Visible Light Communication

An alternative to the wireless transmission with RF spectrums through visible light communication.

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Table of Contents

Table of Figures

1. Executive Summary

Currently there are more than 15 billion Wi-Fi enabled devices in the world, and it's not just cell phones and computers. By 2020 there is supposed to be an estimated 100 billion devices connected to the infrastructure of the internet. The exponential increase in information technology is not just relying on Morse law for the transistor in computer processing but the wealth of technology that can be facilitated. The market share of this development will be in radio frequency and as an aside, the United States currently has more RF repeater companies rather than free space optical communication companies in implementing 5G but we are looking to find roots in the visible spectrum.

The fact is, most household appliances are equipped with Wi-Fi capabilities, and the spectrum allotted for 802.11 protocol (local wireless networks) is becoming increasingly saturated and scarce. If we look at long haul communication systems, we see that in the past decades the industry has migrated from traditional copper cables to fiber optic systems. Optical systems provide greatly increased bandwidths and bitrates, and here we propose the same concept. Light enabled wireless technology is very similar to Wi-Fi technology in the sense that it is a local wireless transmission, however the signal is light instead of in the radio frequencies. Since light frequency is much higher on the EM spectrum light enabled wireless technology systems provide bandwidth many times greater than Wi-Fi. In addition, light enabled wireless technology is considerably more energy efficient, since the transmitter in the system is a diode instead of a conventional radio transmitter. Visible light communication or (VLC) is also a secure means of data transfer, the modulating light itself represents the data stream, and since light does not penetrate walls or diffuse beyond line of sight there is no way to remotely intercept the data. VLC systems are also non-hazardous to other electrical systems in terms of interference, making them more versatile in settings like airplanes or areas of high electromagnetic sensitivity.

Our VLC system uses two sets of receivers and transmitters to enable full duplex. One of the transmitters uses a laser and the other uses the same laser coupled with photodiodes on one printed circuit board to create the duplex system. In a practical environment, there would be no atmospheric turbulence such as in indoor environments, however there may be required optical lenses in an outside environment. As the internet of things (IoT) continues to evolve, the various devices in the home will require connectivity. This rate of increase is going to impact the ability of our wireless transmitting devices to carry that bandwidth which is where light enabled transmission can be application specific and for consumer use where there is a direct interaction. Furthermore, light communication in IoT has applications in a scenario such as theme parks, consumer stores where at each type of merchandise or exhibit can have independent data be transmitted to a multimedia device for the consumer such as in augmented reality.

In this report, we document our project from start to finish, including tables in figures giving details to the particulars. We also discuss the reasoning behind our component choices as well as their advantages/disadvantages. Relevant technology to the project is discussed including background information. Finally, we go over the design as a whole breaking down the motivation behind it, the expectations of it, and the performance using it.

2. Project Description

2.1 Project Background

In locations which are hard to reach and reside in environments which are not conducive to electromagnetic transmission, transferring information of internet of things devices may require a different type of physical link. In direct comparison against a radio frequency data transmission the power efficiency and security will always be in favor of light communication because of the fundamental difference in beam divergence, which translates into the amount of power the target receives and the area of external interception of the signal. The efficacy of the RF link may be readily installed because of their non-direct line of sight and atmospheric turbulence, however with correctional algorithmic mechanics and adaptive optics, these differences can be mitigated.

Light communication physically is able to transmit magnitudes of higher order bandwidth and data rates because of the spectral regime of light in terahertz in comparison to the maximal megahertz to gigahertz radio spectrum. The form factor of light devices can be lighter, and smaller because of the power associated with the respective devices leading to ergonomic designs.

2.1.1 Existing Projects and Products

In the realm of free space optics and transmitting information over light, there have been numerous attempts to create communication systems before and currently companies have fully integrated products, however these designs are not accessible, and not for a marketplace for consumers, but business to business communication. It is our hope and goal to be able to design a product which can allow for the undertaking of understanding such industry.

There are several companies which come to mind when it comes to free space light communication. However ViaLight Communications, which is efficient in the high data rate and long-distance information transmission through light, has carefully designed and applied their technology in several situations at data rates of above 10 Gbps and distances of >20 km. Specifically they create links for commercial aerospace systems, connecting unmanned aerial vehicles (UAVs), the backbone for connecting aircraft with high demanding rates of information from ground to air, and even have compensatory skills for atmospheric turbulences, weather conditions and statistically maximized ground station availability.

Figure 2.1. The Vialight communication system as depicted from an aerial view.

Backbone connectivity for the skies and beyond
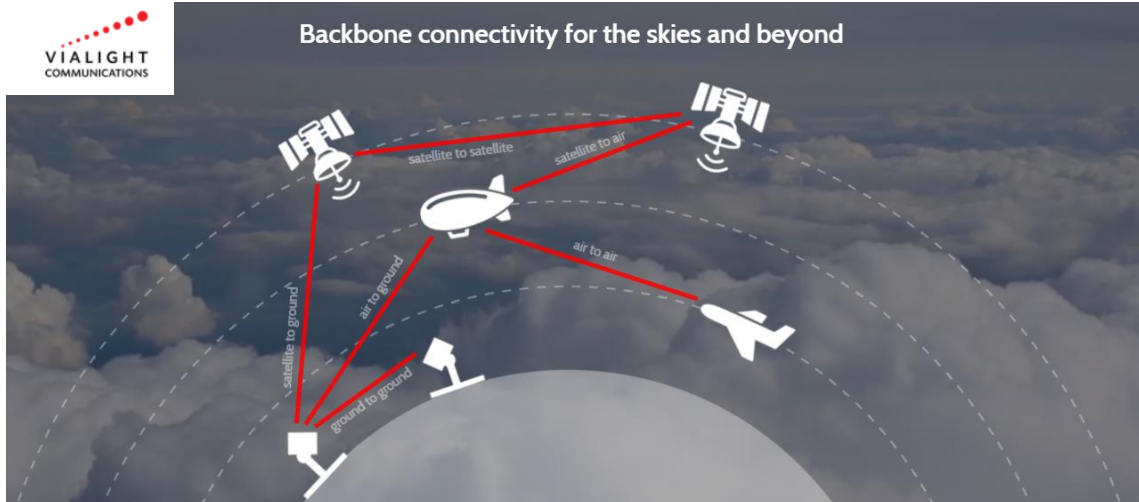
In addition to free space laser communications where there are dynamic movements in technology, this technology is particularly relevant in last mile mesh networks and expanding the reach of that connection. By expanding upon existing radio infrastructure such as cell towers and transmission and fiber optic lines, optical infrastructure has no interference capabilities in terms of propagation of the communication channel.

ViaLight has a custom ability to create stable ground to ground laser Ethernet transceivers. From their website, "Laser Ethernet transceivers (LETs) that can be used with third party optical assemblies to realize high-speed laser communication links. The LETs support data rates of up to 10Gbps with Advanced Optical Link Protection (AOLP) technology – an adaptive data protection mechanism specifically for the atmospheric optical fading channel."

An open source project called Koruza located at http://www.koruza.net has implemented a wireless optical internet access system which allows for an optical link in high density urban networks with minimal investment. The system is capable of 1 Gbps, 0.05 mrad beam divergence at less than 150 m. The advantage to their product is there is no lock-in black box technology which limits the consumer to upgrading all of the system instead of just a particular hardware update. Their company started with an idea of a very affordable laser Ethernet transceiver (VALET) for short and transformed into an extensive small form factor and relatively simple solution.

Clarification is necessary in that a visible light communication system is not exactly laser Ethernet transmission and can use high powered LED to illuminate a room and a LET met only be direct line of sight. A typical VLC system compensates for reflection, and absorption off of Lambertian surfaces such as what would be in a home and therefore the line of sight is within a certain regime of angularity or in what the brightness dissipation would allow (more on brightness theory later). Visible light communications is the name which is applicable to a wireless communication where the chosen medium is light with a spectral range of 400 nm

– 700 nm. The communications signal is overlaid on top of the illumination aspect of the – oftentimes white – light. The requirements for a VLC network would be multiple device configuration which is essentially a multi input multi output system. The network would be able to provide service to a laptop, TV, smart phone, wearable device, and comparable multimedia connections as opposed to a direct connection in which a LET may only be capable of.

Harold Haas a German professor at the University of Edinburough in the Scottish capital first showcased in 2011 how light fidelity (LiFi) technology works with the media organization TED (technology, entertainment, design). The company he created out of his laboratory enterprise. The system had a LED light which could be used in a regular high hat type implementation and had a USB compatible device as the receiver and uplink which was the relative size of a business card. The appearance of the device allows for the consumer to maintain the experience of integrated product.

The way the LiFi system was presented was that the LED was modulated with a signal consisting of various light intensity variations. The optical signal was detected and converted into an electrical signal which was transferred to a computer instead of a multimedia device. The USB receiver had an infrared LED to provide full duplex bidirectional wireless access at the speed of 43 Mbps up and down respectively. The average rates of installation hovered around 25 Mbps and maintaining full duplex interaction.

More specifically, the broadband white light can communicate simultaneously with multiple multimedia devices. If that specific multimedia devices changes white light sources, the system automatically adjusts in what is an adaptive algorithmic best connection. The LiFi-X Dongle as seen in Fig 3. is the fastest data transmission and current state of the art technology in the consumer marketplace.

Although we may not be able to directly replicate this type of device, the goal of the project is to get the group into the mode of understanding in undertaking such a product.

Figure 2.2. The Lifi-X Dongle as produced by PureLifi for their 2017 product release.

With the help of a French Company Lucibel, the first office demonstration was in February 2017. It has not been reported and the current price is negotiable per deployment. Haas believes with higher volume the cost certainly will go down. A competing company to Haas' implementation of LiFi is OledComm even has products on amazon, in France for 2 Mbps deployment.

2.1.2 Wireless Optical Communication

The idea of wireless optical communication in a technology which enhances the reach of optical communication into the home for the last connection. The idea was created to solve FTTD's (Fiber-to-the-Device) problems in delivering information. In technologies such as fiber to the home, optical signals reach homes from the service provider which controls an optical network terminal. The final connection to the consumer deemed "last mile" is usually serviced via an Ethernet coaxial cables from the ONT. With an Ethernet solution, there are inefficiencies because of the difference between electrical and optical speeds. The speed of light should be used up until the device level. An objective of wireless optical communication is to eliminate the wires and cables between as many devices as possible. Imagine a scenario where the smart TV can connect to the internet and the sound bar, the blue-ray player, and other things without RF. Furthermore, a CPU can go online without an internet modem because the optical network terminal can be readily linked into the optical wireless infrastructure, and therefore the devices can receive the information at break neck speeds and without interference bandwidth limitations.

2.2 Objectives

2.2.1 Motivation

The group members decided to create a communications project and the medium chosen was light. This project should demonstrate how the group was able to focus on a problem such as wireless communication and cultivate a robust, efficient product from a reasonable approach and a thorough execution. The ability to work in a group and identify key ways to compliment strengths together, which are vital aspects of an engineering team, is introduced. By finding out how to go from an initial idea and follow through to make a product, present the material in question, and write a report the group will be addressing requirements set out to obtain an engineering degree from the University of Central Florida.

2.2.2 Goals

Our goal is to provide an easy to assemble and robust optical wireless transceiver. The internet transmission will be directed through a modulated light beam which can be in any part of the visible spectrum. The system will have a readily available information display which is software based to check the transmission information such as speed, bandwidth, error rates, IP address, and verifiable connection to the internet. The interface should allow for the user to understand the top-level application extracted information and if possible implement more information with a microcontroller to show optical power and attenuation for understanding the balance.

The hardware should be able to be impacted and be weather resistance. The device should be accurate, and efficient. The efficiency over the RF repeater should be apparent and the easily identifiable troubleshooting particulars. We are striving to make the design as sleek and robust as possible to not make it intrusive and the final product should be more than capable of upgrades.

2.3 Requirements Specifications

Unless a specific component is mentioned "The product" refers to our VLC design and its components and accessories as a whole.

- The product shall be no larger than 5 cubic in.
- The product shall weigh no more than 5 lbs.
- The product shall contain an LED, a power supply, and an Ethernet port.
- The product shall be able to transmit data at a rate of at least 5 Mbps.
- The product shall not interfere with existing wireless communication infrastructure.
- The user side of the product shall be compatible with any Ethernet equipped computer.
- The user side of the product should be able to have a USB to Ethernet converter option.
- The product can function as a repeater for Ethernet connection.

- The connected information should be able to be free of errors to the defined amount in the standards.
- The product shall be non-hazardous to the user.
- There should be fail safe mechanical mechanisms.
- Caution warnings for light illumination should be supplied.
- Usable, intuitive, and easy to learn.
- The product shall cost less than $300.
- The product shall not use more than 45 V supply at a time.
- The product will not use more than 1.5 A at a time.

2.4 Market and Engineering Requirements

The house of quality represents a visual overview of the system requirements. In order to obtain the above relationships our product should be well engineered and tested. The trouble shooting aspect is the root of where the practice of understanding our project.

Figure 2.3. The house of quality of the system specifications.

Figure 2.3. The house of quality of the system specifications.

Customer Requirements		1) Speed	2) Tx Efficiency	3) Energy Use	4) Weight (fixture)	5) Size (receiver)	6) # of Users	7) Cost
		+	+	−	−	−	+	−
1) Cost	−	⊕	+		+	+	⊕	
2) Size (receiver)	−	−	⊕	+				−
3) Speed	+			⊖	−	−		⊕
4) Energy consumption	−	+	+				+	
5) Ease of installation	+				−			+
		>5 Mbps	>90%	<1 10 W	<3 lbs	<7 in²	≥1	<$250

Correlations:
⊕ Strong Positive
+ Positive
⊖ Strong Negative
− Negative

Relationships:
+ Positive
− Negative
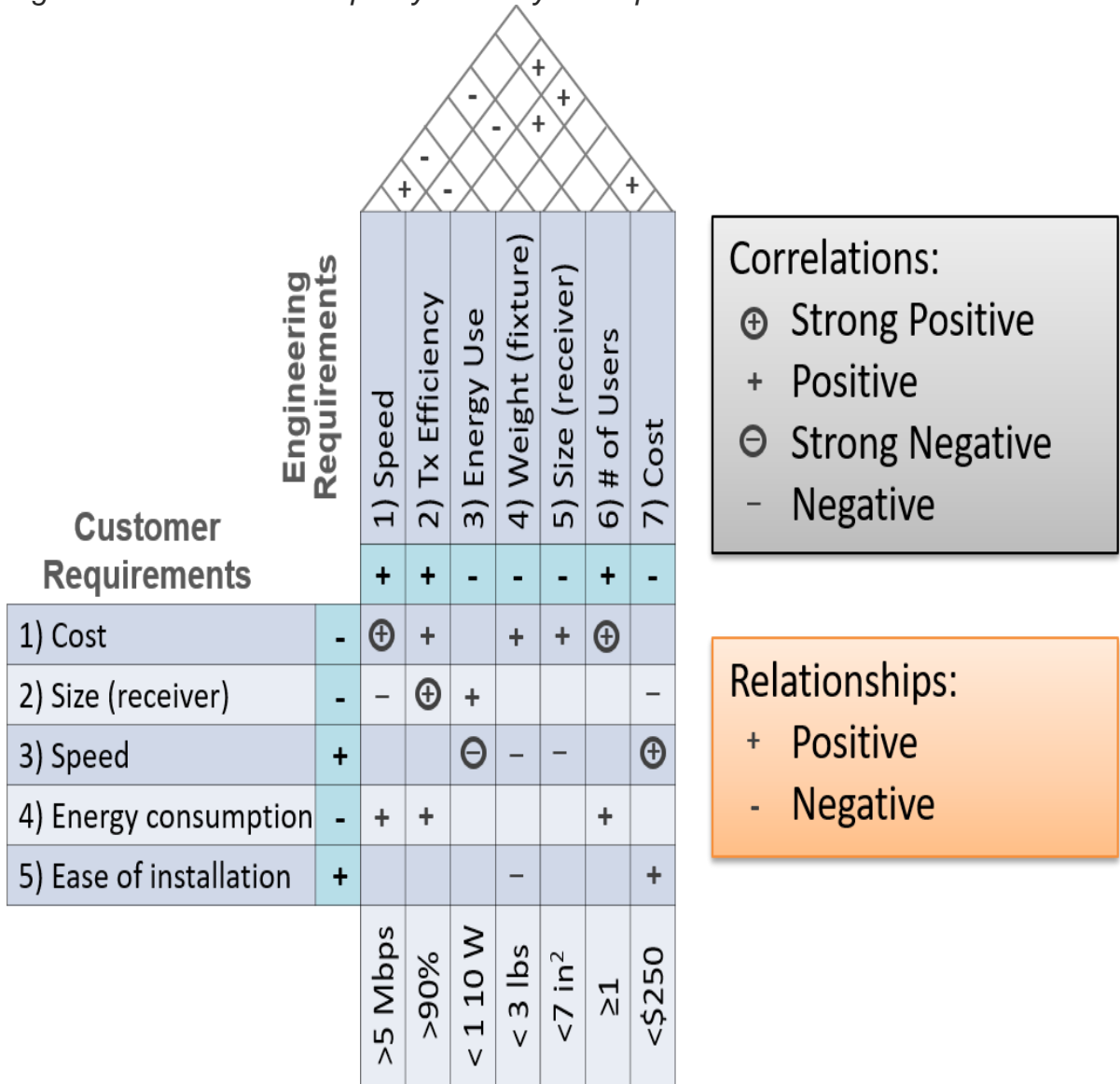
The two sides of the house of quality are the customer requirements and the engineering requirements. The items listed on the left are potential needs of the customer in order to be satisfied with the product. Here cost refers to the total price a customer would pay for a VLC system. In this scenario, the size of the receiver is referring to the size of the device that plugs into the user's PC. Although the VLC system uses two transceivers, the network switch side of the system is negligible in size. Overall things such as cost, size, and energy consumption all benefit the customer if they are lesser. The ease of installation and speed are a positive factor where "more" is better. The VLC system makes use of existing internet infrastructure and is comparable to the price and speed of current internet-enabling devices.

Across the top of the "house" are engineering requirements, that are meant to be taken into account when designing the system itself. There are duplicates from the customer requirements because they are key factors when designing the system. For instance, the cost of engineering refers to the amount of money to research, develop, and manufacture a finished product, the lower this number the better. The Tx Efficiency is an interesting requirement, because VLC makes use of existing infrastructure the system can only be as fast as it's connected counterparts. This means that the VLC system needed to be designed in a way that there was as little circuit parasitic as possible, and that all the components can operate well above the speed of any given infrastructure.

2.5 Distribution and Hierarchical Layout

Even though senior design is a group work, we still need to make sure each group member gained the most educational value from this project. Our team has a weekly meeting, however, when it is necessary, we do have a biweekly meeting. The different topics of this projects design and construction have been divided according to work load for each person and the respective interests of the team members.

In order to establish the distribution of responsibilities to the project, the following layout in Fig. 2.4 is a hierarchical overview of the design of the project. The red indicates work done by the photonics team in Benjamin Stuart and Garrett Bennett, the blue is the responsibility of Zhitao Chen, and the green in the work by George Salinas. The purple indicates the joint decisions by the electrical and photonics team. The basis of our project inherently combines the understanding of electronic systems on to optical considerations.

Figure 2.4 The project distribution and hierarchical layout.
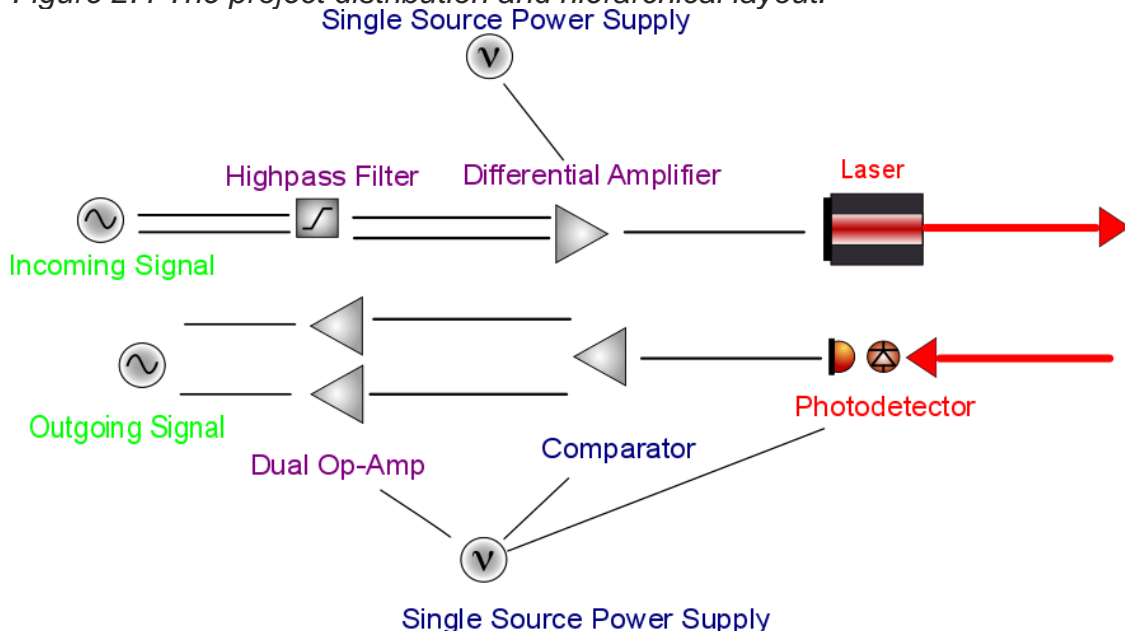
2.5.1 Contribution Breakdown

For our project, the team can be broken down into three categories, we have the optics, the electronics, and the software. Ben and Garrett, as part of the optics team were tasked with the optics portion of the project including opto-electronics. Responsibilities include selecting all optical components including but not limited to the photo-diode, the laser diode or LED, the focusing elements such as lenses, and the implementation encompassed by all the aforementioned components. In addition, the optics team was heavily involved in selecting the electronics used to control the optical devices where needed, as well as the overall design/layout of the system. On the electronics portion of the team is Zhitao, he was tasked with the design and implementation of all power components including power supplies and amplifiers as well as fundamental electronic components. In addition, Zhitao was tasked with the design of the PCB for the system. On the software team is Jorge, he was tasked with the generation of a signal representing a standard internet connection, as well as the recovery of said signal. In addition, Jorge was tasked with writing software to capture and analyze data going through the VLC system.

2.6 Design Comparison

When investigating the theory and operation of transmitting information over light, the group determined two separate types of transmission – light communication with lasers or with white light emitting diodes or LEDs.

The process of developing a transceiver for both prototypes was pursued and documented for the white LED in chapter 5. The prototype construction was attempted in chapter 7 was for the 10 Base-T LED construction while chapter 8 will focus more on how to create the PCB for a laser diode optical transceiver. The group was unable to successfully demonstrate either the 10 Base-T or the 100 Base-T for the white LED system, however, after further review we have concluded in demonstrating a workable transceiver system based upon laser light transmission. Although the laser system will not be able to light up a room, or looked at directly, it is a powerful tool in situations where laying a physical cable is not feasible such as underwater communication, or rough terrain. The team has made great strides in understanding of communication systems in light and Ethernet protocols and feels this project has helped in creating that understanding.

3. Research related to Project

There are only two ways which can be used in photonic information transmission, that is free space or fiber optics. The differences in each medium gives rise to different problems such as transmission wavelength, absorption, and scattering loss.

The ideal situation is where there is no absorption or scattering at a given transmission window. Although photons intrinsically are immune to electromagnetic radiation in the radio-frequency domain, i.e. they are less prone to decohere or lose their phase or polarization, the absorption and scattering causes power loss, and decreases the signal to noise ratio. Absorption loss is primarily the default in fiber optics in that the material such as silica absorbs the light, whereas, free space communication has difficulties in turbulence and scattering such as Mie scattering. Our project will utilize optical free space communication and therefore it is paramount to understand the proper adjustments.

3.1 Relevant Technologies

This section will cover the various technologies we considered for our projects, including different applications within separate subsystems. The direct implementation will be presented with the relevant basic understanding required for the physics to engineering execution.

3.1.1 Transmitter Technology

LED

LEDs or Light emitting diodes are a solid-state technology that convert electrical signals into light waves. Starting with the basics, a diode is the simplest form of a semiconductor. The semiconductor can act as either a conductor or an insulator. When considering materials that allow or deny the flow of electrons the concept of energy bands comes into play. For conductors, the valance band and the conduction band of an element or material touch each other, for an insulator these two bands are far apart, for a semiconductor they are somewhere in the middle. Fig. 3.1 shows this concept.

Figure 3.1: A visual representation of the band structures of three different kinds of elements
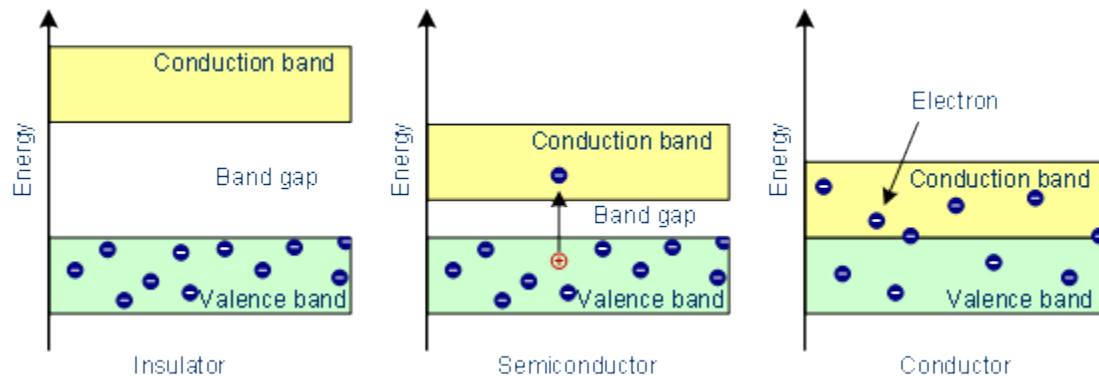
There are two types of semiconductors intrinsic and extrinsic, for this document we will be focused on extrinsic only. Extrinsic semiconductors are generally made from group IV elements on the periodic table. They can be broken into two major categories, n-type and p-type. N-type semiconductors have an excess of electrons, whereas p-type semiconductors have an excess of holes. In order for this to happen the base material must be doped with another element. N-type semiconductors are doped with group 5 elements and p-type are doped with group 3 elements. LEDs are the cause of combing these two types of semiconductors into what's known as a p-n junction[1], illustrated in Fig. 3.2.

Figure 3.2: The figure illustrates the process of biasing an LED and the consequence of electrons and holes mobilizing and recombining in the active region. The result of the recombination produces light because energy must be conserved. Below the physical illustration is a band-diagram representation, normally the valence and conduction bands between the n-type and p-type are far apart respectively, however biasing with voltage shifts them closer.
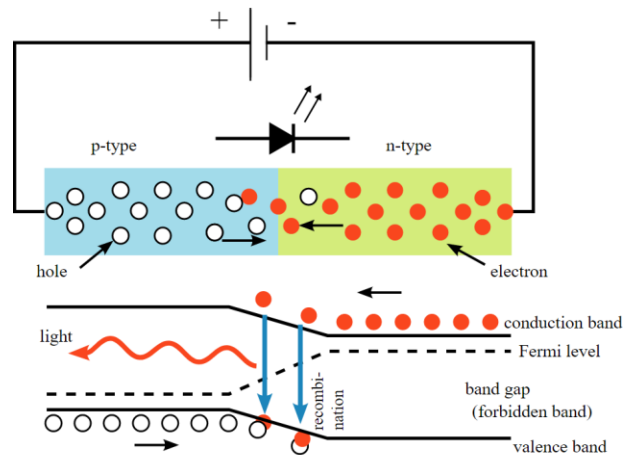
When voltage is applied to the LED electrons from the n side move towards the p side and holes from the p side move toward the n side. In the center is a recombination region where the holes and electrons combine into single pairs commonly referred to as EHPs or electron-hole pairs. Since there is an energy difference between the electrons and holes when they recombine there is an energy dissipation in the form of light and heat. In order for this process to occur the junction must be forward biased, the required voltage bias is a function of the materials and changes according to substrate, dopants, acceptors, etc. LEDs generally only require a few volts to operate. The color of emitted light is also directly proportional to the bandgap of the p-n junction represented by the equation $E_g = \frac{hc}{\lambda}$, where "hc" is Planck's constant multiplied by the speed of light, lambda is the wavelength of emitted photons, and Eg is the bandgap of the LED. For the VLC project we are using a broadband LED, it emits multiple wavelengths and gives the appearance of white light.

Laser Types

In addition, there are several types of lasers which fundamentally differ in structure and functionality in a design because of their package layout, optical configurability (wavelength tunability), chemical composition, and mechanical construction. The different types of semiconductor lasers include but are not limited to:
- Fabry-Perot Diode Lasers
- Heterostructure Diode Lasers
- Distributed Feedback Lasers
- Quantum Cascade Lasers (QCL)
- Vertical Cavity Surface Emitting Laser (VCSEL)

Fabry-Perot Diode lasers are pumped from a semiconductor laser into a resonator cavity. The resonator cavity creates longitudinal modes with a wide spectral selection than may be necessary, therefore it is not a good candidate. Heterostructure diode lasers have coherent output, easy to work with packaging

14

and small spectral width. Distributed feedback lasers utilize a diffraction grating in the semiconductor material to eliminate wavelength dispersion and create a small spectral width, however their packaging is not as easy to utilize in our design. Again, although the characteristics of VCSEL, and QCL are appealing in high power conversion efficiency, spectral selection, and discrete packaging, their overall form factor requires more understanding to incorporate into our design. Given our time constraints and monetary budget, our choice will be heterostructure diode lasers.

Some other types of lasers which exist:
- Gas Lasers
- Excimer Lasers
- Solid State Lasers

Gas Lasers use a gas as a gain material for population inversion. When a current is sent through the electrodes of the cathode and anode the energy from the electrons create an excitation in the gas atoms from electron collisions, thus creating a population inversion. Excimer lasers are photolithographic lasers which operate in the EUV spectrum to engrave integrated microchips in semiconductor manufacturing. Solid state lasers are created by optically pumping a crystal which acts as a gain medium for then transforming the incoming light into a different wavelength based on the transmission spectrum. The later types of lasers are out of the scope of this project because their properties require complex mechanical construction.

Laser Diode

In this project, we will be using a heterostructure laser diode. We will commonly refer only to the name laser diode, and as the name states they are lasers based on diodes, and are commonly abbreviated LD. Diodes were previously mentioned in the last section on LEDs. A laser diode has the same basic structure as an LED in the sense that it contains p-type and n-type semiconductors. However, LDs are made with an additional region between the p-n junction, this region is intrinsic in nature, having no dopants. Laser diodes have a threshold current which must be reached before lasing can occur. Before this threshold laser diodes emit spontaneous light just like an LED. When the threshold current is reached the optical gain is exceeding the optical losses for the cavity. The cavity of a laser diode is created by the edges of the semiconductor, usually polished and cleaved to create a highly reflective side (99%) and a completely reflective side. This cavity provides an oscillator for the emitted photons to travel back and forth.

When photons are injected and transporting through the cavity there is a chance that a photon can elicit an electron and hole recombination. The response is the emission of a photon duplicate to the one that elicited the recombination. When this process occurs and the amount of emitted light has become greater than the amount of absorbed light inside the cavity lasing occurs. By combining p and n

junctions with differences in bandgap a waveguide can be created as shown in Fig. 3.3.

In Fig. 3.3 is a generalized illustration of what a laser diode might look like the blue colored portion of the illustration represents the contacts in which current or voltage is applied. The rest of the top surface of the device is insulating material, thus confining the emitted light in the X direction. Moving down there is a p-type layer, flanked by two n-type layers. Below the active layer is a layer of insulating material. The two n-type layers have a higher refractive index than the p-type layer thus creating a "waveguide" and confining it in the Y direction. The face of this diode will have an extremely reflective coating about 99% while the rear will be 100% reflective, the 1% of light that escaped is the beam of the laser. The shape of the active layer defines the shape of the beam. It follows that a rectangular aperture that is horizontal in this case, will produce a beam that diverges in the vertical direction, and vice versa. It also follows that the smaller the aperture the larger the divergence rate.

Figure 3.3 A generalized illustration of what a laser diode might look like.
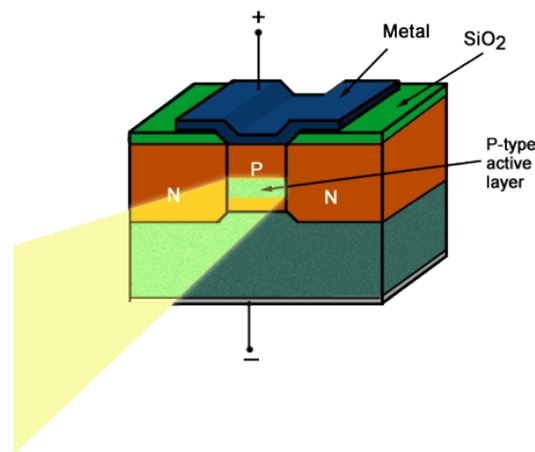
Naturally, all transmitters have a divergence however the reason why lasers for RF communication have been so highly pursued in military situations is the lack of divergence angle. The small change in divergence allows for the chance of interception to be minimal and reception to be relatively line of sight, the drawback is the cost of transmission distance in terms of power efficacy. The reason why lasers have a small divergence angle is because of interrelating aspect of the waist and the divergence. In Gaussian beams, the waist of the beam is point of least diameter as seen from the axial point of view, also referred to as the propagation direction. The waist of the beam and the divergence angle are proportional when one increases, as does the other.

Figure 3.4. A diagram showing a laser diode being used as a transmitter, its beam diverges by and angle θ over the length L, a lens is placed at that length to intercept the beam and focus onto a receiver.
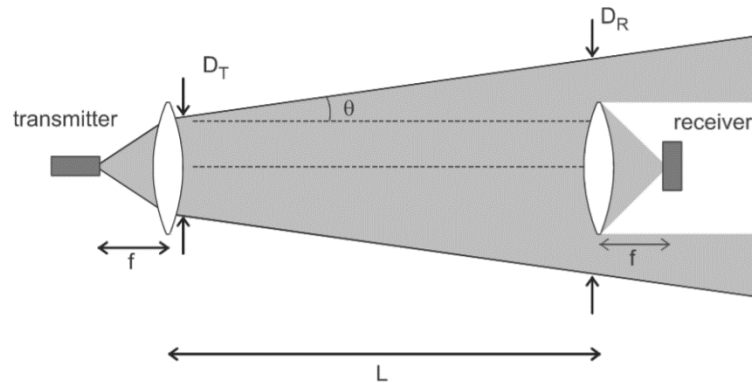
Furthermore, laser diodes have power to current graphs which explain the threshold characteristics. The laser diode will only produce significant optical power when driven above the threshold current. The threshold current is refered to as the required bias current as seen in Fig 3.5. Below threshold, the photons are produced by spontaneous emission and have a larger spread of energies the device operates in the LED mode. Above threshold, only the photons with energies that experience the largest gain will become lasing photons and therefore the spectrum is narrow, and the devices operates as a laser diode. In addition, thermal dependencies of temperature effect power to current output whereas with an increased temperature, the current required for the same power is higher. Usually a linear approximation can be made within the small temperature range however since our system is inherently analog experimental data should be established to where this cut off temperature is. The reason why this is useful is because the output optical power can essentially slave the input current to the device to match the modulation signal.

Figure 3.5. The optical power to current graph, displaying the bias current point and the threshold current dependence on temperature.
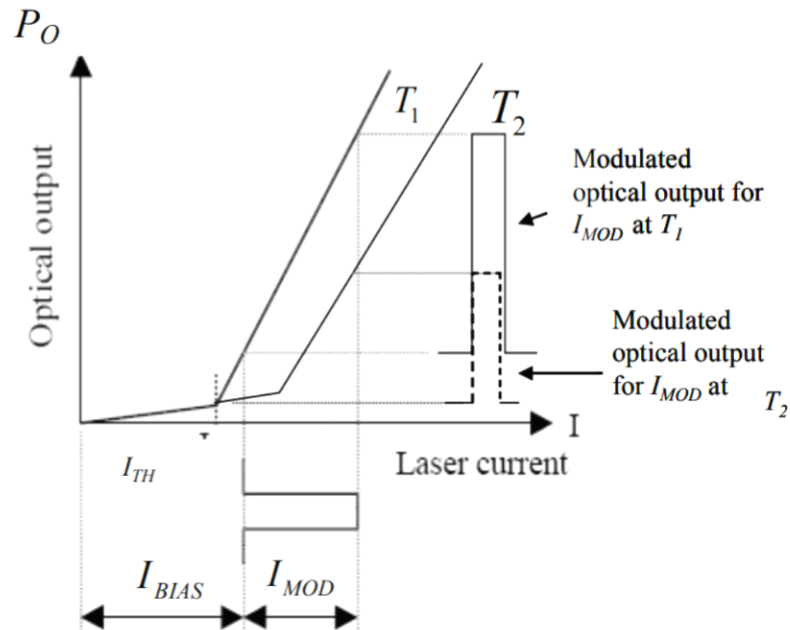
Ethernet

Ethernet technology was invented in the late 1970s and has been a crucial part of networking ever since. It was developed as a local area network technology meant to allow any devices connected by Ethernet to communicate with one another. It works on the Physical layer as well as the Data Link layer. Originally Ethernet made use of single coaxial cables, and then developed into twisted pair cable, and nowadays fiber optic cables. The most common medium for Ethernet is twisted pair cables that can be classified as category 3, 5, 5e, 6, 6a and most recently 8.1/8.2. In 1980 IEEE decided to standardize Ethernet technology under the group 802.3 as it was becoming so wide-spread. In 1990 Ethernet moved to a twisted pair cabled medium under the name 10BASE-T. 10BASE-T networks have a speed of 10 Mbit/s and are ran on category 3 cabling. Several years later came "Fast Ethernet" under the name of 100BASE-T, these networks were rated at speeds of 100 Mbit/s and required at least category 5 cabling. A few years after that came 1000BASE-T which has a network speed of 1000 Mbit/s and requires category 5e or category 6 cabling. More information is provided in the next section. Most Ethernet connection use an 8P8C port as shown in Fig. 3.6. This type of port is found across millions of devices and enables them to communicate on local area networks just by simply plugging them in. The impact of Ethernet is still relevant today as new standards are still being implemented some 40+ years later.[2]

Figure 3.6: An 8P8C connector, meaning eight positions eight contacts is an almost universal connector for Ethernet devices. It is crimped onto the end of a twisted pair cable (which contain 4 pairs) and each wire takes a single position on the face of the connector.
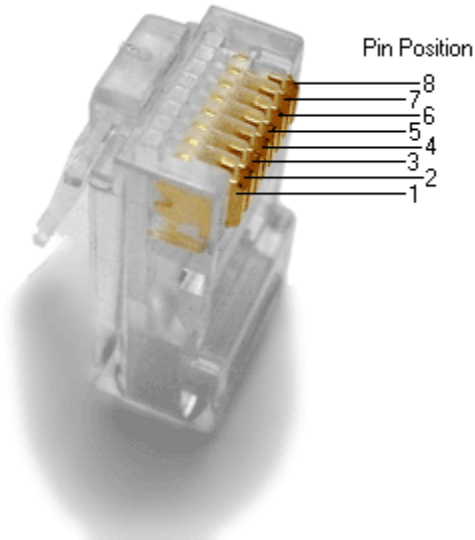
Twisted Pair Cables

Twisted pair cables have been the medium of choice for local area networks for the past 30 years. Fig. 3.7 shows a comparison between the different unshielded twisted pair (UTP) categories. The reason the pairs are twisted is together is to remove electromagnetic interference. In practice, the number of twists per meter is something that aids in how much capacity the cable can carry. In the table in Fig 3.7, we can see the cable category, its application, and its data rate. One parameter missing is the bandwidth measured in MHz. The required bandwidth is a function of the desired speed and symbol value of the data. The symbol value changes with each generation of Ethernet in order to facilitate faster connections. 10BASE-T uses Manchester coding, essentially the signal takes one of two values +2.5 V or – 2.5V. 100BASE-T uses MLT-3 where the signal can take values of +1, 0 or -1 V. Gigabit connections use PAM-5 where the values are +1, +0.5, 0 -0.5, or -1 V. You can see that the symbol value has gone from 2 to 3 to 5. Using Nyquist Bandwidth Theorem given as $C = 2 * B * Log_2(M)$ where C is the bitrate, B is the bandwidth and M is the symbol value. For instance, a 10 Mbps connection using Manchester encoding (M=2) requires 10 MHz of bandwidth. Similarly, 100BASE-T requires about 32 MHz of bandwidth. Even though it's not listed each category 3, 5 and 5e cables are only rated for 100 MHz max. However, if we use Nyquist theorem to solve for the bandwidth for a 1 Gbps connection we find that it is around 215 MHz. How can that be? The previous technologies 10 and 100 BASE-T were only using 2 of the 8 wires that are inside a UTP cable (1 pair). Gigabit Ethernet is achieved by splitting 1000 megabits into 4 separate pairs, which is 4 transmit and 4 receive. Now solving Nyquist theory for 250 Mbps we find that we only need 62.5

MHz for each line, well below the cable rating of 100 MHz.[2]

Figure 3.7. A comparison chart between the different categories of unshielded twisted pair cables. They are measured according to their data rate, and application.

UTP Categories - Copper Cable				
UTP Category	**Data Rate**	**Max. Length**	**Cable Type**	**Application**
CAT1	Up to 1Mbps	-	Twisted Pair	Old Telephone Cable
CAT2	Up to 4Mbps	-	Twisted Pair	Token Ring Networks
CAT3	Up to 10Mbps	100m	Twisted Pair	Token Rink & 10BASE-T Ethernet
CAT4	Up to 16Mbps	100m	Twisted Pair	Token Ring Networks
CAT5	Up to 100Mbps	100m	Twisted Pair	Ethernet, FastEthernet, Token Ring
CAT5e	Up to 1 Gbps	100m	Twisted Pair	Ethernet, FastEthernet, Gigabit Ethernet
CAT6	Up to 10Gbps	100m	Twisted Pair	GigabitEthernet, 10G Ethernet (55 meters)
CAT6a	Up to 10Gbps	100m	Twisted Pair	GigabitEthernet, 10G Ethernet (55 meters)
CAT7	Up to 10Gbps	100m	Twisted Pair	GigabitEthernet, 10G Ethernet (100 meters)

Multiplexing

If there is one thing that can agreed upon in the world of telecommunications it's that faster speeds are better. Multiplexing is a concept that is used to describe multiple signals over a single medium. There are a number of different kinds of multiplexing and each is used in different settings for different purposes. Time division multiplexing (TDM), is one of the most widely used and adopted forms of multiplexing because inherently is independent of the type of network. Time division multiplexing works by simply stacking separate data streams behind each other in the time domain. Consider a pair of rotary dials that had 10 holes in them, each hole represented a channel or user. Now consider 10 pipes separated by a stream connected by the dials, and that were each sending 1 unit of data at a rate 10x slower than the speed of the rotary dial. For every one revolution of the rotary dial each pipe would send 1 unit of data into the stream. On the receiving end, the opposite occurs where another rotary dial is synced with the first one to transfer the data across the stream from pipe 1 to pipe 1, pipe 2 to pipe 2 and so on and so forth. In practice, the speed at which this occurs is unperceivable to the users (in this example the pipes). Fig. 3.8 represents this concept.

Figure 3.8. A graphical representation of TDM, you can see the signals one after another, the loop network makes sure the first channel exits into the first channel and so on.
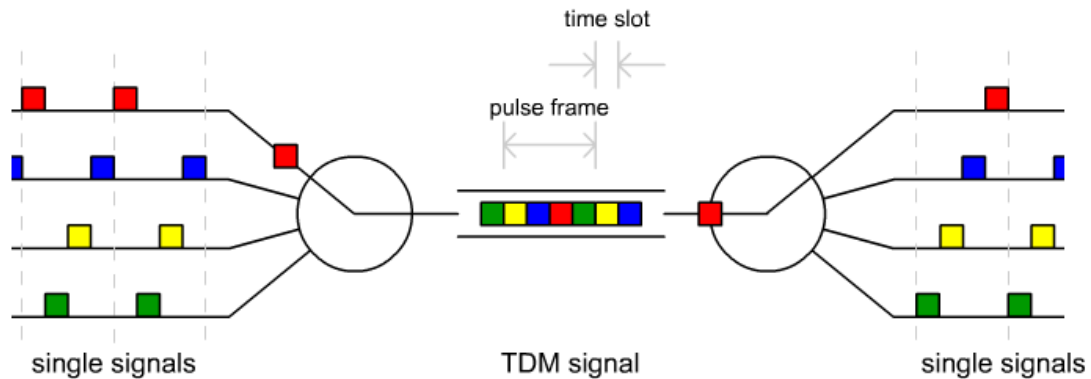
Another form of multiplexing that is commonly used is frequency division multiplexing (FDM). Frequency division is one of the most common forms of multiplexing in analog systems. This is especially apparent in systems of AM and FM radio, and television broadcasts. Frequency division in principle works just how the name says, a certain band of frequencies are allocated to each channel. Fig. 3.8 shows this concept. For a real-life example, you can look at FM radio stations, the spectrum starts at about 88 MHz and ends at about 108 MHz. When you change the dial on your radio (tune it) you see that the stations are separated by 200 KHz channels. This method allows multiple signals to be broadcast simultaneously through the same medium (air). In optical fibers FDM is just considered as using different colors for different channels which is also referred to as wave division multiplexing. Since the signal carrier is in the THz region in fiber optics, when FDM is employed the channel bandwidths are extremely large. Some VLC systems use this technique by implementing a multicolored LED. To elaborate a regular white light LED is usually really a single diode that is blue and the color is transformed when it is mixed with yellow phosphor giving a white appearance. However, there are white light LEDs like those in your television that combine three colors red, blue, and green to form a white light source. When implemented into a VLC system each light can be modulated individually thus produces a 3-channel multiplexed system given the area of reception has appropriate filtering.

Figure 3.9. A graphical representation of FDM, this shows three 20 KHz channels occupying about 60 KHz of total bandwidth.
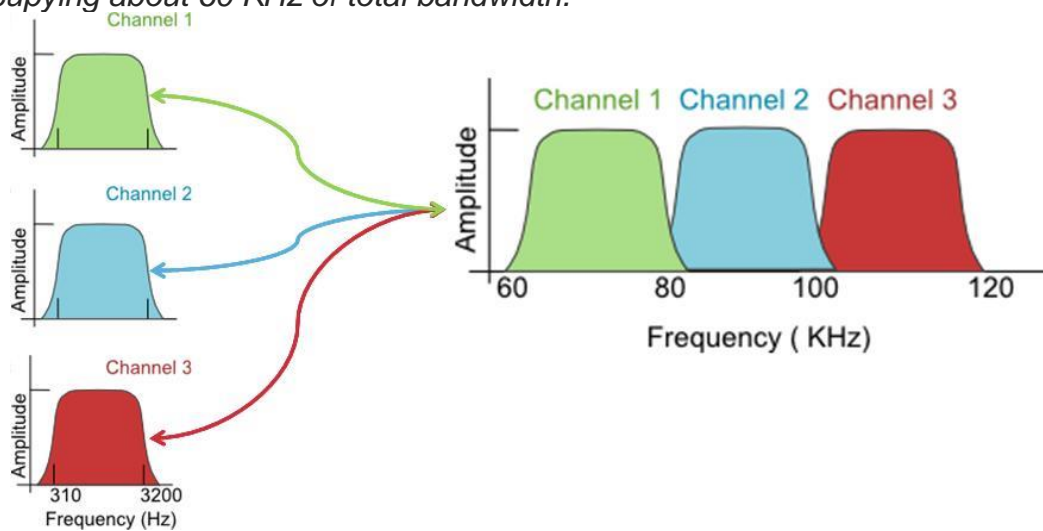
A third form of multiplexing is space division. This technique involves using separate paths of transmission making each connected device a direct link. For example, a local area network is inherently space divided, because each device requires its own Ethernet link to connect to a switch our router. Then the only information down any given transmission line is only meant the device connected to it. There are forms of this in wireless communication under the acronym of MIMO. MIMO stands for multiple input, multiple output, it is a technique where multiple transmitters and receiver operate at the same time. There is a natural occurrence in radio waves called multipath, because they can be reflected and "bounce" around they reach the receiver at different intervals. The path that each signal takes provides it with unique characteristics such as its arrival time or phase. Using signal processing the signals can be separated into different data streams thus allowing multiple users. Fig. 3.10 has a crude representation of this occurrence.

Figure 3.10. An approximate representation of multipath and MIMO
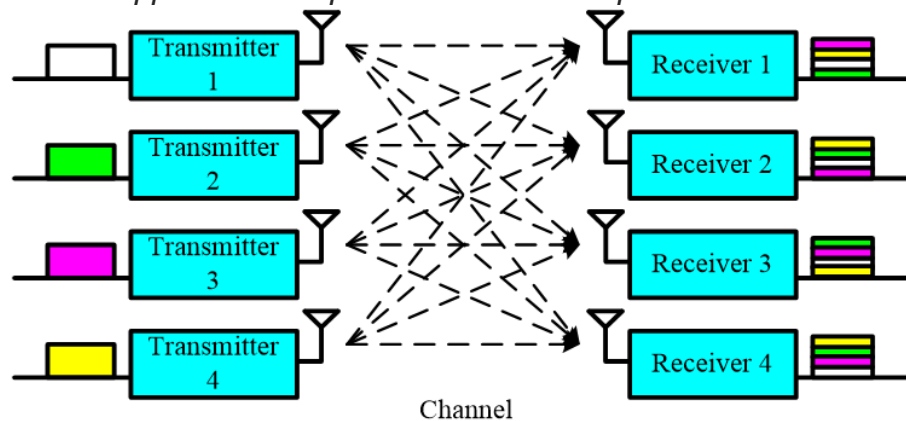
3.1.2 Receiver Technology

Photodevices

The 'heart' of a photodevice converts light into electric current because of the properties of semiconductors. Photodiodes illuminated by light and without external bias can generate electric current, and we refer to this mode of operation as photovoltaic. The photoconductive mode is characterized by an external bias. When an external bias voltage is applied, photodiodes conduct current and the current to voltage graphs have a linear regime. When light is absent, only a smaller 'dark' current can flow under reversed bias. When under illumination, photons absorbed in the semiconductor create electrons and holes that can essentially move from the electric field across the photodiode. The amount of electron and hole pairs created and thus maximal electric current is proportional to light intensity.

There are several significant receiving devices for light, however their uses have applications which their functions are interrelated. The various names for receiving devices are PN junction, phototransistor, photovoltaic and solar cell, which are the same concept, a PIN photodiode characterized by its thin and discrete P-type outer layer for maximal photon penetration and electron generation, and finally a photoconductor.

The photoconductive effect takes place when there is incident light on a photoresistor, or photoconductor. The photons are absorbed in the semiconductor and create free carriers that conduct electric current across the diode. The quantity of free carriers created and the electric current is proportional to light intensity given by $I_L = KP$ where K is the responsivity of the device. This is the meaning of photoconductive mode. In low light energy situations and monochromatic wavelengths, the conductance is a useful tool in measuring the optical power without a power meter however for our purposes the response time limits the applications of communication. In Fig 3.11, incident light is on a photoresistor and the resulting output is seen with a time constant delay according to the resistor and capacitance of the device.

In a photoconductor, the photo-absorption is proportional to the density of the impurity material which determines the penetration of light distance into the material and an extrinsic semiconductor with less minority carriers would have a slower charge recombination time. The transit time of this slow carrier represents the duration of this photoconductive process and affects the bandwidth of photoconductive detectors. Therefore, the fundamental limit of the bandwidth is the minority carrier recombination lifetime. The photoconductor or a photoresistor has a resistance proportional the incoming optical power which is the photoconductive effect.

Figure 3.11. A photoconductor illuminated with filtered white light. The current and voltage change in accordance with the modulated incident light.
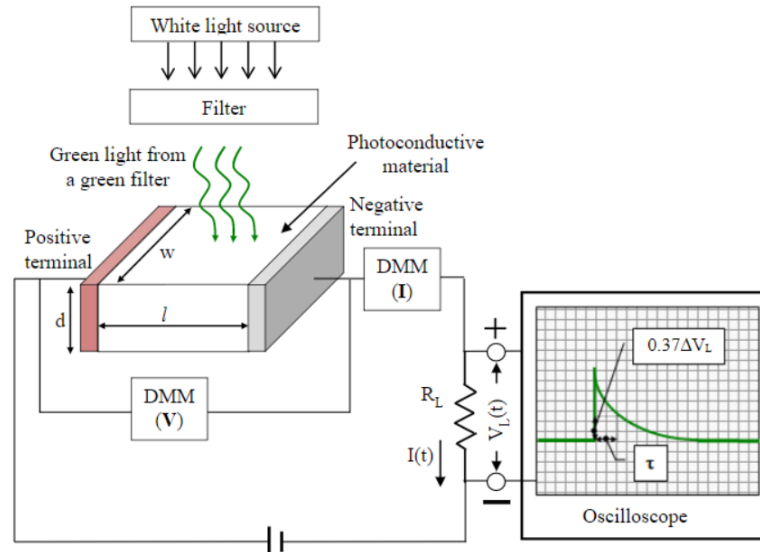
The solar cell converts incoming light into electrical power from the photovoltaic effect. There are free carriers or electron hole pairs which are created and these free carriers are extracted into the external load. During photovoltaic mode of operation there is no external applied voltage, however the holes from the p-type to the n-type from light injection creates an internal forward bias. The current is flowing from the n-side to p-side which creates a reverse current. Power is then delivered to an external circuit. There are intrinsic resistances in this device and their values effect the conversion efficiencies of the solar cell. The conversion efficiency measures the devices ability to create electricity from light. In recent years further improvements to the solar cells have driven the price down and performance to all-time lows and highs respectively.

Photoconductors are made of both intrinsic and extrinsic depending on the required application. The PN semiconductor devices typically are used as a photoconductor while a PIN semiconductor is used as a photodiode in order to have a larger depletion region. PN Solar cells have a small n-type neutral region and larger depletion region and a bank of a p-type in order to generate more electron hole pairs. The extrinsic photoconductors have responsivity and response time which are relatively low and this type of photoconductors is useful for detecting low energy. After determining the characteristic wavelength from the dopant material configuration, the ability to obtain the sensitivity factor which in turn can be a decision point in receiving the operating output mode of current or voltage of the photoconductor is found. The sensitivity of detecting impulse of light for the photoconductor is highest in the current mode.

For a photodiode in the photoconductive mode of operation the semiconductor is reverse biased and power is delivered to the photodiode. For the PIN photodiode,

the large reverse bias increases the depletion region and area of detection, which in turn decreases the transit time and the capacitance of that region. The decreased transit time and capacitance allows for the device to operate at larger frequencies.[3]

Figure 3.11. The PIN Photodiode diagram in reverse bias illustrating how a photon can induce free carrier (electrons and holes) transport.
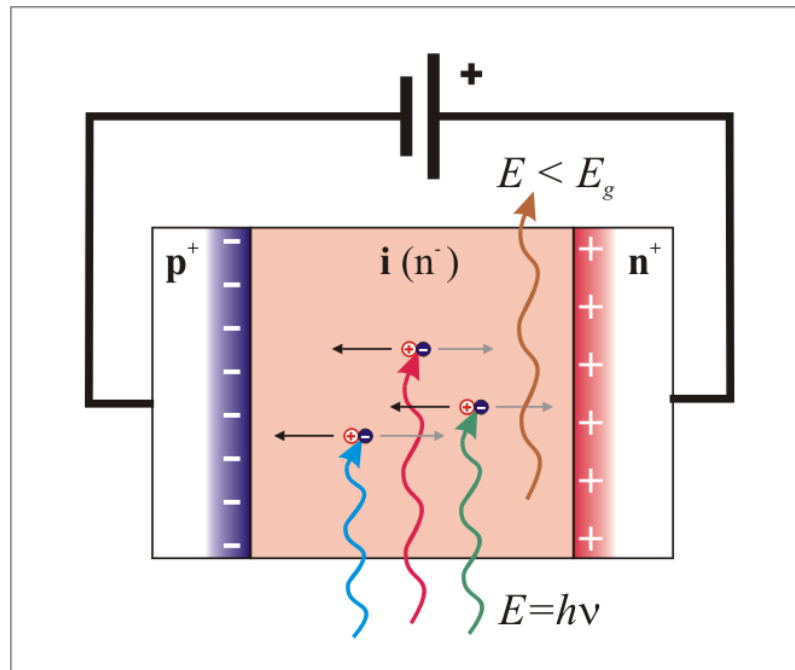
The spectral response of the device is a critical point of reference for every photodiode because it shows the range of the applicable responsivity. Depending on the dopant material which controls the bandgap and thus acceptable energy photon which can induce free carrier transport, each photodiode device has a particular range. The Fig 3.12 shows the typical spectral response characteristics seen from a photodiode manufacturer, and the goal of the group is to find a device which is specific to the lighting device which we are using. Therefore if both devices are suitable for each other we should get the best response out of the photodiode.

Figure 3.12. The spectral response of typical Hamamatsu corporation fast speed photodiodes.
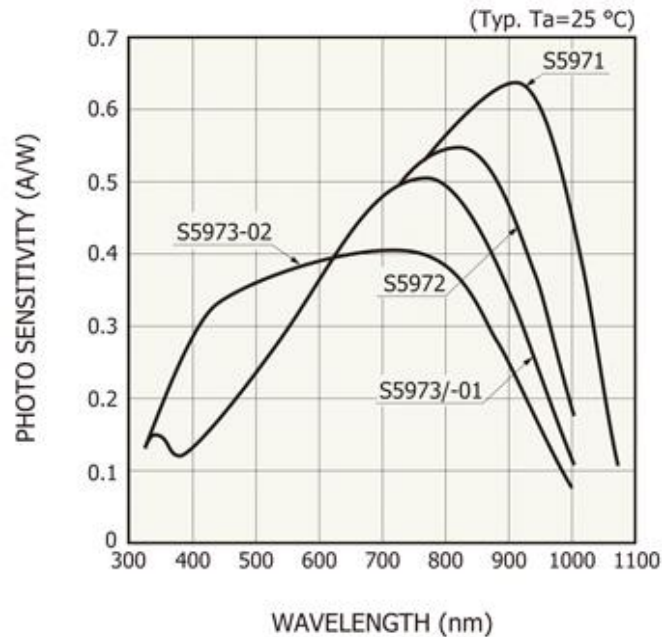
For a photodiode, the response time and bandwidth should be able to show the devices ability to react to a modulated input optical wave. However, there is a trade off in which if the incident optical power is modulated faster than the voltage change time constant, then the device will not react in time to receive the signal. The sensitivity of the device from the responsivity determines the optical powers which can still be utilized. The typical photodiode will have a reverse bias current which will interfere in detection to a certain degree in low illumination settings. An I-P curve can be made to show the point of noise equivalent power and the range of the device where too much power will create saturation.

Saturation is a problem because it will eliminate the resolvability of the signal. Even with filtering mechanisms, if the photo-device saturates there is no ability to reconfigure the signal with an analog system. The only metric which would be able to adjust for saturation is a feedback power meter to relay back to the transmitter to adjust the optical signal. Although this is on a surface a conceivable idea, the team feels as if the requirements do not merit such a solution, however, it would require an additional microcontroller device.

Figure 3.13. The I-P curve for a typical background light on a PIN and LED illumination to determine the reverse bias current and dynamic range.
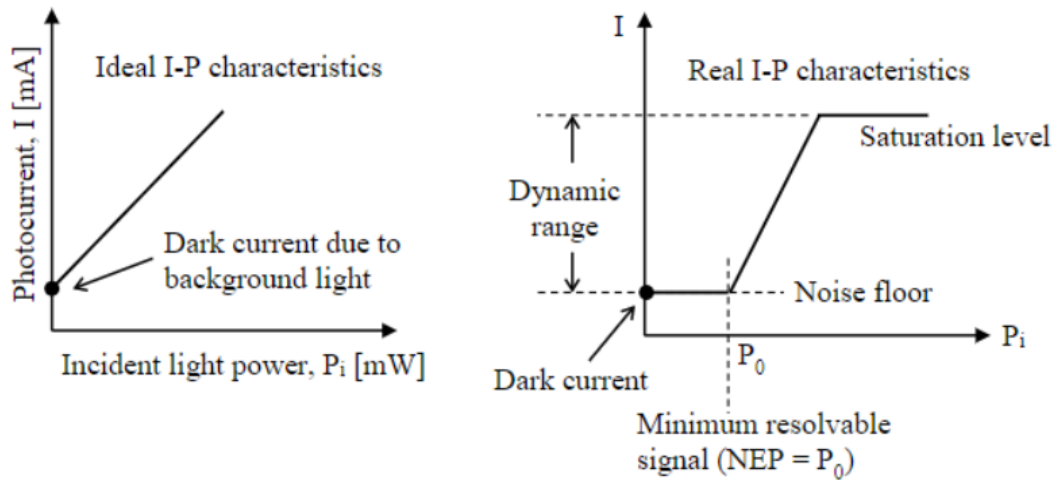
We are not going to mention as in depth about the inner workings of a phototransistor but note they can be used in receiving intensity modulated light but their frequency response is not efficient. Using an LED which was modulated with a square wave at 10 KHz, we can test the output of a photodiode and a phototransistor. The orange trace is the output of a standard visible light phototransistor and and the blue trace is the PIN photodiode output. Their respective circuits are slightly different but the picture of the waveforms essentially shows the distortion on the phototransistor as compared to the PIN at even as low as 10 kHz Square wave.

Figure 3.14. The relative output of a square wave white LED at 10 Khz for a phototransistor in orange and a photodiode in blue.
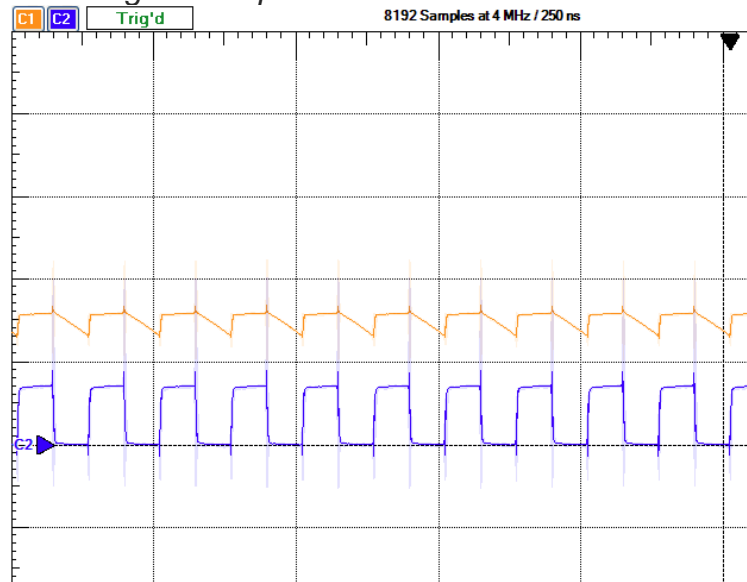
Photodiodes can be used in a wide range of applications however their structural material changes depending on the region of the spectrum. Therefore, depending on the application the detector can be chosen to match the power levels, spectrum, and speed.

3.1.3 Detection Statistics

In order to explain more about how error detection occurs, a little background on photon statistics is necessary. The statistical distribution of the number of photons depends on the nature of the light source. For coherent light with constant optical power P, the corresponding mean photon flux $\Phi = \frac{P}{h\nu}$ (photons/s) is also constant, but the actual times of registration of the photons are random. If the number of photons detected in a time T is n, then the mean value of n is $\bar{n} = \Phi T = \frac{PT}{h\nu}$. The probability distribution $p(n)$, i.e., the probability $p(0)$, of detecting no photons, the probability $p(1)$, of detecting one photon, and so on, may be measured by experimental observation. However due to the tedious nature of the required equipment and the practicality of a product, a Poisson distribution approach can be used. If the registration of photons are statistically independent, the Poisson distribution is obtained: $p(n) = \frac{\bar{n}^n \exp(-\bar{n})}{n!}$ where n = 0,1,2,3,4… photons for $\bar{n}$ mean number of photons. The uncertainty $\sigma_n = \sqrt{\bar{n}}$, which the presence of $\bar{n}$ photons is accompanied by an inaccuracy of $\pm \sigma_n$ photons.[1]

Table 1: The photon detection choices.

	Detection	**No Detection**
Photon presence	Signal Recorded - 1	Missed signal error, BER
No Photon Presence	Dark current, noise in system	Signal absent - 0

The probability of error, or bit error rate (BER) at 0 photons with high power is $p_e = \exp(\bar{n})$. The design of any instrument for sensing must take into account the signal to noise ratio because the detector can produce a response without light. The typical value required for a reasonable system is at least 10^{-6} for the BER.

The noise which is introduced into the system should be identified. The noise includes four different types in readout noise, shot noise, dark noise, and fixed pattern noise. The readout noise is from the electrical circuit such as wires and insertion loss. The shot noise is the variation in the current due to photon flux. The dark noise is the variation in electrons generated without an incident light which passes through the system created by recombination. Fixed pattern noise is a variation is a in the photo-response due to the physical interface of the detection area. The noises can be accounted for in the signal to noise ratio.

3.1.4 Electrical Processing

Operational Amplifiers

Since we are working on the transmitter data, we need an op-amp to be high slew rate and also high speed. Slew rate is the change of voltage per unit of time. Slew rate and bandwidth tend to be linked - high speed op-amps tend to have fast slew rates, otherwise there will be a mismatch in data in to possible data out.

The Hamamatsu recommended high speed photodetector circuit is in Fig. 3.17. The PD is PIN photodiode, R_L, R, R_f are values for specific operational amplifier gain calculations. Where I_{sc} is equivalent to the electrical analysis of the diagram.

$$V_o = I_{sc}(1 + \frac{R_F}{R_L})$$

Figure 3.15. The high-speed photodiode circuit (Courtesy of Hamamatsu).
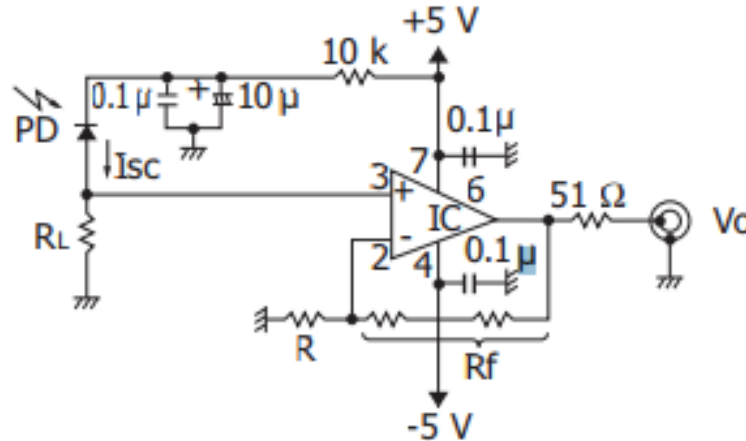
Differential amplifiers

Differential amplifier is the amplifier that amplifies the difference between two inputs. The output is $V_{out}=A_V(V_{IN}{}^+-V_{IN}{}^-)$. In the transmitter side, we are using the single ended output that combines the signal which comes from the Ethernet. In the receiver side, we are using the single ended input that convert back to a differential output.

Common Mode Rejection Ratio

The common mode rejection ratio (CMRR) is a number that describes how well an input or output will reject noise or how well "balanced" a balanced line is. It is relatively easy to calculate CMRR. CMRR is measured in decibels (dB) of the differential mode gain and the common mode gain. In terms of signal fidelity, it is an important parameter for determining the attenuation of any noise entering the

system. The instrumentation amplifier chosen for the design of the system is one with a very high CMRR so that it is efficient in eliminating large offset signals. The target goal is to have a CMRR of equal to or greater than 70 dB, which is common among integrated circuit differential amplifiers.[4]

3.2 Strategic Components and Part Selections

For 10BASE-T Ethernet Manchester Coding is the format of the line code. This means that the signal can take two separate values, either a +2.5 V or –2.5 V. In order to create a signal that is able to drive and LED we need to combine the differential into a single. To do this we need a differential receiver, however there are a number of devices in the market which are differential receivers and amplifiers, and they are compared below. The transmit lines from the Ethernet cable will plug into the receiver-amplifier, the signal from the amplifier will directly drive the LED. On the other end, a photodiode will receive the signal and pass it to an amplifier. The amplifier needs to provide a sufficient amount of output current and also needs to be high speed. A few of these are compared below. After being amplified, the received signal will need to be converted back into a differential, we can accomplish this using a differential driver. Then it will be passed to the receiving lines of the Ethernet cable, and finally to the computer. The process is the same when going from the computer to the network switch. In general, an op-amp requires two separate supply voltages, denoted as +Vs, and –Vs. In order to have one single power supply we can enlist the use of a voltage converter while still maintaining a single power supply, these take a positive input voltage and produce a negative supply.

3.2.1 Differential Receiver Amplifier

A differential receiver is needed to convert our differential Ethernet signal into a single ended signal. This has many benefits as it is much easier to work with than a dual transmission line, form this we can drive an LED, a photodiode, or any single sided optoelectronic device. This device will take a differential input signal, Vin+ and Vin-, and generates a single ended signal, Vout. The single ended output signal, Vout, is the difference between the differential input signals. Below is a comparison of a few different differential receivers.

AD8130

One of the differential receiver that we considered for transmitter was the AD8130. The AD8130 is differential-to-single-ended amplifiers with extremely high CMRR at high frequency. Therefore, they can also be effectively used as a high-speed instrument for amplification or for converting differential signals to single-ended signals. The AD8130 is a low cost, low noise, and with every high frequency 270MHz. It has very high common mode rejection ratio which is good for twisted-pair cable without corruption by any external noise. It is designed as a receiver for the transmitter for high speed signals over twisted-pair cables. AD8130 has a very

high slew rate (1090 V/μs) which allows for the signal to be represented correctly. The device however has a high input impedance. The AD8130 can be supplied by a wide power supply range from single +5 V to ±12 V, allowing wide common mode and differential-mode voltage ranges while maintaining signal integrity. The gain of the device is based on the feedback resistors. The gain equation is the same as that of a conventional op-amp: $G = 1 + R_F/R_G$. The pin configuration used while testing unity gain in fig 3.18. For unity-gain applications using the AD8130, R_F can be set to 0 and be seen as a short on the circuit.

Figure 3.16. The unity gain circuit for an AD 8129/30
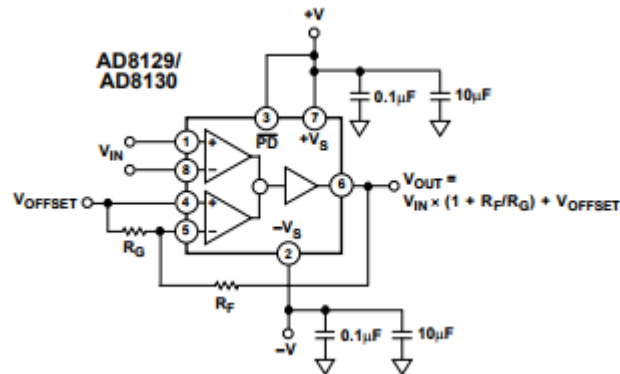
In this design, our goal is to take a differential Ethernet signal into a single ended signal while maintaining low power. Also, we want it to be in the high frequency and high slew rate. AD8130 meets our requirements but also AD8130 already has three amplifiers internally which take care of the impedance. It already has three ICs built in which can also convert a differential line to a single ended line. This single-line signal is then transmitted out however it still has a high impedance required of 1 MΩ.

MAX4444

Another option for the differential receiver that we considered for transmitter was the MAX4444. MAX4444 is differential-to-single-ended line receivers which offers high-speed and low-distortion performance. It is using a three-op-amp instrumentation amplifier architecture, and this IC has symmetrical differential inputs and a single-ended output. MAX4444 has extremely high slew rate. It operates at a frequency of 550MHz. It has 120mA output capability which allows the device to be directly coupled to a data acquisition system. It is suited to drive a coaxial cable. The high output current capability can easily drive the resistor impedance of common coaxial cables. It has s 55dB common mode rejection ratio, which is kind of a poor noise rejection criteria compared to other devices. The power supply range are from -5V-5V which is good for our design. The gain of a MAX4444 has an intrinsic RF in the gain equation making it harder to work with and may not produce any unity gain. The problem with this device is the output current is not sufficient for illumination.

THS4503

Another differential amplifier which has been considered is the THS4503. The THS4503 is from Texas Instruments. The THS4503 is high-performance fully differential amplifier. It is used for differential to single ended conversion. One good thing about this THS4503 is that the common mode rejection ratio is high. It has very good noise rejection criteria. Another advantage of the THS4503 is the power supply. It has a wide power supply range, and the power supply range is from -5V to 15V. However, the high frequency is not necessary although it has an excellent slew rate and it is kind of expensive compared to the other ICs.

EL4430

The EL4430 is an instrumentation amplifier which is ideal for differential to single ended converters. It has two sets of inputs; one which is connected to the signal and does not respond to its common-mode level, and another which is used to complete a feedback loop with the output. It can be operated on 5 and 15 supplies with no AC degradation. EL4430 has an excellent common mode rejection ratio. It is 70 dB which is very good noise rejection. The power supply range are from -5v to +5v. The EL4430 is stable for a gain of 1.

MAX4390 and MAX4392

MAX4390 and MAX4392 are dual-supply, rail-to-rail, voltage-feedback amplifiers that employ current-feedback techniques to achieve 500V/µs. This family of devices are a unity-gain device capable of 85 Mhz output. It also has rail-to-rail output which essentially allows both input sides to have an input and output voltage swing which stay linear. The device only consumes 5.5mA of current in order to be in the quiescent mode of operation and offers the ability to come with only 6 pins. The pins include VCC, VEE, the two input pins, a disable and the output pin which can drive the diode. This IC family operate from 4.5V to 11V supply. The output voltage swings to within 200mV of each supply rail. Local feedback around the output stage ensures low open-loop output impedance to reduce gain sensitivity to load variations. MAX4392 consume only 5.5mA of quiescent supply current per amplifier while achieving an 85MHz -3dB bandwidth, 27MHz 0.1dB gain flatness, and a 500V/µs slew rate. Both ICs have excellent harmonic distortion and differential gain/phase performance make these amplifiers an ideal choice for a wide variety of video and RF signal-processing applications.

The following tables are used to compare a few of the integrated circuits that were researched for our differential amplifier. An important factor is that we need a unity gain for our design at high frequency.

Table 2. The differential amplifiers comparison.

Specifications	AD8130	MAX4444	THS4503	EL4430	MAX 4390
Frequency -3 dB	270MHz	550MHz	370MHz	250MHz	85 MHz
Cost	$4.06	$3.25	$9.61	$2.45	$1.84
Common Mode Rejection Ratio	70 dB	55 dB	80 dB	70 dB	90 dB
Power Supply Range	2.25 V - 12.6 V	-5V - 5V	-5V - 15V	-5V - 5V	Single 4.5V to 11V or Dual ±2.25V to ±5.5V Operation
Noise	12.4nV/√Hz	25nV/√Hz	6.8nV/√Hz	26 nV/√Hz	2.1 nV/√Hz
Mounting Type	Surface Mount	Surface Mount	Surface Mount	Surface Mount	Surface Mount
Package Type	Tube	Tube	reel	TSSOP	TSSOP
Slew Rate	1090 V/µs	5000 V/µs	2800 V/ µs	380 V/µs	500 V/ µs
Output Current	40mA	120mA	150mA	30mA	50 mA

As we can see from tables above with all the features of each differential to single end integrated circuit. All ICs are at a sufficient frequency, and high speed which is good for the data transmitting. The table below is the summary of advantage and disadvantage of the all ICs that are compared side by side.

Table 3. The advantages and disadvantages of the differential amplifiers

Differential amplifier	Advantage	Disadvantage
AD8130	High frequency, unity gain, high CMMR	High input impedance
MAX4444	High slew rate, high output current	No unity gain, bad power supply
THS4503	High output current, low noise	Low CMMR, high cost,
EL4430	Low cost, stable unity gain	High Input impedance
MAX4390/MAX 4392	Low cost, stable unity gain	Low output impedance

The MAX 4390 is a simple implementation and has a small footprint on a PCB. The output impedance is only 0.6 Ω which is low and easily integratable into a design. The device only operates on 5 V and can be supplied with various power supplies.

Pin configuration of MAX4390 used while assembly PCB manually

Pin	Name	Description
1	out	Output

2	V$_{EE}$	Negative Power Supply. Connect a 0.1µF capacitor to GND.
3	IN+	Noninverting input
4	IN-	Inverting input
5	Disable	Disable. Connect to VCC to enable
6	V$_{CC}$	Positive Power Supply. Connect a 0.1µF capacitor to GND

Pin configuration of MAX4392 used while assembly PCB manually

Pin	**Name**	**Description**
1	OUTA	Output
2	INA-	Amplifier A Inverting Input
3	INA+	Amplifier A Noninverting Input
4	V$_{EE}$	Negative Power Supply.Connect a 0.1µF capacitor to GND.
5	INB+	Amplifier B Noninverting Input
6	INB-	Amplifier B Inverting Input
7	OUTB	Amplifier B Output
8	V$_{CC}$	Positive Power Supply. Connect a 0.1µF capacitor to GND

3.2.2 Operational Amplifier

An operational amplifier (commonly called an op-amp) is a is an integrated circuit that amplifies the difference between two input voltages and produces a single output. The op-amp is prevalent in analog electronics, and can be thought of as another electronic device. it is fundamentally a voltage amplifying device designed to be used with external feedback components such as resistors and capacitors between its output and input terminals. These feedback components determine the resulting function or "operation" of the amplifier and by virtue of the different feedback configurations whether resistive, capacitive or both, the amplifier can perform a variety of different operations. Originally, they were the basis for analog computation. In this scenario, we are actually using a transimpedance amplifier, which converts current (from the photodiode) into voltage, and then amplifies. Below we have compared possible op-amps choices.

LM7171

The LM7171 is a is a very high speed, voltage feedback amplifier. This IC can be used in video amplifiers, professional video cameras, HDTV amplifiers, CATV, fiber optics signal processing, and pulse amplifiers. The biggest attraction comes from its 4100 V/s slew rate. It consumes only 6.5 mA supply current while providing a unity-gain bandwidth of 200 MHz. It also has other great features such as low differential gain and phase. one advantage of this op-amp is that it has very high output current. The configuration of resistors around Pin 2, 3, and 4 serves the purpose of level shifting. Technically, they are called voltage dividers. They help to shift signals along the amplitude. It also has other great features such as low differential gain and phase and high output current. It has very high open loop gain which is 85 dB making the noise for the photodiode less significant.

OPA380

OPA380 is a high performance transimpedance amplifier. It is high speed operation with 90MHz gain bandwidth. It features extremely high precision, excellent long-term stability, and very low noise. It is ideally suited for high-speed photodiode applications. The signal bandwidth of a transimpedance amplifier is highly depends on the gain bandwidth of the amplifier and feedback resistor. The OPA380 is also suited for fast control loops for power level on an optical fiber input. The power supply range of OPA380 is from 2.7V to 5.5V. Due to high precision and low noise characteristic, a dynamic range of 4 to 5 decades can be achieved. The OPA380 performance results from an internal auto-zero amplifier combined with a high-speed amplifier. The OPA380 has been designed with circuitry to improve overload recovery and settling time over a traditional composite approach.

CA3100E

CA3100E is a large signal wideband and high speed operational amplifier. It has an output current of 15mA. It has a unity gain cross over frequency of approximately 38 MHz and an open loop, 3 dB corner frequency of approximately 110 kHz. The slew rate of the unity gain amplifier is 25V/μs. This device is used for video amplifiers and high frequency feedback amplifiers. The CA3100 circuit contains both bipolar and PMOS transistors on a single monolithic chip.

LMH6629

LMH6629 is a high speed, ultra-low noise transimpedance amplifier. It has an input voltage noise only 0.69 nV/√Hz. The LMH6629 operates on 2.7-V to 5.5-V supply with and outputs that swing to within 0.8 V of the rails for ease of use in single supply applications. It has very high slew rate at 1600V/ μs. The output current is as high as 250mA with the bandwidth of 900MHz. It is commonly used for photodiodes. The excellent noise and bandwidth enables applications such as medical diagnostic ultrasound, magnetic tape and disk storage and fiberoptic to

achieve maximum high frequency signal-to-noise ratios. The LMH6629 is a high gain bandwidth. The transimpedance gain is set by Rf.

OPA695

This device can also be used for differential input and has a single input. Capable of creating a high output power with minimal distortion for cable-modem upstream line drivers, a 450 MHz at 8 dB makes the device an excellent candidate for the receiver. The device was originally created for Surface Acoustic waves and high resolution RGB applications but with some alterations it can work as the first stage in the receiver. The voltage supply is 5 V and can handle up to 4300 V/µs slew rate. The advantage to this device is the low supply current of 12.9mA and the ability of a low supply current drop. The distortion performance of this device is appealing for the signals we are using.

The following tables are used to compare a few of the integrated circuits that were researched for our transimpedance amplifier. The tables provide critical information in the frequency response of the device, cost, CMMR, power supply range, noise, slew rate, and output current.

Table 4. The comparison specifications of the TIA Op-Amps

Specifications	LM7171	OPA380	CA3100E	OPA695	LMH6629
Frequency - 3 dB	220MHz	90MHz	38MHz	450MHz	900MHz
Cost	$2.81	$5.36	$38.55	$2.45	$4.88
Common Mode Rejection Ratio	85dB	110dB	90dB	N/A	70dB
Power Supply Range	±15V and ±5V	2.7V - 5.5V	14V-36V	5V	2.7-5.5
Noise	14nV/√Hz	3nV/√Hz	26 nV/√Hz	26 nV/√Hz	0.69nV/√Hz
Mounting type	Surface Mount	Surface Mount	Surface Mount	Surface Mount	Surface mount
Package Type	Reel	Reel	PDIP	Reel	Reel
Slew Rate	4100V/µs	80 V/µs	25V/µs	4300V/µs	1600V/µs
Output Current	100mA	150mA	15mA	20mA	250mA

As we can see from tables above with all the features of each operation amplifier. All ICs are at a sufficient frequency, and high speed. They all have high common mode rejection ratio. However, it is apparent that the slew rate of the LM7171 and

the OPA695 is twice of any of the other devices. The table below is the summary of advantage and disadvantage of the all ICs that are compared side by side.

Table 5. The advantages and disadvantages of the TIA Op-Amps.

TIA Op-Amp	Advantage	Disadvantage
LM7171	Wide supply range, Slew rate	High noise
OPA380	High output current	Low slew rate
CA3100E	Wide supply range	High noise, high cost,
LMH6629	High output current, low noise	Low CMRR
OPA695	Low cost, high slew rate	Low output current

We are going to use OPA695 because of the overwhelming high slew rate and the simple power supply. The device has a reasonable advantage in implementation and the distortion is minimal in our design.

Pin configuration of OPA695 used while assembly PCB manually

Pin	Name	Description
1	NC	Not connected
2	IN-	Inverting input
3	IN+	Noninverting input
4	$-V_S$	Negative supply
5	NC	Not connected
6	Output	output
7	$+V_S$	Positive supply
8	DIS	Not disable(enable)

3.2.3 Differential Driver

A differential driver takes a single ended signal, and converts it into a differential output signal. This is a possible device for taking the output of an optoelectronic component such as a photodiode, and producing a data signal that can be amplified for the Ethernet output.

This device will take a single ended input signal, Vin, and generates two output signals, Vout+ and Vout-. The differential output signal, Vdiff, is the difference between the two single-ended output signals. A few possible considerations for this role are compared below.

AD8131

The AD8131 is the compliment chip to the AD8130. The AD8131 is used for single-ended input to differential output driver. The AD8131 differs from conventional op-amps in that it has two outputs whose voltages move in opposite directions. It has fix gain of 2 without using any external components. It has a good advantage over other op-amp for driving signals over long line transmission. AD8131 is a differential driver that will provide a transmission of high speed signals over low-cost twisted pair cables. It is used for analog video signals or for other high-speed data transmission. It is suited for driving Cat5 twisted pair with minimal line attenuation. It has considerable cost and performance improvements over discrete line driver solutions. The AD8131's differential output also helps balance the input for differential ADCs, optimizing the distortion performance of the ADCs. It has very high slew rate and high frequency. The power supply range is from 2.7V to 5V which works just fine.

MAX4448

MAX4448 is a small signal bandwidth amplifier. It is a single ended to differential line driver that is designed for high speed communication. The device is capable of creating a transmitter signal over twisted pair cable. It is well-suited to drive twisted-pair cables. It uses a current feedback for greater bandwidth. It has bandwidth up to 330MHz however, the slew rate is not suitable for our application. The low-power enable mode reduces current consumption below 5.5mA and places the outputs in a high-impedance state. It can deliver differential output swings of ±6.2V from ±5V. One good thing about this device is that it has excellent differential gain/phase and noise specifications make these amplifiers ideal for a wide variety of video and RF signal-processing and transmission applications. The MAX4448 is stable with minimum gain of 2.

THS4120

THS4120 can be used in a simple single ended to differential conversion. The THS4120 has power supply at 3.3V, with 100 MHz frequency at -3 dB, with a common mode rejection ratio of a range of 64-96 dB. The THS4120 features a power-down pin which lowers the quiescent current from 11 mA down to 120 µA, ideal for reducing system power. The slew rate of THS4120 is low, only 50 V/µs. The input voltage noise is 5.4 nV/√Hz at 10 kHz. The power supply range is going to be a problem for this IC. The device outputs only 3.3V max when we need 5V for transmission.

The following tables are used to compare a few of the integrated circuits that were researched for our differential driver. The important fact is that we need cover single ended input to differential output as well as suitable to transfer data.

Table 6. The comparison of the differential driver specifications.

38

Specifications	AD8131	MAX4448	THS4120
Frequency -3 dB	400MHz	330MHz	100MHz
Cost	$4.72	$3.4	$6.55
Common Mode Rejection Ratio	70 dB	N/A	64-96 dB
Power Supply Range	-5V -5 V	4.5V - 5.5V	-3.3V
Noise	25 nV/√Hz	23nV/√Hz	5.4nV/√Hz
Mounting type	Surface Mount	Surface Mount	Surface Mount
Package Type	Tube	Tube	Tube
Slew Rate	2000V/μs	50 V/μs	50V/ μs
Output Current	60mA	130mA	110mA

As we can see from tables above with all the features of each single ended to differential integrated circuits. All ICs are at a sufficient frequency, and high speed which is good for the data transmitting. The table below is the summary of advantage and disadvantage of the all ICs that are compared side by side.

Table 7. The advantages and disadvantages of the differential drivers.

Differential Drivers	Advantage	Disadvantage
AD8131	High frequency, high CMMR, high range of power supply	Low output current
MAX4448	High slew rate, high output current, Low cost	High noise
THS4120	High output current, low noise, high CMMR	High cost, low slew rate, bad power supply

However, it may not be required if the transimpedance amplifier can feed into a comparator. Initially we thought that the AD8131 would feed into an amplifier such as the LM7171, however the differential drivers are an important consideration in making a receiver design.

Pin configuration of AD8131 used while testing

Pin	Name	Description
1	$-D_{IN}$	Negative input
2	V_{OCM}	Common-Mode Output Voltage. Voltage applied to this pin sets the common-mode output voltage with a ratio of 1:1.
3	V+	Positive Supply Voltage
4	+OUT	Positive Output.

5	-OUT	Negative Output
6	V-	Negative Supply Voltage.
7	NC	No Connect.
8	+D$_{IN}$	Positive Input.

3.2.4 Comparator

A comparator is essentially an op-amp operated in an open-loop configuration with either a high or low saturated output signal. As the name implies, a comparator compares two voltages to determine which is larger. The comparator is usually biased at voltages +VS and −VS, although other biases are possible. One major difference between a comparator and op-amp is that a comparator need not be frequency compensated. Frequency stability is not a consideration since the comparator is being driven into one of two states. Since a comparator does not contain a frequency compensation capacitor, it is not slew-rate-limited by the compensation capacitor as in the op-amp. Below is a comparison of a few possible comparator.

LT1713

LT1713 is single/dual comparator featuring rail-to-rail input, and rail-to-rail complementary output. It is 7ns at 20mV overdrive and 8.5ns at 5mV overdrive. The comparator has low power input which is 5mA. LT1713 is designed to be used in variety of systems such as high speed automatic test equipment, high speed triggers, line receivers, and window comparator. It uses a supply voltage range from 2.4V to 12V. The LT1713 has an internal TTL/CMOS compatible latches for retaining data at the outputs. Each latch holds data as long as the latch pin is held high. Latch pin hysteresis provides protection against slow moving or noisy latch signals.

TLV3501

TLV3501 is a push-pull output comparator featuring a 4.5 ns propagation delay. It has rail to rail input, and output, and directly drives either CMOS or TTL logic. The power supply requirements for the TLV3501 range from 2.5V to 5.5V. It also has a low supply current requirement at only 3.2 mA. It features high-speed response and includes 6 mV of internal hysteresis for improved noise immunity with an input common-mode range that extends 0.2 V beyond the power-supply rails.

MAX9691

MAX9691 is a single/dual ultra-fast ECL comparator capable of very short propagation delay (1.2 ns). The power supply requirements range from -5.2V to 5V. It has differential inputs and complementary outputs that are fully compatible

with ECL-logic levels. It is commonly used in high speed line receivers and high-speed triggers. It also features large gain-bandwidth characteristics.

TS3011

TS3011 is rail-to-rail high speed comparator features a high-speed response time. It has propagation delay of 8ns. The TS3011 offers micro power consumption as low as a few hundred microamperes, thus providing an excellent ratio of power consumption current versus response time. The TS3011 includes rail-to- rail input and push-pull outputs. The power supply operates from 2.2V to 5V.

The following tables are used to compare a few of the integrated circuits that were researched for our comparator. An important factor of those comparator should have low propagation delay time.

Table 8. The comparison of the comparator specifications.

Specifications	LT1713	LTV3501	MAX9691	TS3011
Propagation delay time	7 ns	4.5 ns	1.2 ns	8 ns
Cost	$2.55	$5.43	$5.48	$1.165
Single or Dual	Single/Dual	Single	Single/Dual	Single
Power Supply Range	2.4V to 12V	2.7V-5.5V	5V and – 5.2V	2.2V-5V
Mounting type	Surface mount	Surface mount	Surface mount	Surface mount
Package Type	MSOP	SOIC	TSSOP	ECOPACK
Output Current	20 mA	74 mA	50 mA	Low

As we can see from tables above with all the features of comparator. All four comparators have suitable power supply to our design. They also have short propagation delay time. The table below is the summary of advantage and disadvantage of the all ICs that are compared side by side.

Table 9. The advantages and disadvantages of the comparators.

Comparators	Advantage	Disadvantage
LT1713	Wide power supply range	Low output current
LTV3501	High output current	Expensive
MAX9691	Shortest propagation delay time	Expensive
TS3011	Low cost	Low output current

We are going to use LT1713 in our design because of the power supply range and the overall low cost to package type and output current.

Pin configuration of LT1713 used while assembly PCB

Pin	Name	Description
1	V+	Positive Supply Voltage, Usually 5V.
2	+IN	Noninverting Input.
3	-IN	Inverting Input.
4	V-	Negative Supply Voltage, Usually 0V or – 5V
5	Latch enable	Latch Enable Input. With a logic high the output is latched
6	GND	Ground Supply Voltage, Usually 0V.
7	Q	Noninverting Output.
8	Q-	Inverting Output.

3.2.5 Voltage Converters

A voltage converter is a CMOS based device that converts a single supply voltage into the opposite polarity or increases the amount of voltage output while at a decrease in current output. We can use these in order to have a consistent power supply, while being able to supply the amps with both + and – voltage or more voltage than what is reasonable from an external power supply. Below is a comparison of a few possible voltage converters.

ICL7660S

The ICL7660S is a CMOS switched-capacitor voltage converter that inverts, doubles, divides, or multiplies a positive input voltage. It is a charge-pump voltage converter. It works by first accumulating charge in a bucket capacitor and then transfer it into a reservoir capacitor. A great feature of this device is that it is designed to provide a simple, compact, low-cost solution where negative or doubled supply voltages are needed for operation. It does not require an external diode when in a high voltage regime. It has wide supply voltage range are from 1.5 V to 10 V and it combines low quiescent current and high efficiency.

LTC1044A

The LTC1044A provides several voltage conversion functions: the input voltage can be inverted, doubled, divided, or multiplied. It has wide operating supply voltage range which from 1.5 V to 12 V and has a 97% minimum open circuit voltage conversion efficiency as well as a 95% minimum power conversion

efficiency. It also used for conversion of both 10V to ±10V Supplies and 5V to ±5V Supplies. One advantage about this device is provides several conversion functions without using inductors.

MIC2605

The MIC2605 is a constant frequency boost converter. It operates by taking a DC input voltage and regulating a higher DC output voltage. It has wide input voltage range from 4.5V to 20V. This device can be used for broadband communications, positive output regulation, local boost regulation, and DLS applications. High power density is achieved with the MIC2605/6's internal 40V/0.5A switch and Schottky diode, allowing it to power large loads in a tiny footprint. It can operate at a high frequency which is 1.2MHz and with a selective duty cycle. The duty cycle which refers to the switch on-to-off time ratio and can be calculated as follows for a boost regulator: $D = 1 - \frac{V_{in}}{V_{out}}$. The duty cycle required for voltage conversion should be less than the maximum duty cycle of 85%.

ADM660

ADM660 is a CMOS switch capacitor voltage convertor. It is a charge-pump voltage converter that can be used to either invert the input supply voltage giving VOUT = –VIN or double it. Input voltages ranging from +1.5 V to +7 V can be inverted into a negative –1.5 V to –7 V output supply. The voltage conversion task is achieved using a switched capacitor technique using two external charge storage capacitors. It has extremely high output current which is 100mA. It is used for handheld instruments, portable computers, remote data acquisition, and op-amp power supplies. In order to optimize capacitor size, it uses a frequency control input pin to select 25 kHz or 120 kHz charge-pump operation.

The following tables are used to compare those voltage convertors.

Table 10. The comparison of the voltage converter specifications.

Specifications	ICL7660S	LTC1044A	MIC2605	ADM660
Inverting Mode	Yes	Yes	Yes	Yes
Cost	$3.01	$5.43	$1.18	$2.94
Voltage conversion efficiency	98%	97%	99%	N/A
Power Supply Range	1.5V -10 V	1.5V-12V	4.5V-20	1.5V-7V
Mounting type	Through hole	Surface mount	Surface mount	Through hole
Package Type	Tube	Reel	Reel	TSSOP
Output Current	20mA	20mA	low	100mA

As we can see from tables above with all the features of voltage convertor. All four can be in inverting mode. They have very high voltage conversion efficiency. They are wide power supply ranges. The table below is the summary of advantage and disadvantage of the all ICs that are compared side by side.

Table 11. The advantages and disadvantages of the voltage converters.

Voltage Converter	Advantage	Disadvantage
MAX1044	Wide power supply	Low output current
LTC1044	Wide power supply range	Low output current, expensive
MIC2605	Lowest cost, highest efficiency,	Low output current
ADM440	High output current	Voltage conversion efficiency is high

We are going to use MIC2605 in our design because of its ability to change voltages. In our application, the laser will require a relatively low input current and the power supply need only regulate a reliable output voltage. The operational amplifiers, and differential drivers should be able to manipulate that voltage into a suitable regime for operation.

Pin configuration of LT1713 used while assembly PCB

Pin	Name	Description
1	V_{OUT}	Output Pin: Connect to the output capacitor.
2	V_{IN}	Supply (Input): 4.5V to 20V input voltage.
3	V_{DD}	Internal regulated supply. VDD should be connected to VIN when VIN ≤ 7V.
4	EN	Enable (Input): Logic high enables regulator. Logic low shuts down regulator.
5	SS	Soft start
6	FB	Feedback (Input): 1.25V output voltage sense node. VOUT = 1.25V (1 + R1/R2).
7	SW	Switch Node (Input): Internal power BIPOLAR collector
8	P_{GND}	Power ground
EP	EPAD	Exposed backside pad for thermal cooling.

Voltage Regulator

LM78M05CT

LM78M05 three-pin positive voltage regulators. The device can regulate a voltage according to the passive components. It employs built-in current limiting, thermal shutdown, and safe-operating area protection, which makes them virtually immune to damage from output overloads. It has fixed voltage regulators meaning no external feedback resistors are required to set the output voltage. Input and output capacitors are also not required for the device to be stable. However, input capacitance helps filter noise from the supply and output capacitance improves the transient response. The output current is in excess of 0.5A and the output voltage of 5V and 15V. This device can be used in variety of application such as printers, electronic point of sale, and TVs.

Pin configuration of LM78M05CT used while assembly PCB

Pin	Name
1	Input
2	Ground
3	Output

3.2.6 LED

When focusing on visible light communication using LED's there a numerous considerations in their details. An LED is a light emitting diode, the details of operation and design are mentioned in an earlier chapter. There are thousands of LEDs in the market, the key in this instance is finding and LED and photodiode compliment that share the same operating range. There are some requirements for the LED however, we need one that is white in appearance in order to maintain the common color of everyday lighting if we wanted to create a system based off of LED's. Another condition is that the LED must be through-hole, meaning it has two pins and can be inserted into a PCB. The vast majority of LEDs in the market do not fall into this category, making the selection a little more difficult. In the datasheets from companies there is not a standard on LED optical power output of -3 dB frequency characterization so it would require purchasing and testing which is out of the scope of this project. However, included in our final design are SMD LED's on the market which can be used indicator lights for the power supply.

For now, we are going to present some SMD LEDs and as the design continues go into further details of laser diode specifications. Included in the table of LED comparison is operating temperature, cost, color, power supply range, mounting type and forward voltage and forward current. The operating temperature is standard for the purchasable SMD LEDs from - 40 ºC – 85 ºC because of regulatory compliance. The cost of the single SMD LED's are taken into consideration however their price relatively negligible and decreases as the amount of LED's

needed is ranging anywhere from $0.40 to $1.00. Speaking more on a technical side color is the perception of the optical spectrum and can change according to the observer. The absolute color is only resolvable with a spectrometer. The power supply required or forward voltage differs per color of the LED. The indicators are going to be used for the presence of the 5V power supply and 35V from the DC booster supply.

Table 12. The comparison of the SMD LEDs.

Light Emitting Diode	HSMQ-C170G	HSMQ-C170Y	HSMQ-C170R
Operating Temperature	- 40 ºC – 85 ºC	- 40 ºC – 85 ºC	- 40 ºC – 85 ºC
Cost	$0.94	$0.41	$0.66
Color, Peak in nm	Green, 527 nm	Yellow, 586 nm	Red, 626 nm
Forward Voltage	3.4 V	2.1V	1.9V
Mounting type	Surface mount	Surface mount	Surface mount
Forward Current	20mA	20mA	20mA

3.2.7 Photodiode

One of the most important components of the entire design is the photodiode. Unlike the LED, a PIN photodiode must be reversed biased in order to function properly. Most photodiodes require a significant amount of voltage, making it difficult when designing a power supply. In this scenario there are several approaches, the first involves selecting a photodiode that has a very broad acceptance range, making it suitable for any kind of LED emitter. The second option is to get a photodiode that is very narrow in its acceptance range, but that limits the kind of emitter we can use. In either case the cost of a decent photodiode is quite large. The last option, and realistically, the best is to buy a common photodiode that is cheap and has a broad acceptance range at the cost of performance over some wavelengths. Below we have shown a couple of photodiode options and compared them.

BPV10

The BPV10 is a thru-hole or leaded PIN photodiode. It has an extremely large operating bandwidth of 250 MHz and is compliant with RoHS directives. The response range of the BPV10 is 380 to 1100 nm, which makes it a perfect candidate for the VLC system. The BPV10 is also packaged in a clear radial case, giving it a twenty-degree half angle (the angle at which sensitivity is reduced by 50%).

SFH 203 PFA

The SFH 203 PFA is a silicon PIN diode featuring a thru-hole package type and cylindrical casing. The operating range for this photodiode is 400 nm to 1100 nm, making it too a good candidate for the VLC receiver. This diode has a frequency response of 200 MHz, and is also compliant with RoHS directives.

SXUV5

The SXUV5 is a thru-hole silicon photodiode. It features a rounded casing and an extremely fast response time. This photodiode unlike the others doesn't have an acceptance range, rather a single wavelength that it excels at detecting. The SXUV5 has a center wavelength of 800 nm and a bandwidth of 1 GHz. It also has a large half angle at forty degrees. The next two tables provide a specifications comparison between the three photodiodes.

Table 13. The comparison of the photodiode candidates.

Specifications	BPV10	SFH 203	SXUV5
Operating Temperature	- 10 ºC – 40 ºC	- 10 ºC – 40 ºC	- 10 ºC – 40 ºC
Cost	$1.11	$0.29	$363.95
Response, Peak in nm	400 – 1100 nm, 950 peak	400 – 1000 nm, 900 peak	Near IR, 800 nm
Reverse Voltage	5 – 60 v	5 - 50 V	20 V
Mounting type	Through hole	Through hole	Through hole
Forward Current	70 uA	9.5 uA	10 uA
Frequency Response	250 MHz	270 Mhz	1 GHz

Table 14. The advantages and disadvantages of the photodiodes

Photodiode	Advantage	Disadvantage
BPV10	Large response range, good output current	High reverse voltage to be effective
SFH 203	Cheapest, with good range	Low output current
SXUV5	Low reverse voltage, very fast response	Extreme price

The photodiode which will be used is the SFH 203. The cheapest with a peak able to cover visible to infrared will be an advantage in transmitter selection. The forward current of this device allows for small noise to be input into the system. Without noise, there are less integrated circuits needed for compensation.

3.2.8 Laser Criteria

In the market, there is a vast number of products which can be used as a functioning light transmitting laser. The laser is an optical device which can transmit an electrical signal by employing a two sets of modulation techniques, internal/direct modulation or external modulation.

The internal modulation techniques arise from the operation of the change in intensity from the changing of the supplied voltage or current to the operating point of the laser. External modulation techniques include changing the optical phase, polarization, or amplitude by an adjacent electro-optical device that can split and create two or more separate beams which have phases that constructively or destructively interfere. The internal modulation technique is the method chosen because of the inherent analog characteristics which it contains. Internal modulation also known as gain switching is pumping the population of electrons briefly over the threshold for light output in very short intervals. Although the analog signal may be unreliable in data transmission, the receiver system has a comparator which recreates this signal into a discrete structure for the TCP/IP protocols which are mentioned in chapter 6.

In our project due to time constrains and limitations of budgeting, semiconductor laser such as VCSEL, Distributed feedback, QCL and Fabry-Perot lasers are not going to align with our construction abilities. The laser which we will use have a packaging type where they are built with an internal heat sink metal and not an electrically pumped heat sink. We will not select butterfly packaged lasers which are made with 14 pins for temperature control and electrical control, our laser will only be able to be directly modulated with the electric current.

The laser we are choosing is going to be in the visible spectra in order to have an easier time aligning the diode to the photodetector and for the actual presentation to an audience. In order to narrow down the selection the criteria must be established according to some of the following characteristics: operating temperature, so we can have a good sense of how long the device can operate before overheating, cost because it is important to keep the budget in mind, operating voltage or turn on voltage which the device can turn on, working current to know how much current we should limit the device to, wavelength to know the spectral distribution of the device, output power limit to know how much power the device emits according to the maximum output rating and finally the mounting type to know how to construct the device in the product integration.

Jameco Valuepro 154145

This 650 nm laser has been designed to have a manufactured internal heat sink to dissipate the heat generated from the output. The operating voltage is in the range of the transmission in 3 V making it an ideal candidate, and the current is within the range we need being < 40 mA. The required current is a 30 mA over threshold where it is in the linear region with ± 10 % capabilities. The through hole of 2 pins is the desired mounting type because there is an internal ground.

Lilly Electronics 532MD-30-5V-TTL

This 532 nm laser has also been designed to have an internal heat sink to dissipate the heat generated from the output and has a similar outward appearance. The operating voltage is in the range of the transmission in 5 V and the current is greater than 265 mA for the threshold which makes the selection a poor choice. The through hole of 3 pins requires an external grounding which actually is not a problem if the PCB design was correctly adjusted. In addition to the price, the device will be a bad candidate.

Thorlabs ML925B45F

This 1550nm laser has not been designed to have an internal heat sink, but rather a thermal electric cooling device to maintain the temperature. The operating voltage is too low, and would need a reconfigured PCB design because of the voltage and additional ground pin. The current drawn and the output power are within the confines which we are aiming for, however the price is 10x the visible 650 nm laser.

Overall the specifications are listed in the table below which should give a better scope as to the justifications of product selection.

Laser Specifications	Jameco Valuepro 154145	Lilly Electronics 532MD-30-5V-TTL	Thorlabs ML925B45F
Operating Temperature	-32.8°C to 149°C	＋15 ℃ - 35 ℃	-32.8°C to 85°C
Cost	$3.49	$25.80	$48.50
Operating Voltage	3 V	5 V	1.5 V
Working Current	< 40 mA	> 265 mA	< 50 mA
Wavelength	650 nm	532 nm	1550 nm
Output Power	< 5 mW	30 mW	5 mW
Mounting Type	Wires, through hole 2 pins	Through hole 3 pins	Through hole 3 pins

The following table summarizes the characteristics for their advantages and disadvantages for the laser criteria.

Photodiode	Advantage	Disadvantage
Jameco Valuepro 154145	Operating voltage and current value, low price, 2 pins	Low output power
Lilly Electronics 532MD-30-5V-TTL	High output power	High price, high current required
Thorlabs ML925B45F	Low current and low voltage	High price

Overall, we will pick the Jameco Valuepro 154145 for the low price and electrical characteristics which go along with the electrical design that the MAX4390 can output. The laser at < 40 mA has been experimentally shown to have a threshold current at 12 mA, and therefore it can very well meet the criteria of staying within the linear range of the device and act as a gain switcher.
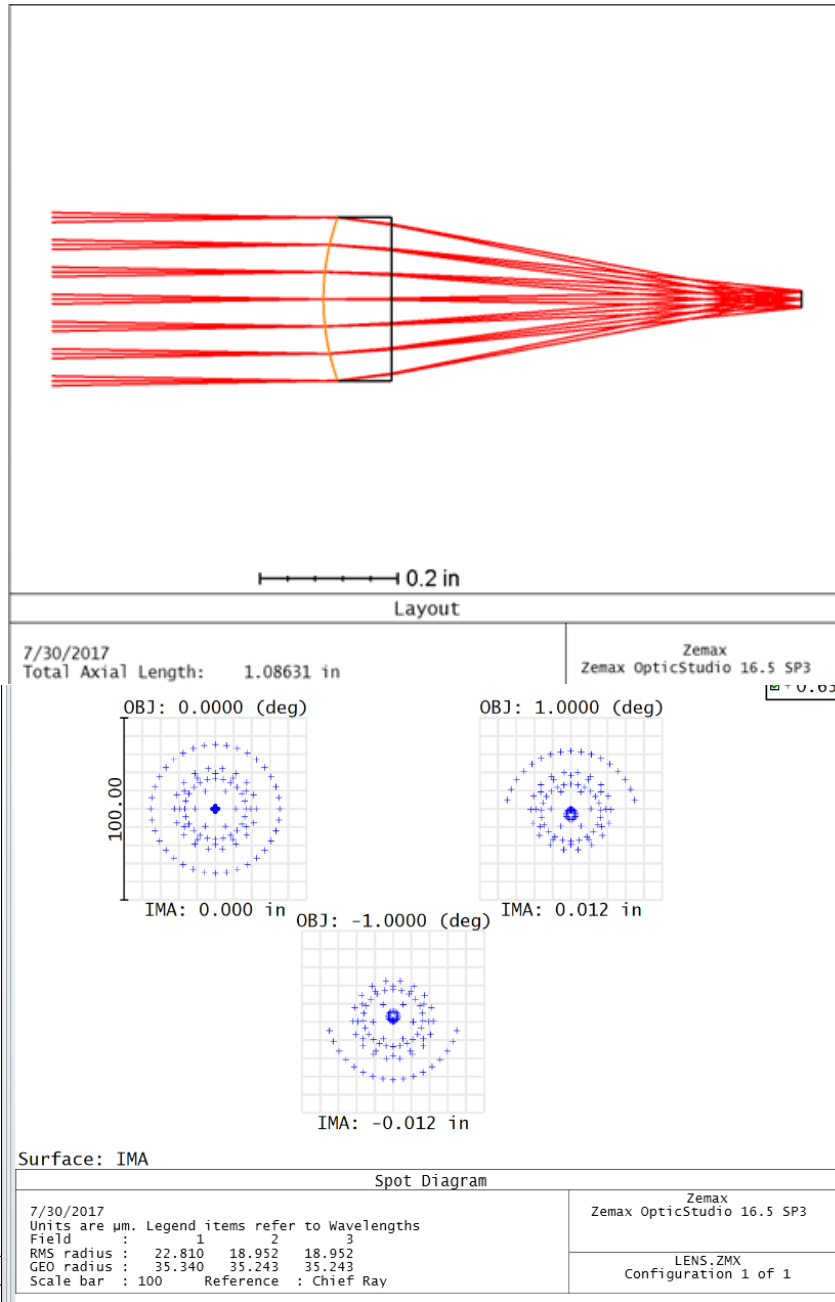
3.2.9 Focusing Optics

When considering a product such as VLC there are physical limiting factors that can be overcame in order to improve the overall effectiveness of the system. The idea here is to collect the beam incident on the receiving device and provide a more concentrated spot on the photo-diode. Since the two photodiodes on either end serve as the receiver for their respective devices assisting them in the collection of photons improves their efficiency. On the transmitter side of each device we will attach a collimating lens. Collimating the beam will reduce its divergence to nearly nothing allowing the beam to maintain integrity as it reaches the receiver. This is where optical elements come in.

The best choice for the focusing on to the receiver is a short focal length plano-convex lens which is designed for the peak laser wavelength. The reason being is that is can take a well collimated beam and neatly readjust the beam into a smaller spot size, reducing the stray light and improving optical radiation incident onto the device.

For the optics comparison, the aim of the piece is to select a F#, where it can collect more light. The "f-number," is defined as F# = F/D where F is the focal length and D is the diameter of the lens. The lens which would produce the smallest spot size from a collimated monochromatic input beam would be a plano-convex lens because the surface of a biconvex lens will have one surface which will want to expand the beam and the other will compensate, however with a plano-convex this is going to happen. The F# or speed of a lens can relate to the beam divergence or convergence in a spot size which can be approximated as $\theta = \tan^{-1}$

F/D = $\frac{\lambda}{\pi\omega_o}$ so a smaller F# can create a smaller spot size and thus more reception of light.

For an example on lens quickness, a particular lens seen in Fig. 3.1, this lens is from Newport Corporation entitled "Plano-Convex Lens, N-BK7, 6.0 mm Diameter, 17 mm EFL, Uncoated." The F# of this lens is trivially 2.833 which would increase in "fastness" if the diameter was larger. The lens can be simulated in an optical design software called Opticstudio, which allows for the user to make an infinite sum of an optical train lenses and see the results. The simulator is only a calculator and can only perform to the commands given, however, intrinsic in the design of the program is an optimizer which can pick the best criteria of selection such as spherical, coma, or astigmatic aberrations. The "Root Mean Square" or RMS spot size is a metric for visually understanding the effects of stay light or aberrations on detection quality. The smaller the spot size, the more control of the light to focus.

Layout

7/30/2017
Total Axial Length: 1.08631 in

Zemax
Zemax OpticStudio 16.5 SP3

OBJ: 0.0000 (deg)

OBJ: 1.0000 (deg)

100.00

IMA: 0.000 in

IMA: 0.012 in

OBJ: -1.0000 (deg)

IMA: -0.012 in

Surface: IMA

Spot Diagram

7/30/2017
Units are µm. Legend items refer to Wavelengths
Field   :   1   2   3
RMS radius :   22.810   18.952   18.952
GEO radius :   35.340   35.243   35.243
Scale bar : 100   Reference : Chief Ray

Zemax
Zemax OpticStudio 16.5 SP3

LENS.ZMX
Configuration 1 of 1

For the transmitter side, a simple aspheric plano-convex lens will do the trick of collimating the beam. In this scenario, the lens would be placed opposite the direction of the receiving lens so that the laser beam is incident on the planar side of the lens. An aspheric lens as the name suggests is shaped in a way such that the surface is not one single radius, nor is it continuous, as seen below.

Fig. 3.2 An aspheric lens courtesy of Edmund optics
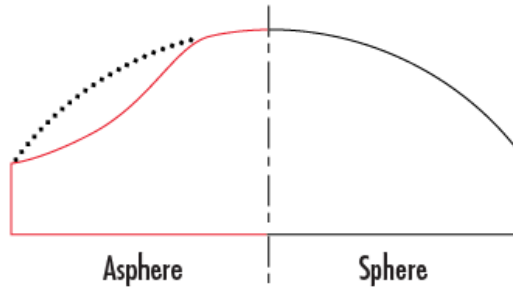
Asphere | Sphere

Generally, aspheres are optimized for non-continuous incident angularity, whereas the beam may not be as efficient in power at all angles equally meaning aspheres are also intolerant to spherical aberrations, some possible lens choices have been listed and are compared below.

LA1116

The LA1116 is a plano-convex lens made from BK7 type glass manufactured by Thorlabs. It has a diameter of 6 mm and a focal length of 10 mm, therefore it has an F# = 1.667 which is fast enough for our system. This lens is uncoated and has a wavelength range of 350 nm to 1800 nm where the transmission of the lens is over 90% light passing through for N-BK7, and a 10 mm thickness sample. The lens is thickest in the center at just 2.5 mm and 1.5 mm at the edges with around a 5% thickness tolerance. Therefore the 90% transmission rate is probably higher, meaning more power to the respective devices. This ensures that the lens will not impede the design of the device box. This lens is RoHS compliant and is sold as is not mounted. The cost of the LA1116 is $20.30.

4. Related Standards and Realistic Design Constraints

4.1 Standards

Standards are a set of specific characteristics that guide product and system design in the developed world. While standards are not enforceable by law, the point of them is to ensure that new products meet a certain level of safety, performance, reliability, compatibility etc. As a whole, standards provide common ground between different companies, and organizations across the world. For the VLC project, the IEEE has a number of standards that are relevant, as well as UL,

and RoHS. In this section we discuss the various standards related to the design and implementation of the VLC project as well as their impact on the project.

4.1.1 IEEE 802.3i

The Institute of Electrical and Electronics Engineers, sometimes referred to as "I triple e", is a worldwide professional association consisting of scientists and engineers. The IEEE is a nonprofit organization that provides a number of services from publishing, to education, holding conferences, to maintaining societies and developing standards. The IEEE 802 standard is one of the most recognized across the world, it relates to local and metropolitan area networks. The 802.3 sub-standard is the overall category defining standards for the physical layer of local and wide area networks. For the Visible Light Communication project the 802.3i standard is particularly important. This standard was published in 1990 and is commonly known as 10 Base-T, it defines the requirements for 10 Mbit/s speed across twisted pair cables. 10 Base-T Ethernet uses category 3 cabling and is encoded in Manchester coding, the channel bandwidth is 10 MHz and cabling must be rated for at least 16 MHz.

4.1.2 Design Impact of IEEE 802.3i standard

The IEEE 802.3i standard has huge impacts on the VLC system. Because the 802 category is accepted worldwide as local and wide area network standards there is no room for selection in regards to how our data is carried from the service provider to our equipment. Because of this, the signals that are available to try to convert to light are already predefined. For instance we can choose to convert a 100Base-T signal, a 10Base-T signal, a 1000Base-X, etc. into a driving signal for our transmitters. With that being said the component selection is also limited to electronics that are capable of receiving and transmitting high speed electrical signals.

4.1.3 IEEE 802.15.7

The 802.15 group of standards covers wireless personal area networks. The 802.15.7 subset particularly relates to short-range optical wireless communications. This standard defines the guidelines for what qualifies as visible light communication. Products under this standard utilize wavelengths from 190 nm to 10000 nm, they complement existing services and provide protection from electromagnetic interference.[5]

4.1.4 Design Impact of IEEE 802.15.7

The 802.15.7 standard effects the VLC project in terms of how the device performs and is implemented. By the standards definition the actual data link between two VLC devices must provide no EM interference. This limits how we can modulate the LED or laser diode. For instance we could not use amplitude modulation, because of its potential to interfere with other ongoing transmissions. So in this case the best option is to impose the signal directly onto a DC bias and use a type of OOK modulation.

4.1.5 UL 1310

UL (Underwriters Laboratories) is an organization recognized by the American National Standards Institute for created standards. UL 1310 is a safety requirement for class 2 power units, which are defined as units that utilize an isolating transformer and have a maximum rating of 42.4 volts AC. In terms of safety requirements, the 1310 standard ensures that device enclosures are rigid and able to resist likely abuse. They also have overcurrent and over-temperature protection, as well as protection from feedback voltage. Products that have been tested and meet the UL product safety specifications are marked with the UL Logo. The UL Mark in *Fig. 4.1. UL is the stamp that appears on power supply devices and* is an indication that either Underwriters Laboratories or an equivalent nationally recognized testing laboratory has tested the equipment, and is an easy way for manufactures to show that their device has met safety standards.

Figure 4.1. The Underwriters Laboratories signature of verification.

4.1.6 Design Impact of UL 1310

To be in compliance with the UL 1310 standard there are a couple design parameters that must be met. The first is the voltage rating, in the general sense this should not be a problem. However in practice some photodiodes require a large amount of reverse voltage to be applied all the way up to 60V DC. If we were to use a simple transformer this would be an issue, because it does exceed the UL's rating. So now we have to use some form of amplifier to convert our basic supply voltage (most likely 5V) to a significant enough value to drive the PD.

4.1.7 RoHS

RoHS stands for restriction on hazardous substances, it was first introduced in 2003 and took effect in 2006 in the European Union. The United States doesn't have a law regulating the use of hazardous materials however similar legislation to the RoHS has been implemented by most countries around the world. In order to sell products internationally they must meet these requirements, and in compliance with the RoHS devices must have minimal levels of lead, mercury, cadmium, and chromium.

4.1.8 Design Impact of RoHS

In order to comply with the RoHS directive, we don't have to do anything on our end. Almost all manufacturers of integrated circuits and opto-electronics already adhere to this rule. All of our parts can be found on suppliers' websites, such as Mouser or DigiKey, who are in compliance with RoHS.

4.1.9 Power Supply Standards

The CUI has divided circuits into different classifications based on their voltage and specifications, the table below lists these.

Table 15. The power supply standards from the CUI.

Circuit Definitions	
Hazardous Voltage	Any voltage exceeding 42.2 V AC peak or 60 V DC without a limited current circuit
Extra-Low Voltage (ELV)	A voltage in a secondary circuit not exceeding 42.4 V AC peak or 60 V DC, the circuit being separated from hazardous voltage by at least basic insulation.
Safety Extra-Low Voltage (SELV) Circuit	A secondary circuit that cannot exceed a certain voltage under normal operation or in the event of a fault. In the event of a fault voltage an absolute limit of 71 V AC peak or 120 V DC must not be exceeded
Limited Current Circuits	This type of circuit ensures that while experiencing a fault the maximum possible current drawn is not hazardous. The limits for this are for frequencies < 1 kHz the steady state current drawn shall not exceed 0.7 mA

	peak AC or 2 mA DC. For frequencies above 1 kHz the limit of 0.7 mA is multiplied by the frequency in kHz but shall not exceed 70 mA. For accessible parts not exceeding 450 V AC peak or 450 V DC, the maximum circuit capacitance allowed is 0.1 µF. Δ For accessible parts not exceeding 1500 V AC peak or 1500 V DC the maximum stored charge allowed is 45 µC and the available energy shall not be above 350 mJ.

The CUI has provided a collection of standards that pertain to power supplies and electronic equipment in general. The Conformité Européene or CE Mark is a stamp of approval that signifies a device has met a certain level of safety, health, and environmental standards. It was introduced some 30 years ago and is used by manufacturers to declare their product meets the requirements. The VLC project will use a simply transformer power supply and would be required to meet this standard, along with the others previously mentioned.

4.1.10 PCB Standards

The IPC was founded as the Institute for Printed Circuit Boards, but has since changed to the Institute for Interconnecting and Packaging Electronic Circuits. The IPC is recognized and respected across the globe for providing standards in PCB design, construction, quality, etc. The broadest coverage of the IPC PCB standards is acceptability (IPC-A-610E), providing standards for component orientation and soldering criteria, as well as surface mount IC requirements. The standard also provides a requirement for the PCB to be clean, marked, and coated, as well as Lead-free. The VLC project design does require the assembly of two separate PCBs. The PCB manufacturing is outsourced in this scenario and these standards should be met by the sub-contracted company. Our components are Lead-free by nature.

The standards provided by the organizations and institutions around the world provide an underlying level of quality, safety, and reassurance that can be given to consumers. There is also a common language that is found in these standards as device manufacturing occurs across many different companies across the globe. It is important that we try to meet the criteria even in prototyping and elementary design stages.

4.1.11 Design Impact of PCB standards

Since we will not be making the PCB ourselves, the design impacts of this particular section are minimal. As long as we choose a manufacturer who is in compliance with the standards listed above we should be ok.

4.1.12 Laser Safety Standards

Classifications of lasers are controlled by an international institute called the International Electro- Technical Commission (IEC) and the Center for Devices and Radiological Health (CDRH), which is an arm of the Food and Drug Administration. The classifications for different laser systems may differ slightly in their description according to the respective institution, they have been unified.[6] We are using a Class IIIa or 3R laser which is referred to as safe when handled carefully and not directly exposed to intrabeam viewing.

Lasers are multifaceted devices which can have serve the user as long as the standard operating procedures are followed. The user should recognize the type of laser viewing exposure interactions which are possible in order to avoid excessive exposure. This is not a complete scope of the standards; however, we feel it is important in explaining the direct methods of avoiding risk. The following pargraph is only to be an over view and NOT considered a substitute for a knowledgeable and trained Laser Safety Officer (LSO) with the duties and responsibilities as defined in the ANSI Z136 standard published by the American National Standard Institute.

There are methods of understanding how viewing laser radiation can take place, however, the primary rule is avoid looking at the laser directly or from reflected mirrors. The first is intrabeam viewing which is looking at the collimated beam directly and trying to see output, this creates a small laser spot on the retina which is dangerous to the eye, only with direct medical permissions can certain lasers be used, when using visible to near infrared spectrum, (390 nm - 2500 nm), direct eye exposure should be avoided at all costs. The second is specular reflection, this is where the beam is incident on a reflective surface and the beam is the same in danger, again avoid looking directly at a reflected beam at all costs. The third way of is diffusive reflection, this is where a beam hits a rough surface and scattered light can be viewed. The scattered beam is incoherent and has a larger area hitting the retina meaning less light, however, if the diffuse reflection is too intense injury may still result. All retina injury can be serious and permanent.

4.1.13 Design Impact of Laser Safety Standard

In order to be compliant with laser safety standards we must adjust the design of the device accordingly. It would be easy to use a laser diode that has a high output, that would take a lot of strain off the photodiode, and would increase the working distance considerably. However, in order to be safe, it's best to use a laser diode that is relatively low in power, we then would compensate by using focusing elements.

4.1.14 Software Standards C++

The International Organization for Standardization (ISO) is responsible for releasing standards for the C++ programming language. The current standard is ISO/IEC 18882:2014, informally known as C++14, it was introduced in 2014. It is important for the ISO to continually update the C++ standard as the core language and library constantly expand to meet the requirements of technology. This specific standard is meant to instruct programmers on the implementation process of the standard. In addition, each new release of the standard aims to improve known issues with previous versions as well as expand the capabilities. C++ is a general language and is paramount to the operation of many electronic devices and machinery.

4.1.15 Design Impact of C++ Standard

The main focus of the software in this project is to analyze data being passed through the VLC system, to verify that the system is actually acting as an internet enabled device. In order to do this a program must be written in a compiler and run on the computer making use of the VLC system. With that being said a compiler that accepts C++ is required to make this happen, for this project our computer engineer will be using Visual Studio to carry out this task.

4.1.16 Electronics Housing Standards

This standard is provided by the National Electrical Manufacturers Association, it details the requirements for safe electronic housings. Available for reference in the NEMA standards publication 250-2003, the document lists the types of enclosures as well as the requirements for each. Our device type according to the NEMA standard is type 5 described as an enclosure constructed for indoor use, that provides protection to personnel against hazardous parts. The enclosure must also provide protection to the equipment inside from solid foreign objects such as dirt, settling airborne dust, lint, fibers, etc.

4.1.17 Design Impact of Housing Standard

In order for the VLC project to look professional in its design and appearance a housing will be constructed for the electronics to reside in. Our design and final product will follow the standards provided by NEMA and provide the electronics with protection from their environment. In order to do so we need to identify the type of material we will make the housing out of and then identify a company/service to provide it. The housing will most likely be plastic, and will be 3D printed. Our housing design can be found in chapter 5 along with a detailed account of its features.

4.2 Design Constraints

With the design of any new product for system there comes constraints. Whether these are customer defined, budgetary, legal, etc. each constraint must be taken into account before a complete set can be created. For most products, there are checks and balances between each constraint, for instance a larger budget often results in better components. Or a legal constraint might affect the manufacturability of the product. In all constraints are a realistic part of new design, below is a collection of the constraints that effect the VLC project and it's outcome.

4.2.1 Economic and Time Constraints

Currently internet access can be obtained by a few dollars' worth of hardware and a subscription to an ISP, so our VLC system needs to be competitive in price. For VLC, we wanted to keep the budget under $300, this is an economic constraint that limits what kinds of components we can buy, and how much the product could retail for. Comparatively, however, current LiFi systems can run upwards of $2000. With that being said there is an obvious tradeoff between the speed of a system and the project budget. In either case VLC provides energy efficiency and is especially applicable in commercial environments where buildings are lit the majority of the time. If implemented on a wide scale VLC would have a huge impact on energy and cost savings for anyone switching from a standard wireless access router.

Time is a very real constraint that effects every aspect of life not just engineering, for this instance though, our time is limited to several months. We started this project in the middle of May, and were given just 12 weeks to design and prototype. Following that period there is an additional 16 weeks to turn the prototype into a working product, where it will then be presented and reviewed by faculty. For this project speed is one of the most important features of the system, time directly effects that characteristic in this situation. For instance, improving the speed of VLC is not as simple as upgrading hardware, because it is a complimentary system it requires research and must be treated as an entirely new product. Since time can never be gotten back it is important to create deadlines and goals to be upheld so that you have constant knowledge of where you stand in terms of completion.

4.2.2 Environmental, Health and Safety Constraints

Environmental constraints can be very taxing on a company when designing a new product. You must take into account whether or not your product produces pollution (air, water, or noise), what kind of impact it has on its direct surroundings, and what kind of waste occurs in the process. For VLC, there are no emissions such as gasses, wastes, noise, vibrations etc. However, there are manufacturing concerns as with any electronic device. As previously mentioned some electronics use hazardous materials and are limited by RoHS regulation. Or VLC system uses silicon and copper based component and does not contain any hazardous

material. VLC systems also save energy, using light as a transmitter and Ethernet as a power supply you eliminate an unnecessary cost of a Wi-Fi router. In regards to operation VLC does not produce any kind of electromagnetic interference, because the carrier signal is in the THz region it is safe for EM sensitive environments.

Health and Safety constraints can really be combined into a single category of limiting factors. When considering these two constraints there are two primary groups, the sellers and the consumers. In terms of installation there are no health and safety concerns that are inherit to the device. When being operated, there are no health and safety concerns that need to be considered by the consumer. Our design, as previously mentioned, does not use hazardous materials, and produces no wastes including (noise, gasses etc.). VLC operates using LEDs in the visible spectrum, and modulates at a MHz rate, so there are no concerns for those who have epilepsy or similar conditions. In all VLC is a very safe technology for users.

4.2.3 Environmental Spectral Window Distribution

The ability to propagate light over a certain distance will dictate how far the information can travel. Neglecting the efficiency of the detector and optical efficiency in the transmitter, the Power received is equivaled to $P_R = \frac{P_T A_R}{(\theta d)^2} \exp(-\alpha d)$ where P_T is power transmitted, A_R is the receiver area, θ is the divergence angle, d is the distance traveled and finally α is the attenuation of decibels/km. The transmission properties from the atmosphere in the near infrared wavelength range under clear weather conditions is in the figure below[7], forming the basis for a wavelength selection guide in the outdoors. For example, the windows located near 850 nm, 1060 nm, 1250 nm, 1560 nm have very low attenuation and give the group a wide selection.

Figure 4.2. The attenuation coefficient as a function of wavelength.
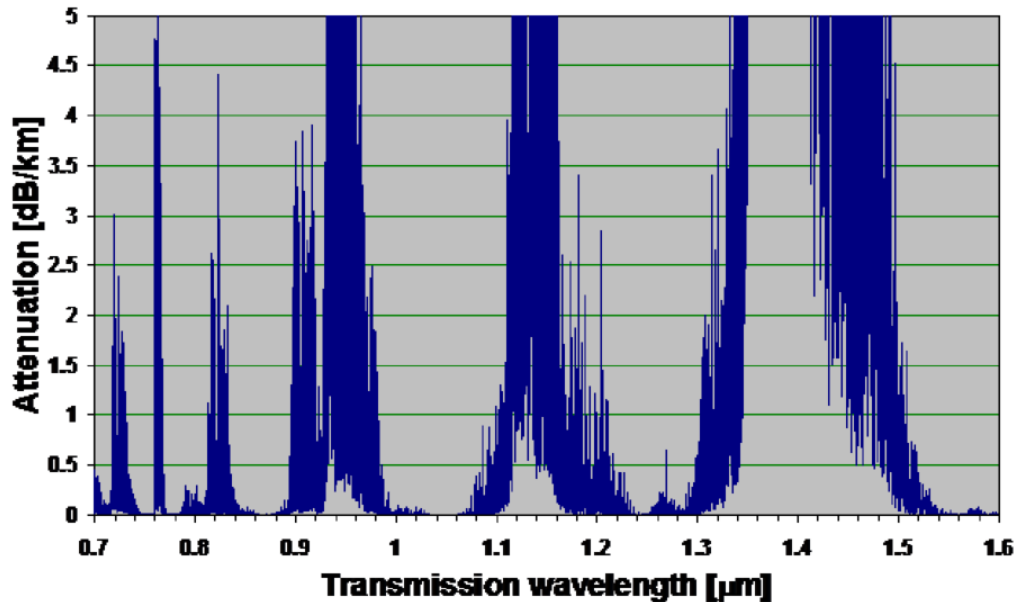
4.2.4 Social, Political, and Ethical Constraints

Social and Political constraints can be viewed as a design favoring one group of people and against another. They can include a product that is against government laws and regulations, they can include a product that relies on publicly funded works or services. We can conclude that there are no political constraints that are obvious or apparent to the VLC project. Social constraints are in the same boat, VLC is a product meant for everyone and there are no prerequisites to using it. Ethical constraints are considered when designing the product and are taken into account in terms of how the product or service will affect the safety and/or health of its users/workers/competitors. For instance using radioactive materials, using designs or data that are protected under copyright, sacrificing safety for appearance or cheaper materials. In some cases of VLC infrared LEDs may be used for the uplink. IR LEDs that are in the lower region say 700-1400 nm can be dangerous to the retina and eye if overexposure occurs. Safe IR LEDs are above 1400 nm because the majority of the wave dissipates in the water of the eye and isn't focused onto the retina. However safe IR LEDs are quite expensive, and in many cases are not used in products.

4.2.5 Manufacturability and Sustainability Constraints

Some manufacturing properties include nanoscopic scale, high stiffness and rigidity, no contact surfaces, no machining vibration, extremely accurate natural frequencies, specific alloys/metals etc. The equipment to manufacture such devices is very expensive. For our VLC project we have chosen pre-fabricated parts, and once a PCB is created it will feature a single power connection, and a

single Ethernet port. Our design also features plastic casing, so there is no need for alloys or other special metals.

Sustainability is not only a constraint but also a very real selling point for any product. Nowadays people want to know that their things are going to last, without having to buy replacement parts. Our design is purely solid state, meaning there are no moving parts, the system is also meant to be stationary so use of the product does not pose regular wear and tear. The component most susceptible to issues is the LED itself, however today's LEDs have an active life of 25000 – 50000 hours. In perspective that's around 3 – 6 years of constant use. In this instance VLC is meant for indoor use, so the effects of weather are not a constraint for our product.

4.3 LAN (Local Area Network)

A local area network (LAN) is a group of computers and associated devices that share a common communication line or wireless link to a server. In this project, our physical link communication UTP (Unshielded Twisted Pair) plus visual light will be our medium where data will be transmitted. Typically, LAN encompasses computers and peripherals connected to a server within a distinct a distinct geographic area such as an office or a commercial establishment, in the scope of this project will be just two computers connected through the Ethernet connection.

Figure 4.3 Hierarchical LAN data transfer.
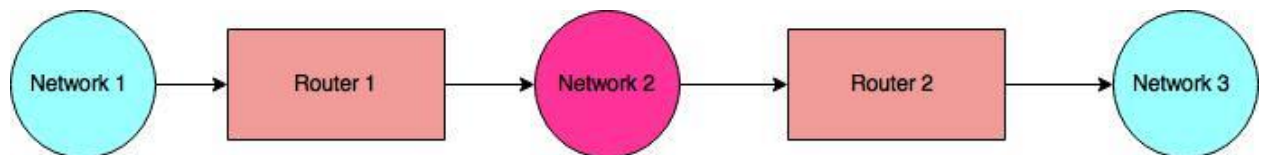
A local area network may serve as few as two or three users or several hundred users in a large office. In the figure above movement of data has gone through a number of routers to go from network 1 to network 2. Ethernet and Wi-Fi are the two primary ways to enable LAN connections, in this project will make use of Ethernet. [8]

4.3.1 Full Duplex and Half Duplex Operation

The standards for Ethernet were originally built using a truly shared medium (a single coaxial cable connected to several stations). The same cable was used for both transmission and reception. This factor leads to smaller footprints in design of physical cables. Since the Ethernet is based on the idea of a shared medium, if a station sends a packet, everybody on the line receive it. The case of data collision exists when there is only a one way channel in half duplex mode. In our case, 10BASE-T uses a "UTP" cable to replace coaxial cables. UTP cables allow full-

duplex because they contain separate wires for transmission and reception. Therefore, that leads to the question, which is better half-duplex or Full Duplex communication.

4.3.2 Carrier Sense Multiple Access with Collision Detection (CSMA/CD)

The CSMA/CD method assesses short area networks like LAN and most notably in early Ethernet technology it was documented and developed. Again, in this project the network layer is based on the standards for 10BASE-T described in the IEEE 802.3.

This method uses a carrier-sensing scheme in which a transmitting station detects collisions by sensing transmission from other stations while transmitting a frame (digital data transmission). When this collision is detected, the station stops transmitting that frame, transmits a jam signal, and the waits for a random time interval before trying to resend the frame. In a figure presented below there is a demonstration of the data collision.

Figure 4.4. Data collision framework for half-duplex functionality.
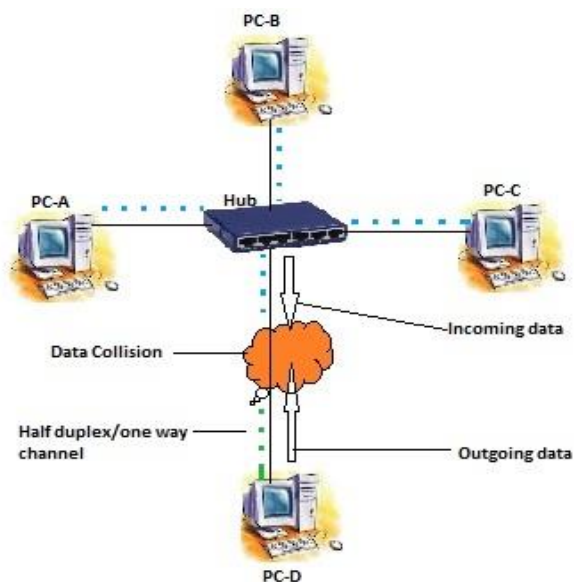
Again, Half-duplex uses a protocol called "CSMA/CD" (Carrier Sense Multiple Access with Collision Detection).

In Half-duplex:
- Before transmitting, each station has to listen to make sure the line is free ("Carrier Sense").
- Still, it is possible that two stations transmit just at the same time. A complex protocol has to exist to abort ("Collision Detection") and resume transmission later.

10BASE-T uses "unshielded twisted pair" cables ("UTP" cables) to replace coaxial cables. UTP cables allow full-duplex because they contain separate wire pair to transmission and reception.

In Full-duplex:
- You get twice the bandwidth.
- Each station has a dedicated medium and can start transmitting at time without complication (CSMA/CD doesn't apply anymore).

Full-duplex is inherently better and the next question is how to get our 10BASE-T network to work in full duplex?

Full duplex does not function in regular Wi-Fi networks. On an aside about Wi-Fi communication, Wi-Fi routers are electronic devices which modulate and schedule the flow of information for a Wi-Fi frequency capable device. The specific standard for Wi-Fi is IEEE 802.11 which works at half duplex. The term Wi-Fi is just the trademark for this standard. The biggest obstacle in creating full-duplex Wi-Fi is self-interference. The interference is more intense than the actual signal being transmitted. [9]

4.3.2 Hubs and Switches

Although for the purpose of this project we won't be using any of these devices for the link communication mentioning them can help understand how the bandwidth will behave in case where more than two computers are connected and the bandwidth does not slow down.

10BASE-T is a "star-topology" network. it requires the use of a concentrator appliance to connect multiple computers together. There are two types of concentrator available: "hub" or "switch." A hub is simple electronic device that provides electrical separation between each link but still connects them "logically" together. It forces the communication to be half-duplex. Worse, at any given time, only one computer can speak. So, the network bandwidth is shared among all the computers. A switch (or "switching-hub") is a more complicated electronic device that isolates each computer link both electrically and logically. It does that by storing internally each transmitted data before re-transmitting it. Each computer can speak whenever it wants: that allows full-duplex communication. Even better, each computer has a full link bandwidth for itself. And since the medium is not shared, each station receives only packets intended to itself (privacy is improved).

In summary, for 10BASE-T networks:
- Hub-ed: half-duplex on each link, with 10Mbps shared among all the computer, reduces the bandwidth with each computer shared.
- Switch-ed: full-duplex on each link, with 20Mbps (10Mbps each way) dedicated for each computer, so the transmission gets faster.

Figure 4.5. Hub and Switch behavior in multiple connections.

Standard Hub

Switch
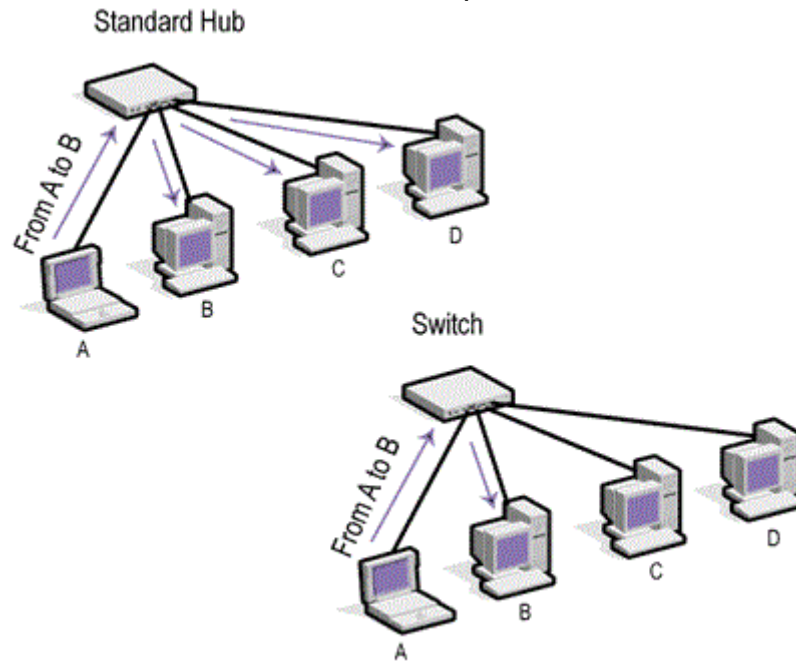
Network Interface Card (NIC)

A network interface card (NIC) is a circuit board or card that is installed in a computer so that it can be connected to a network. In network interface client-server, we implement some libraries in C# to make use of this attribute on TCP connection. Personal computers and workstations on a local area network (LAN) typically contain a network interface card specifically designed for the LAN transmission technology.

5 Project Hardware Design Details
## 5.1 Transmitter System Model

The objective of this project is to design a transmitter which can transmit with a data rate of at least 5 Mbps over a considerable distance for indoor application, however there may still be abilities to have analogous transmission in outside and other environments given some sufficient testing. The idea presented is that there need to be a transmitter with enough bias and a receiver with enough amplification. The frequency response of the white LEDs listed by manufacturers are not supplied which makes the enterprise of part selection and verification hard to implement. And, further amplification on the transmitter portion is certainly possible for the brightness with a correct MOSFET design.

In attempting to design our transceiver we went through a couple iteration attempts. The first iteration was trying to create a 100 Base-T system. One of the factors in prototyping this circuit was to implement the QFN package into a breadboard, and more information will be provided in a later chapter. The circuit was found through "Foundations of Visible Light Communication Circuits" (FVLCC)[10]. It was the initial premise for establishing our prototype. The authors of FVLCC had designs for LED's which do not have enough luminous flux to light up a room. Furthermore, we tried and prototyped this schematic but after correspondence with the author, he recommended to us that this specific design would never be able to implement 100 Base-T VLC transmission because the schematic from the book is just a plausibility of the idea. Since there is a significant market and lucrative aspect of these systems, the RJ45 to transceiver board is harder to find in open source.

The 100 Base-T transmissions definitely can be achieved, however, given our limited understanding of high speed electronics in prototyping, there was most likely errors in diagnosing the problem. There has been numerous experiments with 125+ Mbit/s NRZ and DMT modulation format white LED transmission,[11,12] however they were using arbitrary wave form generators and not MLT-3 encoding. The circuit for the 100 Base-T transmission in the FVLCC made use of the MAX3967A chip however, these chips are designed for infrared transmission as is accustomed in fiber optic transmission. The next section will highlight how to use this specific LED driver in what can be used in later attempts. The main problem occurred in creating the PECL signal input.

The second approach was to implement the 10 Base-T system from the FVLCC as seen in the Fig 5.1. The components were ordered for prototyping and the system still would be an analog interpreter of 10 Base-T ethernet signal onto a modulated LED. The difficulty in this set up was the use of unspecified resistor and potentiometer values. In addition, the group figured out that the LED always experienced a bias input above the standard Manchester encoding voltage which made the modulation scheme indiscernible to the photodiode on the oscilloscope even after amplification unless we used low frequencies such as 10 kHz.

Figure 5.1. Ethernet Connected 10Base-T VLC Transceiver device from "Foundations of Visible Light Communication Circuits" Prototype Design Premise.
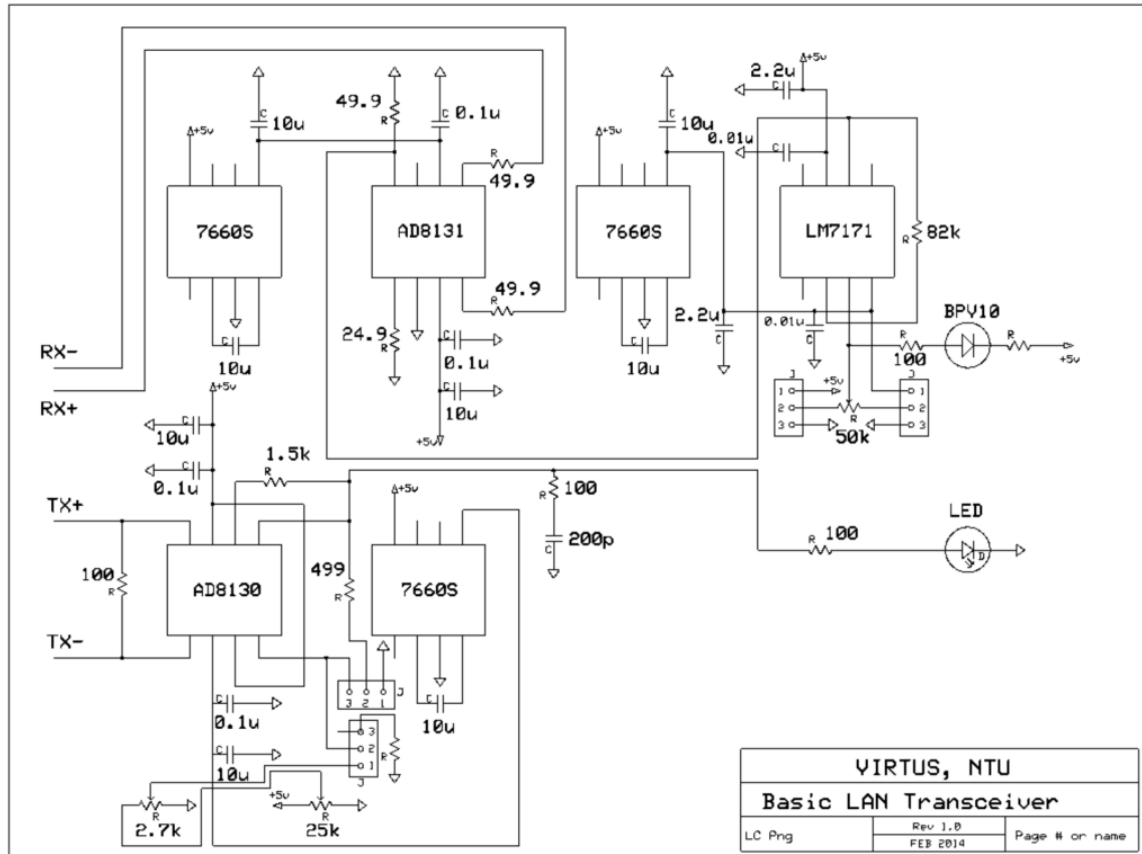
5.2 Transmitting Driver Background

The transceiver model for 100 Base-T using an LED driver will involve the ability to convert the Manchester encoding, or MLT-3 code from a 10 Base-T signal or 100 Base-T signals respectively into a suitable regime for an LED. The MLT-3 signal is inherently not applicable for LED illumination because it is a -1 V, 0 V, - 1 V signal at around 300 ns. Therefore, we need to convert this into a suitable signal for LED modulation. The MLT-3 needs to be converted into a NRZ or PECL signal which is suitable for LED modulation for the MAX driver. A media converter should have been used in creating this function, however, the group could not find one without purchasing an evaluation board and the ones we found as in the work by Perera[13], was out of business. The idea is to build a robust system which can convert the Ethernet signals MLT-3 (analog) to digital signals as in binary or NRZI before feeding them into the MAX3967A. NRZI signals are also referred to as PECL (positive emitter-coupled logic). At the receiver, the conversion will be binary back to Ethernet. Before receiving the MLT-3 code, it should have been possible to utilize the driver.
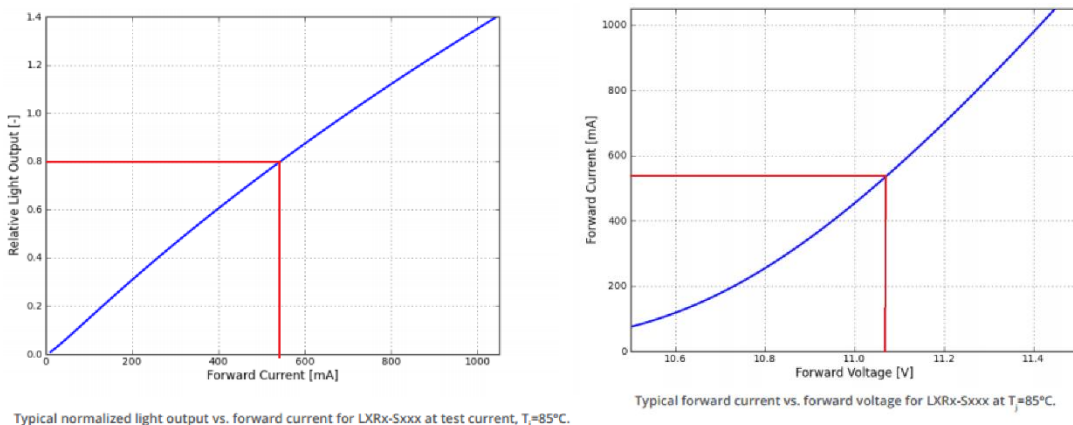
5.2.1 White LED Modulation Background

The ability to use a white LED as a modulating RF transmitter is from the fact that the modulation bandwidth is capable of a few MHz and after some equalization techniques upwards of 30 MHz[11]. A laser diode however has magnitudes of more bandwidth to modulate because of the low dispersion and spectral distribution.

The group had determined that the we should consider the quiescent point of bias operation for a commercially available LED such as the Lumileds LXR7-SW40 which can operate at 700 mA and 11.1 V. The operating point or the quiescent point for bias operation will depend upon the individual LED inputted into the system. Ideally, we could easily change our system to meet this point.

From the Lumileds data sheet there is a recommendation that "The average current for each cycle does not exceed the maximum allowable DC forward current at this junction temperature – The maximum amplitude of the ripple does not exceed 15% of the maximum allowable DC forward current at this junction temperature. At 10% duty cycle with pulse width of 10ms." Therefore, we may have to use a different LED because of the slow pulse width then this specific one. In addition, we need to find an LED which has leads in order to initialize bread boarding.

Figure 5.3. The quiescent point of bias for an LED in terms of IV and relative light output vs current (Courtesy of Lumileds).

Typical normalized light output vs. forward current for LXRx-Sxxx at test current, T$_j$=85°C.

Typical forward current vs. forward voltage for LXRx-Sxxx at T$_j$=85°C.

5.3 LED Driver

To build a VLC system, an LED driver plays a significant role in the design. For fiber optic transceivers, these are readily used. When it comes to building an oscillator for data transmission, the switching speed has to be fast to provide the required data rate. The LED driver should be fast enough to support the specified data rate. So, the MAX3967A was chosen as a preliminary led driver because of its excellent supporting information and ability to order in small quantities. It is a LED driver for fiber optic transmitters operating at data rates up to 270Mbps. The

circuit recommended by the manufacturer is seen in figure 5.2. The circuit was then built on a protoboard

Figure 5.2. The MAX3967A recommended reference diagram (Courtesy of Maxim Integrated).
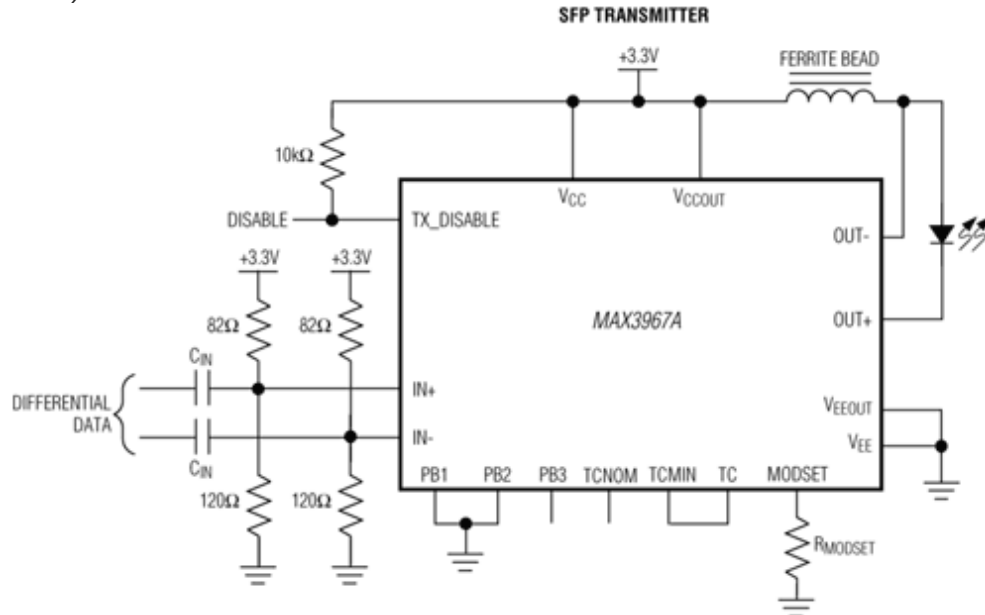
The driver is made in a quad flat no leads and commonly refered to as QFN package. The purpose is for a small form factor and the material physically and electrically connect integrated circuits to printed circuit boards when professionaly done. The QFN could be made into a dual inline package (DIP) for bread board assembly by manucturing PCB electrical connections as seen in the figure below. However in high speed applications there is a trade off in connecting the board as a DIP.

Figure 5.3. The attempted implementation of a MAX3967A operational circuit.
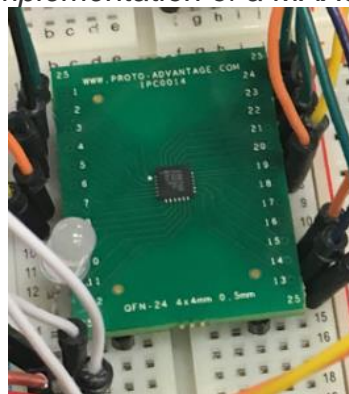
5.3.1 Laser Ethernet Transmitter Design

For the 10 Base-T VLC transmitter we need to take the differential signal from an Ethernet line and drive a laser diode. The ethernet signal needs to be converted into an optical signal which is varied in optical intensity and can be read by a photodiode and then reamplified into the ethernet port of a computer. The operational amplifier which is mentioned before is a differential receiver. The MAX 4390 provides a bias point of operation for the laser diode, and with a potentiometer RV1 we can select the current supply. The current should be able 19 mA for the laser diode we select.

The TX channel supplied from the ethernet port is added to the laser diode through AC-coupling. The C23 and C7 capacitors are AC couplers and the inductors L1 and L3 isolate the frequency from the DC offset current. Then the resistors R24 and R6 set the amplitude of the laser output.

The laser diode is constantly on in laser mode and can be seen by the user. The modulation swing of the signal should be about 25% of the bias point and still maintain the ability to stay above the bias point of operation.
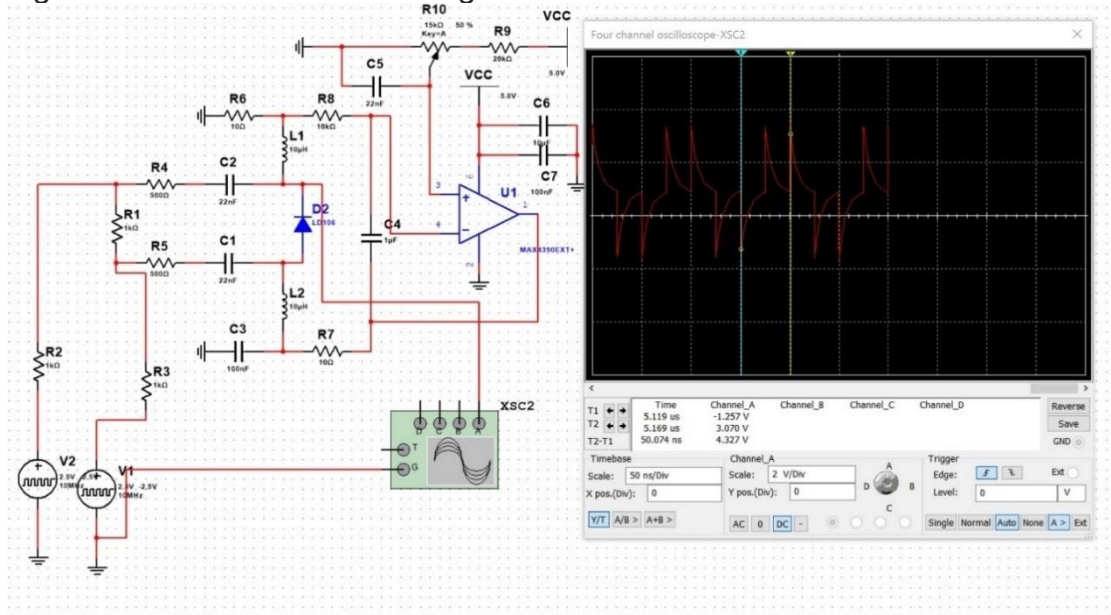
5.3.2 Transmitter Component Layout

The third iteration was to attempt to use a laser diode as the medium of choice. A laser diode has considerable bandwidth, low power and pin point directionality; therefore, it can still meet the goals of the project. The laser diode needs less current to drive the device so therefore different integrated circuits can be used. As mentioned earlier in chapter 2, it required analytical thinking to meet the project goals and this is the process to achieve it.

Initially the transmitter was put together on NI Multisim to get a picture if the device can handle the frequency required. However, there was difficulty because the laser diode could not be modeled on the program and the Ethernet signal was not readily available for the data to test. Given that, we were able to see that the design clearly could put out a good voltage and the current could be controlled with the potentiometer.

The design can be further figured out with assembly, and it is going to be slightly easier once the PCB is assembled. The transmitter was verified to work under the frequency conditions also known as the transient response. This helps determine the maximum data throughput of the device.

Figure 5.4 The NI Multisim configuration of the transmitter circuit.

The transmitter design was then compiled on KiCad which is an open source circuit designer and PCB interface. The advantage to visualizing the design on the simulation software is that the layout can be diagnosed component by component. The software was chosen because of the ability to make our own integrated circuit models because it saved time than learning other interfaces. The layout can be converted into a PCB with their integrated transformation environment. Each component if it didn't exist was reconfigured into a footprint capable of being placed on to a PCB and manufactured.

Figure 5.5 The KiCad configuration of the transmitter circuit.
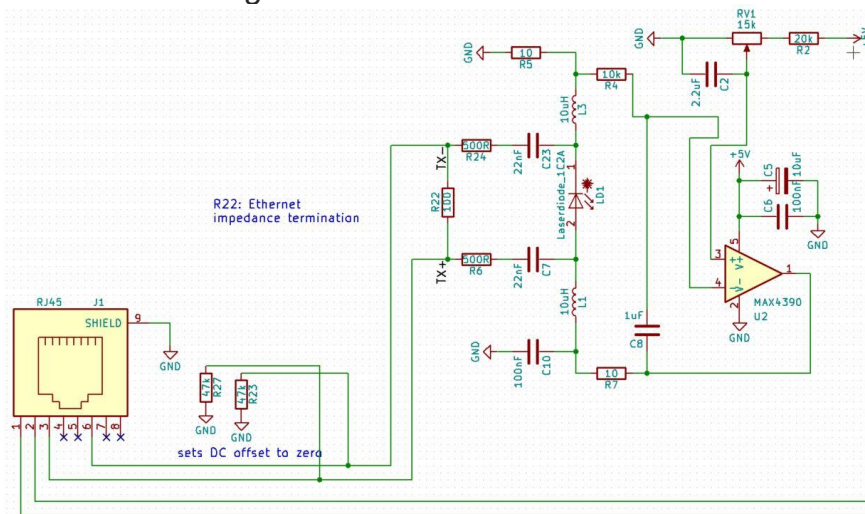
5.3 Receiver System Model

5.3.1 Receiver Components

The receiver system is main purpose is to convert the optical signal generated from the transmitter and drive an electrical signal into the pair of RX cables in the Ethernet jack. The design starts with a transimpedance amplifier (TIA) or differential driver OPA 695. The TIA changes the photocurrent of a reverse biased photodiode into a voltage signal with a gain resistor of 1 kΩ controlling the output. The high bias voltage of the photodiode is controlled via the MIC 2605. The DC jack on the board should be fed into the MIC 2605 where it can be translated into a voltage of 24 V for the device.

After the TIA OPA 695 the signal is still weak where it needs to be amplified further. In order to convert this into a desirable signal for the Ethernet port, a comparator device LT1713 can be used. A comparator is a type of IC which provides an inverted and non-inverted output which essentially means it is going to see if a voltage is above or below a threshold level and redefine it back if it is above that threshold or make it zero if below threshold. Since Manchester encoding is square waves this will redefine out the signal properly.

Since the signal is coming out as a square wave, it still would need to be defined in the proper peak-to-peak of 5V into a 100 Ω differential, however another buffer operational amplifier needs to be implemented. An IC which acts as a dual operational amplifier is used the MAX 4392. The MAX 4392 redefines the signal back into a reliable one for a RX in the Ethernet cable.

5.3.2 Receiver Layout

For U1 of the diagram OPA 695, the R1 resistor controls the current into the photodiode and the C1 is a bypass capacitor to negate the effects of the AC signal into the photodiode. Then the R10 and C24, R14 act as a current control and low pass filter respectively. The R3 is the gain controlling resistor and C3 is not connected but added to the PCB design in order to have a bit of leeway.

The LT1713 operates with the same set of bypass capacitor and current controlling resistor as U1. After passing through a high pass filter in C9 and R11 the signal is ready to be compared for the IC. The R17 allows for maximum gain of the LT1713. The output coming out of this device should look like a perfect square excluding the ripple effect of the Fourier components. Lastly the MAX4392 redefines the output for termination back into the ethernet jack.

Figure 5.6 The KiCad configuration of the receiver circuit.
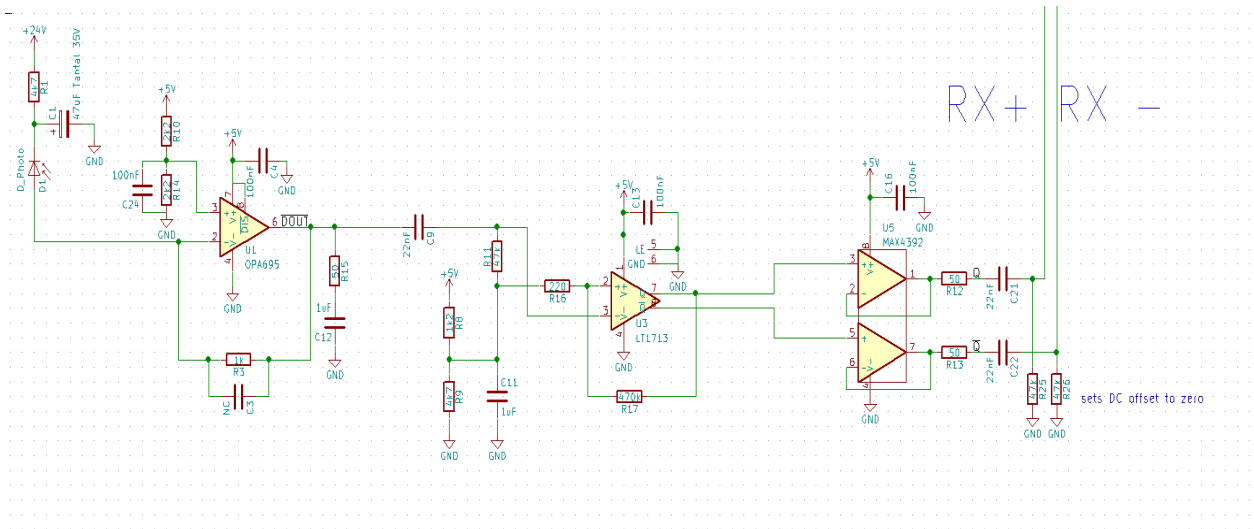
5.4 LAN Connectors

We chose RJ45 as a LAN connector for 100Base-T VLC transceiver. The RJ-45 is an 8-pin/8-position plug or jack and is commonly used to connect computers onto Ethernet-based local area networks (LAN). The type of RJ-45 connector that we are using this project is which is a transformer with magnetics. It is single port RJ-45 connector with integrated LED indicator lights. The Han Run is specifically designed to be used for 100 Base-T Ethernet with automatic changing from 10 Base-T or 100 Base-T. The reason why there is a transformer is to keep the VLC transceiver isolated from shorts. There can be significant ground offset between Ethernet nodes, and in order to address the shortage problem is to use opto-isolators, or transformer coupling. The Han Run provides transformer coupling and a more integrative would be required to connect a non-magnetic ethernet jack and an opto-isolator so the former is preferred.

Figure 5.7. Ethernet RJ-45 connector HY 911103A pin configurations. TX+(PIN1), TX-(PIN2), CT(PIN3), CT(PIN4), GND(PIN5), GND(PIN6), RX+(PIN7), RX-(PIN8).
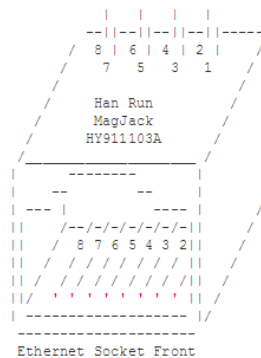
RJHSE-5380

RJHSE-5380 is Ethernet a telecom connector. It was introduced by Amphenol in 2006. RJHSE is modular jack with built-in LEDs that meets Ethernet CAT 5 performance. It has single and multi-ports. 5 from 5380 stands for Right angle, 8 positions, 50µ" gold plating, 3 from 5380 stands for Shield with top and side tabs (single port has top tabs only), 8 from 5380 stands for 8 contacts, 0 from 5380 stands for LED code, both left LED2 AND RIGHT LED1 are blocked. RJHSE 5380 is going to be used in our design to connect two identical board, to transmission data. It is connecting on the one side, and send/receive optical transceiver on the other side. When both boards pointed at each other, the boards mediate the Ethernet signal from one RJHSE 5380 connector to the other. Both LED1 and LED2 are blocked.
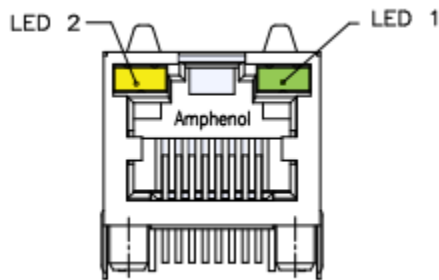

5.5 Power Supply

The power supply consists of a barrel jack, a fuse, a voltage regulator LM78M05CT, and a boost regulator MIC2605. It gives power to a device enclosure that houses the printed circuit board, to turn on LED and photodiode. You may refer back to section 3.3 as the reason why we use LM78M05CT and MIC2605 in our design. Now we are going to talk about what is a barrel jack and fuse. Also, we are also including which one we are going to use.

Barrel jack is a coaxial power connector. It is used for low voltage device. There are many different sizes of barrel jack. Contact ratings commonly vary from unspecified up to 5 amperes. The smaller types usually have lower current and voltage ratings. The DC Power Connector, Jack, 3A, 1.95 mm will be used in our design.

Fuse is an electrical current interrupting device that operates to provide overcurrent protection of an electrical circuit by creating an open circuit condition in response to excessive current. In our design fuse is used as a conduit between an electrical power source from DC barrel jack and an electrical component. The 5X20mm 315mA Fast-Blow Fuse 250v 315mA will be used on PCB.

The power supply is regulated through a standard transformer into a barrel jack which accepts 12 V and the linear voltage regulator LM78M05CT creates a 9 V transformation for the MIC2605 to implement. The boost regulator will generate the high voltage about 30V to implement the photodiode. The LM78M05 has indicator LED's to make sure the system is receiving the correct voltage. In addition, there are several rails of power created for the device. The MIC 2605 is then used to increase the voltage to the photodiode for the 30V rail. It is required that 12V DC 3A power supply with a 1.95 mm coaxial male plug be supplied in order to achieve the desired input voltage for PCB. The fuse is used to protect the circuit, if we short the LM78M05CT, the fuse will blow out. In addition, the boost regulator MIC 2605 is not protectable by the fuse.

Figure 5.8 The KiCad configuration of the power supply circuit.
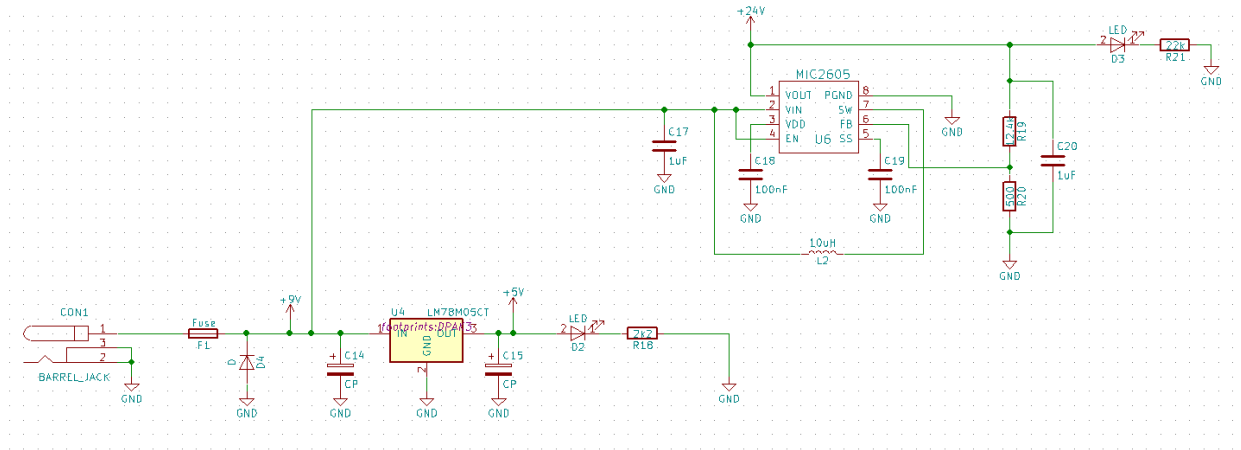
5.6 Device Housing

The VLC project will be put into an enclosure to make it more professional, in its appearance, as well as its ability to resist general wear and tear. Below is a 3D rendering of our initial device enclosure design made in AutoCAD. The box itself is quite small at only 3" x 3" x 1.5" in the order of length, width, then height. The front of the box contains two holes cut out for future lens placement, the purpose of these lenses is discussed in chapter 3. The back face of the box contains a hole for the RJ45 jack to be easily connected to electronics inside the box without having to open it. The two sides are lined with vents to help keep the electronics cool while in operation. There is also a barrel jack opening for the power supply that is not shown in this rendering. Finally, there is a lid that is secured by 4 screws to keep the contents safe and locked inside. This is a preliminary design and is subject to change.
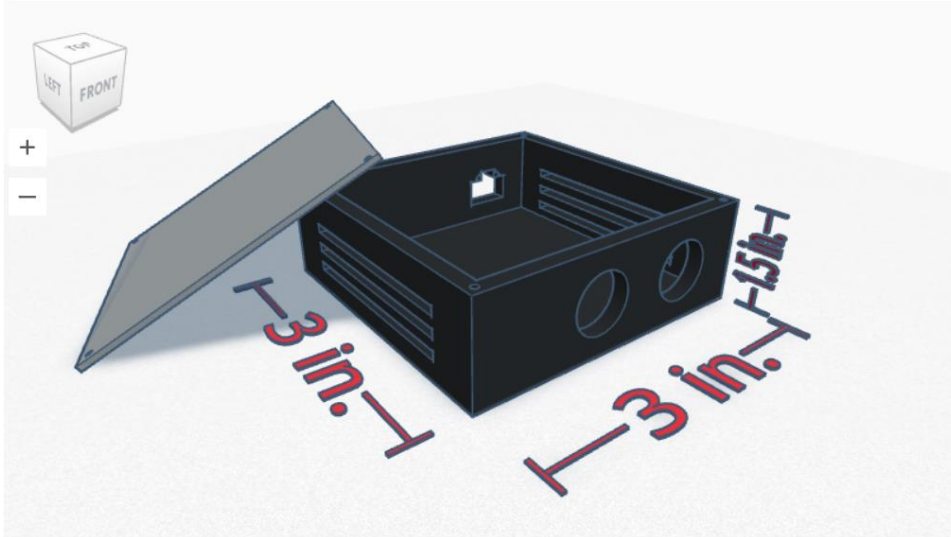
6. Project Software Design Details

This program, mostly called by users as a *Sniffer,* would be able to capture all the information sent from one computer to the other. This way, a user that is connected

to the internet and sets up this program on the device would be able to capture all the incoming or outgoing packets of information from the respective machine. This program would be called the Package Sniper Terminal.

The environment which is more effective for the transmission of data packets is in small networks, which in this case would be just a Local Area Network (LAN) composed for two PC machines, one connected to the transmitter and the other to the receiver boards. In this project, we aim to highlight the functionality of the software program. The creation of this *Sniffer* would be just a simple program in which the general characteristics of some simple layers such TCP (Transmission Control Protocol) and UDP (User Data Protocol). The interface would be tested out together with the realization of the GUI (Graphical User Interface) at the user level.

6.1 Objective

Develop an instant receiving application and a readily available information display for the computers to have a "talk web interface". Our software is based in covering the principles or protocols related to the client-server model. This project's components are compound by two computers, so based on this, the network is considered a LAN (Local Area Network). Even though there is an "open" medium such as visible light communication. Hence, this software-based section will follow the standards on TCP/IP model. Furthermore, this section focuses on explaining to readers a set of functions, protocols and tools to help the programmer to determine the source, in this case a network. Also, this project will provide a professional monitor user interface with all the measurements such as bandwidth, speed, incoming bytes for the final presentation.

Figure 6.1. Client-Server Communication
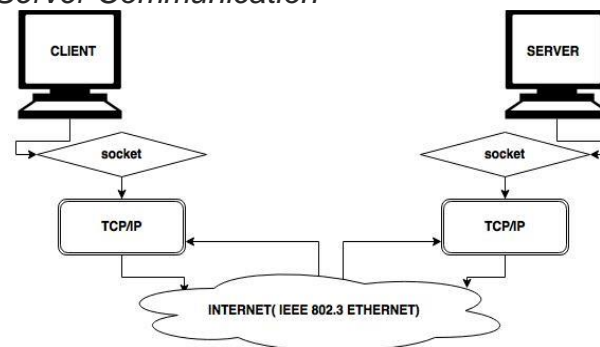
Interfacing with the level of transport in this system may require sockets, so this component will be a major topic to explain in the software. Socket programming is something which will take over mostly the whole part of coding part. Since in this project it is unnecessary to tediously go into the details of the programing code, the group still feels it is necessary to explain the "Pseudocode" so a reader can know how this program works. The Design of the GUI (Graphical User Interface) will be preliminary, so that any design in this section may change in the future.

6.1.1 Analysis

The development of this "Terminal" tool will be shown in phases of analysis, design and implementation. Firstly, the analysis is dedicated to the understanding and modeling of application and the domain in which it works. The initial input of the analysis phase is a description of the problem to be solved and it provides a conceptual overview of the proposed system. The output of the analysis is a formal model that captures the corresponding aspects of a networking data transmission: the verification of the link communication measurements such as bandwidth, speed, incoming and outgoing bytes and others. The requirements that were required were:

- Having a knowledge of the TCP/IP protocols.
- Having a knowledge on socket programming.
- How a Local Area Network (LAN) works.
- What a Client-Server communication is.

Through these essential requirements, with a little help of some others attributes that will be mentioned later on, it is possible to find a good communication between two computers and obtain its measurements, so we can prove the characteristics of this type of communication through visual light.

6.1.2 Software Development

The software development on this project, from the economic and business point of view, is focused on satisfying user needs. Therefore, it could be said that the fundamental problem of the software development is how well integrated it could be in the future so the user satisfaction can be solved together with the hardware part of this project, so the whole project packet would end up in a way that through each iteration of the hardware development, the software should not require a relatively large change. The attempt to satisfy user needs could bring out new challenges since customer feedback is the driving factor of product development. This leads to the creation of a software that holds all the necessary parameters for the design.

The software must meet the requirements of the TCP/IP protocols and networking standards of IEEE 802.3 Ethernet and that of the system and the user. The utilization of this software also has to be applied in limited conditions meaning without even the visible light communication medium, since the scope of this software is just to show the data transmission on a LAN, in this case just two computers. Despite this, the robustness and versatility of this tool will create the ability to understand the scope of the hardware implementation.

6.1.3 Software Reutilization

Software reuse is a technological alternative to increase performance and save time. Although software reutilization may be seen for some people as not loyal, it

is, in reality, an alternative to complete the specification of new applications improving the quality and productivity of the process of engineering requirements in the context of enterprise software production. An essential aspect of software reuse is the delimitation of reusable artifacts. Intuitively, reutilization is directly associated with reuse of source code to build a new software product. In this project, we make use of this alternative to improve our software's purposes.

6.2 Program Information and Overview

The transmission of data and reception inside a multimedia device involves internally the applied knowledge of networking and protocols. Since VLC is purely hardware and following the rules of this course, we will not show any code information in this report, but we will make a quick overview in some protocol concepts which we think may highlight key aspects of the design, but may not analyze them in depth.

6.2.1 TCP/IP Protocol

Although this project would be based on 10BASE-T Ethernet, using UTP (Unshielded Twisted Pair) cable as the physical medium to carry information, the responsibility relies as well on some protocols that are part of Transport Layer which are TCP and UDP. To begin with, what is a protocol? A protocol is a set of formal rules for their interaction in a computer network. The TCP/IP protocol is located at a lower level than the application layer and higher than Network layer following the TCP/IP stack model.

Figure 6.2. The block diagram analysis of the TCP/IP stack model.
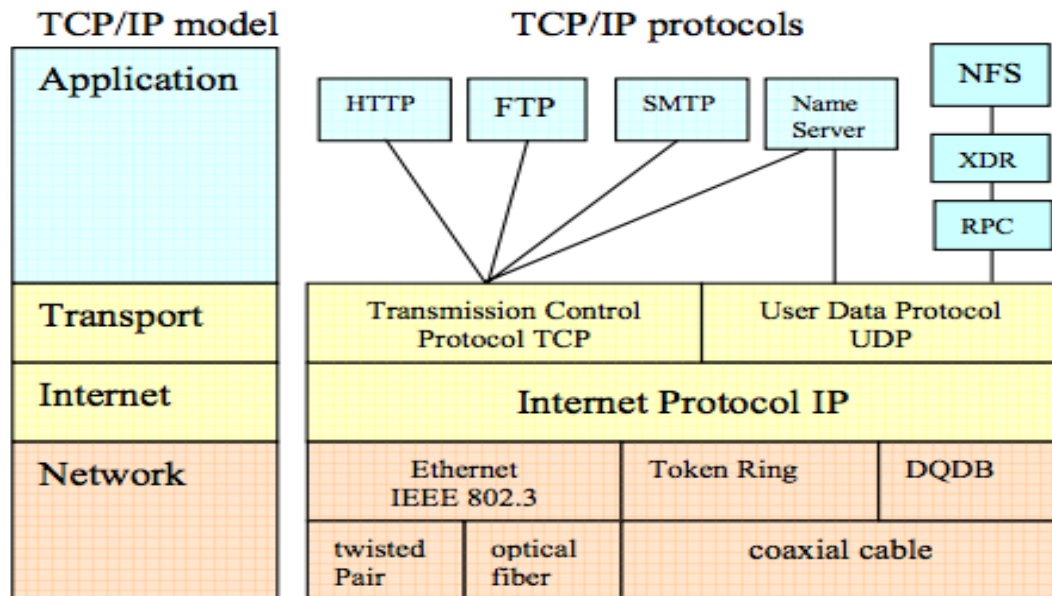
6.2.2 Network Layer

The lowest level is the network layer in which is included also the physical layer. Here we refer to the physical environment by which transmits the information. Generally, it will be a cable, although it is not ruled out as any other means of transmission such as waves or satellite links. The upper layer of the network protocol determines how computers send and receive the information through the physical medium. Also, we will talk about the standard connection between the MAC (Medium Access Control) and PHY (Physical Layer).

6.2.3 Internet Layer

This layer defines the way a message is transmitted through different types of networks until they reach their destination. The main protocol of this layer is the IP although there are other protocols at this level such as ARP, ICMP and IGMP. This layer provides the addressing of IP and determines the optimal route through the routers that must follow a packet from source to destination.

6.2.4 Transport Layer

This layer no longer cares about the route that messages follow up to get to their destination. It simply considers that the end-to-end communication which is established and verified. In addition, it also establishes the notion of ports.

6.2.5 Application Layer

Once we have established the communication from the origin to the destination, then the crux is what has been communicated over the transmission? This layer provides us with distinct Internet services such as: emails, websites, FTP, TELNET, etc.

6.2.6 IP (Internet Protocol)

IP is the main protocol of internet layer in this case. The protocol defines the basic unit of data transfer between the origin and the destination, traversing the entire network of access points. IP can be either non-connection oriented in which all the packets may have distinct routes between origin and destination or unreliable because the packets can get lost, damaged or arrive delayed.

6.3 Integrated Development Environment & Features to Develop

Following IEEE 802.3 Ethernet standards for the hardware design, TCP/IP protocols for the communication from source to destination and requirements, the software part of this project will be implemented fully in Visual Studio C#, where the user-friendly web interface will have two main sections, the first one will be the Packet Generator, and the second one will be the Sniffer, which will be the one that monitors and captures the following protocols: ICMP, UDP, TCP. The purpose of the software is broken down into two main tasks: checking the speed of information from transmitter to receiver, and how accurate the information is according to the requirement of this project. Furthermore, the aforementioned protocols will be analyzed.

6.3.1 ICMP (Internet Control Message Protocol)

ICMP is a supporting protocol that allows the exchange of control and monitoring messages from end-to-end. Any anomaly detected by the IP protocol causes exchange of ICMP messages between the nodes of the network. Any anomaly in the messages could prevent the data from reaching routers or host.

6.3.2 UDP (User Datagram Protocol)

This protocol is non-connection oriented, and hence it doesn't provide with any kind of error and flow control, rather it uses ways to detect errors. UDP is a very simple but there's no handshaking between UDP sender, and receiver. There is

no preservation of the sequence of information provided by the application. This way, each UDP segment is handled independently of others and can blast away as fast as desired providing no congestion.

6.3.3 TCP (Transmission Control Protocol)

TCP is one of the main protocols of TCP/IP model where whereas the IP protocol deals only with packets TCP enables two host to establish a connection and exchange streams of data. TCP guarantees delivery of data and also guarantees that packets will be delivered in the same order in which they we sent unlike UDP protocol.

6.3.4 Ethernet and TCP/IP Relationship

Ethernet covers the upper layer of the Network Layers and is more related to physical medium plus some low-level elements like message collision detection. TCP/IP worries about getting a message to where it is going. TCP/IP is usually found on Ethernet, but it can be used on other networks as well. If you want to build an application based on Ethernet and TCP/IP just learn the basics of Ethernet, TCP/IP, sockets, ports, and the difference between switches and hubs, and how to 'ping' and address. The following figure reflects the layers for 10BASE-T Ethernet. Ugh

6.4 Software Flowchart

In the Fig 6.3. flowchart expresses the logic of the program, the functions do not appear, although the main attributes do. The data packages are going to be carried out by type of protocol you select in GUI either TCP or UDP. After Host 1 has sent out those packages, the information of those packages such, rate, origin IP, destination IP, port and protocols used, either TCP or UDP, would be shown on the Host-2. I consider this interface could later be extended to obtain a more complex IP scanner and more complete to analyze in depth all packages, but for the purpose of this project, this model is good enough since what we only trying to demonstrate is to show the speed and accuracy of the link communication.

Figure 6.3. Software processing flowchart.
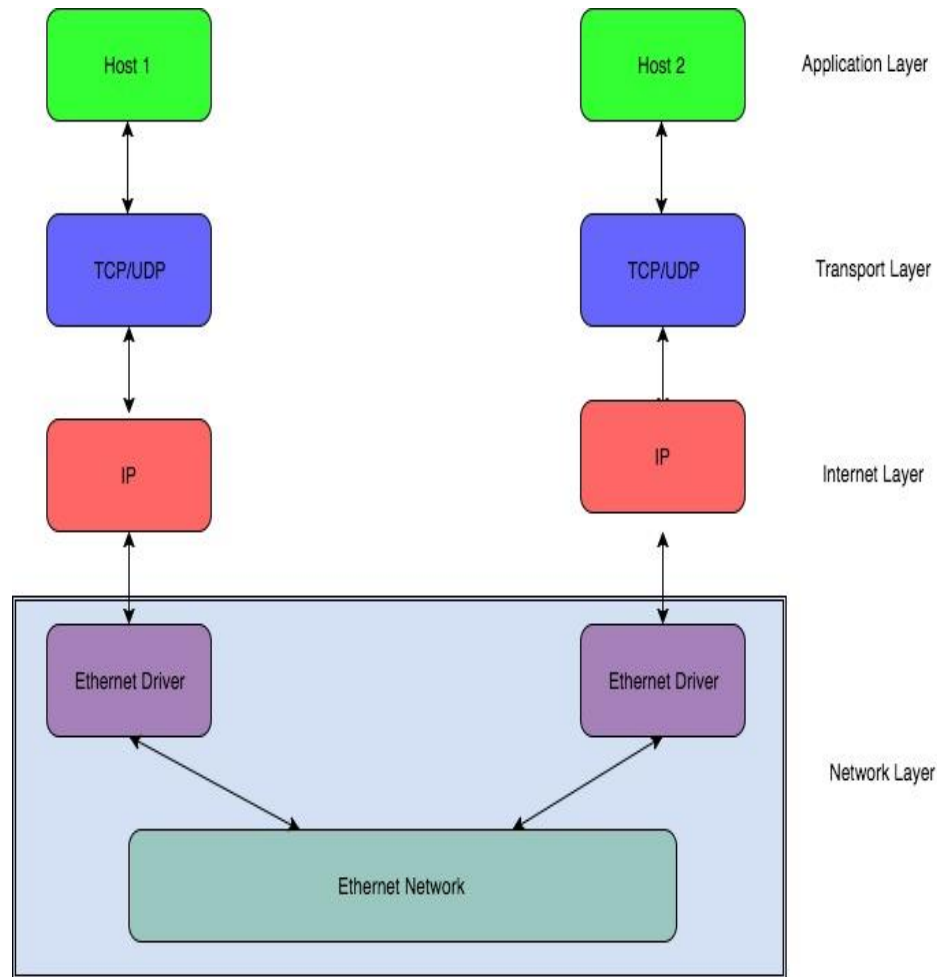
This application is going to generate packages from the hosts terminal and then the packets are going to go into ta TCP or UDP packet and then goes into the IP package and then go into the Ethernet driver packet and finally over the MAC and PHY (Physical Layer), so the information sent over the Ethernet wire (Ethernet Network), so the other host can capture the information.

6.4.1 Program Implementation - Packet Generator

The final result of this program will be able to send and receive the packages from end to end. In fig 24. we can see how the program may look like. This program will have less unnecessary information for the purpose of this project. As it's commented earlier, this would be a first step towards the creation of complete front-end interface. In addition, this program will have some improvements and some additional extension such the rate and incoming and outgoing data. In the image, we can see the MAC (Medium Access Control) and

LLC (Logical Link Control) protocols are located the upper section of the image in the Data Link part of the GUI. In the lower section, we will have a menu to select the IP source and IP destination. Next, we will have to select the type of protocol in which the data will be transported, in this case we'll have the options of TCP, UDP and ICMP for Ethernet.

Figure 6.4. Ethernet Packet Generator (Not actual GUI)

6.4.2 Class Diagram

In this diagram, we express how each package would be represented in the coding part. As a central element, we put a class 'Control Data' (class names can change during the project development), as this class will have just table represented by a 'Hash Table' in the code. This table contains many datagrams which are going to be made of different types of packages if needed. Finally, this class is related to 'Socket' class.

Figure 6.5. Class Diagram representing the packet flow protocols.
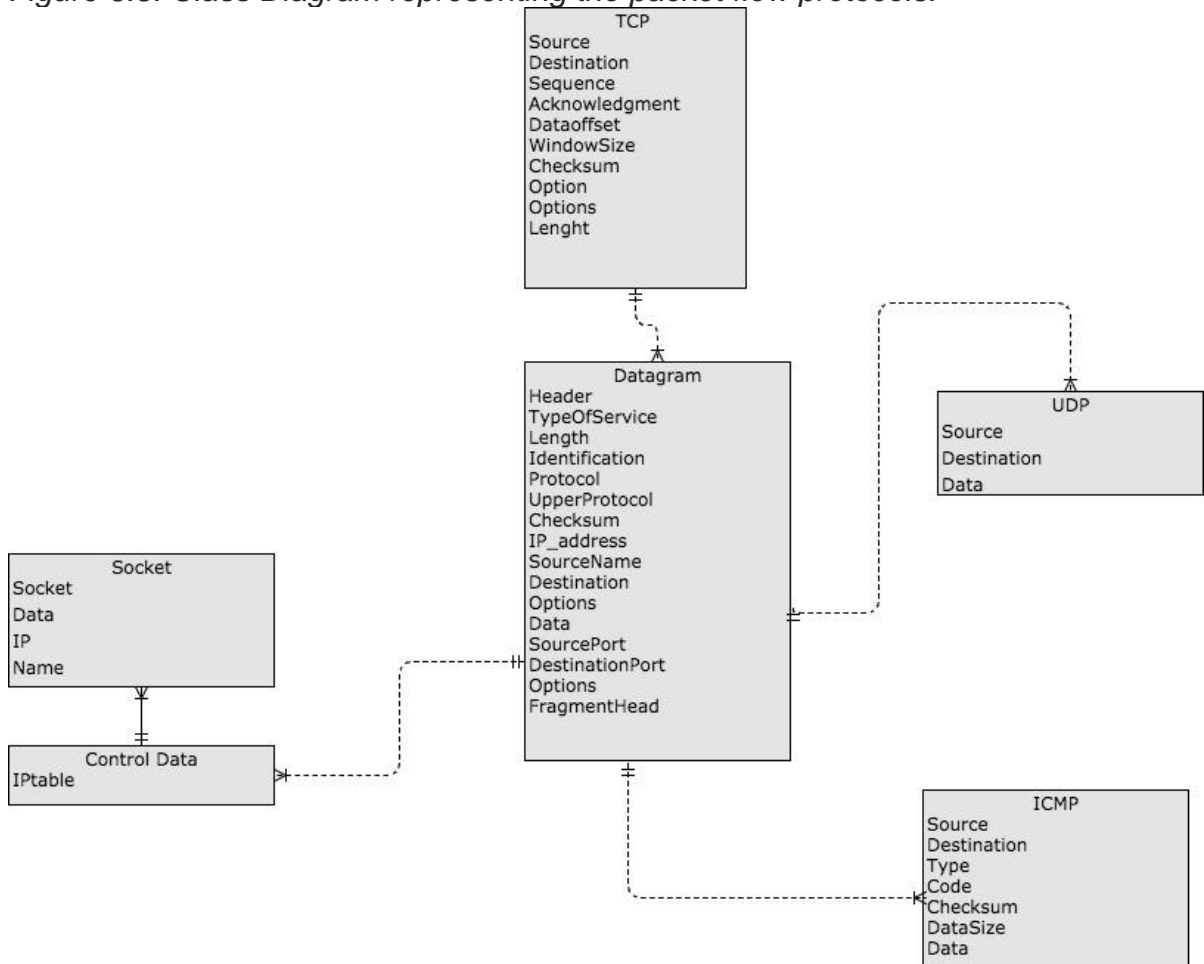
6.5 Application of HTI (Human and Technology Interaction)

To obtain a GUI that is easy and intuitive, we based the creation of this interface on some HTI rules. For this program, we have used the usability techniques discussed to make it clear. In this situations in which a new program is developed, the study of people, technology and the way in which they are influenced by them, then the final product can be more usable for people. But why do I use HTI techniques for the project? What benefits does using HTI bring? The use of these techniques can be thought as loss of time sometimes, but the real fact is it is that we live in technological world full of complicated devices that, in many cases, see more designed to make life difficult for us than to make it easier. In a world of instructions manuals, in which without them we can reach impossible to perform a task, such as programming a video without the manual.

On a relative note for this project, in regards to software, the way to interact with this new technology may go together with some new applications as well a way to illustrate the streaming process to make this idea more vivid. Usually, we are

the ones who must adapt to the device we want to interact with. For this reason, the designed systems will have to be intuitive, relatable and highlight the design features.

6.6 Software Testing

The software testing is necessary to verify the different elements involved in the correct used of fragments and if the protocols used are well implemented. In this project, the software has to be tested together with the hardware to check the physical medium (Unshielded Twisted Pair Ethernet Cable) used in the hardware plus other components involved on the boards. Testing a program means running it under controlled conditions which can allow to observe the outcomes of this project. The software will follow these four levels to have a good functionality:

6.6.2 Unit Testing

During this first round of testing the program is submitted to assessments that focuses on specific units or components of the software to determine whether the components of program is fully functional. The main aim of this endeavor is to determine whether the application functions as designed.

6.6.2 Integration Testing

This testing allows us the opportunity to combine all of the units within a program and test them as a group. This testing level is designed to find interface defects. This is particularly beneficial because it determines how efficiently the units are running together. Keep in mind that no matter how efficiently each unit is running, if they aren't properly integrated, it will affect the functionality of the software program.

6.6.3 System Testing

System testing is the first level in which the complete application is tested as whole. The goal at this level is to evaluate whether the system has complied with all of the outlined requirements and to see it meets the standards.

6.6.4 Acceptance Testing

The final level, Acceptance testing (or User Acceptance Testing) is conducted to determine whether the system is ready for release. During this final phase, the user will test the system to find out whether the application meets the needs of

the project. Once this process has been completed and the software has passed, the program will then be delivered to production.

6.7 GUI Interface Development

Overall the software will be developed in phases. In the block diagram in Fig 6.6, it shows the order of the testing which is sufficiently clear for the user to understand the purpose of the system. The basic flow of events are specified graphically with the interaction of one computer to the other.

Figure 6.6. The hierarchical GUI interface
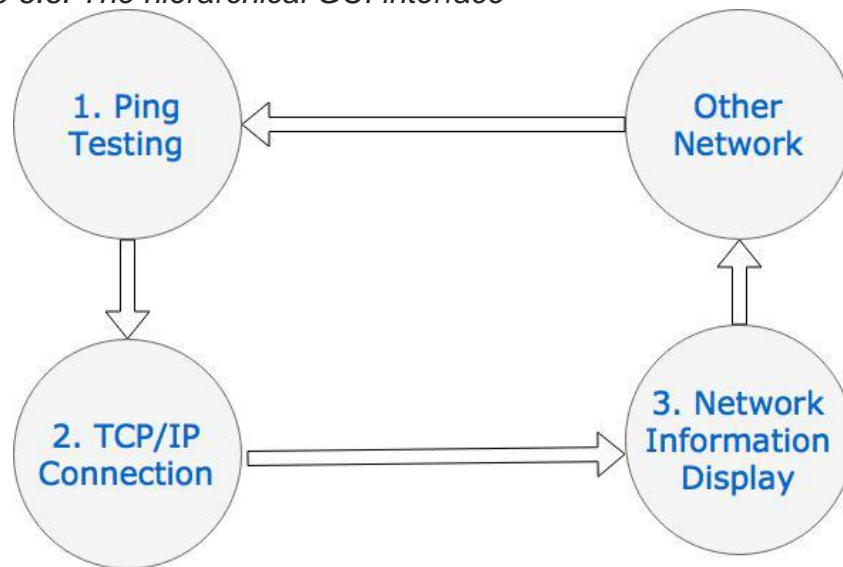
The phases of development are as follows:

1. Ping Testing: this application is fundamental because it will let us know if the connection we are trying reach is active or not.

2. TCP/IP connection: This part of the software is an application that allows us to send messages, files, packets, etc. to a server a get an answer. This application has to be used once the Ping testing has confirmed us that the server is active.

3. Network Information Display: This application is the most important part and most related to what this project tries to demonstrate which are measurements of a link communication through a 10BASE-T ethernet connection. This GUI will show the user the bytes sent and received, and the speed of link of the communication.

6.7.1 Language Selection

Since the beginning of the development of the software, it has been clear that best way to programming this tool was using Visual Studio in C# because this IDE provides a complete development toolkit for building networking applications. .NET Framework is definitely one of the best attributes in Visual Studio for network programming.

The user interface was proposed including the "PING" Testing to ensure the computer can "talk" to server computer, in this case the receiver board will be connected by an ethernet cable to server, here the ICMP supporting protocol is used. The basic structure of the user interface is finally developed by dividing between a not too complex TCP/IP client-server interface, in which the purpose of this is sending information or packets from client to server through the Ethernet. Originally, our thought was to create a File Transfer Protocol (FTP) or a Simple Mail Transfer Protocol (SMTP), but we opted to try just a simple client-server application that has all the necessary GUI components for a packet transferring. Finally, we created network information display which will be explained in detail later on, but the real meaning of this interface is showing the user how the network is acting during the transference of data.

6.7.2 PING Testing

This method relies on a problem in the core of the receiving machine. We created an "ICMP echo" request with the machine's "Hostname". With the "send" button, we send an ICMP echo packet to the target with the correct hostname and if this one exists, then the information of machine we tried to reach will reply together with amount of time it took to be reached out.

Figure 6.7. The Ping testing interface.
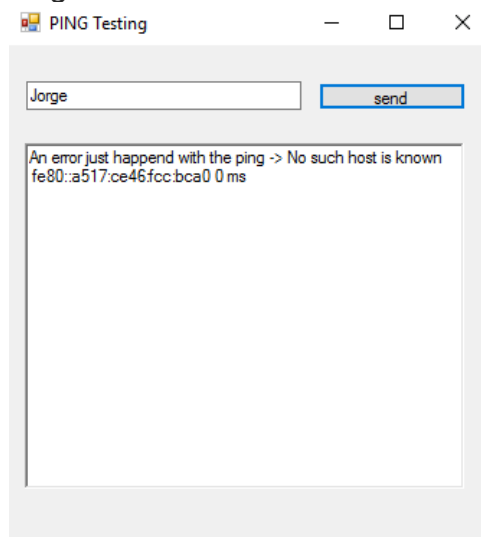
6.7.3 TCP/IP Client-Server

In the application layer, different type of application protocols (SMTP, HTTP, FTP, etc) will interact via ports with Transport Layer. Those port are numbered and the applications will always use the same ports to communicate or transmit information. Once the information in sent out to the TCP by the application Layer, this one breaks the information into packets. It's worth mentioning as well that TCP is the transport layer most used currently.

*Figure 6.8 Application and Transport Layer Interaction*
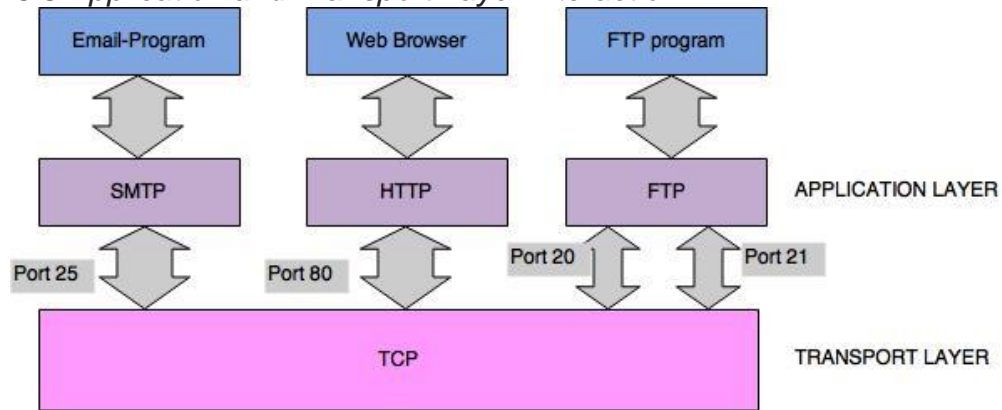
The datagram shows the interaction between the IP header, TCP/UDP header to the data at the physical interface where then the MAC takes over as seen in Fig 6.9.[14]

Figure 6.9. The Datagram structures.
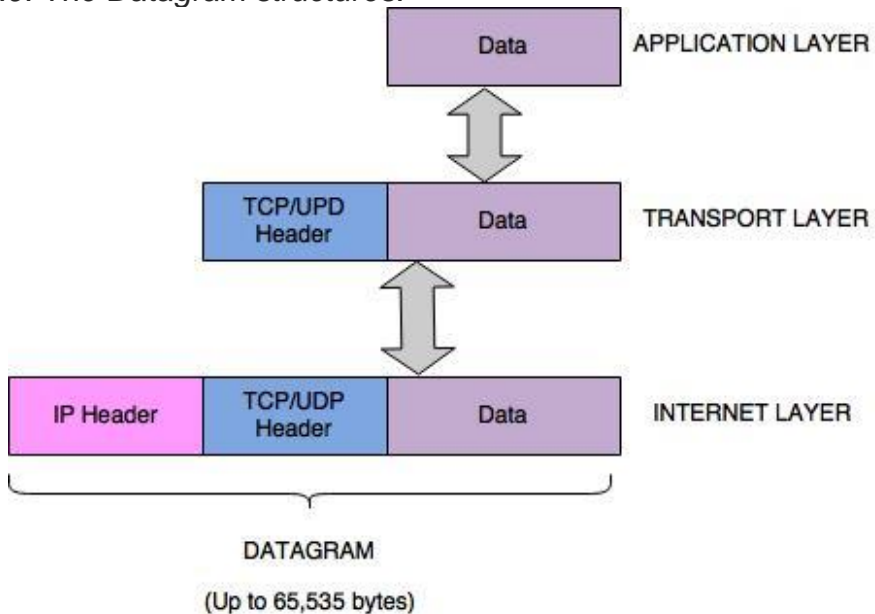
In the transport layer, the header contains number of control information such as, local port, remote port, a sequence number which used by the TCP, and a checksum which is a technique to calculate if the data being transmitted arrived intact or not. This TCP header has between 20 to 24 bytes of longitude. Moreover, in the Internet Protocol, the IP header is the one that receives the information from the transport layer. IP datagram uses at most 65,535 bytes including the header which may take between 20 to 24 bytes.

*Figure 6.10. TCP/IP and Ethernet Layers*
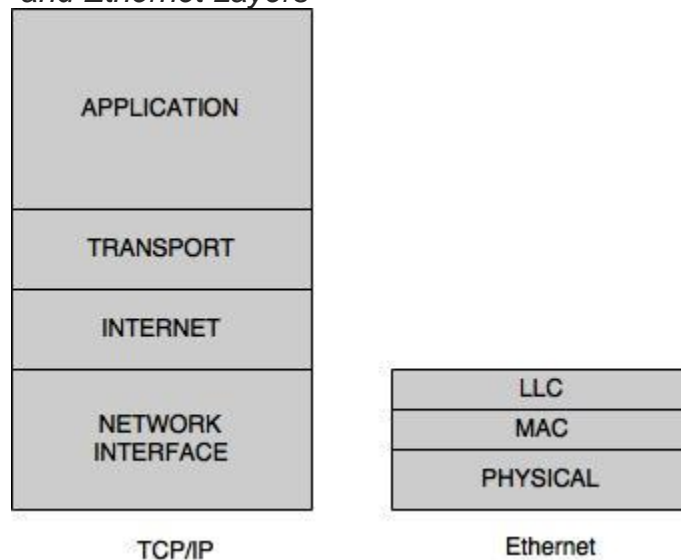
The datagrams generated in the Internet Layers would be transferred to the Network Interface. This Interface is defined by a type of physical network which is typically a ethernet network. Ethernet has three layers, LLC(Logic Link Control), MAC (Media Access Control) and Physical layer.

- **LLC:** this sublayer is responsible for the data transmission between computers or devices on a network
- **MAC:** it's the one in charge of assembling the frame that will be sent out over the network. This layer takes care of adding the origin MAC address and destination MAC address.
- **Physical Layer (Hardware):** this layer is the one that converts the frame generated by the MAC layer into electrical signals through the connection cable.

Now, in this client-server application taking into account TCP/IP protocols, we created two programs, a server and a client. The Server will be "listening" from a port to all the requirements that the Client is sending to the server. [14]

Figure 6.11. TCP/IP Server
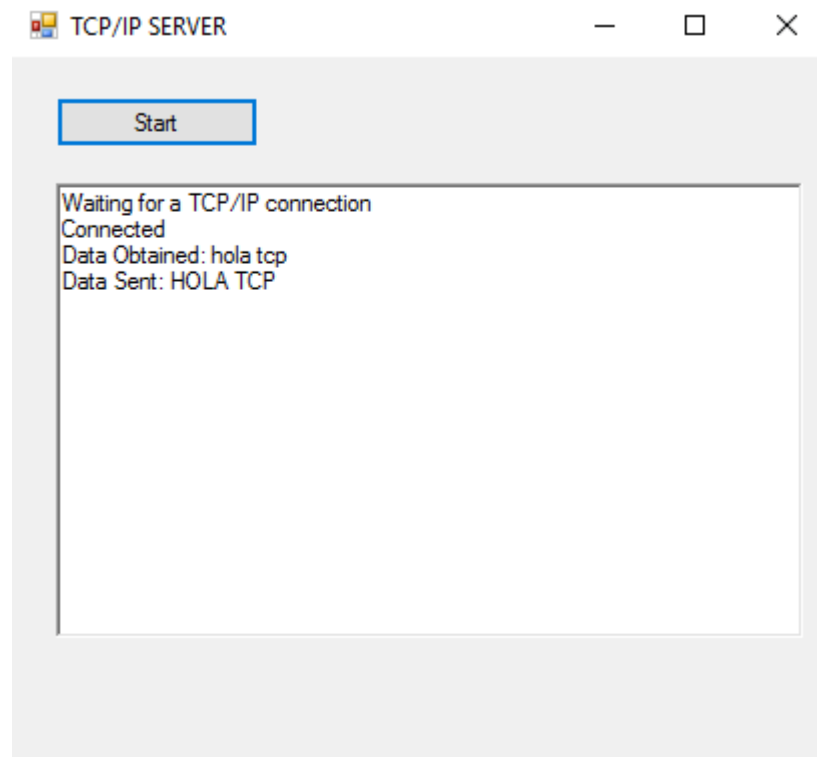
The fundamental purpose of TCP/IP Server Interface is to deal with the connection with the client through an IP address and Port, which is going to be "listening" for any connection. When pushing the "start" button, a message saying "Waiting for a TCP/IP connection" will display which means no connection with a remote computer has been established. Once the connection is accomplished, a "Connected" message will display, and the file (array of bytes) or data will appear from the Client and will be displayed. In summary, the function of the TCP/IP Client interface is basically to send the data to the server based on its IP address and Port number. In this case we wrote "hola tcp" and we got back from the server the same message but in upper case. This uppercase message was made intentionally in the code to indicate that the whole message reached out the server.

In this project, we will make the connection through the ethernet network from client to server, using the same port and the corresponding IP address from both computers and the data which was transmitted. The rates of this transmission will be displayed in the next interface which the network display. Transferring files over TCP/IP works with expected data rate.

6.7.4 Network Information Terminal

Once the two previous interfaces, the PING testing and the TCP/IP client-server have been made, the last one to check is network information terminal. The

following will show the tracking of the data being transferred at the specific network interface selected. The analysis is dedicated to the understanding and modeling of the data during TCP connection.

Figure 6.12. Network Information Display
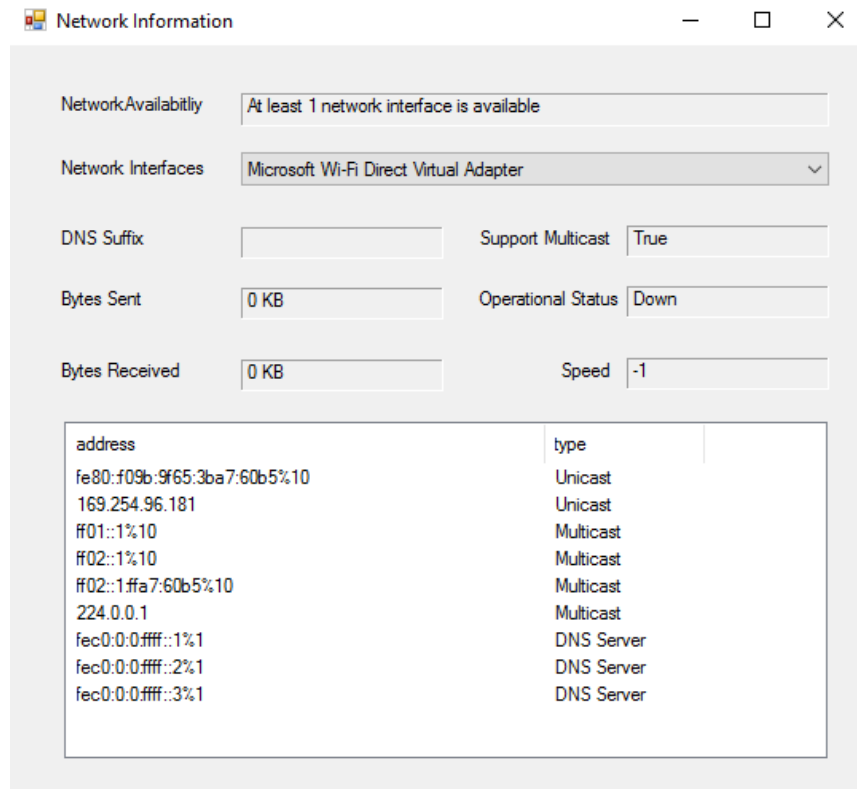
The main objective of this Network Information display is to analyze the measurement of link transmission for the different network interfaces a machine may have. The figure above shows the data of the network interface used to transmit data from one computer to the other. The development of this network display tool is dedicated to giving the user an application to verify the speed of the link communication complemented with other extra features. The features displayed are:

Network Availability: In this attribute, we used "NetworkInterface" class from the library "System.Net.NetworkInformation". This feature helped us to get all the network interfaces available. If there is at least one network working, then a phrase called "At least 1 network interface is available" will show up on the box, otherwise a phrase called "There is no available network" will show.

Network Interfaces: in this attribute, we used "NetworkInterface" class from the library "System.Net.NetworkInformation". This feature helped us to get all the network interfaces, and this way, we could put them all into an array. After that, this array is checked in a 'for loop' to get the description of each network interface and then get them displayed on the dropbox in the interface. If there is no network interface, then then a phrase called "No NICs exist in this machine". Also, if a new network interface is added to the machine, this will be displayed in the dropbox.

DNS Suffix: The DNS (Domain Name System) suffix stands for the registration name of the network interface the machine is connected to. To obtain this attribute, we used two different classes named "IPInterfaceProperties" and "IPAaddressInformationCollection" which are located in the library "System.Net.NetworkInformation". In that information collected, the DNS suffix information is obtained and displayed in DNS suffix box on the interface.

Bytes Sent: This attribute measures the amount of data being sent from one machine to other. In this part, we used the method "BytesSent" from the library "System.Net" which gets the number of bytes that were received on the interface. The total amount of bytes received is then converted to Megabytes (KB) by dividing it by 1024.

Bytes Received: This attribute measures the amount of data being sent from one machine to other. In this part, we used the method "BytesReceived" from the library "System.Net" which gets the number of bytes that were sent on the interface. The total amount of bytes sent is then converted to Megabytes (KB) by dividing it by 1024.

Support Multicast: This attribute measures if the network interface supports multicast communication or not. If the value is true, then it does, otherwise it will be false. In this part, we used the method "SupportsMulticast" from the library "System.Net.NetworkInformation" which returns a boolean value that indicates whether the network interface is enabled to receive multicast packets.

Operational Status: This attribute measure the current operational state of the network interface connection. In this part, we used an 'Enumeration' named "OperationalStatus" which will return the following type of values:

Up: The network interface is up; it can transmit data packets

Down: The network interface is unable to transmit data packets.
This enumeration is found in the library "System.Net.NetworkInformation"

Speed: This attribute measures the speed of the current network interface. In this part we used the property "Speed" from the library "System.Net.NetworkInformation"

In the 'Rich Box', information about the NICs on that current network interface are displayed in either IPv4 or IPv6, which are explained in the IP section. Also, the address type is displayed in the right column which indicates if the IP address is multicast, unicast or anycast.

Multicast: Multicast is a communication between a single sender and multiple receivers on a network. This type of address is displayed due to a class named "MulticastIPAddressInformationCollection" located in the "System.Net.NetworkInformation" library.

Unicast: Unicast is a communication between a single sender and a single receiver over a network. This type of address is displayed due to a class named "UnicastIPAddressInformationCollection" located in the "System.Net.NetworkInformation" library.

Anycast: Anycast is a communication between a single sender and the nearest of several receivers in a group. The term exists in contradistinction to multicast, and unicast. This type of address is displayed due to a class named "IPAddressInformationCollection" located in the "System.Net.NetworkInformation" library. [15]

7. Physical Testing and Prototype Construction

7.1 Testing Conditions

The first step in constructing a prototype is to test individual components, then to test connecting components, and finally the system as a whole. There is a learning curve associated with integrated circuit semiconductor implementations. The reason being is that the relative size and form of the integrated circuits can be hard to see their individual details, therefore careful placement onto breakout boards from the company proto-advantage.com was sought. Even though their DIP packages can be easily realized, there are several physical faults which can limit the performance. The sockets that are used in a breadboard might have different permittivity thus causing reflection, and absorption of the flowing electronics, reducing the output power and changing the phase. The resolving of mismatch of impedances at high frequency is paramount to transmission of signal.

Equipment: In the Senior Design lab, there is a variety of hardware made available for students to test equipment. For this project, we used the following.
- Agilent E3630A Triple Output DC Power Supply
- Tektronix AFG 3022 Dual Channel Arbitrary Function Generator, 25 MHz
- Tektronix DMM 4050 6 ½ Digit Precision Multi-meter
- Tektronix MSO 4034B Digital Mixed Signal Oscilloscope, 350 MHz, 4 Channel
- CSI2205D Micro Control unit DMM auto-ranging Multi-meter

Procedure: The same method(s) was followed to test each component individually, as well as each side of the transceiver and finally the system as a whole.
1. Setup breadboard by connecting all of the grounding rails to one another, and repeat for the power supply rails.
2. Place the components on the breadboard, making sure to leave enough space for passive component placement, as well as jumper wires.
3. Place passive components according to manufacturer spec sheets and the mode of operation for each IC.
4. Double check the circuit to make sure all connections are correct, there are no shorted elements, and no open circuits.
5. Place wires to act as leads for hardware i.e. two wires for input signal, two wires at each output for the oscilloscope, an additional wire at each supply voltage pin to be measured by the multi-meter.
6. Connect the power supply leads from the Agilent power supply to the terminals of the breadboard.
7. Connect the leads from the function generator to the inputs of the differential receiver.
8. Turn everything on I.e. the power supply, the function generator, the oscilloscope, and multi-meter.

9. Set the function generator to an appropriate signal, and tune the oscilloscope to an accommodating resolution.
10. With everything running check each input with the multi-meter to confirm that proper supply voltage is reaching each component.
11. Check the output of each component to make sure there is sufficient voltage being provided from each IC.
12. Finally using the oscilloscope leads, check and record the signal going into each IC and coming out of each IC.

Results: Using the aforementioned procedure(s) we were able to test all of the parts we ordered as well as the system as a whole. We found that the VLC system performs well with a 10 kHz differential input, where the waveform is square. We tested the same wave at 100 kHz and the system resolution was poor. We then used the function generator to produce a modulated signal of the AM variety with a carrier of 1 MHz and the modulation frequency of 10 kHz. The system resolved this signal fairly well, the same signal was used with a sine wave instead of a square and the system resolved that one well too. A detailed account is given below.

7.2 Transmitter Components

In the second iteration of design, which will have a more thorough documentation, we implemented a 10-BaseT VLC transceiver. Included in the transmitter components are the differential receiver, the LED, as well as a voltage converter. The figure below shows the circuit diagram for the transmitter setup. It was created using EasyEDA, a website specializing in online circuit and PCB design. The capacitor values that you see were given by the manufacturers on the data sheet. The AD8130 has been configured for a basic gain circuit, where the gain is equal to the input voltage times 1 plus the ratio between the resistors across pins 6 and 5. In a perfect scenario this setup would produce a single signal at 4x the input voltage. The IC7660s has been configured as a simple voltage converter (Vo = -Vin).

When attempting to use the AD8130, the IC needed to be converted into DIP version with an external vendor. Although there were recommendations that this would be able to hand the frequency we needed to use, when scrutinized on the lab bench, the component was not meeting the requirements.

Figure 7.1. The Transmitter layout for the VLC prototype.
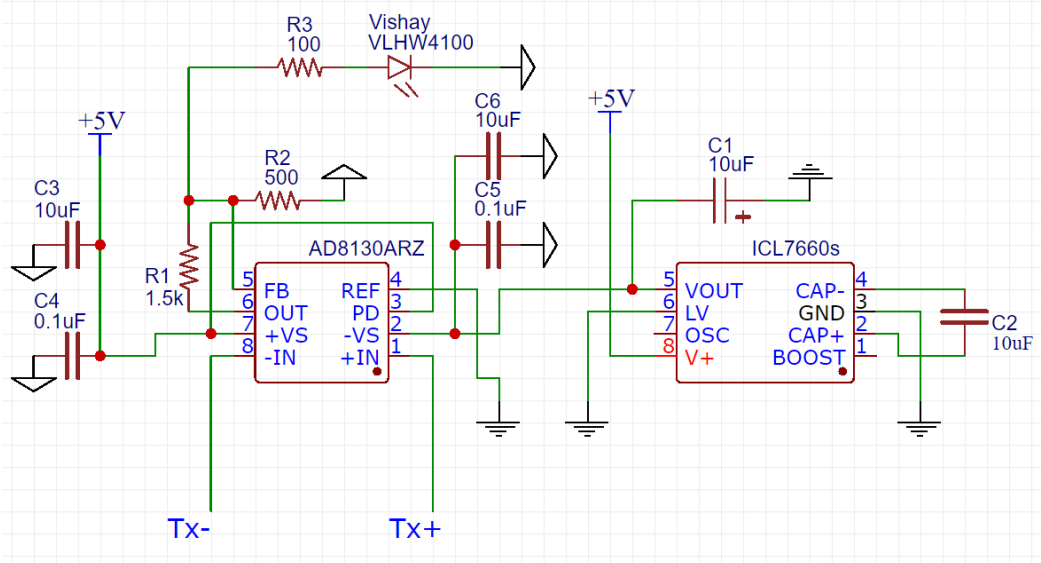
Also included is the breadboard implementation of this design. The IS7660s is on another board and is not shown in the photo. In order to test this circuit, we used an arbitrary waveform generator, specifically a Tektronix AFG300C. Because the AD8130 works by receiving a differential pair, we slaved CH2 to CH1 as a compliment thus creating a differential pair. The wave form was set to square, with a frequency of 10 KHz. The pictures below shows this data.

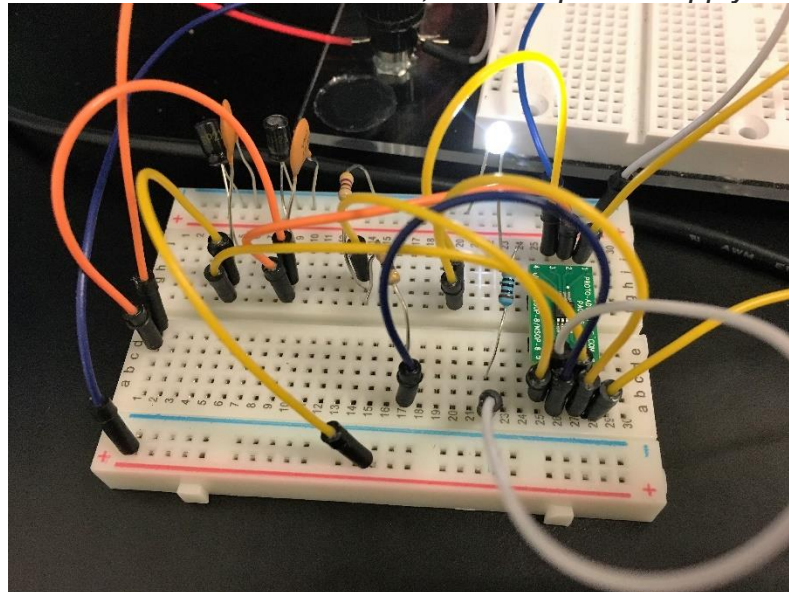Figure 7.2. The transmitter on breadboard, with the power supply on.
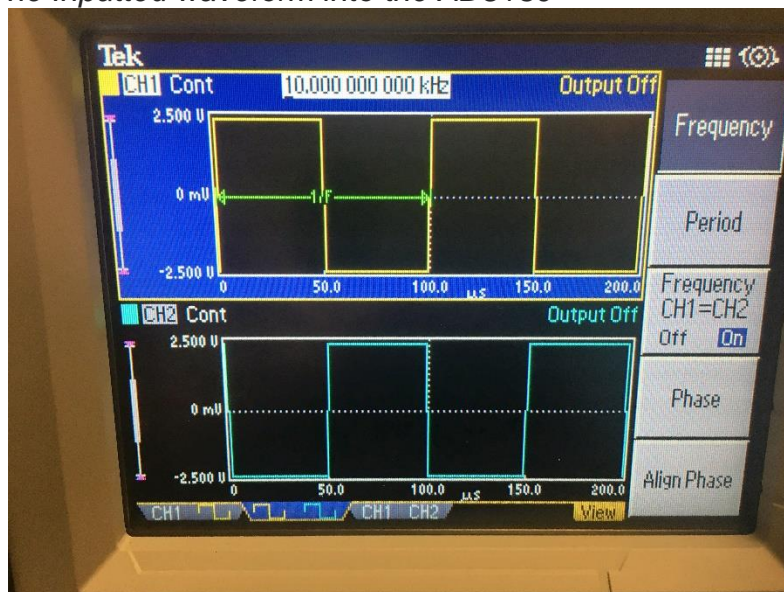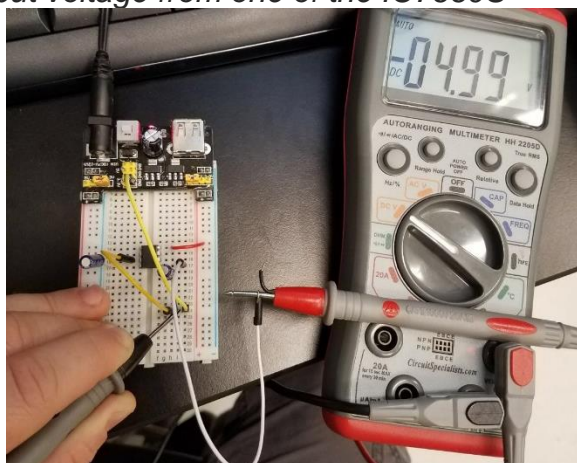
Figure 7.3. The Inputted waveform into the AD8130

Figure 7.4. The output voltage from one of the IC7660S

7.3 Receiver Components

The receiver side consists of the AD8131 to return the single signal back into a differential, an LM7171 amplifier, two voltage converters, and the BPV10 photodiode. The figures below show circuit diagram for the receiver, as well as its breadboard implementation. In the circuit diagram, the two voltage converters are across the bottom, the photodiode goes directly into the LM7171 and the output from that goes directly into the AD8131. The LM7171 is a transimpedance amplifier, thus converting the current produced by the photodiode into voltage. The amplifier was setup for a basic gain configuration with a 70K resistor across the feedback into pin 2 (-In). The AD8131 is said to act as a single-ended to differential driver into a twisted pair.

Figure 7.5. The circuit diagram for the VLC receiver
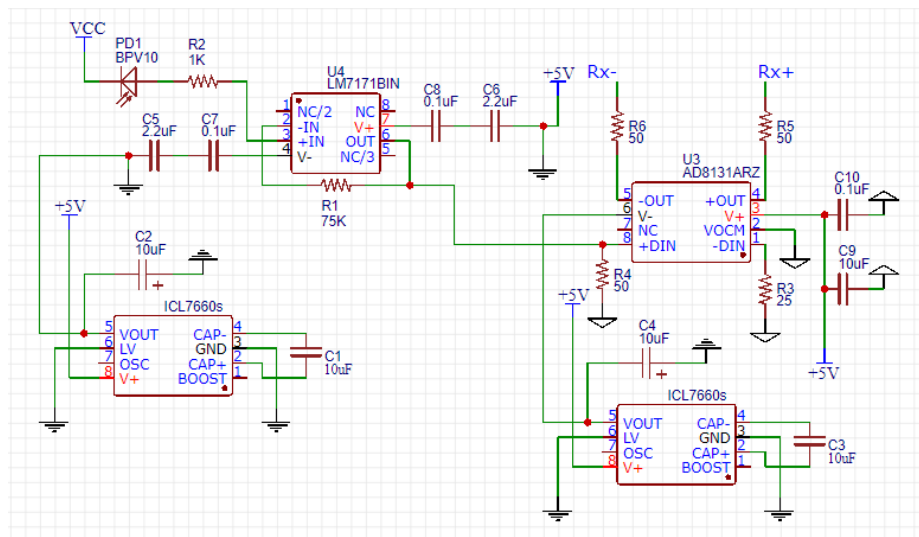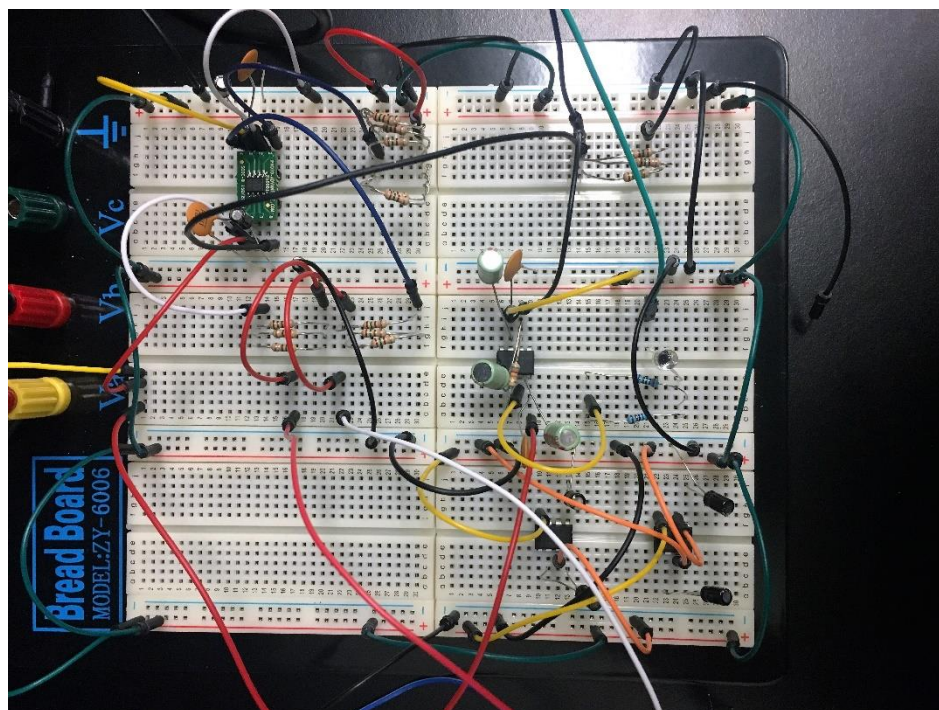

Figure 7.6. The breadboard build of the receiver.

7.4 VLC System

As previously mentioned the input signal into the differential receiver was a complimented pair of 10 KHz square waves. The first of the three figures below Fig 7.7, shows the relationship between the LED and the photodiode. The purple

reading shows the signal going into the LED, the blue reading shows the signal coming out of the photodiode, being amplified and going into the AD8131. We can see that the combined differential square wave that is driving the LED maintains its shape. The second figure Fig 7.8 shows two readings, one for each of the differential outputs. The signal is recreated quite well, and is still in differential format. The third figure in this section also shows the output from the AD8131, however this time the signal going into the receiver is a differential sine wave. While it's not exactly the input it is a reconstruction of the differential signal, and it does maintain the appropriate frequency.

Figure 7.7. The top signal coming from the photodiode, and the bottom signal coming from the LED.
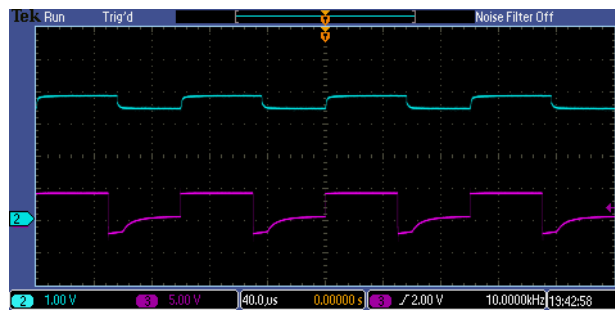

Figure 7.8. The output from the AD8131 after being captured by the photodiode. The input here is a square wave, the output is also square in nature.
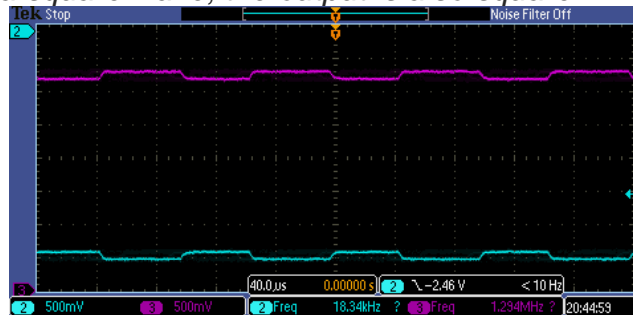

Figure 7.9. The output from the AD8131 after being captured by the photodiode. The input here is a sine wave.
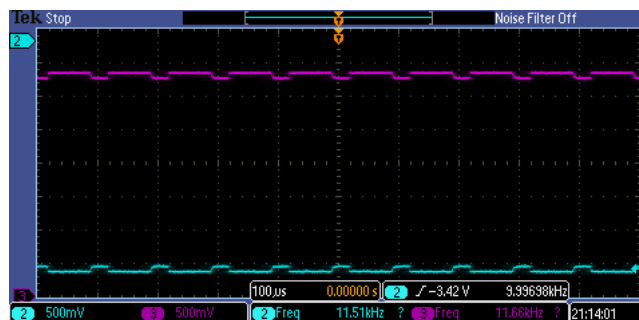
When attempting to document the 100 KHz frequency and higher the resolution of the signal was degraded. There was essentially noise and we could not diagnose the error. Therefore, there was a turn into the main focus of the project as seen in chapter 5.

If there was more time in completing our focus on VLC, we could use different circuit elements in the design and work with experts in high frequency electronics. One such recommendation was from Ethan Png who had recommended the design of a "Ethernet over Light" project which showed promising aspects of transmitting the 31.25 MHz signal required for 100 Base-T transmissions as seen in figure 7.10[16].

Figure 7.10 Simulated transmitter (top) and receiver (bottom) signals for the 100 Base-T Ethernet over light transmission.
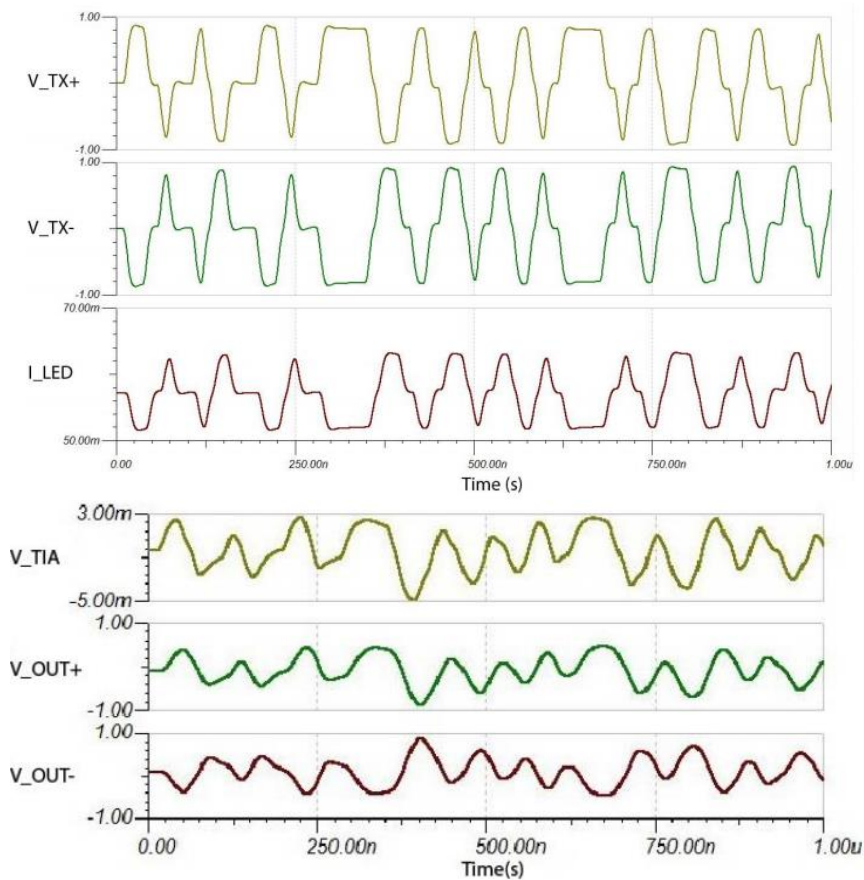
8. Project Construction

After physically testing each individual component, testing the transmitter and receiver, and testing the system as whole, the next stage of product development is to focus on designing a printed circuit board. The most important parts of this step include figuring out which company to purchase the PCB from, as well as how we will mount the components we have selected. The next chapter will give an overview of the techniques and the ancillary material includes a detailed list of parts selected, and purchased.

8.1 Printed Circuit Boards

A printed circuit board or PCB is essentially a board that connects electronic components by micron size electrical wires. It is a component made of one or more layers of insulating material with electronic conductors. The insulator is typically made on the base of fiber reinforced resins, ceramics, plastic, or some other dielectric materials. It can be used for everyday electronic products where form factor is necessary and experimental prototyping is finished i.e. PCB offers many benefits such as it can be very small in size. Moreover, the printed circuit board reduces the need of assembling wires, and in turn improves the appearance of the final product while creating high reliability.

There are many different types of PCB which includes single sided PCB, double sided PCB, Multilayer PCB, Rigid PCB, flex PCB, and rigid-flex PCB. Single sided PCB is the most simple and basic PCB. The components are on one side and conducting wires are on the other side. It has only on layer of conductive material. Double sided PCB is very similar to single sided PCB however, both sides of board contains electronic components and conductive layer. It is the most popular type of PCB in today's industry. It allows traces across and under each wire, increasing density without point to point soldering. Multilayer PCBs as name implied have multiple layers and has a higher density, it includes a layer on top of double sided PCB, which makes it very thick and a high compound design. The price of multilayer PCB is relatively high. Rigid printed circuit boards use a solid, rigid substrate material like fiberglass that deters the board from twisting. Flexible PCBs consist of conductive strips of metal, usually copper, encapsulated with an insulating dielectric material made of polyimide or a solder mask. The benefit of flexible PCB is that it will reduce size and weight and maintain ruggedness. Rigid-flex PCBs combine the advantage of rigid PCBs and flexible PCBs. The circuit includes two or more conductive layers that comprise either flexible or rigid insulation material between each one - the outer layers may have either exposed pads or covers. In our design, we are going to use double sided PCB rigid PCB.

The design and implementation of our own PCB, is a requirement for electrical engineers in to complete the senior design, however, we have no experience with PCB design. This will be a learning experience to design a PCB on our own. In

today's market, there are many different software's available for students to design printed circuit boards for free. One of very good and easy to use software package available to our group is KiCad. The reason why we chose it is because it contains a schematic editor, parts can be placed on many sheets and connected together through ports, and the layout editor allows back annotation to the schematic and auto-routing to automatically connect traces based on the connections defined in the schematic. Also, it offers a full suite of options such as part creation, as well as direct connections to the company's electrical component database.

After we design our own circuit on the PCB reconfiguration software, now we are ready to manufacture an actual PCB. Normally, it is hard for us to manufacture complicated printed circuits onto substrate materials therefore need to send to a professional PCB manufacture company. There are many company out there for us to choose. There are three constraints that we need to keep in mind while manufacture PCB.

First constraint we have is the economic constraint, we want to keep the budget under $300. The second constraint we have is the time constraint, we need to consider how long does it take for manufacture to build PCB and send back to us. Third constraint we have is the minimum order of PCB that we need to order.

The company that has been considered are list below

OSH Park

OSH Park is a community printed circuit board (PCB) order. It is located in the United States. It is an aggregation service that panelizes a number of customer orders into a single panel, then sends them out for fabrication. Standard prices are 2-layer PCBs are $5 per square inch, FR4, ENIG finish, 0.063 thickness, 1 oz. copper, 6/6 spacing, 13/7 drills. The requirement is an order of 3 boards. If we decided to go with a 4-layer board instead it would also include three copies of our board but the price would double to $10 per square inch and the manufacturing process and shipping would take a little longer as well. The price for 2 layers is fairly low that is affordable for students. They are also a favorite of many open-source hobbyists which will allow the design to be easily shared with others.
Design rule for Oshpark
- At least 6 mil minimum trace width
- At least 6 mil minimums spacing between traces
- At least 15 mils of clearance from the traces to the edge of the PCB.
- Hole size must be at least 13 mils
- Annular rings must be at least 7 mils

4PCB

4PCB has student programs for college student in that it offers a very cheap and quick delivery method for when you need your PCB right away. It costs $33 per board which is competitive but not sufficient. A 2-layer full spec printed circuit board would cost 33 dollars and 4-layer full spec would could around 66 dollars. There is no minimum order requirement for this company. Also, it offers a free design tool "PCB Artist" that can be used to develop the design needed. 4PCB offers a free file review which is reviewed by engineers so if there are any errors in design they will be found immediately with no surprises later. This company has very good reviews in respects to quality and cost. However, we need two boards and can get more for almost the same price from OSH Park.

Express PCB

As the name implies, express PCB offers a very fast service, and the time is guaranteed to be 2 days in delivery. The cost of the PCB is a little bit higher than other company, it is at 51 dollars for a 2-layer and 99 dollars for a 5 layer. The shipping charged is 10 dollars for its express shipping. This would be a great option when time is very limited.

PCB-pool

PCB-pool is another company that offer no minimum order, it has multiple locations throughout the world. It has many software choices such as eagle cad, PCAB. The price is a bit higher than 4PCB at 42 dollars for 2-layer and 100 dollars for 4-layer full spec printed circuit boards. The company is located in Germany, which causes a problem, mainly shipping. The international shipping will increase the cost and time of delivery for our PCB design. Even though it has very good reviews, but it is better to order form the United States.

PCB4Less

PCB4Less is a relatively cheap manufacturer, as name mentions. PCB4Less offers a complete line of printed circuit board fabrication with cutting-edge technology and guaranteed ability to deliver. The price for the PCB of 2 layers $19 and 4 layers for $39. There is no minimum order required. And the time takes it delivery is about 5 to 7 days.

Below is the table to compare different PCB Manufacture Company.

Company	Min. order	Time	Cost	Website
Oshpark	3	5 days	$36	https://oshpark.com
4PCB	1	5 days	$33	http://www.4pcb.com/

Express PCB	1	2 days	$51	https://www.expresspcb.com/
PCB-pool	1	8 days	$42	http://www.pcb-pool.com/
PCB4less	1	5-7 days	$19	http://www.pcb4less.com/

After comparing and contrasting the aforementioned printed circuit board manufacturers and weighing their advantage and disadvantage we collectively decided to order PCB from OSH Park. We used OSH Park for our manufacturer company due to its low cost and fast delivery and multiple delivery order for a low price. The reason 4PCB is not used is because it comparatively more expensive than OSH Park as from table above, Obliviously, the PCB-pool will not be used due to high price, and long shipping. Express PCB offer very fast shipping; however, the price is not a good choice, and we are not rush at this moment. PCB4less does not have as good review as OSH Park, and it takes longer time to delivery. The most important thing that will add flexibility to choices in PCB manufacturers will be how much time we can spare. As such, we will need to begin designing the schematic and PCB as soon as possible to take advantage of these options. Otherwise, the rush processing can get very expensive. A good news is by now, we have gotten 5 orders of laser ethernet transceiver board from OSH Park for 12 dollars a board.

8.2 Soldering

The general techniques that can be used to mount an electrical component to a printed circuit board are general soldering of the component, through-hole soldering, and surface mounting technology. Surface mounting technology is more popular nowadays because of demanding for smaller weight and size of packaging. We are going to use all three soldering techniques to solder the components on BS board our self.

Surface mount technology

Surface mount technology is the process by which components are mounted directly onto the surface of the PCB. Surface mount technology components either have smaller leads, or no leads at all this could reduce the resistance and inductance. Surface mount technology component is generally smaller than through-hole soldering. Because of surface mount technology on PCB does not require as many drilled holes, and the components are more compact, higher circuit densities are possible on smaller boards. This is reason why today's technologies are getting smaller and smaller.one advantage of surface mount technology is general less expensive than through-hole soldering. They are often offer a better level of performance and they can be used with automated pick and

place machine that in many cases all bit eliminates the need for manual intervention in the assembly process which will reduced the cost of product. however, there is one disadvantage of surface mount technology which is the construction is not suitable when there are requirements for high power or large high-voltage parts such as in power circuits

Through-hole soldering

Through-hole mounting is the process by which component leads are placed into drilled holes on a bare PCB. The process was standard practice until the rise of surface mount technology (SMT) in the 1980s, at which time it was expected to completely phase out through-hole. One advantage of Through-hole mounting is extremely reliable, as it provides strong mechanical bonds. However, there are many disadvantages of through-hole mounting compare to surface mounting which include the additional drilling makes the production of boards significantly more expensive. Additionally, the presence of holes in the PCB create limitations in terms of the available routing area for signal traces on the layers which are immediately beneath the top layer on multi-layer boards. While a surface mount literally affixes the component to the top surface of the board, through-hole attaches the component to the board by providing holes in the board to allow the component lead to go through the board and exit the opposite side of the board.

General soldering

General soldering connects electrical wiring and electronic components to printed circuit boards. It is a process in which two or more metal items are joined together by melting and then flowing a filler metal into the joint. The metal to be soldered is heated with a soldering iron and then solder is melted into the connection

Surfaced mount technology and through-hole mounting are two types of soldering are popular in today's market. However, in our project, we are going to soldering the components on BS board our self by using all three techniques. We will need a hot air gun during the soldering. We are going to do this PCB with ordinary soldering iron. The footprint on the PCB is deigned to make soldering easily for us.

Since we have no experience on soldering electronic components before, here are some general tip to know before we soldering.

a. First of all, we need to clean all components, tools, and circuit board to be used in soldering process.
b. then we need to choose an alloy which is lead-tin. Usually we use 40% of lead, and 60% of tin.
c. adjusted a soldering iron to appropriate temperature,
d. Select the right flux, flux is an agent that prevents oxidation and removes the thin layer of oxide.

e. Then we need a clamp to hold electronic components, which is usually very small.
f. Select the right electronic component and double check with pins make sure with no mistakes.
g. Soldering on the PCB, hold the soldering iron and heat both the lead and the pad simultaneously. Touch the solder wire in the space between the iron tip and the lead, Keep the soldering iron tip still while moving the solder around the joint as it melts. Allow to the joint to cool naturally and undisturbed, do not blow on the solder joint to cool it.
h. Good soldering joint: will be shiny and concave in nature, will be clean and free of dirt, and will fully cover the pad component lead lays and passing through.

8.3 PCB assembly

After placing the order for the Laser Ethernet Transceiver (LET), and all electronic components, now we are ready to do the PCB assembly manually. We have the footprint as a figure showing below.

All other components will be either reused from the prototyping phase or will be ordered through Texas Instruments, Digi-key, or Mouser depending on surface mount part and through-hole part availability. It is more cost efficient to purchase a surface mount resistor kit and capacitor kit that provide various values and order separately if the kits do not provide all values needed.
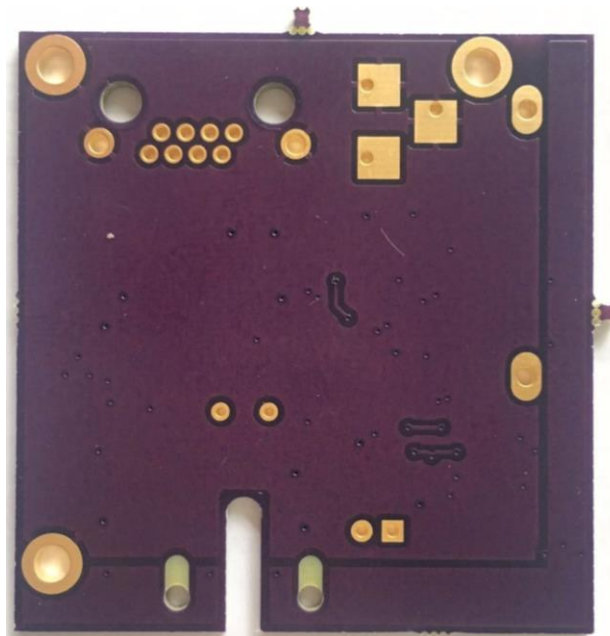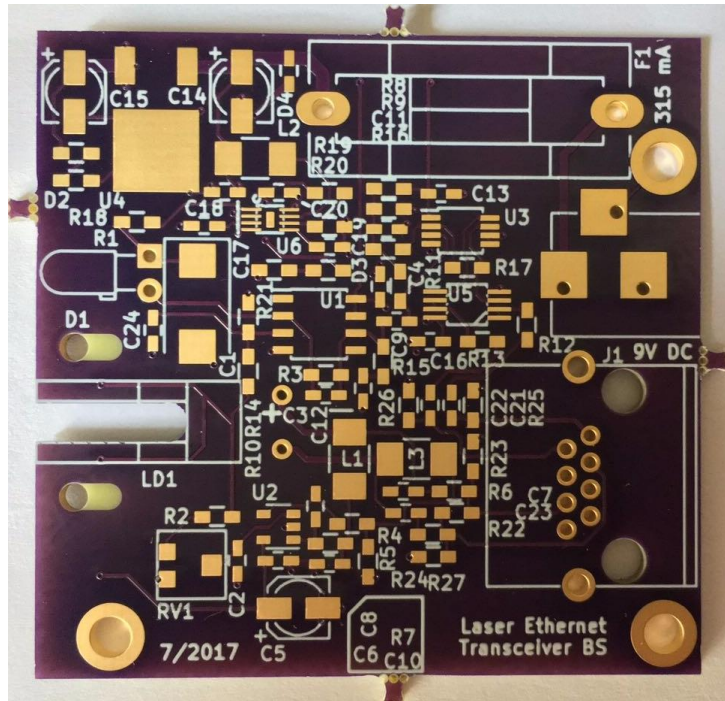
As we can see from picture there are a few items that will be through-hole technology. the standard 5x20 mm 315mA Fast-Blow Fuse Ceramic fuse (F1 on PCB) will be thought-hole soldering on the fuse holder. At position J1 we will through-hole mount a DC Power Connector, Jack, 3 A, 1.95 mm.

All ICs will be soldering on the PCB by using surface mount technique. On the transmit side, at the position U1, we will solder a OPA695. We are also going to solder MAX4392 on U5. We need to be extremely careful with pin, make sure

that we put on to PCB correctly. All pin from ICs has already mentioned on chapter 3. on the receiver side, the MAX4390 will be soldered on U2. LT1713 is a comparator that will be soldered on U3. The power supply of this transceiver will provide by voltage regulator LM78M05CT and voltage booster MIC2605, which will mount on U4 and U6. All the reistors, capacitors, and inductors will surface mount on the PCB.

9. Administrative Content
The Milestone Objectives

Description	Time will take it to complete	Deadline
Senior design 1		
Form Group	1 hour	5/18/2017
1-page project idea	1 hour	5/19/2017
10 pages report	6-10 hours	6/2/2017
Divide and conquer	30 minutes	6/6/2017
Component Testing Start	N/A	6/6/2017
Meeting with Dr. Hagen	30 minutes	Random
Breadboard Testing	N/A	7/3/2017
60 Page report	10-20 hours	7/7/2017
Design PCB	10-20 hours	7/14/2017
100 pages report	10-20 hours	7/21/2017
Final document	8-12 hours	8/1/2017
Order PCB	3 Weeks	8/1/2017
Testing	N/A	Break
Senior Design 2		
Finalize Design	1 days	8/25/2017

Send out second PCB	1 week	9/8/2017
Prototype	1 week	9/17/2017
Testing and redesign	2 weeks	10/1/2017
Finalize prototype	2 weeks	10/15/2017
Peer presentation	30 minutes	11/1/2017
Final report	2 weeks	11/20/2017
Final Presentation	30 minutes	12/1/2017

Bill of Materials

Table below is the summary of the parts that was purchased during the process of development 10 base-T Laser Ethernet Transceiver

Overall the cost of the design is x per board, each component was ordered for the fact that we have six PCB's and that there would be some initial mistakes in creating such a device for the first time. Of course, if there was more of a reason to pursue this product professionally, there are companies which can manufacture every one of the components on to the PCB via machine vision and assembly technology.

One such company which can provide this type of service is smallbatchassembly.com. They claim they can handle this type of creation however, there are some requirements which our board could not make such as fiducials. The fiducial detail was investigated however the group could not come up with the correct way to do it in the time constrains of senior design one.

Appendix A - Copyright Permissions

Benjamin Stuart
Wed 6/28, 12:27 PM

Hey Mr. Ethan Png,

I am a student at the University of Central Florida working on VLC. I noticed in your book there was no picture for the 100 Base-T VLC Ethernet transceiver in chapter 9. Was this prototype idea ever built in the lab? If not why not? Does it not depict the correct electrical connections? I noticed in the maxim 3967A evaluation board there were more passive components necessary. I have all of your components in my lab to build this but it seems like there might be more than what is depicted. Any help would be appreciated.

Thanks for your time,

Benjamin Stuart

Ethan Png <ethanpng@ntu.edu.sg>
Wed 6/28, 11:47 PM
Benjamin Stuart ⩔

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📄 dissertation 2015 VLCLA... 3 MB	📄 ethernet original paper.... 2 MB	📄 thesis 2012 VLCLAN.pdf 7 MB

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💬 | Action Items

Hi Ben,

The designs of 100baseT transceivers are in Fig. 9.6, 9.7, 9.8, Fig. 10.11 and Fig. 10.12. These are the VLC 100baseT plug-in transceivers for media converters. I am sorry we cannot release the 100baseT standalone (direct RJ45) transceivers.

Publications are always selfish (even if they know the invention is not going to be implemented in the near decade). Institutions want to spin companies out of projects, especially in a profit-driven city like Singapore. Therefore, no one would really reveal everything or every project. The reason people don't release 100baseT VLC LAN circuits is because it will be a lucrative source of profit in the future.

That said, it does not mean that you cannot find them on Google search.

I would suggest getting your students to spend 3 weeks just on Googling and doing nothing else (that's what my Prof got us to do). The bits and pieces will lead to your 100baseT VLC transceiver designs.

To make things easier for your students, hereby I attach three documents to help you build your first successful 100Mbps transceiver.

Note that between 10baseT and 100baseT, the transceiver is easy to make, because campus data rate is quite slow, usually lower than 54Mbps. It is not even 100Mbps.

Between 100baseT and 1GbaseT, it is harder. You need a photonics expert and a signal processing expert in your team.

For 100baseT, having a team of people with good background in high speed communication circuits will help a lot. The key issue is the biasing, i.e. the control of noise and signal levelling by the use of capacitors, inductors and resistors.

Design your pcb properly (you cannot do it on breadboard) with the help of pcb engineers. The signal trace design is very important.

You need to have patience with this kind of project. I changed my pcb designs 5 times along the way. I got it working on the 6th version pcb.
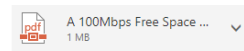
Hello Ethan,

Thank you for your timely response. I was specifically asking about figure 9.5. My question is that circuit diagram a demonstration to the reader as to what is plausible because it seems like the maxim 3967A should have more components according to other people's work? Do you mean that there is too much power loss if I do it on a breadboard? I had a company reconfigure the QFN package into dip package, so the connections should be able to do manually.

Best Regards,
Ben

Hi Ben,

Sorry, I've quite busy.

All the circuits in the e-book work. Fig. 9.3 was done by my 2nd year and final year students.

Of course, your circuit board and the type of wires will be different from mine, so you will have to change the values of or add some resistors and capacitors.

There is no need to give me credit because you will find that along the way the circuit would have changed and it has already become your own work.

These chips are very commonly used, and if you look into their datasheets, they have already provided very useful application circuits.

Warm regards,
Ethan

Appendix B – References

1   Saleh, B. E. A. & Teich, M. C. *Fundamentals of photonics*. (Hoboken, N.J. : Wiley-Interscience, c2007.
2nd ed., 2007).

2   IEEE Standard for Ethernet. *IEEE Std 802.3-2015 (Revision of IEEE Std 802.3-2012)*, 1-4017, doi:10.1109/IEEESTD.2016.7428776 (2016).

3   Kasap, S. O. *Optoelectronics and photonics : principles and practices*. (Upper Saddle River, NJ : Prentice Hall, c2001., 2001).

4   Miller, F. P., Vandome, A. F. & John, M. B. *Common-Mode Rejection Ratio*. (VDM Publishing, 2010).

5   IEEE   Draft   Standard   for   Information   technology-- Telecommunications and information exchange between systems-- Local and metropolitan area networks--Specific requirements--Part 15.7: Standard for Short-Range Wireless Optical Communication using Visible Light. *IEEE P802.15.7/D8, April 2011*, 1-306, doi:10.1109/IEEESTD.2011.5764866 (2011).

6   Willebrand, H. & Ghuman, B. S. *Free space optics : enabling optical connectivity in today's networks*. (Indianapolis, Ind. : Sams, c2002., 2002).

7   Bloom, S., Korevaar, E., Schuster, J. & Willebrand, H. Understanding the performance of free-space optics [Invited]. *J. Opt. Netw.* **2**, 178-200 (2003).

8   Hodson, P. *Local area networks*. (London ; New York : Continuum, c2003.

4th ed., 2003).

9   O'Hara, B. & Petrick, A. *IEEE 802.11 handbook. [electronic resource] : a designer's companion*. (New York, NY : IEEE, c2005.

2nd ed., 2005).

10   Yeo, L. C. P. K. S.   (2016).

11   Vucic, J. *et al.* in *2009 35th European Conference on Optical Communication.* 1-2.

12   Vučić, J., Kottke, C., Nerreter, S., Langer, K.-D. & Walewski, J. W. 513 Mbit/s Visible Light Communications Link Based on DMT-Modulation of a White LED. *J. Lightwave Technol.* **28**, 3512-3518 (2010).

13   Perera, J. P.   (Monterey California. Naval Postgraduate School, 2012-03-14T17:31:01Z., 2012).

14   Kosmas, E.   (ed University of Crete) (May 2012).

15   Rouse,   M.   *Multicast*, <http://searchnetworking.techtarget.com/definition/multicast> (2006).

16   Mark, P. *Ethernet over Light* Electrical and Computer Engineering) thesis, McGill University, (December 2014).

Appendix C – Miscellaneous

The table below list all resistors and capacitors that will be used to solder on the board.

Resistor	Value (OHM)	capacitor	Value(F)
R1	4.7K	C1	47u

R2	20K	**C2**	2.2u
R3	1K	**C3**	Not connected
R4	10K	**C4**	100n
R5	10	**C5**	10u
R6	500	**C6**	100n
R7	10	**C7**	22n
R8	1.2K	**C8**	1u
R9	4.7K	**C9**	22n
R10	2.2K	**C10**	100n
R11	47K	**C11**	1u
R12	50	**C12**	1u
R13	50	**C13**	100n
R14	2.2K	**C14**	10u
R15	50	**C15**	10u
R16	220	**C16**	100n
R17	470K	**C17**	1u
R18	2.2K	**C18**	100n
R19	12.4K	**C19**	100n
R20	500	**C20**	1u
R21	22K	**C21**	22n
R22	100	**C22**	22n
R23	47K	**C23**	22n
R24	500	**C24**	100n
R25	47K		
R26	47K		
R27	47K		

The inductors are going to use surface mount technique. The table below list all inductor components as well as its value.

inductor	Value(H)
L1	10u
L2	10u
L3	10u

Part Name	Datasheet link
AD8130	http://www.analog.com/media/en/technical-documentation/data-sheets/AD8129_8130.pdf
MAX4444	https://datasheets.maximintegrated.com/en/ds/MAX4444-MAX4445.pdf
THS4504	http://www.ti.com/lit/ds/symlink/ths4505.pdf

EL4430	https://www.intersil.com/content/dam/Intersil/documents/el44/el4430-31.pdf
MAX4390/MAX4392	https://datasheets.maximintegrated.com/en/ds/MAX4389-MAX4396.pdf
LM7171	http://www.ti.com/lit/ds/symlink/lm7171.pdf
OPA380	http://www.ti.com/lit/ds/symlink/opa380.pdf
CA3100E	http://www.experimentalistsanonymous.com/diy/Datasheets/CA3100.pdf
LMH6629	http://www.ti.com/lit/ds/symlink/lmh6629.pdf
OPA695	http://www.ti.com/lit/ds/symlink/opa695.pdf
AD8131	http://www.analog.com/media/en/technical-documentation/data-sheets/AD8131.pdf
MAX4448	https://datasheets.maximintegrated.com/en/ds/MAX4447-MAX4449.pdf
THS4120	http://www.ti.com/lit/ds/slos319d/slos319d.pdf
LT1713	http://cds.linear.com/docs/en/datasheet/171314f.pdf
TLV3501	http://www.ti.com/lit/ds/symlink/tlv3501.pdf
MAX9691	http://datasheets.maximintegrated.com/en/ds/MAX9691-MAX9693.pdf
TS3011	http://www.st.com/content/ccc/resource/technical/document/datasheet/30/a0/b8/2c/ef/81/44/d0/DM00035351.pdf/files/DM00035351.pdf/jcr:content/translations/en.DM00035351.pdf
ICL7660S	http://www.intersil.com/content/dam/intersil/documents/icl7/icl7660s-a.pdf
LTC1044A	http://cds.linear.com/docs/en/datasheet/1044afa.pdf
MIC2605	http://ww1.microchip.com/downloads/en/DeviceDoc/mic2605.pdf
ADM660	http://www.analog.com/media/en/technical-documentation/data-sheets/ADM660_8660.pdf
LM78M05CT	http://www.ti.com/lit/ds/symlink/lm78m.pdf