# Laser Data Transmission Using Air as a Medium (LDT-AIR)

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***Abstract* — The LDT-AIR project employs free space communication techniques to produce a product that can transmit information safely and securely. Each subsystem of the project was designed, tested and implemented to produce one final product. Optimization of this communication technique will lead to auspicious means to transmit information.**

***Index Terms* — Free-Space optical communications, laser driver, transimpedance amplifier, unidirectional communication, data transmission, noise filters, op amp.**

## I. Introduction

Since the dawn of the digital age the demand to move large amounts of information as fast as possible has been unquestionable. The LDT-AIR project members have decided to continue the advancement in the movement of information by exploring the fundamentals of free space communication. The inherent restrictions of free space optical communications are scattering and environmental factors. Due to these restrictions the LDT-AIR project set precedence on bit error, range, and resistance to environmental factors while a secure communication transmission. Some secondary priorities are consumer cost, and portability to ensure the LDT-AIR remains as competitive as possible with industry demand. All above mentioned restrictions considered, the following product was produced.

## II. System Components

The LDT-AIR project will be divided into subsystems for simplicity. These subsystems were chosen to optimize the project as a whole.

### *A. Power Management*

Both the transmitter and receiver require power to operate effectively. On the transmitter side buck converters were chosen to maximize efficiency which reduces the overall temperature within the transmitter housing. Two regulators were designed satisfy input voltages of the microcontroller and the laser driver. A 3.3V voltage regulator was designed utilizing a Texas Instruments TPS62122DRVR 6 pin buck converter. Figure 1 is a schematic representation of the TPS62122 converter in a regulator circuit design.

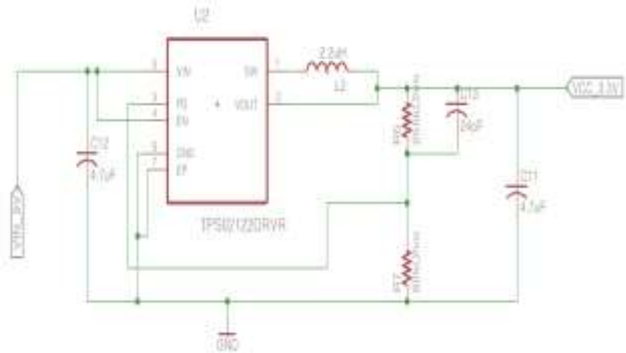

Fig. 1: 3.3V voltage regulator design using Cadsoft Eagle.

This regulator can only output a maximum of 75mA, meeting the required 22mA supply current to the laser driver and the 65mA maximum current of the laser diode. A 5V regulator was also designed incorporating the Texas Instruments TPS62153RGT 16 pin buck converter. This converter was configured to output 5V at a maximum of 1A. Figure 2 is a schematic representation of the TPS62153 converter in a regulator circuit.

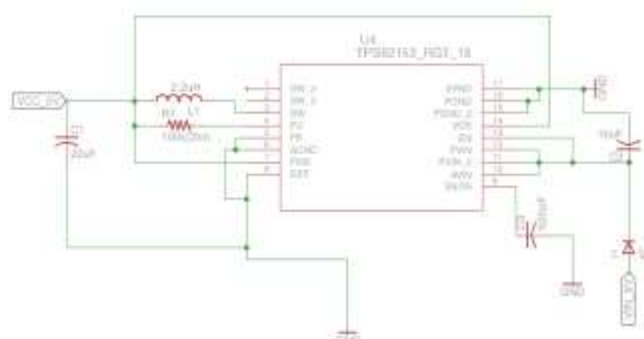

Fig. 2: 5V voltage regulator design using Cadsoft Eagle.

This regulator was designed in to meet the requirements of the microcontroller development board.

### *B. Laser Transmitter*

The LDT-AIR project employs a distributed feedback (DFB) laser operating at 1.55µm with a power 4mW. Multiple quantum wells within the DFB laser ensured a narrow linewidth at the desired peak wavelength. A peak wavelength of 1.55μm at 4mW is a safer alternative to the visible spectrum. The cornea of the human eye represents approximately 70% of the total focusing power. The refractive index of the cornea, omitting nonlinear effects, is 1.336. Figure 3 is a graph of wavelength absorption in water of refractive index 1.33.

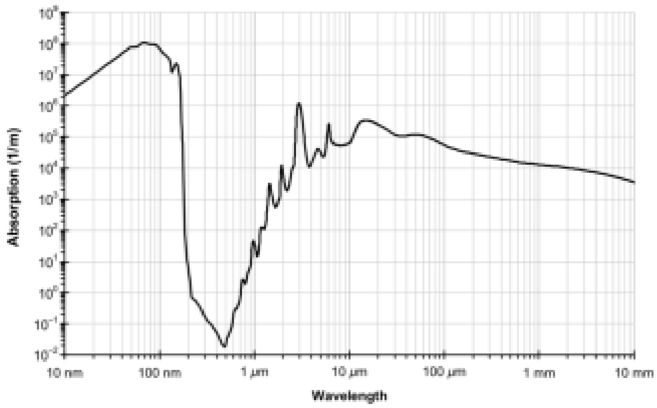


Fig 3: Absorption vs. Wavelength of water.[1]

A wavelength at 1.55μm absorption is four orders of magnitude higher than at 0.5μm. This allows for any power incident on the cornea to be absorbed. The human eye is not designed to focus near infrared light.

Incorporating the correct lens is critical a critical aspect to laser transmission. Using Eq (1) the numerical aperture (NA) of the single mode fiber at 1.55μm with a 4.5μm beam radius was 0.1096. The acceptance angle is then determined from Eq. (2) to be 6.295°. Employing a 1 inch lens the maximum distance the lens can be away from the fiber end is approximately 115mm. This validated our selection of a planoconvex lens distributed by ThorLabs with an effective focal length of 30mm.

$$NA = \frac{\lambda_0}{\pi \omega_0} \quad (1)$$

$$\theta_a = \frac{sin^{-1}(NA)}{n_a} \quad (2)$$

The lens is designed to be focusable to a distance out to 7m. The lens contains a focusing distance of 24mm. See the testing section for design method.

In order for the laser to function within its required specifications a laser driver was incorporated. Figure 4 is a schematic representation of the laser driver circuit, utilizing the Maxim MAX3736 laser driver.

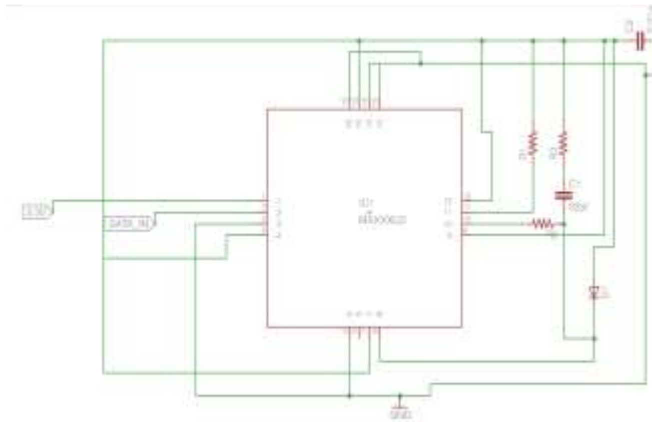

Fig 4: Laser driver design using Cadsoft Eagle.

This constant current source, unlike competitors, contained only 16 pins and operated at a low frequency. This corresponded to decreased noise levels within the transmitting signal. The Maxim MAX3736 also was more than half the price of its competitors. The limit of this driver is current flow to the laser driver. In its current configuration the driver operates at its maximum output current. This leads to extreme heating of the component, which was compensated with an attached heat sink.

*C. Receiver*

Utilizing optoelectronics and free space optical communications we are able to send data via an infrared laser and convert an optical signal into an electrical signal. Since the laser has a wavelength of 1550 nm we will need to choose a photodiode that has a peak responsivity of 1550 nm. So for the receiver circuit we chose part number FGA01 which is an InGaAs photodiode from Thorlabs. The responsivity of the chosen photodiode is shown in figure 4. The photodiode has a maximum reverse bias of 20V, maximum reverse current of 2mA, and an optical power damage threshold of 18 mW. One major issue with this photodiode is the small active area, at 0.12 mm in diameter. However to compensate for this limitation the manufacture included a coupling ball lens with a diameter of 1.5mm. Figure 5 represents the spectral response of the FGA01 photodiode from ThorLabs.

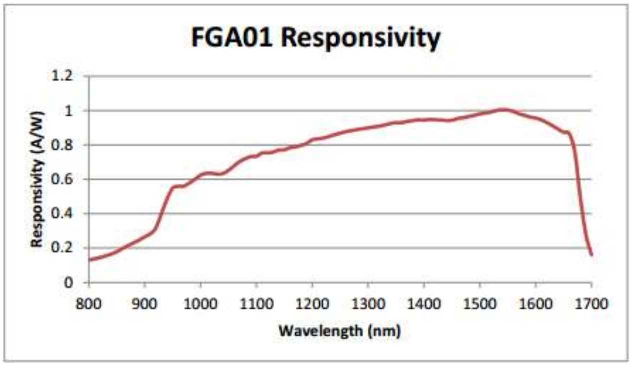


Fig 5: Responsivity of FGA01

After receiving the photodiode we conducted preliminary test to ensure the device was not flawed. Using a basic noise filter circuit as shown in figure 5, we confirmed the photodiode was indeed operational. However, as the output voltage from the basic noise filter circuit was very low we require a voltage large enough to give a response to the microcontroller being used. Figure 6 is a basic noise filter utilized in the receiver design.

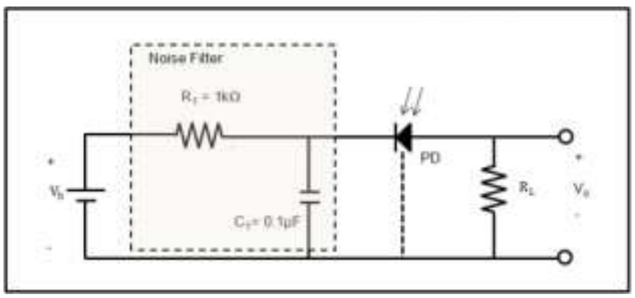


Fig. 6: Noise filter.

By applying an amplifier to the photodiode we can successfully increase the voltage to the required 5 V need by the microcontroller. Two operational amplifiers were used in this design and their part numbers are AD744Q and OP27EP. The AD744 has a gain bandwidth of 13 MHz with a wide supply voltage up to ±18 V and is used as the preamplifier. The OP27EP has a gain bandwidth of 8 MHz with a supply voltage up to ±22 V and is used as the main amplifier. A non-inverting amplifier circuit, shown in Figure 7, was applied to both the preamplifier and the main amplifier. With the design of this circuit the output voltage polarity will remain the same as the input voltage polarity.

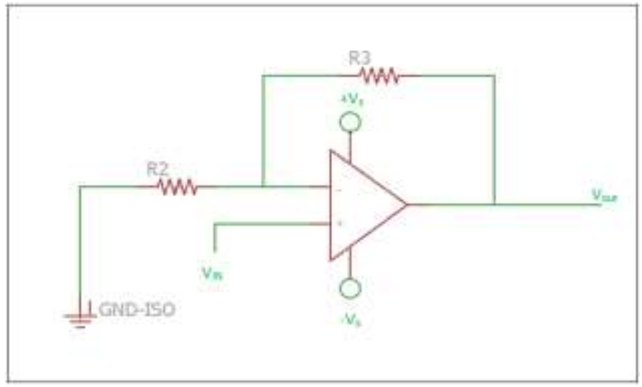


Fig.7: Non-inverting Amplifier schematic using Cadsoft Eagle.

## D. *Microcontroller*

The microcontroller that is utilized in this project is the STM32F746G-DISCO. It uses an ARM Cortex M7 Core microcontroller (STM32F746NGH6) that has a clock rate of 216MHz with a max GPIO output rate of 108MHz. It also includes a 10/100 Mb Ethernet port, multiple interruptible 16-bit and 32-bit timers, and three 12-bit ADCs which assist in the testing phase.

Within the project, there will be one microcontroller attached to both the transmitter and receiver sides. On the transmitter side, the microcontroller will be connected via an Ethernet cord to the computer which the user will utilize to pass data to be transmitted via laser. The microcontroller will act as the modulator as it pulses the given signal with a simple on-off through one of the GPIO ports found on the microcontroller. This pulsing will result in a time modulated signal that the receiver will be able to collect using a predefined time constant to wait between each binary packet.

On the receiver's side, the process is mirrored and reversed. Once a user on the receiver's end establishes a connection to the microcontroller, the microcontroller sits in an idle state waiting for an on signal from the transmitter. Once the on signal is received, the microcontroller processes all on-off pulses as a digital signal and strings these bits into bytes of headers and data which can be handled.

*Code Structure:* There are three pieces of software which are used in the entirety of this project. The first is a console program running on both PCs at both end of the connection, and two C++ embedded programs running on the microcontroller. Each program will be discussed in detail in the following sections.

*Console:* The console program is a Java application which utilizes the built in Java Socket API to establish a connection from the PC to the microcontroller via the Ethernet port. Using the console, the user will be able to send simple ASCII messages and binary files. The console on both PCs will utilize the same code, as it will extend the functionality to move the project from a unidirectional connection to a bidirectional connection in the future.

*Transmitter:* The program running on the transmitter microcontroller is a C++ embedded application utilizes FreeRTOS to enable threading which allows for a faster runtime and lwIP which adds a simple, lightweight Ethernet stack to the microcontroller. The application itself follows an Object Oriented Programming style approach, and consists of three main functions: Input, Encode, and Transmit.

*Input:* This stage will read in user-generated data from a personal computer. While the program is active, it will constantly take in any new data from a user to be read in and pass it to the next staging process.

*Encode:* This stage will receive data from the previous input stage and decide how to handle this data. In most cases, it will attempt to convert the data received to a binary format and create an "IP-style" packet. The packet will consist of a header, which includes general information to be used by the receiver, and the payload, which is the user entered data. The information that will be contained in the header of the packets are flag and error codes to detect if a packet has failed or has suffered any interference during transmission. The header will also contain information pertaining to the current packet, including payload size, packet number, and data type.

*Transmit:* This stage will receive the packet from the Encode stage. It will take that received packet and pulse a GPIO pin on the microcontroller which is connected to the transmit circuit. The pin will pulse a current either on or off, with which the circuit will decide how to pulse the laser.

*Receiver Microcontroller:* The microcontroller on the receiver side of the project will act as the demodulator, as it will be able to differentiate the pulses sent by the transmitter by the software running on it. Since the incoming data will be time modulated, a delay is set in the software to tell packets apart from each other. This delay is what affects the total frequency or bit rate of the project. The code structure of the receiver software will also follow an object oriented approach, in which it will be sectioned out into four main stages: input, decode, decipher, and output.

*Input:* This stage will be the most active stage during the receiver's runtime. It will be in an idle state until a signal is received. Once that signal is received, the input stage will read in the full string and pass it to the decode stage.

*Decode:* This stage will receive the signal data or packet from the previous stage and deconstruct it into one continuous string to be deciphered in the next stage. The most difficult challenge in this stage will be to successfully reconstruct the signal, especially in the vent of loss or interference. If the signal cannot be properly decoded, it will not be able to be deciphered and result in an error.

*Decipher:* This stage will take in the decoded binary string and attempt to deconstruct the header and payload portions of the packet. If the stage is successful in deconstructing the header and payload, the payload and packet identifier will be passed on to the next stage to be output. The header is used to ensure the current frame of the receiver matches that of the packet sent by the transmitter. If the frames do not match, the receiver will assume that the previous packet has been lost, and will report an error.

*Output:* This stage will receive the converted payload and packet identifier, which will have been passed as an ASCII String to be either printed out to the user or saved into a binary file for the user to access. This will be achieved via an Ethernet connection from a PC to the receiver end microcontroller to exchange data.

*Handling lost or corrupted packets*: Due to budget constraints, there were no plans to expand this project to have a bidirectional channel. This limits the ability to deal with loss and corruption effectively via traditional networking means, where the receiver would request for the packet to be resent. The only currently available remedy is to detect when an error occurs and report it to the terminal or to try to limit our bit rate through framing the packets properly. These erroneous packets have to be dealt with each in their own way and will be discussed separately in this section.

*Packet loss:* In an attempt to deal with packet loss, the packet header is used to hold information from the transmitter which the receiver will be able to utilize to determine if an error has occurred. During the packet's creation, header information is added such as a Sequence number, size of the payload, and a timestamp. The sequence number or SEQ will act as a packet's identifier, and conventionally the SEQ number will increase by the size of the payload.

*Packet corruption:* As with packet loss, there is no efficient way to deal with packet corruption. The most effective option is to report the error when it is obtained. A packet can be corrupted from numerous external variables, such as signal interference, power fluctuations, and environmental factors. Aside from removing as many sources of interference as possible it is difficult to account for all errors.

## III. TESTING

Once the project is designed and prototyped, each major subsystem needed to be tested extensively before putting the entire project together. This ensures that each subsystem performs its purpose properly and eases the difficulty of merging the system with another. This section focuses on both hardware and software testing. Testing these will ensure a project that meets all specifications requirements, determines functionality, and maintains quality of the entire project.

*A. Transmitter Testing*

How the signal will transmit through the air is a vital component to maximize efficiency. In order to begin testing on the transmitter the group will first construct the housing. Figure 8 is the transmitter housing.

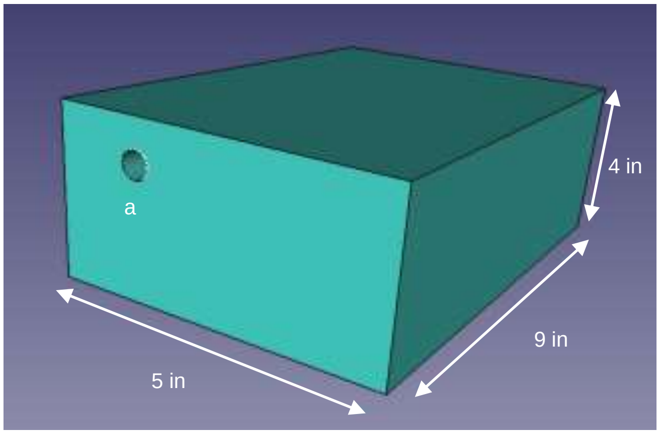


Fig. 8: FreeCAD rendering of the Transmitter housing used in the project.

The two major functions required of the transmitter housing for initial prototype testing is having the adjustable feet and a secure location for the laser to be mounted. The laser is adjustable according to the needs of the test. Table 1 yields the test results for the transmitter:

**Table 1: Distance Test Results**

| *Distance (m)* | | *Power(mW)* | |
|---|---|---|---|
| Laser to Lens | Laser to PD | ON | OFF |
| 0.0206 | 0.686 | 4.45 | 0.043 |
| 0.0159 | 2.388 | 4.05 | 0.043 |
| 0.0159 | 3.404 | 3.15 | 0.036 |
| 0.0159 | 4.394 | 2.51 | 0.025 |
| 0.0159 | 5.436 | 1.63 | 0.020 |

These results were obtained using Newport Model 1918-R power meter with a Germanium photodetector. Consistent results were obtained allowing us to reach a working distance of 20ft.

*B. Receiver Testing*

There were many setbacks during the testing of the receiver circuit. The most severe of theses came in narrowing down the correct IC amplifier to use. The original design was overly optimistic with the speeds we desired to reach which led us to design the receiver with a high-speed transimpedance amplifier. This TIA (THS4631) has a unity gain bandwidth of 210 MHz. The circuit used for the transimpedance amplifier is shown in figure 8. Using Eq. (3), to calculate the required feedback capacitance where $C_s$ = 2pF, GBP = 210MHz, $R_2$ = 10 kΩ, and $R_L$ = 1 kΩ.

$$C_F = \frac{\frac{1}{\pi * R2 * GBP} + \sqrt{\left(\frac{1}{\pi * R2 * GBP}\right)^2 + \frac{4 * Cs}{\pi * R2 * GBP}} = 0.6pF}{2} \quad (3)$$

The resultant capacitance was small enough to be negligible for our purposes. This concluded the test of the TIA however the resulting signal was noisy. We were unable to determine what the root cause of the issue was and our efforts to correct the noise were unsuccessful. A complete redesigned of the circuit was performed with two operational amplifiers discussed earlier.

The redesigned circuit is shown in figure 9. The photodiode was reversed biased with a positive voltage and connected in series to produce an input voltage for the preamplifier circuit. The following circuit was the main amplifier. The resistor values used for the preamplifier are: $R_1$ = $R_2$= 1kΩ and $R_3$=10kΩ. The following voltage gain (A) was 11 or 20.83dB. The bandwidth was 100 kHz and the resulting gain bandwidth product was 1.1MHz. For the main amplifier $R_4$=4.7kΩ and $R_5$=12kΩ with a voltage gain (A) of 2.12 or 6.56dB. The bandwidth was 100 kHz and the resulting gain bandwidth product was 655.8 kHz.

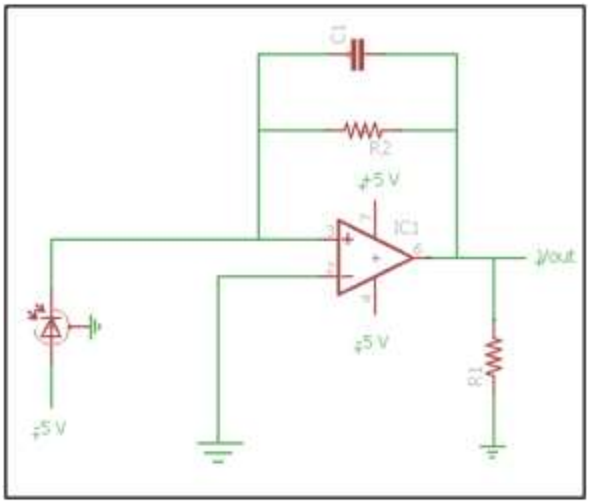


Fig. 9: Transimpedance amplifier schematic designed using Cadsoft Eagle

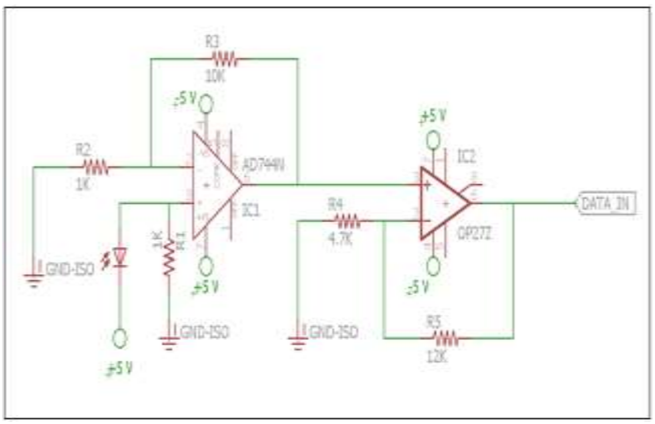


Figure 10: Redesigned amplifier circuit using Cadsoft Eagle.

Figures 11 and 12 are the measurements made with an oscilloscope using a function generator to power the laser.

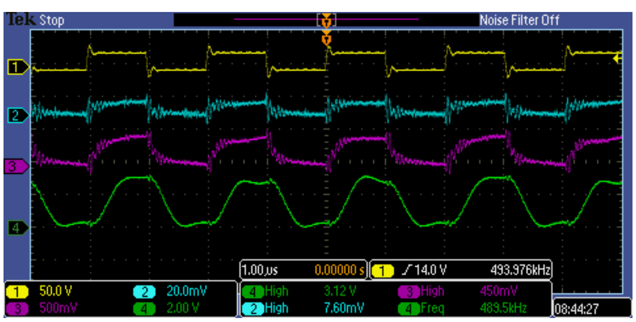


Fig. 11: Oscilloscope reading at 500kHz.

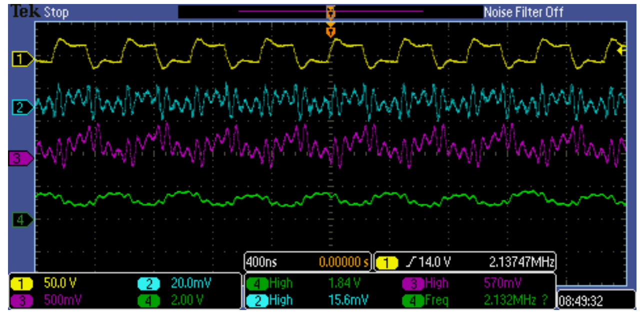


Fig. 12: Attempt to achieve 2 MHz

*C. Microcontroller Testing*

Testing the microcontroller was broken up into four testing stages. The first stage tested to ensure that the data being transferred from the PC to the microcontroller was being encoded properly to be sent. This was achieved efficiently with no difficulties as the data link between the PC and microcontroller was straightforward to set up.

The second stage was to ensure that the coming incoming data is being decoded properly with as little errors as possible using an IR LED emitter and an IR Photodiode. This setup worked efficiently up to approximately 8 kHz, however the rise and fall time of the low cost IR photodiode was not fast enough to efficiently handle the higher speeds necessary. This can be seen in the figure below.

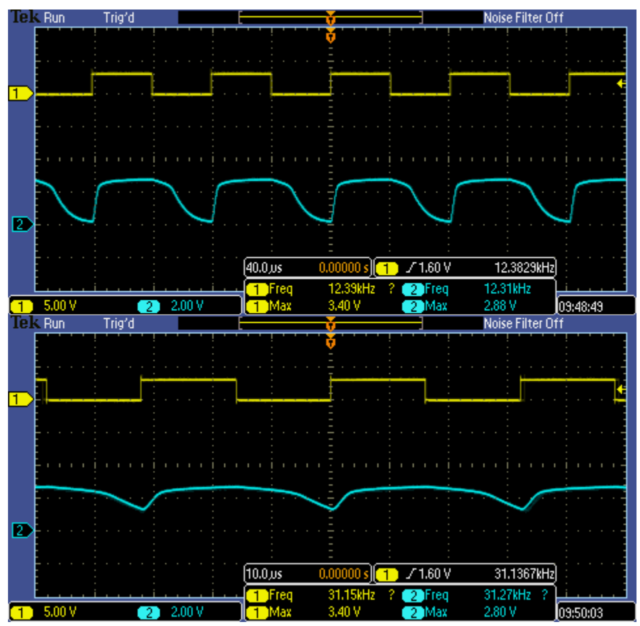


Fig. 13. Oscilloscope readout of IR LED emitter (1 Yellow) vs IR Photodiode (2 Blue). Note the rise and fall time of the photodiode as the frequency applied increases from 12kHz (top) to 32kHz (bottom)

The third stage was a stress test to see how fast the transmitter and receiver could exchange data. Currently, the max bit rate achieved with no bit error was approximately 5KHz. However these results were achieved using the IR LED Emitter and Photodiode pair, not with the Laser and the FGA01 Photodiode. There should be room for improvement here once the entire system is online. During this stage, we had to account for the size of the binary file being sent to the microcontroller. Since the microcontroller has a flash size of 1MB, larger files sizes had to be broken down into smaller chunks to be passed in one at a time until the entire file had been passed.

## IV. Conclusion

The main goals of this project were to create a durable, easy to assemble high-speed network without a large amount of infrastructure necessary. Due to the extensive research efforts of the group and a bit of trial and error, the group was able to see these goals to fruition by designing, and creating our version of the Laser Data Transfer system. By dividing the entire project into each subsystem, we were able to allow each member to bring their individual strengths to the project and complete the tasks more efficiently.

The project also exposed the group to strict budgetary restrictions and the effect of a project overhaul late into the design cycle. These setbacks in turn affected a lot of our original timeline and design; however we managed to create a working product within the timeline. Due to these setbacks we were unable to create, design, and order a PCB in time. Although no PCB is present in the final project, we collectively learned how to use Eagle Cad to design our original PCB. PCB design is a great and useful skill to have at our disposal moving forward. Seeing a project from start to finish with all of the paperwork, testing, troubleshooting, meetings, and presentations gave our group a small glimpse as to what is to come in our future careers.

## V. Biographies

Derek Clark, age 24, is receiving his Bachelors in Photonic Science and Engineering. He is an active member of the armed services. After his service to the United States Derek hopes to continue his education while obtaining valuable industry experience working for a company devoted to the defense of the United States.

Joshua Jordan is a 24 year old Photonic Science and Engineering student. Working on this project was not only challenging for Joshua but it was rewarding, and as his final semester is coming to a close he was able to experience real world engineering problems. He plans on continuing his education at UCF to earn his Master's degree and start his career as an optical engineer.

Kenneth Figueiredo is a 22 year old Computer Engineering Student. He hopes to apply the knowledge he gained while at the University of Central Florida in the field of Software Engineering. Kenneth has shown interest in furthering his studies for a Master's degree in a Computer Security field. He also has shown interest in joining the workforce as a Software Developer.

## V. References


[1]https://en.wikipedia.org/wiki/Electromagnetic_absorption_by_water

[2]W. H. Cantrell, "Tuning analysis for the high-*Q* class-E power amplifier," *IEEE Trans. Microwave Theory & Tech.,* vol. 48, no. 12, pp. 2397-2402, December 2000.

[3]W. H. Cantrell, and W. A. Davis, "Amplitude modulator utilizing a high-Q class-E DC-DC converter," *2003 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, pp. 1721-1724, June 2003.