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Progress report for:
Synthesising musical tones using
multiplexed light spectrum analysis

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Executive Summary

This document reports the project progress for synthesising musical tones using multiplexed light spectrum analysis. The project approach couples the analysis of visible spectrum light to create digitally synthesised musical tones. The project combines optoelectronic and communication systems to create a commercially viable prototype of a synaesthetic high quality digital electronic music synthesiser with audio latency under 10ms. This progress report demonstrates the work completed to date in achieving the project's critical objectives. This document outlines the functionality of the two modules that constitute the final project, the transmitter and receiver. A report on the results of a feasibility study conducted to aid in the project design and a discussion on the transmission data is presented. This report concludes by reporting on the tasks required for completion in Semester 2.

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Glossary

AC	Alternating Current
ADC	Analog-to-Digital Converter
BER	Bit Error Rate
CRO	Cathode Ray Oscilloscope
DAC	Digital-to-Analog Converter
DC	Direct Current
FPGA	Field Programmable Gate Array
LED	Light Emitting Diode
PCB	Printed Circuit Board
QAM	Quadrature Amplitude Modulation
RGB	Red, Green, Blue
R _x	Receiver
RZ	Return-to-Zero
T _x	Transmitter
VHDL	VHSIC Hardware Description Language
VSL	Visible Light Spectrum

1 Introduction

This project will produce a device that generates musical tones resulting from the analysis of transmitted visible spectrum light (VSL) over a finite communication distance. This project fuses optoelectronic and communication systems that will produce a high quality digital electronic music synthesiser with audio latency under 10ms. The device has a transmitter (T_x) and receiver (R_x) module; with user interaction only at the T_x and audio output at the R_x . This project requires many core electronic engineering methodologies encompassing analog and digital design, communication protocols, signal processing techniques and software development.

1.1 Rationale

Creating musical tones with analog synthesisers is not a new concept nor making a digital equivalent, however by using VSL to create musical tones adds a synaesthetic component to the average synthesiser. The visual component to creating music adds a further dynamic control to an artist's ability to paint a picture with their music. Recently, many researchers have created novel electronic music synthesis devices [4, 3, 2, 6, 7]. Their approaches have had successful results, however no commercial products have been developed from this academic research. This project aims to develop a prototype for a light based musical synthesiser which will form the basis for a commercially viable product.

Engineering skills of analog and digital design, communication protocols and signal processing methodologies will be used in this project. Analog design will be used for controlling intensity levels of transmitted light (from T_x) and in active signal filtering and audio amplification (on R_x) using operational amplifiers. Digital design will be used for user interaction (on T_x) and software design will be relied upon heavily on both the T_x and R_x modules. Communication protocols will be implemented to transmit data pertaining to user interaction from the T_x to the R_x module so as to differentiate between ambient light and the light being transmitted. Digital signal processing

techniques will be used to disambiguate the received signals from T_x and to create a digital equivalent of an analog synthesiser.

1.2 Project Objectives

The project objectives consist of two categories. Firstly, critical objectives; those that must be met under any circumstances in order to validate a successful project. Secondly, desirable objectives; those that can be considered extra goals for the project, but are not critical to its success. A list of critical and desirable project objectives are listed in Table 1 and Table 2 respectively. The critical objectives are unordered as all must be met to contribute to the success of the project. The desirable outcomes are also unordered due to the spiral project management model [1], whereby the precedence of a desirable outcome will be affected by the circumstances that demand priority at that point in time.

Critical Objectives
Transmit RGB Light from user key press
Transmit modulated user control data
Detect RGB Light from a one metre distance
Detect modulated user control data
Create synthesised waveform based on detected signal
Output synthesised waveform via powered speakers or mixing desk
Audio latency under 10ms

Table 1: Critical Project Objectives

Desirable Objectives
Develop a second advanced prototype board Construct or purchase a housing for the units Increase the transmission distance Create a user manual for the product Add MIDI input and daisy chain to the T_x Add MIDI output to the R_x Add balanced audio output to the R_x Audio latency under 5ms

Table 2: Desirable Project Objectives

2 T_x Breakdown

The T_x module is responsible for user interaction and transmission of the resultant VSL for the light synthesiser. User interaction is in the form of seven keys, one slide switch and three control knobs. The slide switch provides the user with the ability to switch octaves on the synthesiser, while the control knobs affect the attack, sustain and decay of the synthesised audio waveform. The seven keys represent the seven musical notes: A, B, C, D, E, F and G. The pairing of frequencies of sound and those of light have been well documented, resulting in a correlation between musical notes and colour [5] (see Table 3).

Note	Colour
A	Red
B	Orange
C	Yellow
D	Green
E	Blue
F	Indigo
G	Violet

Table 3: Pairing of Musical Notes and Colour [5].

This module will replicate the colours of Table 3 using RGB component LEDs (see Figure 1) and associate them with the seven keys mapped to the musical notes in Table 3. To achieve this, the ratio of RGB LED component intensities will vary for each note. The proposed colour choices for each note must be tested with the selected LEDs in order to confirm that the range is acceptable. Alternative note and colour mappings may be investigated if the proposed colour choices are not capable of being produced with the RGB LEDs.

Synthesisers use envelope shapers that control the synthesised audio output. This module will also consist of three user definable knobs that allow for the sustain, attack and delay of the waveform to be altered. This control knob data is sent by the RGB LEDs across the communication channel to the receiver. As data other than colour is being sent across the communication

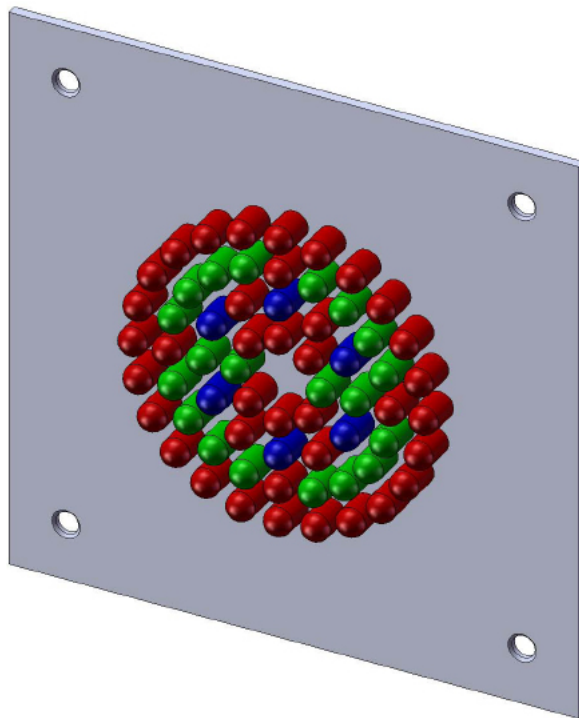


Figure 1: T_x LED Transmitting Module.

channel, a modulation technique is required for transmission. The exact modulation technique must be investigated taking into account that light should always be visible from the module and that the data sent will be asynchronous. With the possibility of all seven keys being pressed at once, the modulation technique must also cater for all data being sent within a specified time period, thus some form of time division multiplexing will be investigated. The effect of ambient light could also impact on the modulation technique, adding the criteria that the modulation method work under AC conditions.

The T_x will use a Spartan 3E FPGA to process user input into a modulated data stream of VSL that will be decoded by the R_x .

3 R_x Breakdown

The R_x module is responsible for detecting and decoding the modulated data stream of VSL arriving from the T_x , one metre away. The receiver detects the incoming stream using photopic detectors for each RGB LED component. The received data stream is decoded to retrieve the control knob data. Using the decoded control knob data and the output of the photopic detectors, this module has all the data it needs to synthesise a sound. The synthesised tone is made audible through dual RCA socket outputs used by mixing desks or powered speakers.

Each musical note is represented by its corresponding colour from Table 3, thus the generated waveform will consist of the specified frequency pertaining to the musical note. The resultant waveform will depend on the decoded modulated data stream that specifies the sustain, attack and delay of the waveform and the frequency of the mapped detected colour. The photopic detectors will need to be considered with respect to the modulation technique that will be investigated. These detectors will need to be able to differentiate between the received light, so that a distinct evaluation of the received RGB LED component values can be made. Using optic filters as an option to assist in the colour discrimination component of the R_x will be tested. The one metre receive distance of the unit will need to be tested, as well as the optical output power of the LEDs in order to quantify the exact range of the device. The sensitivity of the photopic detectors will also impact on the maximum distance the unit will attain.

The final generated waveform is converted to an analog signal that is then sent through two RCA sockets that lead to external powered speakers or mixing desk to produce the final audible tone. This module will use a Spartan 3E FPGA to decode the received data stream, differentiate between detected colours and create the synthesised tone.

4 Feasibility – T_x / R_x

The initial tasks for this project were to construct a set of tests that would determine whether the project concept would be able to be realised through physical components. These initial tests formed the feasibility analysis of the T_x and the R_x . This section will outline the work done in this area.

4.1 Experiment Setup

The first set of experiments were used to determine the distance that could be achieved under ideal and non-ideal conditions. Ideal conditions are under no ambient lighting, while non-ideal conditions are in broad daylight. The initial tests were conducted using several different types of widely available 5mm LED packages:

- Kingbright 5mm Full Color RGB Lamp
- 7,000mcd High Intensity 5mm Red LED
- 10,000mcd High Intensity 5mm Red LED
- 5,000mcd High Intensity 5mm Green LED
- 10,000mcd High Intensity 5mm Green LED
- 5,000mcd High Intensity 5mm Blue LED
- 10,000mcd High Intensity 5mm Blue LED

The light was detected using a TAOS TSL253R light-to-voltage sensor. The TSL253R had a responsivity of 137mV at 635nm with a rise and fall time of 14 μ s. The TSL253R was a photodiode and amplifier in one package and did not have any selective wavelength properties, thus optical filters were required to be placed around the viewing window (see Figure 2) of each light-to-voltage converter. All of these tests used the TSL253R as the R_x .

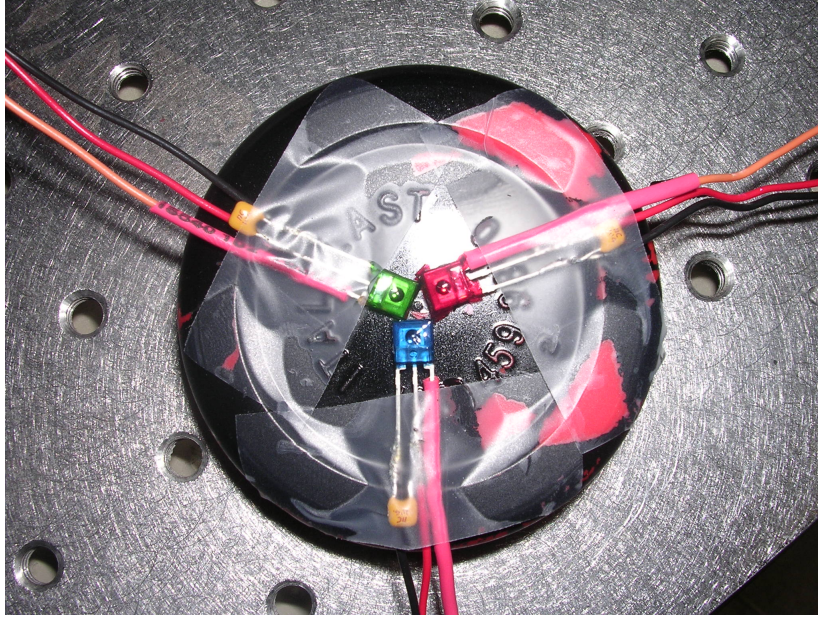


Figure 2: Closed System Photopic Detector Arrangement

A closed system test was devised to perform measurements under ideal conditions (see Figure 3). For this, a 42cm cylinder with a diameter of 60mm was used. End caps were placed at either end, with one end being the T_x while the other was the R_x . A 1kHz RZ pulse stimulated the T_x while a CRO was used to detect the output voltage from the R_x .

The tests comprised of determining the detectable voltage from each RGB LED with each corresponding RGB photodetector (the filtered TSL253R packages). These measurements were important for the recognition of discernable colours, the basis of this project. By being able to find a correlation between the output voltage of the red LED with the red filter, the green LED with the green filter and the blue LED with the blue filter, it would be possible to translate this back into current ratios so that the range of differentiable colours could be determined. This test was also used to examine the ability of the RGB photodetectors to discriminate from which light source the final contributions were received.

Results of these tests are in Table 4 (for the 5mm RGB single package LED) and Table 5 (for the 5mm RGB individual package LEDs –7,000mcd Red;

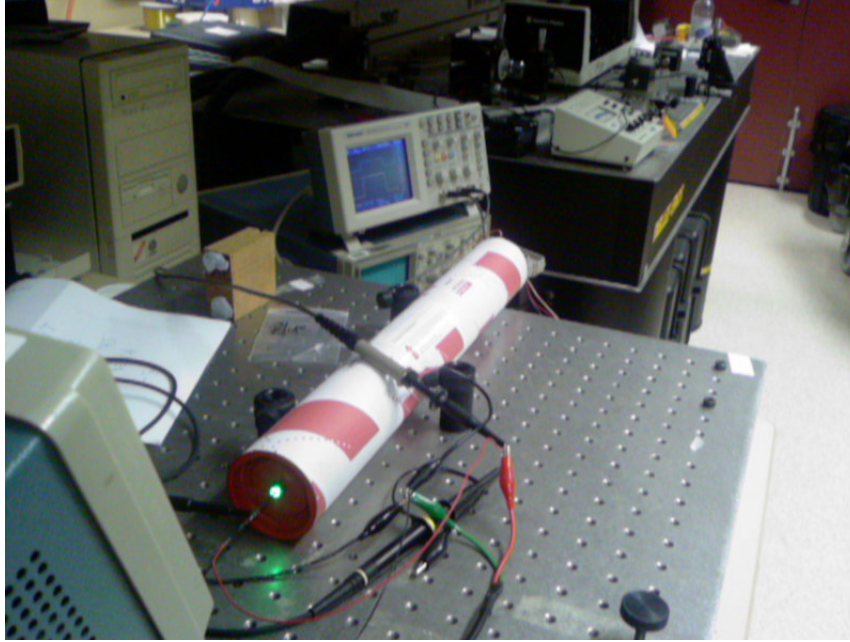


Figure 3: Closed System Overall Testing Setup

5,000mcd Green; 5,000mcd Blue).

LEDs/Filters	Red	Green	Blue
Red	50mV	20.2mV	12mV
Green	6.2mV	8.8mV	7mV
Blue	13.4mV	14.8mV	58.4mV

Table 4: Closed System Testing: 5mm RGB Single Package – The diagonal voltages are not ideal.

LEDs/Filters	Red	Green	Blue
Red	3.60V	1.32V	1.34V
Green	154mV	1.48V	1.22V
Blue	608mV	1.17V	4.08V

Table 5: Closed System Testing: Individual 5mm RGB Packages – The diagonal voltages are more suitable.

The closed system testing resulted in determining that individual high intensity LEDs are more suitable for this project than a single RGB LED package. The next experiment used three high intensity LEDs with the same

luminous flux of 10,000mcd. The tests were conducted for the ideal and non-ideal case. The non-ideal experimental setup was similar to the closed system test, except the cylinder was removed so that the T_x and R_x were exposed to ambient light. The open system experiment was performed under ‘Cool White’ coloured fluorescent tubes to simulate broad daylight.

The result of these experiments are shown in Table 6 (for the ideal case) and Table 7 (for the non-ideal case).

LEDs/Filters	Red	Green	Blue
Red	4.16V	1.84V	800mV
Green	90mv	1.3V	960mV
Blue	224mV	500mV	1.62V

Table 6: Closed System Testing: Individual, 10,000mcd 5mm RGB Packages – The diagonal voltages show signs of respectable ratios that can be differentiated.

LEDs/Filters	Red	Green	Blue
Red	3.52V	2.16V	1.4V
Green	96mV	1.08V	1.2V
Blue	184mV	400mV	1.06V

Table 7: Open System Testing: Individual, 10,000mcd 5mm RGB Packages – The diagonal voltages show a discernable drop in differentiable voltages and are compromised by the red LED.

The results obtained from the open and closed system testing of the individual 10,000mcd 5mm RGB LEDs was that under non-ideal conditions, the red LED was dominant. This result was attributed to the RGB photodetectors being susceptible to ambient light, as the package had no way of filtering this other than with the optical filters.

4.1.1 Determining Filter Types

The ‘optical filters’ used in the previous experiments were regular sheets of coloured cellophane. Although not an ideal medium to use for filtering because their spectral characteristics could not easily be matched to the LEDs; however, they were a cheap alternative to expensive selective optical

wavelength filters. Other combinations of cellophane and coloured sources were used to better approximate the spectral response of the LEDs, these were: blue/purple cellophane, purple cellophane, yellow/green cellophane, lemon mint Tic-Tac packaging (greenish colouring)/green cellophane, extra strong mint Tic-Tac packaging (bluish colouring)/blue cellophane. The results of these experiments are omitted for brevity, however the analysis of these results was that better filtering would be required for the RGB photodetector or a different choice of photodetector.

As the TSL253R light-to-voltage converter could not decouple the DC (ambient) light, an alternative photodiode arrangement was examined. The EPIGAP selective photodiode range was chosen for its inherent ability to filter optical wavelengths due to the technology used to construct the photodiode. These are narrow bandwidth, high spectral sensitive devices for red, green and blue visible wavelength ranges. Using these photodiodes it would also be possible to bypass the DC component by incorporating a filter into the pre-amplifier stage of the R_x .

The spectral responses for the green and blue EPIGAP selective photodiodes are shown in Figure 4 (for the green selective photodiode) and Figure 5 (for the blue selective photodiode). Professional camera filters from LEE Filters were obtained in the event that cross-over occurs between the green and blue LEDs for the blue selective photodiode.

4.2 Determining the optical power received

Having determined that the project will use the EPIGAP selective photodiodes, a hypothesis of the quantity of high intensity 10,000mcd RGB LEDs required for the project was made. To make this hypothesis, a series of calculations based on the data available for each RGB LED and RGB photodiode was used in conjunction with radiometric and photometric equations.

The LED datasheets provide the viewing angle, θ , spectral wavelength range, λ_v , and luminous intensity, φ_v . These values in conjunction with the CIE

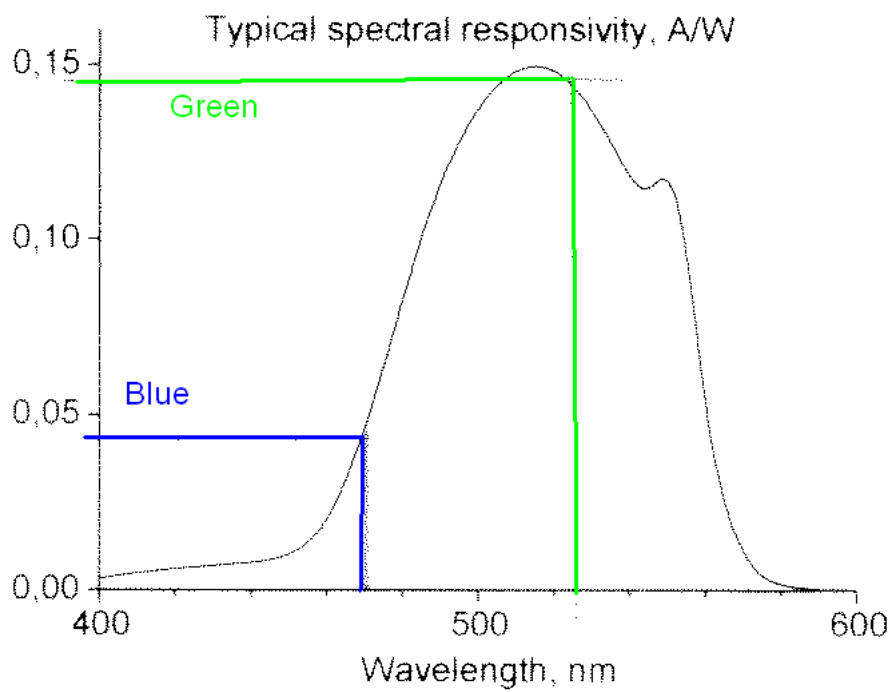


Figure 4: EPD-525-0-1.4 Spectral Response – Showing the relative spectral responsivity for the blue and green wavelengths of the selected LEDs

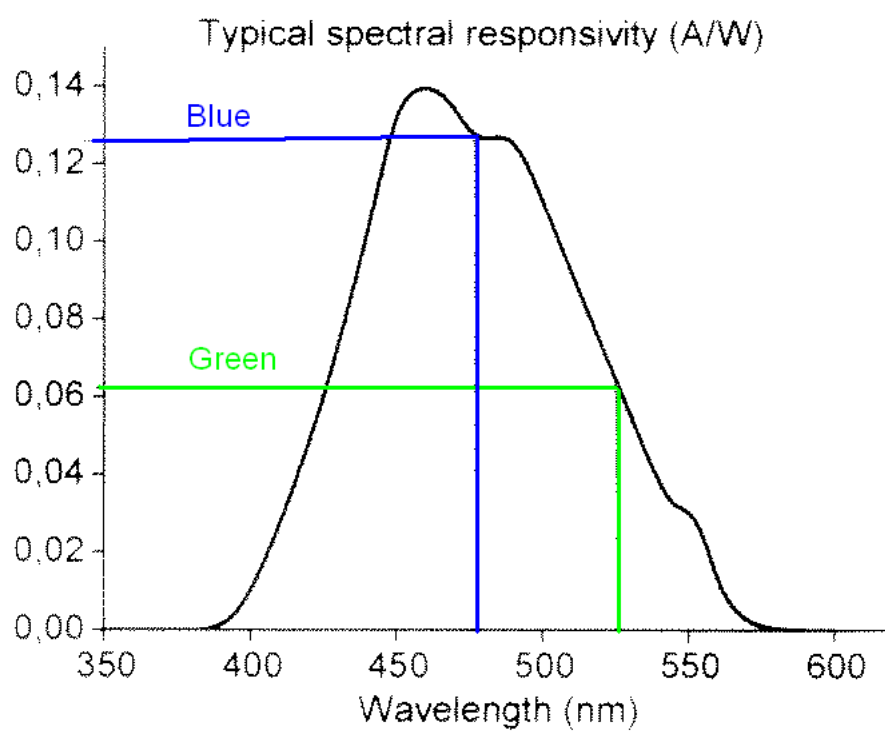


Figure 5: EPD-470-0-1.4 Spectral Response – Showing the relative spectral responsivity for the blue and green wavelengths of the selected LEDs

Photopic Luminous Efficiency Function, $V_\lambda(n)$, can be used to find the radiant intensity for each RGB LED in watts per steradian.

$$\varphi_v = 683 \cdot \varphi \cdot \int_{\lambda_v} V_\lambda(n) d\lambda$$

$$\varphi = \frac{\varphi_v}{683 \cdot \int_{\lambda_v} V_\lambda(n) d\lambda}$$
(1)

The results of the above calculations are in Table 8.

LED	Spectral Range (λ_v)	Radiant Intensity (φ)
Red	605nm – 645nm	0.484636 W sr ⁻¹
Green	505nm – 545nm	0.19148 W sr ⁻¹
Blue	445nm – 495nm	1.99068 W sr ⁻¹

Table 8: Radiant Intensity Calculations for each of the high intensity 10,000mcd RGB LEDs

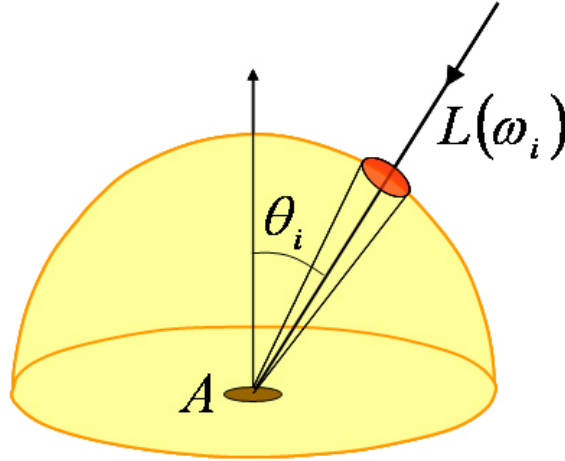


Figure 6: The effect of Radiance, $L(\omega_i)$, on a projected solid area, A , with respect to the solid angle, θ_i .

Using these results, the radiance was calculate, ie, the power per unit solid angle per unit projected source area (see Figure 6).

$$L = \frac{\varphi}{\Omega \cdot dA \cdot \cos(\Theta)} \quad (2)$$

In these radiance calculations, Ω , the solid angle, was evaluated as $\Omega = A/r^2$, with $A = 1$ and $r = 1$, as the projected source area was a 1m^2 square surface. Θ was calculated with respect to the half viewing angle of the LEDs, thus $\Theta = \theta/2$. This reduced Equation 2 to:

$$\begin{aligned} L &= \frac{\varphi}{\Omega \cdot dA \cdot \cos(\Theta)} \\ &= \frac{\varphi}{\Omega_{(L \times W)} \cdot \cos(\theta/2)} \\ &= \frac{\varphi \cdot r^2}{A \cdot \cos(\theta/2)} \\ \therefore L &= \frac{\varphi}{\cos(\theta/2)} \end{aligned} \quad (3)$$

LED	Radiance ($\text{W sr}^{-1} \text{ m}^2$)
Red	0.484636
Green	0.193133
Blue	2.021389

Table 9: Radiance Calculations for each of the high intensity 10,000mcd RGB LEDs.

The results in Table 9 were used with the available data for the active area and responsivity of the photodiodes to establish a relationship between each RGB LED and its corresponding RGB photodiode. These calculations are summarised in Table 10.

LED	LED L	L Photodiode	Photodiode Responsivity
Red	484nW mm^{-2}	62.92nW	26.42nA
Green	193nW mm^{-2}	231.6nW	57.9nA
Blue	2021nW mm^{-2}	2425.2nW	727nA

Table 10: RGB LED Radiance acting on its corresponding RGB photodiode.

The results from Table 10 allow a hypothesis to be formed based on the radiance from one RGB LED acting on its corresponding RGB photodiode at 1m. These results are summarised in Table 11, Table 12 and Table 13.

LED	Response from Photodiode	Number of LEDs for response
Red	420 μ A	15,897
Green	250 μ A	4,317
Blue	300 μ A	412

Table 11: How many LEDs? - A: Results for 1/1000th of the maximum RGB photodiode response.

LED	Response from Photodiode	Number of LEDs for response
Red	100 μ A	3,785
Green	100 μ A	1,727
Blue	100 μ A	137

Table 12: How many LEDs? - B: Results for 100 μ A RGB photodiode response.

LED	Response from Photodiode	Number of LEDs for response
Red	1 μ A	37
Green	1 μ A	17
Blue	1 μ A	2

Table 13: How many LEDs? - C: Results for 1 μ A RGB photodiode response.

From determining the number of LEDs required for different current responses from the RGB photodiodes, a 1 μ A response can be achieved from using 37 red, 17 green and 2 blue high intensity 10,000mcd LEDs. These calculations assumed an even distribution of the radiance is achieved from the LEDs onto the surface at a distance of 1m. To account for these discrepancies, 40 red, 20 green and 6 blue LEDs are chosen as the quantity required for this project. Testing of this numerical approximation will occur once the hardware is built.

4.3 AC Filtering

The closed and open system experiments determined that the TSL253R was not capable of decoupling ambient light from its resultant output. The rea-

soning for this can be shown in Figure 7. It is evident that the TSL253R light-to-voltage converter insufficiently handles ambient lighting as a result of having an internal transresistance amplifier. The $16\text{M}\Omega$ feedback resistor with the internal capacitance increases the τ of the system, thus affecting the overall system bandwidth.

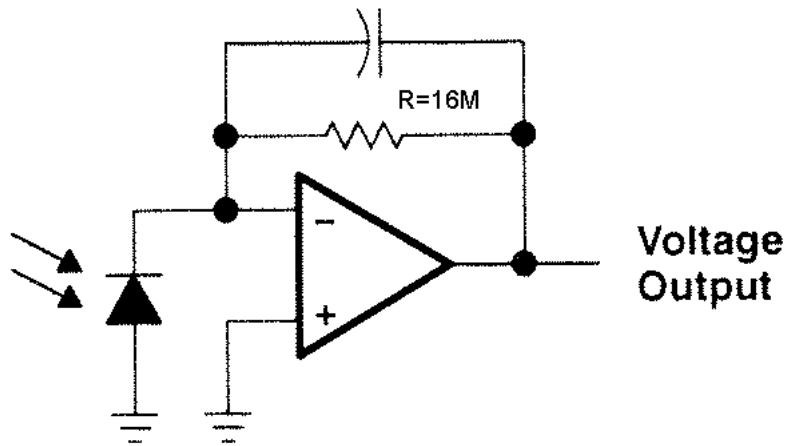


Figure 7: TSL253R Internal Block Diagram – The total rise and fall time of this device was $14\mu\text{s}$

With the selection of the EPIGAP selective photodiodes, an AC coupled amplifier can be used to filter out the DC component of light. The AC component conforms to having a modulation technique that will allow amplitude and data to be transmitted across the communication channel irrespective of DC conditions.

Using operational amplifiers, a Sallen-Key 3^{rd} order Butterworth high pass filter ($f_c = 25\text{kHz}$) and 3^{rd} order Butterworth low pass filter ($f_c = 70\text{kHz}$) was designed (see Figure 8). The choice of these cut-off frequencies is discussed in the next section. The filters were designed with the Filter Pro software package. The resultant filter component values were verified by hand and with the Tina PSpice software package, with the results being extremely similar. This verification process of the filter design provides a high

level of confidence to the applicability of the design in this project. These calculations will be verified with testing once the hardware is built.

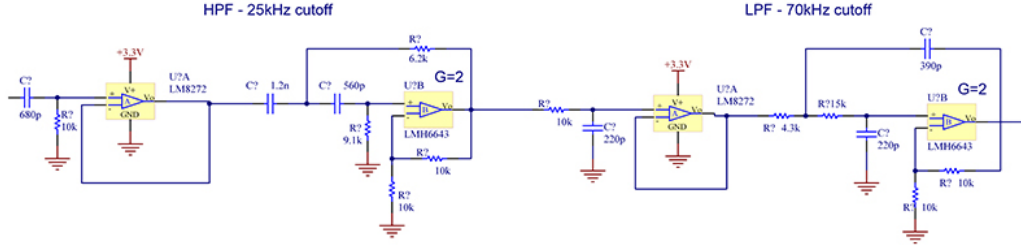


Figure 8: 3rd Order Sallen-Key Active Filters. The first stage is a HPF with $f_c = 25\text{kHz}$, the second stage is a LPF with $f_c = 70\text{kHz}$. Stages have gains of 2.

5 Transmission Data

This project will also transmit data over the communication channel, this data represents the sustain, attack and decay of the resultant waveform. The value of a linear potentiometer determines each waveform attribute and is first converted by an ADC that is input into a Spartan 3E FPGA pin. The potentiometers will be subdivided into twenty-one positions, x , such that $\{x : x \in 0 \leq x \leq 10\}$, thus $21_{10} = 15_{16} = 10101_2 =$ five binary bits.

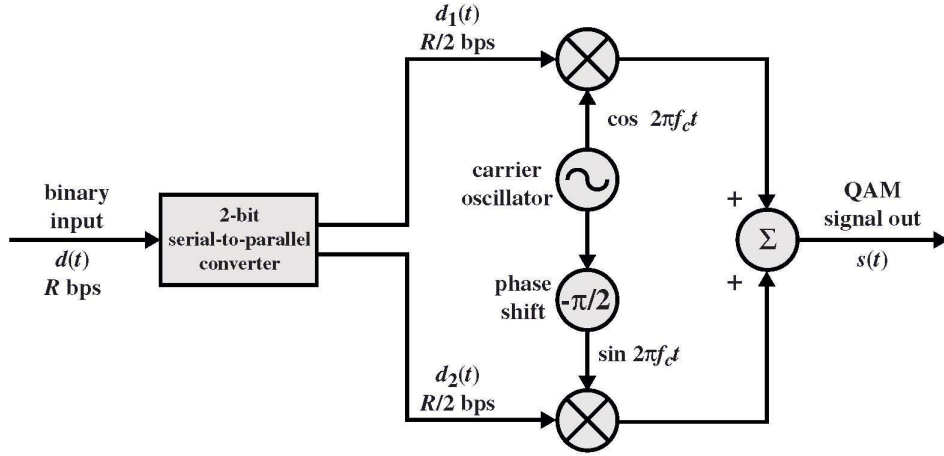


Figure 9: A typical QAM modulator.

A six bit quadrature-amplitude modulation (64-QAM) technique will be used to transmit the data (see Figure 9). This particular modulation technique was chosen as it is able to vary amplitude, thus intensity of the LEDs, and phase, allowing control data to be sent independently of the light intensity.

The framed transmission data consists of:

1. Header packets (6 Baud)
2. Attack Data (1 Baud)
3. Sustain Data (1 Baud)

4. Decay Data (1 Baud)
5. Note A RGB Intensities (3 Buad)
6. Note B RGB Intensities (3 Buad)
7. Note C RGB Intensities (3 Buad)
8. Note D RGB Intensities (3 Buad)
9. Note E RGB Intensities (3 Buad)
10. Note F RGB Intensities (3 Buad)
11. Note G RGB Intensities (3 Buad)
12. Tail packets (6 Baud)

The design choice is made that for each frame sent across the communication channel, the control knob data will remain the same. Therefore, the system will have a baud rate of 36, with each baud containing six bits; the resultant bit rate of the system will be 216.

The minimum bandwidth required for a QAM modulation scheme is calculated from the system baud rate (see Figure 10). A center frequency, f_c of 50kHz is chosen as it is sufficiently higher than any expected DC lighting condition that may affect the transmitted signal. The system baud rate, N_{baud} is 36, therefore the minimum bandwidth of the 64-QAM modulation scheme ranges from 32kHz to 68kHz.

Our filter design from the previous section was designed with a lower cut-off frequency of 25kHz and an upper cut-off frequency of 70kHz compared to the minimum requirements. The 25kHz cut-off frequency was chosen because it is one octave lower than the system's center frequency of 50kHz. The upper cut-off frequency was set to the upper limit of the minimum bandwidth requirement because it is unknown whether the selected photodiodes will be able to detect signals at one octave higher than the center frequency.

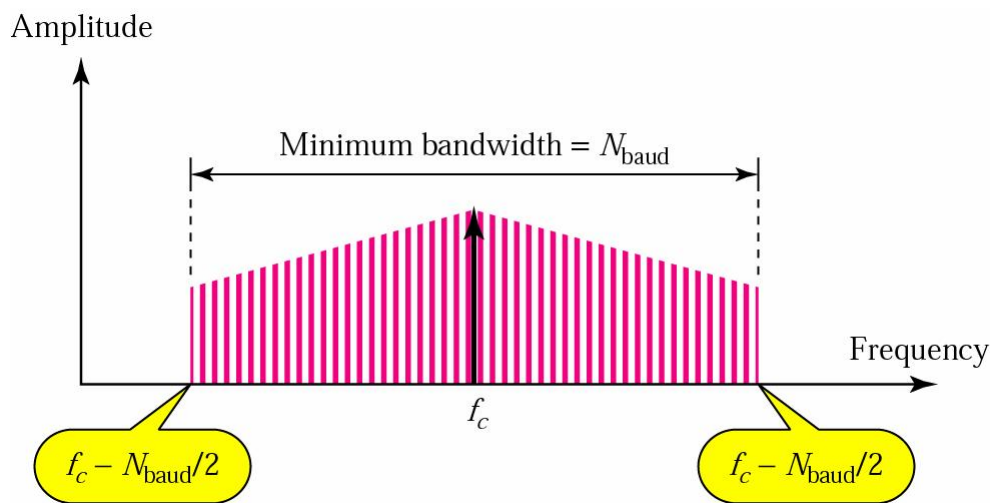


Figure 10: Determining QAM Bandwidth requires that a center frequency be chosen and the baud rate be known.

6 Current Progress

Currently, the T_x module has been designed and routed, with all components sourced and ready for soldering. The EPIGAP photodiodes used on the R_x module have been sourced and the AC filter and photodiode amplifier have been designed. A feasibility study was conducted and analysed so that a solid foundation for which to produce a well planned system design was achieved (using the evaluated mathematical approximations and measurements), and can continue.

6.1 T_x Schematics

The following schematics show in whole or in part the schematics associated with the T_x module for this project. Where multiple design instances are repeated (the QAM Driver schematic and LED Driver schematic), only one instance is presented.

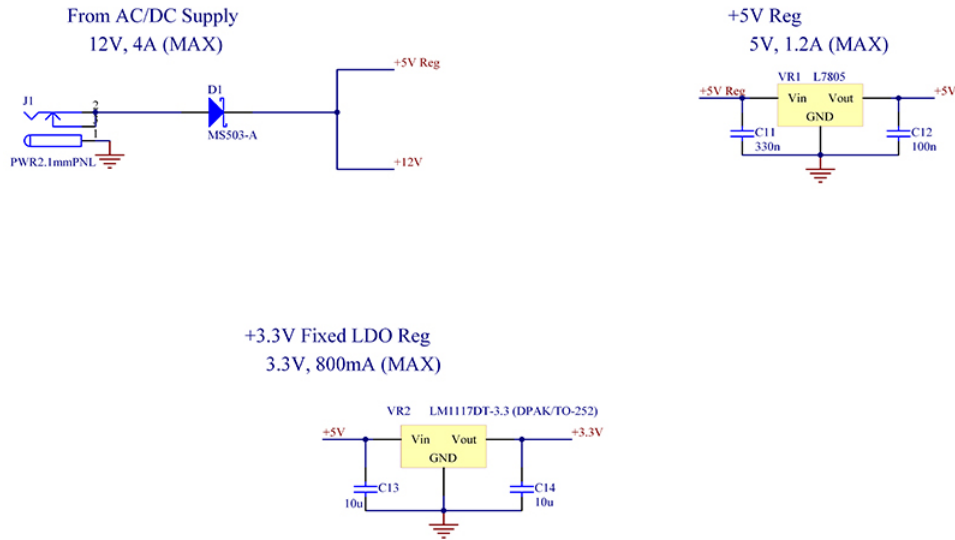


Figure 11: T_x Power Schematic

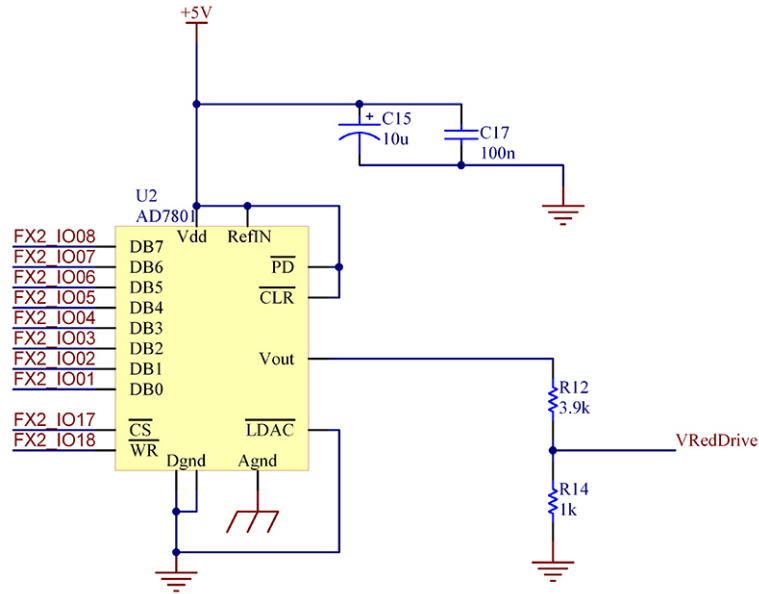


Figure 12: T_x QAM Driver Schematic

6.2 T_x PCB Layout

The T_x PCB construction consists of two PCBs: a motherboard and daughterboard. The motherboard (see Figure 18 and Figure 19) consists of all the components except those that directly govern the LED array, ie, the LED drivers and the LEDs themselves which are on the daughterboard. The daughterboard is attached to the motherboard at right angles so that the LEDs are parallel to the surface the motherboard is placed on.

7 Semester 2 Tasks

The tasks that will be completed in Semester 2 are:

- The R_x schematic and PCB layout;
- Implementation of the VHDL that controls the T_x and R_x ;
- Testing to reconcile mathematical approximations made in Semester 1;

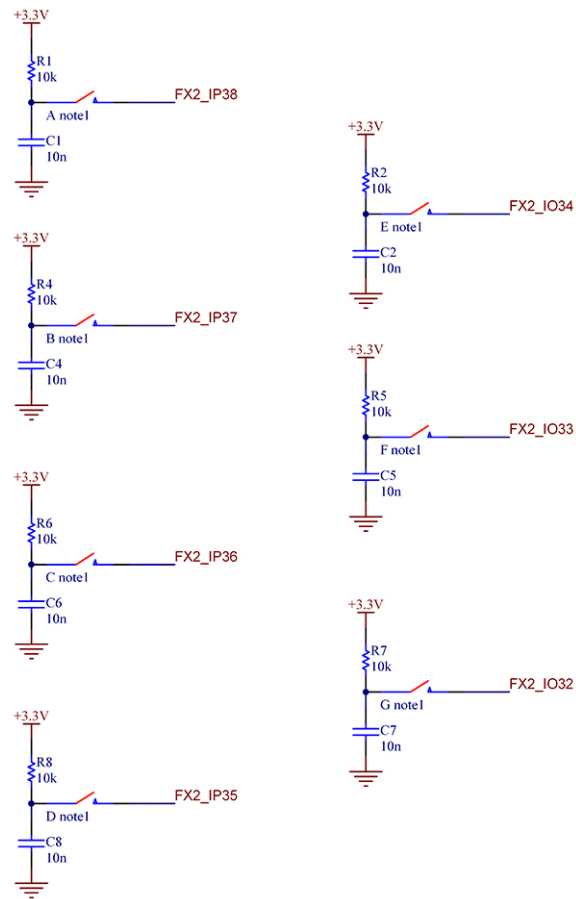


Figure 13: T_x Key Schematic

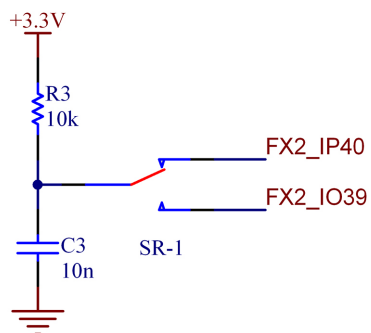


Figure 14: T_x Rocker Switch Schematic

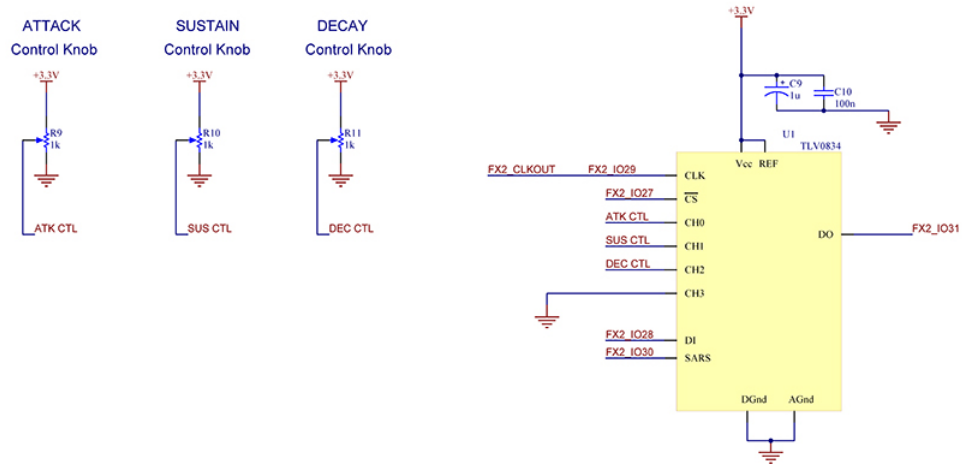
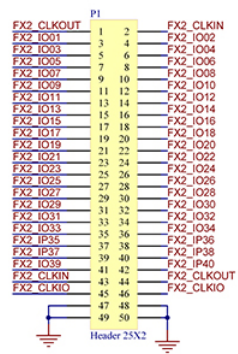


Figure 15: T_x Control Knob Schematic

Spartan 3E SIGNAL Connector



DB SIGNAL Connections

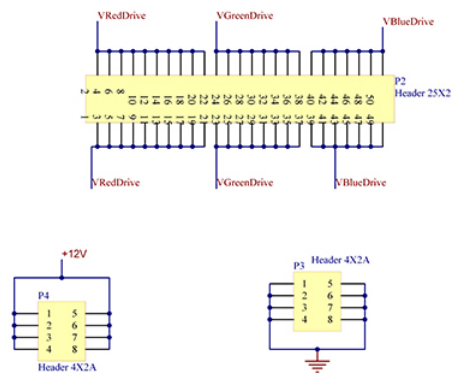


Figure 16: T_x Spartan 3E Connector Schematic

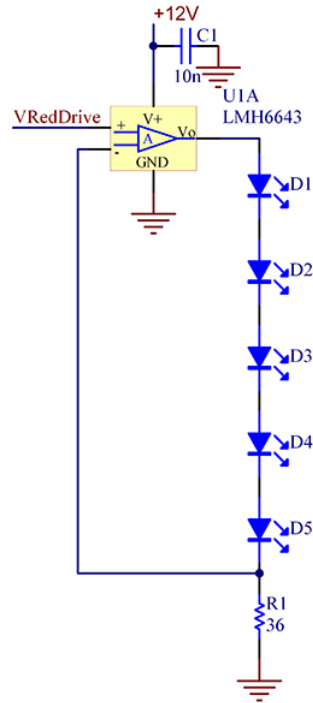


Figure 17: T_x LED Driver Schematic – Only red is shown here

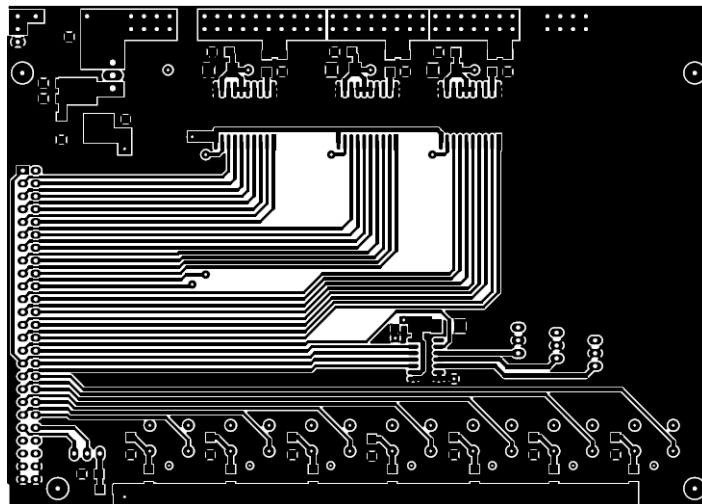


Figure 18: T_x PCB Layout – Motherboard, bottom layer

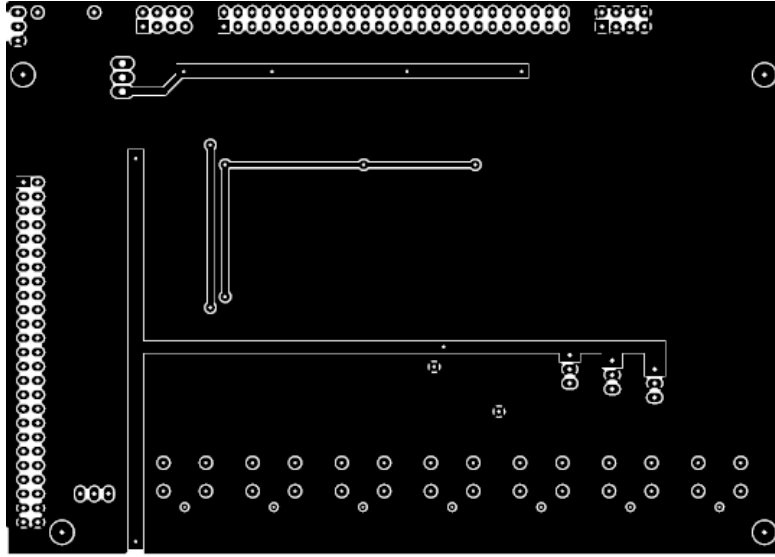


Figure 19: T_x PCB Layout – Motherboard, top layer

- A demonstration of a working prototype that has achieved all critical project objectives.

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