response of the LED driver. This shows that the parasitic capacitance of the LED driver diminishes the amplitude of the signal when the frequency increases.

5.3.2 Trans-impedance Amplifier (TIA)

Introduction

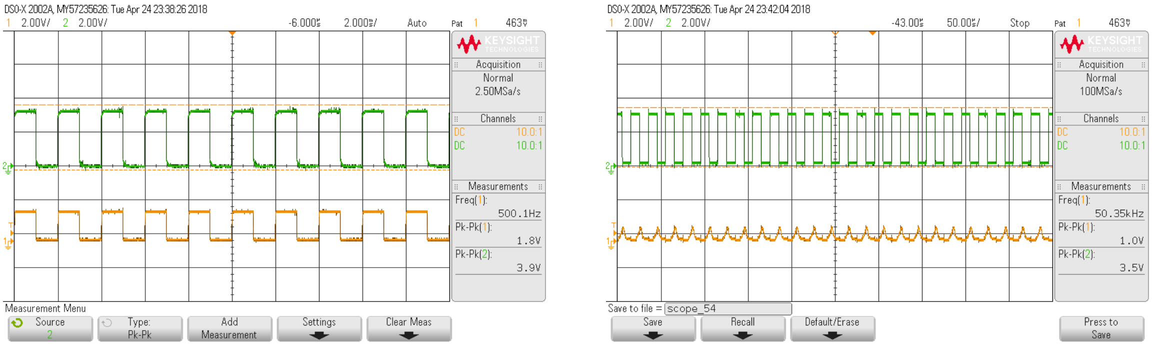
The trans-impedance amplification s an important block that is normally used to amplify the current generated by the photodiode. TIA greatly impacts the performance of the system. A poorly calibrated TIA might cause reduced signal and might also cause instability. The performance of the TIA is measured by measuring the frequency response of the TIA.

Method

To measure the performance of the TIA, the distance between the transmitter and the receiver was fixed at 15cm. This follows by varying the frequency of the transmission in the transmitter. The range of the frequency used was, $F \in [1kHz, 100kHz]$. The peak-to-peak amplitude of the output from the TIA was measured.

Result

Figure 5.3 shows the frequency response for both extremes where as Figure 5.4 shows the frequency response for the TIA. The amplitude was reduced by 50% when the frequency was increased from 1kHz to 100kHz. This result shows that the system designed was not able achieve high speed transmission.



(a) 1kHz

(b) 100kHz

Figure 5.3: Figures of Frequency Response of TIA

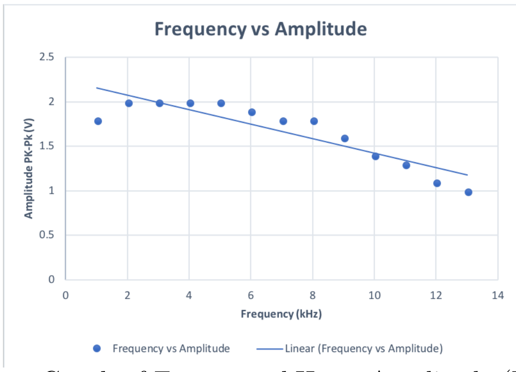


Figure 5.4: Graph of Frequency kHz vs Amplitude (PK-PK) V

Discussion

The main reason that affects the performance of the TIA was the photodiode. We can model the photodiode as shown in Figure 5.5. The junction capacitance of the photodiode, C_j and the feed back resistor, R_f forms a low pass filter. The frequency cut-off of the low pass filter was calculated as follows. $F_c = \frac{1}{2\pi R_f C_{total}}$. The typical junction capacitance of the VTP1188SH photodiode was around $C_j = 180pF$ [6] and $C_f = 7pF$. The maximum resistance of the feedback resistor was $R_f = 50k\Omega$. Hence the cutoff frequency can be calculated as $F_c \approx 17kHz$. This shows that the design was not optimised for high speed transmission. For the current design, the maximum speed of around 50kHz could be used and allowed a good reformation of the digital signal. The limit of the speed could be improved by using a better photodiode that have a smaller junction capacitance such as VBPW34S which has typical junction capacitance of $C_j = 25pF$ [32].

Further more, it is worth mentioning that the photodiode (VTP1188SH) have a peak spectral response of $\lambda = 925nm$. The LED can be chosen such that the emitting photon have the same wavelength with the peak spectral response of the photodiode. This would then increase the performance of the TIA.

Lastly, one of the reason that the TIA only works on a small bandwidth is because of the external noise. This is cause by the fluorescent lighting that was located in the lab that the experiment was located. In Section 5.3.5, we would test and measure the performance of the overall circuit in terms of the fluorescent lighting noise.

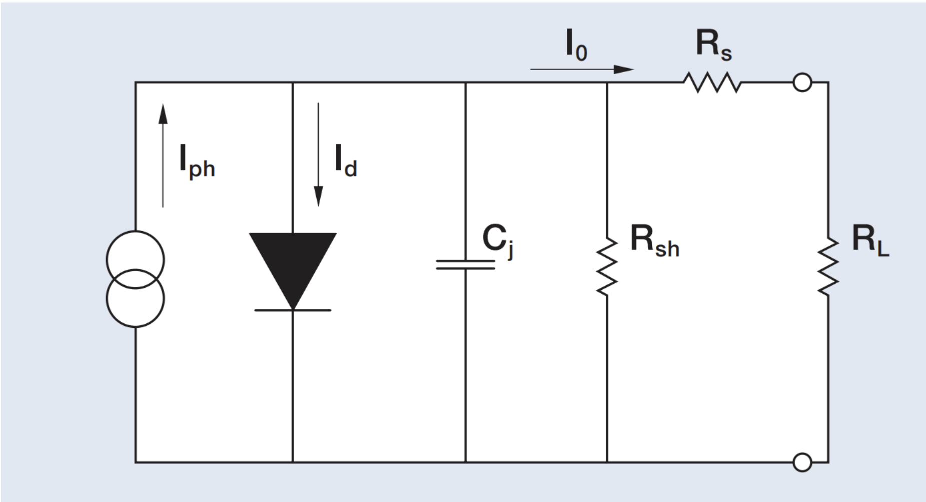


Figure 5.5: Figure of Modelling Photodiode as a diode [33]

5.3.3 Non-Inverting Amplifier and Non-Inverting Comparator

Introduction

The non-inverting amplifier and the non-inverting comparator was used to reconstruct the digital signal by converting the distorted analogue signal due to noise. The performance of this block determines the final output that was going to be passed to the micro-controller. If the signal was not able to be reconstructed, the data being transmitted would then be lost or corrupted.

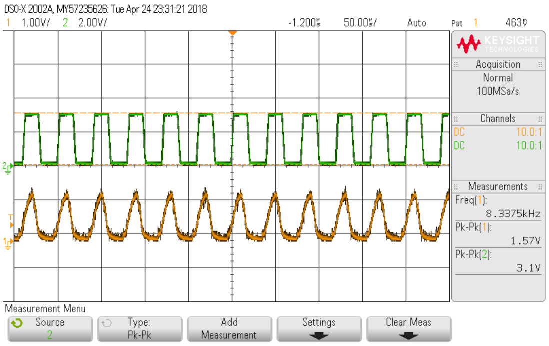
Method

The distance between the transmitter and the receiver was fixed to be 15cm, the input and the output of both the amplifier and the comparator were measured. The frequency of 50kHz was made constant throughout whole the measurement.

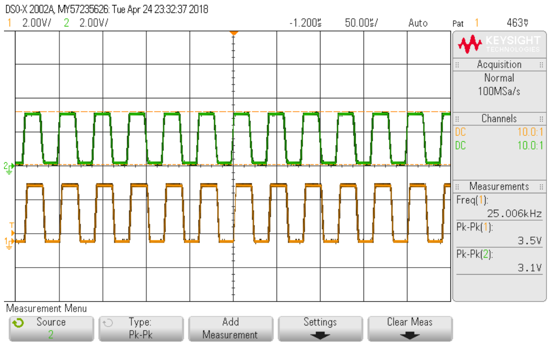
Result

Discussion

Figure 5.6a shows that the signal was amplified with $Gain \approx 1.97$. Figure 5.6b shows no difference between the input signal and the output signal from the non-inverting comparator. This was because



(a) Output from TIA to Non-inverting Amplifier



(b) Output from Non-inverting Amplifier to Non-inverting Comparator

Figure 5.6: Oscilloscope screenshots for both the Non-inverting Amplifier and the Non-inverting Comparator

the signal after amplification was not distorted and reconstruction of the signal would not be needed. However the signal was amplified to have amplitude of 3.5V.

5.3.4 Bit Error Rate

Introduction

One of the key measurements of a communication system is by measuring the bit error rate (BER). When data is transmitted through a communication system, error might be introduced to it. If this happens to a certain extend, this might compromise the system's capability. The calculation of BER is as follows: $BER = \frac{Number of Error Bit}{Total Bits Sent}$.

Methods

The method used here is by testing the prototype. Firstly, the SNR of the receiver after the output of the analog comparator was measured by varying the distance between the transmitter and the receiver. Subsequently, the BER of the system was measured with the appropriate SNR. This was done with transmitting raw data of a known file of 1MegaBits the BER is then calculated as a result by checking number of error bits for the file.

Results

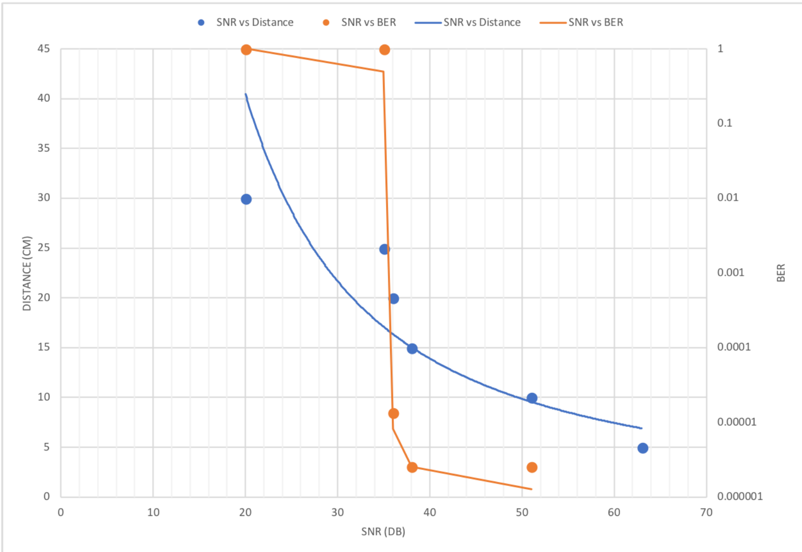


Figure 5.7: Graph of SNR (dB) over Distance (cm) and BER (unit)

Discussion

Figure 5.7 shows both the SNR over distance and also SNR over BER. We can see from the figure that the BER have a huge gap when the SNR crosses 35dB. This shows that the receiver design was more strict to the reconstruction of the digital signal. This was because a comparator was used as the reconstruction block. When the amplified signal did not pass the threshold voltage of the comparator, the data signal would then be lost and corrupted.

5.3.5 Noise (Fluorescent Lighting)

Introduction

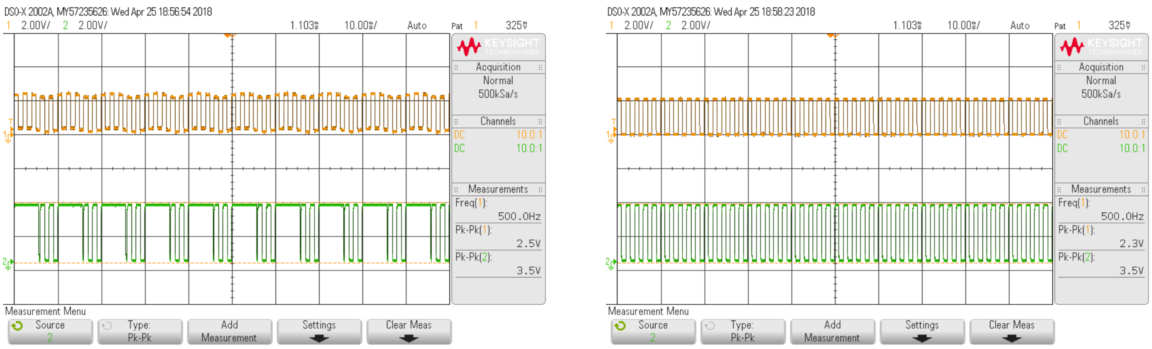
The fluorescent lighting causes unwanted noise that reduces the overall performance of the system.

Method

We measure the noise caused by the fluorescent lighting was measured by measuring the output of the TIA and the output of the comparator with and without the fluorescent lighting switched on with distance between the transmitter and the receiver being fixed to 15cm.

Result

The noise caused by the fluorescent light was shown in Figure 5.8. We can see that the noise of frequency 100Hz is embedded to the signal and causes the comparator output to clip when the input signal reaches



(a) Fluorescent Lighting being Present (b) Fluorescent Lighting being Present

Figure 5.8: Oscilloscope screenshots of the TIA output with the presence of Fluorescent Lighting

the maximum amplitude.

Discussion

We can see even the slight noise that was caused by the fluorescent lighting distorted the signal. If we wanted to achieve a higher distance between the transmitter and the receiver, an good analogue filter should be used to filter out the fluorescent lighting.

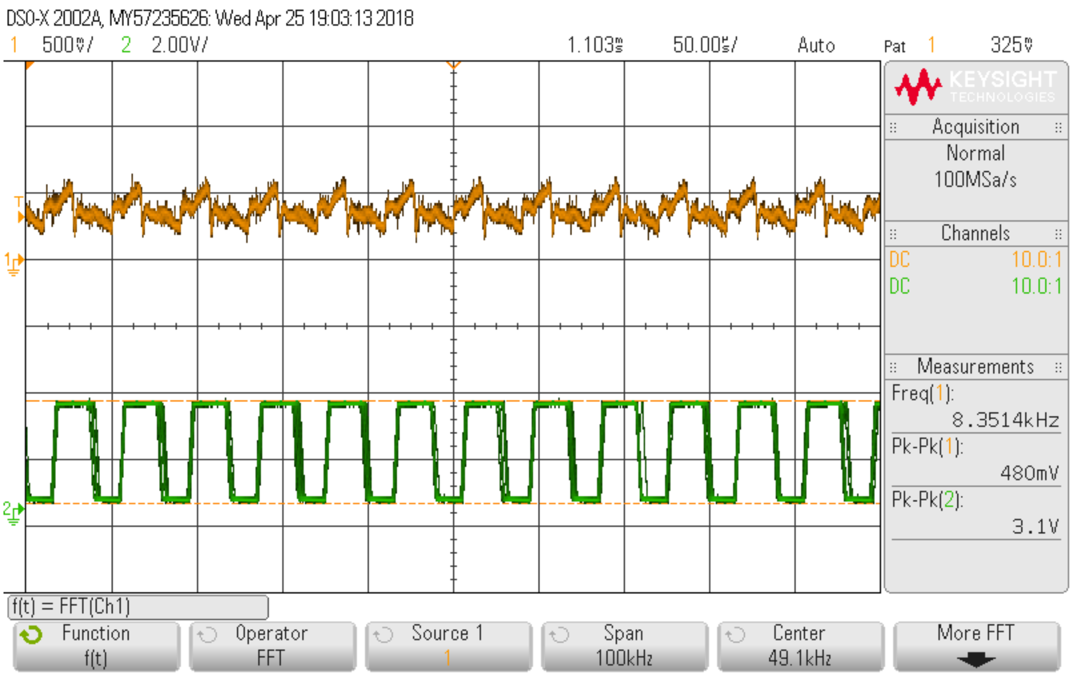


Figure 5.9: Oscilloscope screenshot of showing the TIA output and the comparator without the Fluorescent Lighting, $D = 45cm$

Figure 5.9 shows the TIA output being converted to a digital square wave at the output of the comparator when the fluorescent lighting is switched off with the distance between the transmitter and the receiver being 45cm. This also shows the performance of the comparator with hysteresis since the output stays stable even the output from the TIA is really noisy. Data still managed to be sent and received with a $BER \approx 10^{-2}$

5.4 Assessment

The prototype of the design are able to demonstrate VLC capabilities. This is shown by the prototype capable of transmitting data through using VLC concept. However, we can see that the design does not fully met the functional requirements that was required for the system. The transmission speed does not meet 100kHz and the distance between the receiver and the transmitter is limited to 15cm instead of 1m.

One of the main reason that causes the design to not able to meet the requirements is the choices made for choosing the LED and the photodiode. A more clear and broad research should be made before choosing the right LED and photodiode to suit the requirements needed by the application.

On the contrary note, the design of the system focuses on modularity, where the design is separated into independent design blocks. This allows the system to be maintained and improved easily without having to redesigned the whole system.

5.5 Next Step/Extensions

In this section, we talk about extensions or improvements that could be made to improve the system capabilities. The extensions are divided into 2 categories which are digital and analog extensions.

5.5.1 Analog Improvements

Improving Distance

Distance between the transmitter and the receiver is an important factor that could be improved. For the current system, distance of around 15cm are the maximum distance that provide low **BER** that allows seamless transmission of data that does not compromise the system overall performance

This could be done with using band pass filtering to filter out unwanted noise. This would greatly increase **SNR** of the system and further increase the allowed distance between the transmitter and the receiver. In visible light communications, it is common to have interference of signal that degrades the SNR. This could be commercial fluorescent lights and also any other light sources.

By This could also be done with using a higher power LED or light sources, which would directly increase the SNR. However, this could lead to high power consumption of the system. This would be a tradeoff that needs to be made. Using a LED that emits photon with wavelength that is similar to the peak spectral efficiency of the photodiode would also increase the SNR of the received signal.

Improving Speed

The speed of the transmission is also a key performance measures for communication system. In the current system, the speed of transmission at the physical layer is of $50kbps$. This then leads to around $\approx 16kbps$ in the data link layer after applying modulation and encoding into the data.

By using a better photodiode with low junction capacitance, the bandwidth of the TIA would then be improved.

Automatic Gain Controller

Automatic gain controller (**AGC**) could be implemented to the receiver. The AGC could vary the gain of the received signal due to different distance between the transmitter and the receiver. By using Manchester Encoding scheme, the average signal stays constant. This is particularly useful and would introduce stability for the system.

5.5.2 Digital Improvements

Using DMA for SPI protocol

DMA or short for Direct Memory Access, is a functionality that provide high speed transmission of data. This functionality is provided by the micro-controller (TM4C123GH6PM) that was used in this design. By using DMA, an external DMA controller is used to process data transfer between internal memory to external peripherals. The main micro-processor is then freed from handling memory transfer.

In our design, **SD** card uses SPI protocol in order to transfer data between the internal memory of the micro-controller and to the memory card. SPI could be configured to use DMA and this would greatly improve the overall performance of the RTOS. This is because data transfer between the SD card and the internal memory no longer hogs up the processor and thus a more intense task could be done. This could be a higher frequency of driving the LED that consequently leads to a higher transmission speed.

Error Correcting Codes

Error Correcting Codes could be used to correct incorrect bits after transmission due to noise. Cyclic Redundancy Check (**CRC**) could be used to check the integrity or correctness of the data received received at the receiver side. To simplify current design, CRC are not implemented. However, source code generation in C using Python are available in Github [34].

Wireless Transmission for Transmitter

Specifically for the application that was intended to be used in the museum of communication, the transmitter might be installed and fixed at a non-reachable place such as above the ceiling or inside an sealed container. It might be troublesome to replace new information to the SD card without being able to reach the transmitter installed. Wireless transmission for a transmitter might be used to transmit new data or configure the device. This could be done by adding wireless module such as WiFi or Bluetooth to the transmitter. This would allow other systems such as mobile phones to be able to communicate, configure the transmitter or to replace new information in the SD card.

Chapter 6

Conclusion

The project aim to design a uni-directional visible light communication (VLC) system that could be used in the Museum of Communication. A design of analogue front-end and digital back-end is designed for both the transmitter and receiver. Speed of transmission of 50kHz was achieved in the physical level at a distance of 15cm. In addition, distance of 50cm could also be achieved when there is no external light source that causes interference with the system. The data rate of the system at the application layer is approximately 16kbit/s. The designed system does not able to meet the requirements of the system required such as the speed of transmission is less than 100kHz at the physical level and the distance between the transmitter and the receiver is less than 1m. This is caused by the junction capacitance of the photodiode and low immunity of external noises such as fluorescent lighting.

This project was able to demonstrate the capability of transmitting information using visible light communication. At the end note, the system designed could be used as a base of any simple VLC system, however there are many major improvements that could be made in order to improve the overall performance of the system.

The source code of the software implementation backend and the PCB files which are designed with EAGLE cad are located in the github repository. [1].

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Appendix A

Transmitter Schematic

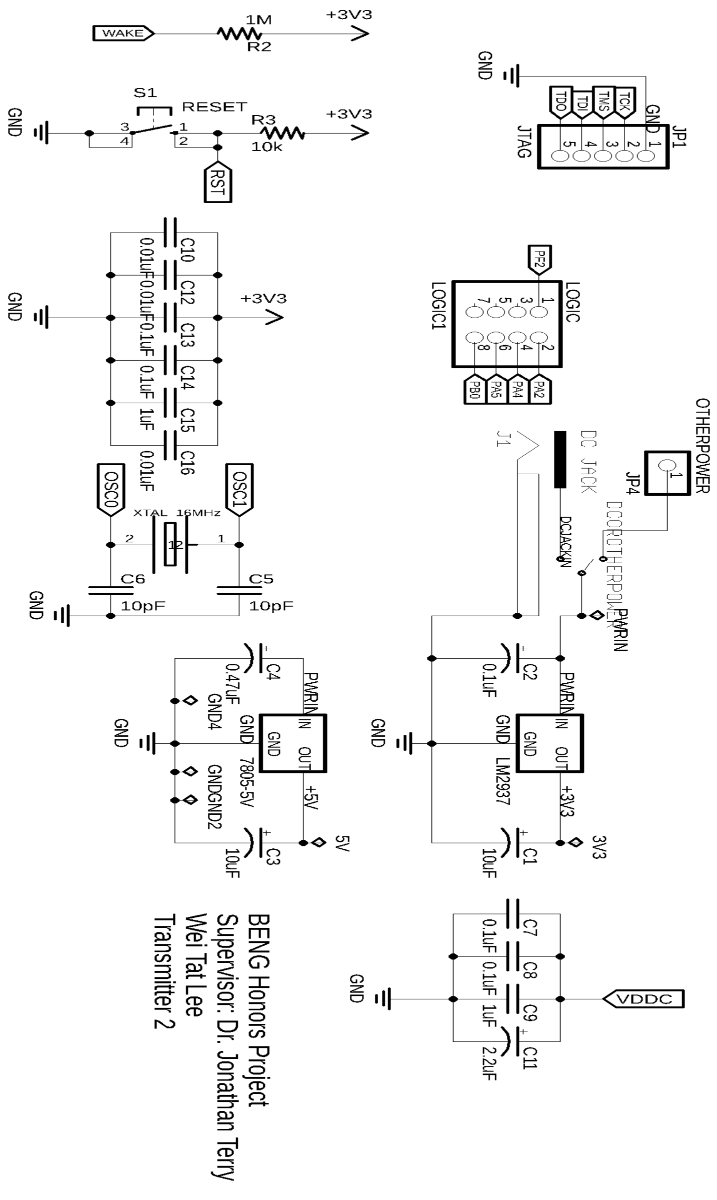

Figure A.1: Transmitter Schematic Part 1

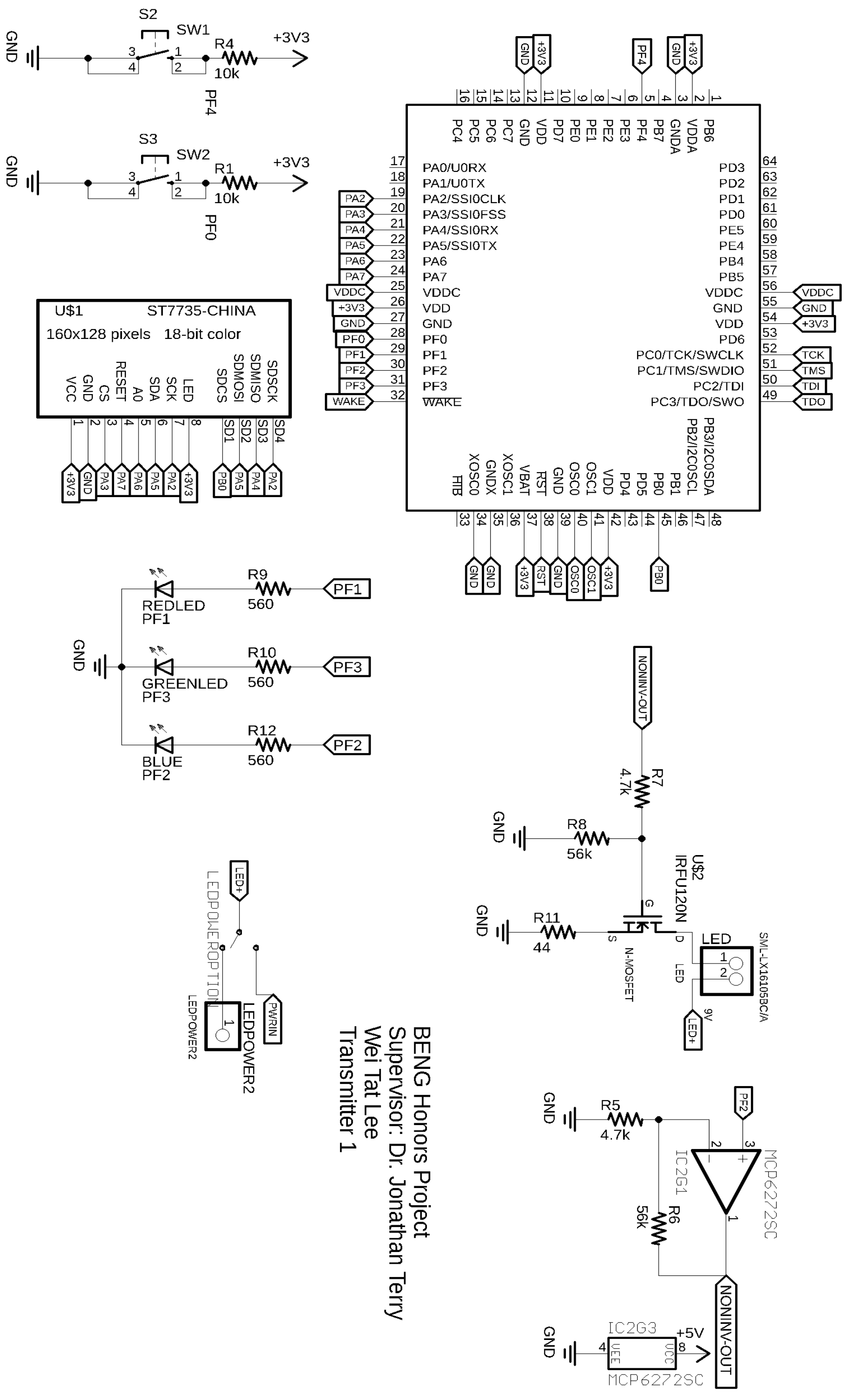

Figure A.2: Transmitter Schematic Part 2

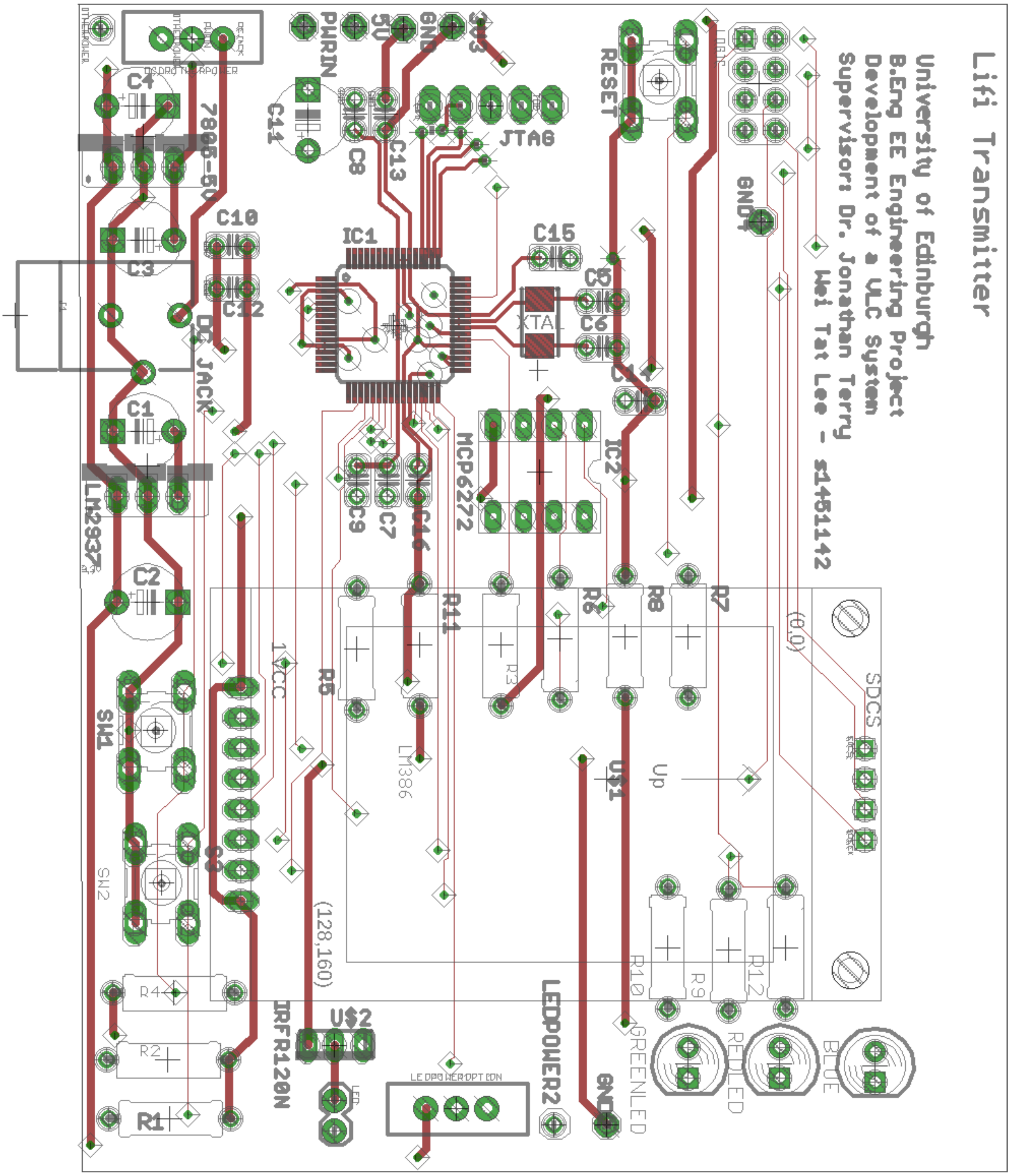

Figure A.3: Transmitter PCB TOP

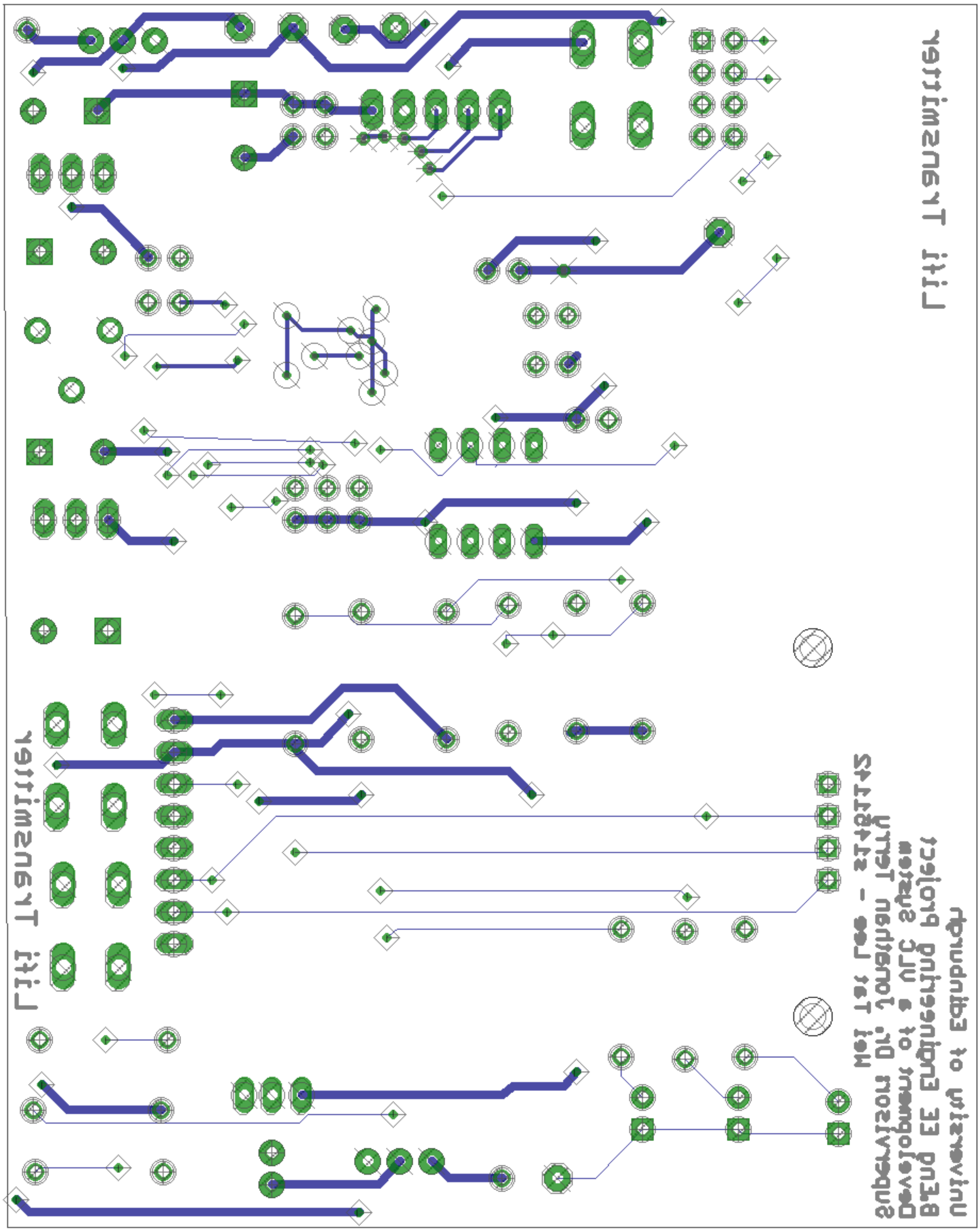

Figure A.4: Transmitter PCB BOTTOM

Appendix B

Receiver Schematic

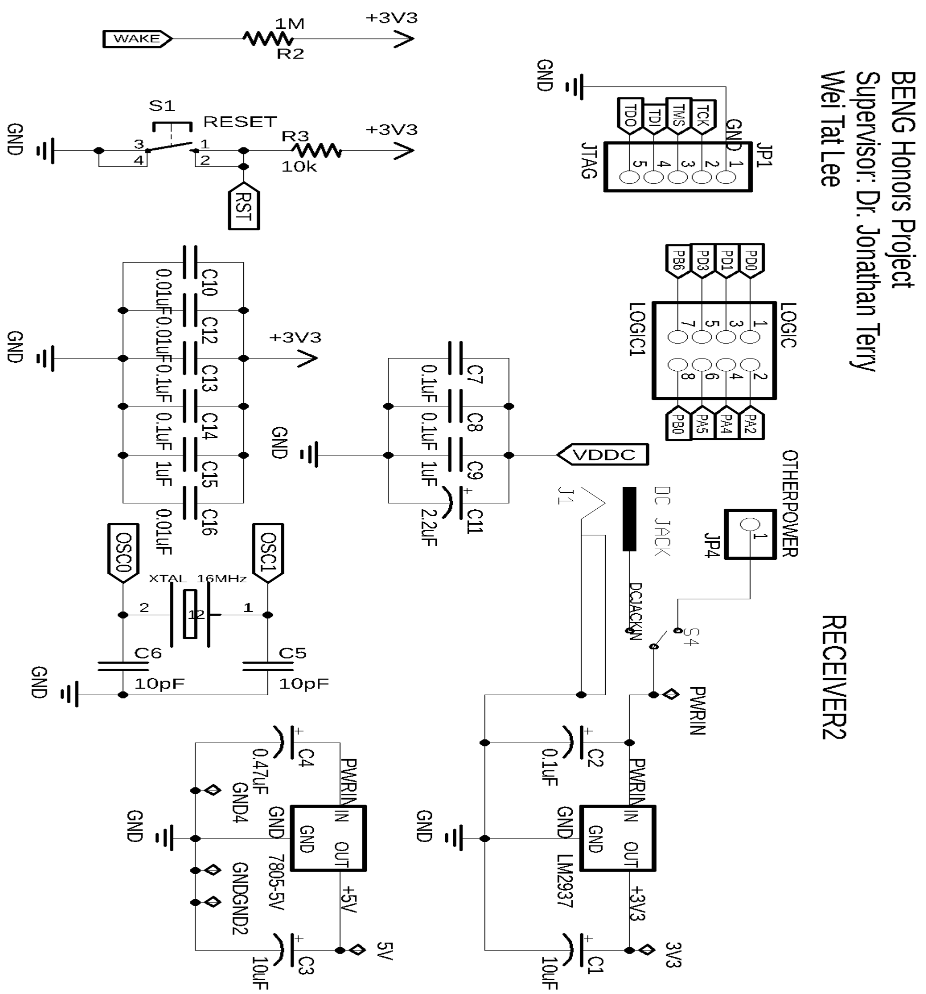

Figure B.1: Receiver Schematic Part 1

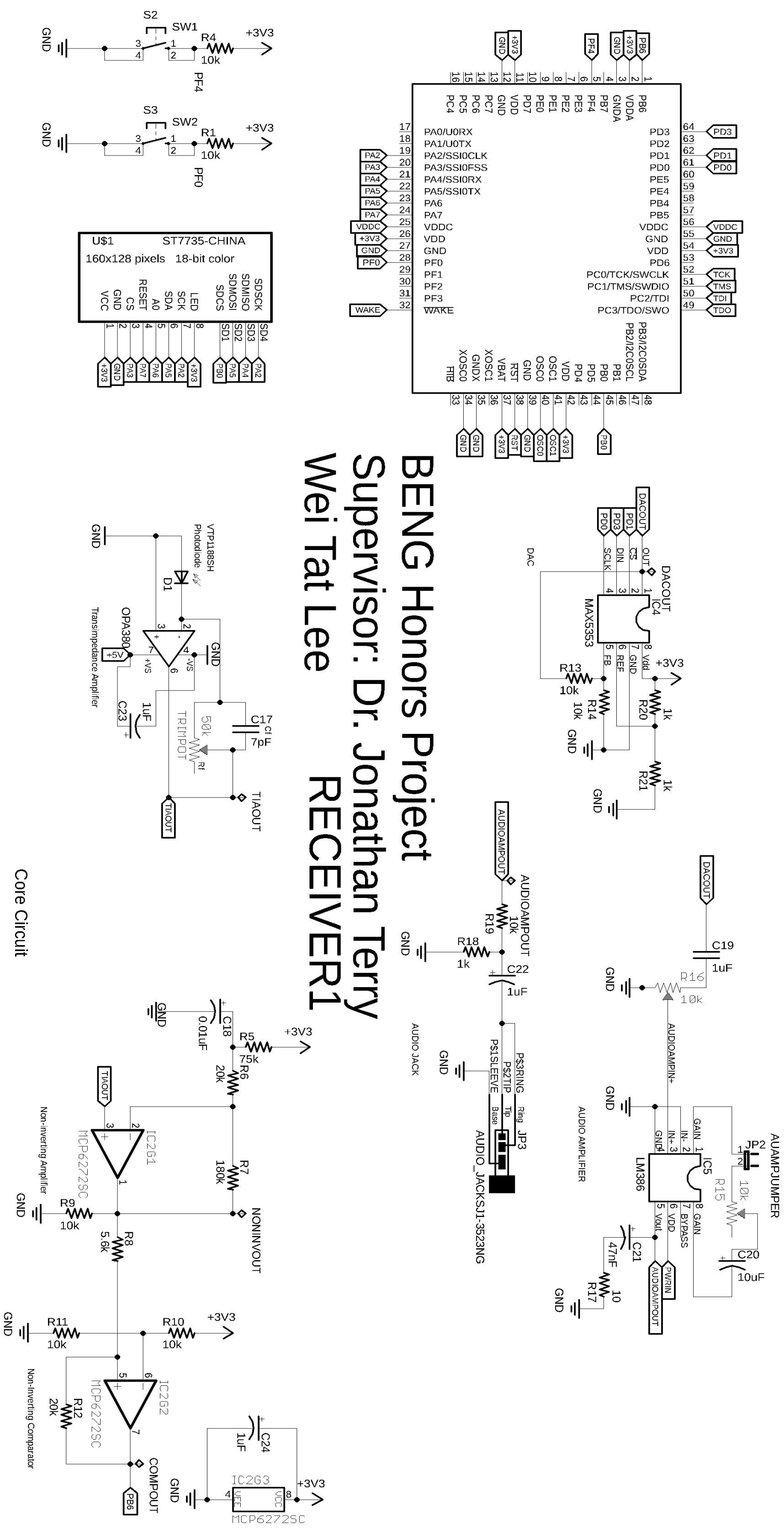

Figure B.2: Receiver Schematic Part 2

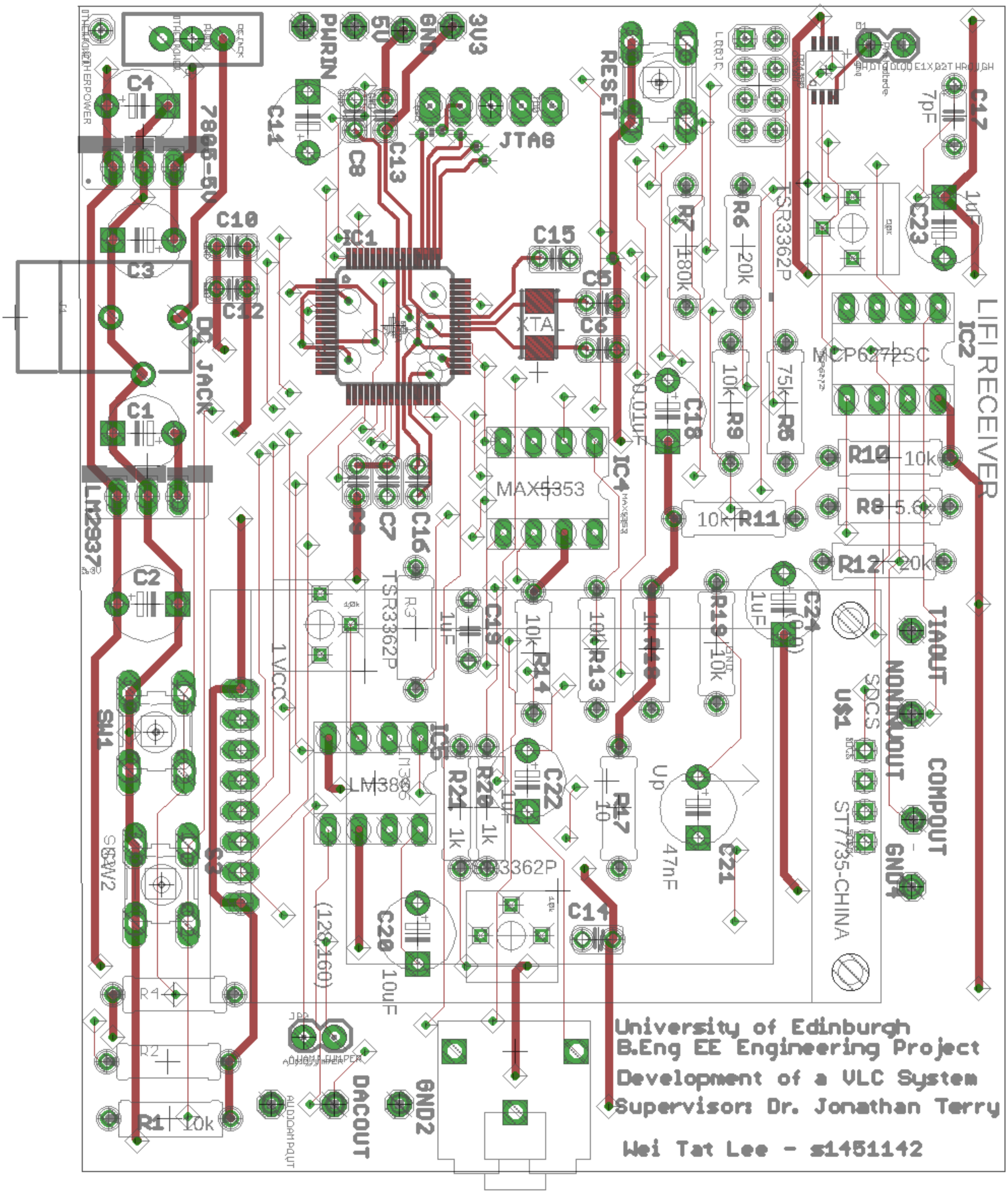

Figure B.3: Receiver PCB TOP

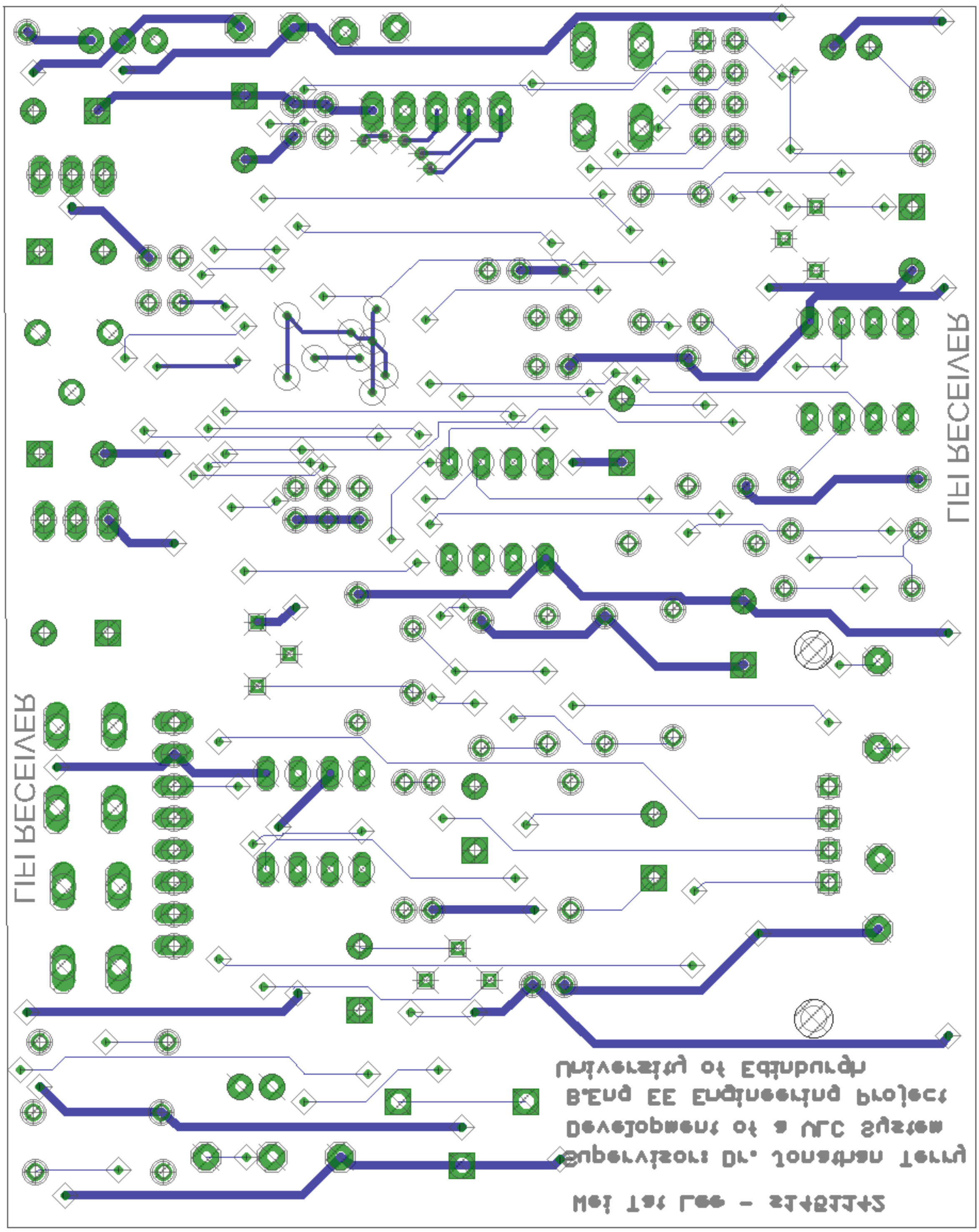

Figure B.4: Receiver PCB BOTTOM